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STATE-OF-THE-ART FOR EVALUATING
THE POTENTIAL IMPACT OF FLOODING ON
A RADIOACTIVE WASTE REPOSITORY

Submitted to

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1. INTRODUCTION

Geologic isolation of high-level radioactive waste repositories requires that natural geologic barriers to waste migration will remain intact during the life of the repository. Quantitative screening criteria have been proposed to identify sites presently suitable for such repositories (Geotechnical Engineers Inc., 1979a; Golder Associates Inc., 1977; Ekren et al., 1974; and others), but relatively few studies have been made to evaluate the potential for future alteration of geologic site containment characteristics after waste disposal. This report, authorized by the Lawrence Livermore Laboratory under Purchase Order 5696709, evaluates the potential impact of ground-surface flooding on the long-term containment characteristics of a deep geologic repository and attempts to relate the potential for future flooding to past floods that have been geologically or historically recorded. Statements and conclusions made in this report regarding the characteristics of and the potential for major episodes of surficial flooding are based upon interpretation and evaluation of numerous studies of this subject that have been reported in the literature.

Screening criteria have prescribed that active floodplains formed less than 500 years ago be avoided when siting a repository (NRC, 10 CFR Part 60). Methods of identifying the extent of floodplains are reviewed herein, but techniques for predicting recurrence intervals and magnitudes of flooding on active floodplains are not treated in detail. Emphasis is placed on identifying the extent and magnitude of surficial flooding on extinct floodplains formed more than 500 years ago and predicting the potential for their reactivation. Important concepts that should be considered when developing repository siting criteria to minimize the possible impact of flooding are underlined in the report.

The impact of flooding on temporary, surface and near-surface facilities of a repository is not considered in this report. Generally, it is recommended that these facilities be located above the maximum possible flood level of adjacent perennial streams, above the water level that might result from upstream dam failure, and beyond the reach of, or readily protected from, flash-flood runoff (National Academy of Sciences, 1975). Procedures followed for the siting and design of flood protection of nuclear power plants are appropriate for the design of near-surface facilities (Eger and Zima, 1979; NRC, 1975). However, the relative risks of flooding in temporary (near-surface) and permanent (deep) high-level radioactive waste repositories are difficult to evaluate. Although short-term floods affecting temporary facilities may be predicted with better accuracy than floods with long recurrence intervals that could damage permanent repositories (Nash and Amorocho, 1966),

more intense radiation levels and shorter migration paths make the consequences of waste leakage from a temporary repository more severe than leakage from a permanent repository. The risks of flooding of deep repositories should be viewed in relation to the hazards involved in the entire waste disposal scheme.

2. EXECUTIVE SUMMARY

This report is a review of the state-of-the-art for evaluating the potential impact of flooding on a deep radioactive-waste repository, namely, for predicting the future occurrence of catastrophic flooding and for estimating the effect of such flooding on waste containment characteristics. Several detrimental effects are identified:

- Flooding can increase groundwater seepage velocities through a repository within the framework of the existing hydrologic system and thus increase the rate of radioactive-waste leakage to the biosphere.
- Flooding may alter repository hydrology by reversing flow gradients, relocating sources of groundwater recharge and discharge, or shortening seepage paths, thereby producing unpredictable leakage.
- Saturation of a vadose-zone repository during flooding can increase groundwater seepage velocities by several orders of magnitude. Even without saturation, infiltration of surficial flood water through the vadose zone to the underlying water table can occur at a rate approaching the hydraulic conductivity of the saturated repository media.
- Flooding can damage repository-media containment properties by inducing seismic or chemical instability or increasing fracture permeability in relatively shallow repository rock as a result of redistributing in-situ stresses.

Short-term flooding frequency and magnitude can be predicted statistically by analyzing historical records of flooding. However, long-term flooding events that could damage a permanent repository cannot be predicted with confidence because the geologic record is neither unique nor sufficiently complete for statistical analysis. It is more important to identify parameters characterizing containment properties (such as permeability, groundwater gradient, and shortest seepage path length to the biosphere) that could be affected by future flooding, estimate the maximum magnitude of flooding that could occur within the life of the repository by examining the geologic record, and determine the impact such flooding could have on the parameter values.

The following recommendations are made to assist in evaluating the possible impact of flooding on deep geologic repositories:

- The potential change in hydraulic head produced by flooding that may occur in the repository area should be compared to the shortest seepage path length to the biosphere to estimate the possible change in repository hydraulic gradient.
- The potential location and magnitude of flooding should be examined with respect to the location of nonhomogeneous, high-velocity flow paths located in or near the repository (e.g., faults, joints and dissolution features).
- The potential for resaturation of the vadose zone above a deep repository should be investigated by comparing possible flood magnitudes and the discharge capacity of aquifers affecting the repository.
- The consequences of flood-induced earthquakes should be considered if the repository area contains faults that could be affected by changes in the stress-field produced by flooding.
- The potential for chemical instability produced by reaction between the repository medium and groundwater should be examined in repositories that may be flooded.

During relatively recent geologic history pluvial lakes (formed during periods of exceptionally heavy rainfall), proglacial lakes (formed in direct contact with the ice front of a retreating glacier), and marine transgression have inundated large areas of the United States. The extent of large extinct proglacial and pluvial lakes that were impounded within the past 20,000 years is well established, and their approximate locations are illustrated in Figs. 6 and 8. Recurrent episodes of glacier damming or inundation during pluvials have been indicated in many of these lakes. Recent climatologic studies predict that conditions leading to the formation of these lakes during glaciation and major pluvials may return within the next 10,000 years. Thus, the consequences of deep inundation should be considered in repositories sited near extinct pluvial or proglacial lakes.

Isostatic subsidence under glacier loads, tectonic subsidence, or increase in the eustatic sea level may increase the apparent sea level in coastal areas north of the previous maximum extent of glaciation by as much as 150 m within the next 10,000 years. The apparent sea level is not expected to rise significantly above the

present sea level in coastal areas not subjected to isostatic or tectonic subsidence unless unanticipated melting of the polar ice caps occurs, which could increase sea level by approximately 60 m.

Although major areas of inundation have been identified by regional geologic surveys, geomorphic and stratigraphic investigations of proposed repository sites are necessary to locate the extent of smaller, previously unmapped lacustrine plains that may be reinundated during the life of the repository. Assemblages of geologic evidence are needed to substantiate the potential for repository flooding, and the technology for recognizing this evidence is well developed. However, more studies are needed to reduce uncertainties regarding the depth and duration of inundation interpreted from geologic investigations.

3. EFFECTS OF REPOSITORY INUNDATION ON RADIOACTIVE WASTE CONTAINMENT

3.1 Groundwater Migration of Radioactive Wastes

One of the most likely mechanisms of radioactive-waste transport to the biosphere is migration via groundwater flow through the repository after deterioration of the waste disposal canister. In the United States, a 1000-year design life has been required for proposed high-level radioactive-waste disposal canisters (NRC, Report 10 CFR Part 60), which represents a very small fraction of the time required for decay of all of the high-level radioactive wastes. However, preliminary designs of disposal canisters have been proposed in Sweden (Ahlström, 1978) that would effectively contain high-level radioactive wastes for more than 100,000 years, thereby significantly reducing the impact of waste migration after natural deterioration of the canister. Because surface flooding can affect groundwater flow, it is important to investigate and compare potential migration rates induced by flooding to the decay rate of a given concentration of radioactive waste to determine if the wastes will decay to a "safe" level of radioactivity before they reach the biosphere.

Adam and Rogers (1978) developed the following parameter to relate the radioactive decay rate to the rate of waste migration by groundwater through a saturated, homogeneous isotropic medium,

$$t = \frac{\lambda Cs}{V}$$

where: t = dimensionless time factor for peak release of radioactive wastes in the biosphere

λ = decay constant for radioactive nuclei (yr^{-1})

C = sorption coefficient for the flow medium

s = flow path length (ft)

V = groundwater flow velocity (ft/yr)

If Darcy's Law is assumed valid for groundwater flow (Hubbert, 1940), the above parameter can be expressed:

$$t = \frac{\lambda C s n}{k i}$$

where: i = hydraulic gradient = $\frac{\Delta h}{s}$ loss of hydraulic head (Δh) over the length of the flow path

n = effective porosity

k = hydraulic conductivity (ft/yr)

Adam and Rogers used the above expressions to estimate the potential dose rate of radioactivity that could be released from a repository by migration through regional groundwater systems in a number of potential shallow and deep repository environments. However, the potential impact of future flooding was not included in these quantitative analyses. The above expressions indicate that the rate of waste migration can increase if the hydraulic gradient or hydraulic conductivity increases or if the flow path length decreases. The impact surface flooding can have on these parameters is discussed in Sections 3.2 and 3.5.

Flooding can also resaturate the vadoze zone and thus change the groundwater flow mechanism. The potential consequences of resaturation on repository containment characteristics is discussed in Section 3.3.

3.2 Impact of Flooding on Saturated Groundwater Flow

Thick zones of nearly impermeable rock buried deep beneath the ground surface have been considered as potential locations for high-level radioactive-waste repositories. Such locations are attractive because low permeability (especially at great depth where fracture permeability is reduced), long seepage paths to the biosphere, and very low seepage gradients encourage long-term containment of the wastes. It is important to examine how sensitive these hydrologic properties are to surface inundation. Two cases are examined: (1) direct contact of the flood area with the repository strata (Fig. 1) and (2) hydraulic connection of the flood area with aquifers bounding the repository strata (Fig. 2).

The repository environment illustrated in Fig. 1 represents an area where regional hydrology is topographically controlled and maximum hydraulic gradients are nearly horizontal. This is characteristic of much of the Basin and Range Province in the western United States (Maxey, 1968) and rugged terrain in massive crystalline rock (Karnsbranslesakerhet, 1977). Lateral groundwater flow occurs between recharge areas in the highlands and discharge areas in the lowlands. The groundwater discharge point often can be fixed by faults or stratigraphic discontinuities. The optimum location of a deep repository in basin and range topography would be near the recharge area so that the seepage distance and time to waste discharge in the biosphere are maximized (Eakin, 1966).

The magnitudes of regional hydraulic gradients are usually approximated by the slope of the water table, which can parallel the regional topographic slope between recharge and discharge areas. Typical horizontal gradients have been measured to vary from 0.004 in sedimentary basins (Golder Associates Inc., 1977) and 0.005 in salt basins (Geotechnical Engineers Inc., 1977) to 0.01 in crystalline rock (Karnsbranslesakerhet, 1977). In Fig. 1 the regional hydraulic gradient (or average slope of the phreatic surface) prior to flooding is $\frac{\Delta h_1}{s}$. Because hydraulic gradients are generally constant with depth beneath the water table (Hubbert, 1940), the groundwater flow gradient at the repository would be equal approximately to the slope of the phreatic surface above the repository.

Fig. 1 depicts schematically the change in water table elevation after flooding of the recharge area. Assuming no change in the elevation of discharge and steady-state conditions, the corresponding increase of hydraulic head drop over the seepage distance in Δh_2 . It is apparent that the effect of inundation is dependent on its location with respect to groundwater recharge and discharge. Inundation in the discharge area conceivably could reduce the head loss and seepage gradient or even change the direction of seepage by transforming the discharge area to a recharge area. However, given the illustrated conditions, the existing hydraulic gradient would be increased absolutely by $\frac{\Delta h_2}{s}$ and relatively by $\frac{\Delta h_2}{h_1}$. The potential influence on the hydraulic gradient at the repository depends on the relative magnitudes of the head loss and the seepage distance.

Inundation will have its greatest impact if both s and Δh_1 are small with respect to Δh_2 . Repository site selection generally should attempt to maximize the length of the flow path, s , in order to minimize the potential impact of flooding on hydraulic gradients through the repository. Even so, flooding could conceivably increase gradients by more than an order of magnitude, which could have important consequences on the repository, depending upon other parameter values and uncertainties affecting the rate of waste migration and depending upon the length of time between waste disposal and inundation.

Fig. 2 illustrates an example in which vertical gradients controlled by subsurface stratigraphy predominate groundwater flow at the repository. Although regional flow in the aquifers may be nearly horizontal, the hydraulic head difference between aquifers separated by the semi-permeable repository medium produces vertical flow localized at the repository. Hydrologic environments of this type have been studied in sedimentary formations (including bedded salt) and extrusive igneous formations exhibiting interlayered strata with high and low permeabilities (Geotechnical Engineers Inc., 1977;

Eakin, 1966; Banks, 1972; Newcomb et al., 1972). In these environments the optimum repository location could depend on the location of the minimum vertical gradient rather than the location of regional groundwater recharge and discharge areas.

Depending upon the continuity and transmissivity of aquifers, inundation occurring at a great distance from the repository can influence flow gradients at the repository. Fig. 3 indicates that seasonal flooding of the Columbia River can increase substantially the piezometer levels measured in shallow aquifers up to 4000 ft from the river (Newcomb et al., 1972). Similar behavior may also be possible in deep aquifers. Increased piezometric levels in confined aquifers can induce increased leakage of groundwater between the aquifers through the semi-permeable repository medium. Leaky-aquifer flow analyses by Hantush (1967a) and Freeze and Witherspoon (1967) have shown the flow rate to be proportional to the hydraulic head difference between aquifers. Thus, the relative impact of flooding on leaky aquifer flow through a repository depends on the location and depth of inundation, transmissivity of aquifers hydraulically connected to the flood area, hydraulic head difference between aquifers prior to flooding, and thickness and permeability of the repository medium separating the aquifers.

Golder Associates Inc. (1977) performed parametric analyses of leaky aquifer flow through layered media and showed that the upper limit of leaky aquifer flow gradients through a repository is restricted by formational characteristics. However, flooding impact analyses assuming these upper-bound gradients may grossly overestimate the potential hazards from repository flooding, and it is recommended to estimate reasonable flood magnitudes that could occur during the life of the repository and calculate the corresponding flow gradients.

Hydraulic gradients through the repository illustrated in Fig. 2 are dependent on the location of flooding. If floods were to recharge aquifer 2 rather than aquifer 1, upward seepage through the repository could be reversed to downward seepage, which conceivably could increase the time for peak release of radioactive wastes.

Flooding may have an even greater impact on seepage through a repository by altering completely the subsurface hydrology. Previous discussions considered increased seepage rates within the framework of the existing steady-state hydrologic environment. However, flooding may relocate recharge and discharge areas, reduce seepage paths and otherwise change the groundwater flow regime to produce seepage that cannot be predicted by analysis of existing conditions. Hydraulic connection with geologic or man-made dis-

continuities that may avoid detection during site investigations (Geotechnical Engineers Inc., 1978b) could permit unanticipated high velocity seepage through otherwise impermeable repository rock. Faults, fractures and unsealed boreholes provide routes for rapid waste migration, and areas known to contain these features should be avoided when siting a repository.

Worst case scenarios of flooding for each geologic repository should consider the possible locations and maximum magnitudes of flooding and potential hydraulic connection directly with the repository through anomalous seepage paths related to the repository site geology and history. These paths could include faults and joints, bedding planes, lava tubes in extrusive rock, solution breccia in salt, old wells, and tunnels and shafts.

3.3 Impact of Flooding on Unsaturated Groundwater Flow

Permanent radioactive-waste repositories have been proposed in environments where the existing groundwater table is deep (Geotechnical Engineers Inc., 1978a; Apps et al., 1978). These environments are usually characterized by arid climates, highly transmissive aquifers, and distant groundwater discharge points which are topographically much lower than the ground surface at the repository site. In the unsaturated (vadose) zone above the water table, fluid migration is normally controlled by gravity and generally follows a downward path away from the biosphere. Unlike saturated media which depend on low permeabilities to resist fluid and waste migration, unsaturated media rely on the absence of migrating fluids to provide containment. Any migration through the vadose zone that does occur normally is controlled by gravity and generally follows a downward path away from the biosphere. However, resaturation by flooding would increase substantially the permeability of previously unsaturated media and could produce relatively high gradients and shorter seepage paths to the biosphere that can reduce the ability to isolate disposed wastes.

The water table will rise if the rate of infiltration is greater than the discharge rate. The potential for saturation of a vadose zone should be examined by considering the likely magnitude of flooding and the discharge capacities of the unconfined aquifer in which the repository is located. Hydrologic studies conducted in the Basin and Range Province (Winograd and Pearson, 1976) indicate that discharge capacities of many of the basins are so large that a much wetter climate would have negligible effect on the water table elevation in the highly transmissive, thick alluvium comprising the unconfined aquifers in these basins. Thus, in some cases, high capacity discharge areas may serve as safety valves against resaturation during catastrophic flooding.

Flooding may increase the infiltration rate of surface water through unsaturated porous media. The hydraulic conductivity of an unsaturated porous medium is a function of the water content (Geotechnical Engineers Inc., 1978a). Depending on the soil type, porosity and initial water content, a 10% increase in water content could increase the unsaturated hydraulic conductivity by 3 to 4 orders of magnitude. With prolonged inundation, an entire vadose zone could become wetted and the infiltration rate could approach the rate of saturated flow. Wetting of the vadose zone could also accelerate the rate of solutioning of impermeable joint fillings (such as gypsum or calcite), which would increase substantially the effective permeability of vadose zone rock. However, the saturation-induced chemical alteration of minerals associated with fractures in rock or soil can lead to a reduction of the hydraulic conductivity of the medium. For example, the swelling of some highly plastic clays (such as montmorillonite) can cause sealing of desiccation cracks in soil (Hillel, 1971). When selecting a repository site that relies on the vadose zone to resist waste migration, it is important to establish if future flooding will resaturate the vadose zone and result in high rates of infiltration to the water table.

3.4 Importance of Time-Variant Seepage in Flooding Impact Evaluation

Previous discussions in this report of the impact of flooding on groundwater flow have assumed steady-state conditions (i.e., changes in groundwater flow induced by surficial flooding are assumed to occur instantaneously). Studies of water table fluctuation normally assume that infiltration causing recharge is transmitted immediately from the ground surface to the water table by uniform percolation. However, the variation of groundwater flow with time should be examined, especially in the case of recharge by infiltration through the vadose zone and subsequent change in water table elevation. If water is ponded at the surface, the rate of surface infiltration is approximated by the saturated hydraulic conductivity of the surface medium multiplied by a vertical gradient of unity (Freeze, 1969). Infiltration through the vadose zone at depth, though, can proceed at a much faster rate. At the infiltration front, hydraulic gradients produced by soil suction (capillary attraction of water into small pores) can exceed the unit hydraulic gradient produced by gravity. The infiltration rate can vary locally, depending on the subsurface soil moisture profile, the distribution of interstitial porosity, and elapsed time after surface infiltration. Numerical solutions accounting for these factors have been developed and may accurately estimate local infiltration rates for short time periods ($t < 1$ month - Philip, 1957). At a

given location in the vadose zone, the rate of infiltration decreases with time as the soil moisture content increases to the value of the saturated moisture content, at which time the soil is considered to be "wetted" and infiltration is driven by gravity rather than by capillary forces. The rate of migration of the wetting front through the vadose zone has been approximated (Philip, 1957):

$$u = \frac{K_o - K_i}{W_o - W_i}$$

where: u = wetting front migration rate

K_o = initial, unsaturated hydraulic conductivity

W_o = saturated moisture content

W_i = initial unsaturated moisture content

The migration rate calculated by the above expression makes it possible to calculate an upper-bound estimate of the time required for wetting of the entire vadose zone beneath the source of infiltration. Depending on the void ratio and initial moisture content of the vadose zone material, wetting can proceed at a rapid rate (for example, 240 m/year through unsaturated Adelanto loam with an initial, unsaturated moisture content equal to 0.20 - Jackson et al., 1965). In arid regions, the rate of advance of the wetting front may be even higher. Generally, if inundation of the vadose zone continues for a relatively short period of geologic time (on the order of tens of years), substantial amounts of infiltration from the surface can recharge even deep aquifers and influence the hydrology of a deep repository.

The rate of change of piezometric head in confined and unconfined aquifers is proportional to the rate of vertical recharge (Rushton and Redshaw, 1979), and is given:

$$\frac{\Delta h}{\Delta t} = \frac{q}{S}$$

where

$\frac{\Delta h}{\Delta t}$ = rate of change of piezometric head

q = rate of recharge

$\sim K_o$, if recharge occurs by steady infiltration through the wetted vadose zone beneath water ponded at the ground surface

S = storage coefficient, or the volume of water stored by a unit increase of head per unit volume of aquifer

Storage coefficients vary from 1×10^{-5} to 1×10^{-3} in confined aquifers and from 1×10^{-2} to 3.5×10^{-1} in unconfined aquifers (Johnson Division, UOP, 1972). Storage is controlled by aquifer compressibility in confined aquifers. Response to recharge is felt almost immediately as a pressure increase through the aquifer (reflected by the low storage coefficient values), and, thus, seepage controlled by the pressure response is not time dependent or localized (see Fig. 3). In an unconfined aquifer, increased storage results from watering previously unsaturated material. Unconfined aquifer response to recharge may occur rather rapidly at the point of recharge (but not as rapidly as in a confined aquifer), but the response will be localized and not distributed immediately through the aquifer. The rate of distribution depends primarily on the groundwater seepage velocity. Thus, the regional water table will respond much more rapidly to localized recharge in an aquifer with high hydraulic conductivity than in an aquifer with low hydraulic conductivity. In the latter case, a groundwater mound will occur at the point of recharge and spread slowly with time, while in the former case the effect of local recharge will equilibrate rapidly to the steady state without local mounding.

Complex analytical and numerical methods exist that can describe the transient shape of the water table resulting from local recharge (Hantush, 1967b), but their accuracy is limited by assumptions of two-dimensional, isotropic groundwater flow that fail to model accurately true groundwater seepage. Nevertheless, they permit estimates of time-dependent responses of unconfined aquifers to local recharge.

In summary, because of the time required for storage of radioactive wastes, time-dependent seepage may be important only in the consideration of groundwater mound migration from local recharge of an unconfined aquifer with low hydraulic conductivity. Response of confined aquifers to recharge is widespread and almost instantaneous, and infiltration through the vadose zone to the water table beneath flooded areas can occur rapidly. Transient flow characteristics can be calculated only after extensive aquifer testing, and even then with large uncertainty. For the purpose of preliminary evaluation of the impact of flooding on a deep repository, steady-state flow conditions should be assumed. Neglect of transient flow will be conservative and may provide an added factor of safety. Only if aquifer characteristics can be confidently established should transient flow be considered in long-term impact evaluations.

3.5 Impact of Flooding on Repository Media Properties

3.5.1 General

Dramatic increase of the water table elevation or ponding of considerable depths of water that could result from flooding near a repository may alter the containment characteristics of the repository medium as well as the characteristics of the ground-water flow regime. The effect of resaturation on vadose zone repository permeability was discussed in Section 3.4. Repository media characteristics also can be influenced by changed in-situ stress distributions effected by reservoir loading or unbalanced chemical equilibria induced by changing solution concentrations. These impacts on the assessment of waste containment characteristics are discussed below.

3.5.2 Permeability

Nelson and Handin (1977) expressed the hydraulic conductivity of fractured rock as:

$$k = k_m + \frac{e^3 \cos^2 a}{12b}$$

where a = angle between flow gradient and fracture plane

e = mean joint opening

b = mean joint spacing

k_m = hydraulic conductivity of the rock matrix

In many rock types considered as potential geologic repository media (such as crystalline rock), k_m is negligible when compared to the hydraulic conductivity of joints. Although hydraulic conductivity of joints is also a function of joint roughness and geometry, it is beyond the present state-of-the-art to estimate quantitatively the effects of these characteristics. Thus, it is assumed that processes increasing the size and frequency of rock fractures will proportionally increase the rock permeability.

Rock fracturing is controlled by rock strength, stress history and changes in applied stress. Studies by Sharp and Louis (1972) have shown that fracture deformation produced by a given stress increment generally decreases

with increased confining stress. Thus, rock subjected to large overburden stresses may be highly resistant to fracturing. In a tectonically stable province in Sweden, hydraulically continuous fracturing in granite is limited to the upper 200 m of bedrock, despite repeated surficial loading by severe glaciation and ponded water (Karnsbranslesakerhet, 1970). Consequently, reservoir loading probably would have little or no effect on fracture permeability in deep granite repositories (>200 m below ground surface), but the potential impact on shallow repository rock properties should be considered. If the effective confining stress in a shallow rock repository is reduced by flooding, fracture dilatancy could increase substantially the in-situ permeability (Zoback and Byerlee, 1975). Snow (1972) showed that the effective stress decrease produced by flooding of a jointed rock mass depended on the orientation of the principal effective stresses and whether flooding increased the water table elevation within the rock or the depth of water ponded over the rock. For a typical case in which the minimum principal stress is horizontal and equal to the intermediate principal stress, and for an increased water table elevation within the rock equal to h , the confining stress would be reduced by $\gamma_w h$, where γ_w is the unit weight of water (62.4 lbs/ft³). If, for the same initial in-situ stress distribution, flooding increased the depth of water ponded over the repository, the horizontal confining stress could be reduced by $\frac{2\nu - 1}{1 - \nu} \gamma_w h$ where ν is Poisson's ratio for

the repository rock, and h is the changed depth of ponded water (the vertical effective stress would not change with the depth of ponded water).

The sensitivity of shallow and deep repository rock permeability to confining pressure can be contrasted by examining field and laboratory data showing the relationship between permeability and confining stress in crystalline rock (Figs. 4 and 5). If the water table elevation over a shallow repository in crystalline rock (less than 50 m deep) increased 30 m, the resulting decreased confining pressure could increase repository permeability by a factor of two. However, an equivalent water table elevation increase over a deep (greater than 500 m) repository would have a negligible effect on repository permeability.

Some bedrock types have large fracture permeabilities even at a great depth. Columbia River Plateau basalts

greater than 980 m below ground surface can exhibit "fracture" hydraulic conductivities as large as 0.5 m/day (National Academy of Sciences, 1978). However, these fractures resulted from cooling after deposition in surficial flows, and it is unlikely that stress changes induced by surface inundation will affect fracture permeability at this depth.

Fractures in rock can be filled with relatively impermeable material that greatly reduces permeability. However, increased flow gradients resulting from impounded water could erode infilled material in shallow fractures and increase significantly rock permeability. This has been found to be an important source of potential seepage beneath dams on fractured rock (see, for example, United States Bureau of Reclamation, 1962).

3.5.3 Stability

It is important to ensure that a geologic repository will be stable against movement during the required waste containment period. Flooding of the repository could redistribute in-situ stresses, reactivate movement along dormant faults and increase the seismicity of the repository area. Reservoir-induced seismicity has been observed at locations of large man-made reservoirs, and correlations have been made between water impoundment and local seismicity (Carder, 1970). Earthquakes with Richter magnitudes up to 6.5 have been attributed to water impoundment in man-made reservoirs (Howells, 1972). Much smaller magnitude earthquakes also have been correlated to seasonal flooding of the Mississippi River (McGinnis, 1965). The potential for reservoir-induced seismicity depends on the possible magnitude of stress redistribution (reflecting the potential depth and lateral extent of flooding) and the presence of faults in the zone of stress redistribution. It has been shown that the age of faults is not an important factor (McGinnis, 1965), but inundation depths exceeding 80 to 100 m (260 to 325 ft) generally are required to trigger significant earthquake activity (Howells, 1972; McGinnis, 1965).

If a proposed repository site in a tectonically stable area has been subjected to severe flooding in the past and has not exhibited fault movement, it is unlikely that future flooding of comparable magnitude will induce an earthquake. However, if the proposed repository contains faults that have not been subjected to flooding or is located in a tectonically active area, the impact of flood-induced earthquakes on repository containment should be considered.

Repository instability may result from chemical activity initiated by flooding. Acceleration of corrosion, hydration or dissolution processes by increased groundwater flow gradients could shorten the projected time of effective containment. Increased flow gradients in the vicinity of the waste disposal canister could increase the rate of corrosion of the waste canister (Braithwaite and Molecke, 1977). This could have an important impact on repository integrity if long-term containment is to be provided by the canister and not the geologic environment. Hydraulic gradient increases that may be produced by flooding should be compared to thermal gradients produced by radioactive waste decay in the canister to determine the controlling influence on the rate of corrosion. Hydration of subsurface anhydrite deposits to gypsum accompanied by great pressure and uplift has been observed in Texas, Oklahoma, and New Mexico where water has been impounded over bedded salt. Hydration initiated by seepage from surface reservoirs has occurred in strata up to 500 ft below ground surface and has expanded anhydrite volumes up to 35% (Brune, 1965). With large confining stresses, such expansion can proceed with explosive force (as much as 10,000 psi - Brune, 1965) and cause buckling and fracturing of overlying rock, which can increase the rate of subsurface salt dissolution.

Near Carlsbad, New Mexico, leakage from McMillan Reservoir initiated hydration which caused extensive fracturing and resulted in subsidence of as much as 40 ft after accelerated dissolution. Construction of flood-retaining structures overlying anhydrite deposits has required remedial measures to prevent reservoir leakage and maintain stability. Because even short-term sealing against leakage cannot be guaranteed, sustained flooding over a repository containing anhydrite deposits could threaten stability of repositories and produce fractures allowing detrimental seepage.

The relationship between groundwater flow and salt dissolution rates was examined in laboratory experiments by Durie and Jessen (1964) and Snow and Nielson (1970). They found that the velocity of groundwater at the boundary of a salt deposit probably would be orders of magnitude smaller than gravity-induced fluid velocities due to density contrasts in brine (measured to range from 0.5 to 2.0 cm/sec in laboratory simulations of

the chemical environment at the boundary of a bedded salt deposit - Snow and Nielson, 1970). Although injection of fresh water would be necessary to allow continued dissolution, convection flow gradients produced by unlike brine concentrations would control the dissolution rate. Unless high velocity groundwater flow through open fractures adjacent to a bedded or domed salt repository is possible, flooding probably would not accelerate salt dissolution significantly.

3.6 Conclusions

Flooding can have two primary impacts on the containment characteristics of a geologic, high-level radioactive waste repository:

- a. Alteration of the repository hydrologic environment or increase of groundwater flow gradients within the existing environment, thereby decreasing the time for radionuclide migration to the biosphere, and
- b. Alteration of in-situ stresses and material properties of the repository rock, thereby increasing repository permeability.

The magnitude of these impacts depends on the existing hydrology; the depth of the repository and its location with respect to the water table and potential groundwater recharge and discharge areas; the presence of geologic discontinuities that may provide high velocity seepage paths; and the location, duration, and magnitude of flooding.

It has been shown that flooding will have the largest impact on shallow repositories and repositories located above the existing water table. The depth required to minimize the effect of flooding on repository stability and containment properties depends on the magnitude and location of potential flooding and the physical and chemical nature of the repository medium. The influence of geologic and man-made discontinuities on repository permeability and the accessibility of these discontinuities to surficial flooding are reduced with increasing depth. Flow gradients through deeper repositories generally are less sensitive to flooding than flow gradients through shallow repositories. Site selection studies for repositories should compare the minimum possible seepage path length to the biosphere with the potential change in hydraulic head that could be produced by flooding for the purpose of flood impact analysis. Examples of how this might be done are given in Section 5.

The impact of flooding on repository containment should be examined in the context of the uncertainties inherent in defining accurately the existing hydrologic conditions at a repository site. The error margins introduced by uncertainties in present modeling techniques may exceed the consequences of potential flooding. More studies are needed in this area to assist in establishing appropriate screening criteria for selecting radioactive waste repository sites.

4. ESTIMATING THE RECURRENCE OF CATASTROPHIC FLOODING IN THE UNITED STATES

4.1 Prediction Techniques

Evaluating the potential for repository flooding requires predicting the occurrence and nature of future geologic and climatic processes. Quantification of future recurrence intervals of flooding in probabilistic terms using statistical analyses is possible for the short-term (American Society of Civil Engineers, 1953) but is tenuous for the long-term. Formulae have been developed to predict short-term peak flood discharge and frequency using the following data: historically recorded precipitation volumes and intensities, runoff potential and distribution with respect to watershed properties and geometry, and baseline stream flow characteristics. Hydrographs can be constructed to indicate runoff rates and distributions in the watershed for a given amount of precipitation, and flood magnitudes can then be calculated by adjusting the hydrograph to maximum precipitation volumes probable during future storms. Flood frequencies can be predicted generally up to 100 years into the future by fitting storm events and stream flow records to a Log Pearson Type III probability distribution to obtain the necessary statistical parameters.

Nash and Amorocho (1966) have shown that floods with return periods substantially exceeding the length of historical records can be predicted statistically only if sampling error due to non-representation of the entire record is considered and flood frequency conforms to an assumed probability distribution. However, there is no evidence to indicate that geologic processes occur at other than random (unpredictable) intervals. An attempt to fit past geologic events to a proposed probability distribution for long-term predictions involves uncertainties that cannot be evaluated statistically, such as variability of boundary conditions and errors inherent in identifying past processes by examining the geologic record (Kitts, 1976). Marsily et al. (1977) concluded that the potential impact of geologic processes on the long-term integrity of a repository should not be measured in terms of probability coefficients for the occurrence of these processes. It is more important to identify parameters influencing repository containment, estimate the possible range of parameter values that could result from geologic processes acting during the required containment period, and determine the corresponding impact on the repository.

The previous discussion of the effect of inundation on a repository showed that the impact of flooding on a wide variety of

geologic repositories depended on the depth and duration of inundation. Because of the low permeabilities and seepage rates characteristic of most proposed repository media, flooding would have to continue for a considerable length of time (on the order of hundreds of years) to reduce significantly the time for leakage to the biosphere, and inundation depth during this time would have to be quite large to increase flow gradients to an appreciable degree in a deep repository. Therefore, only major episodes of flooding would have important consequences on repository containment.

The containment period when flooding could have a detrimental impact is also an important consideration. Ahlström (1978) indicated that the containment period should be limited to the time required for decay of reactor waste to a level of radioactivity equal to that of natural uranium ore. Bredehoeft et al. (1978) examined decay rates of radioactive waste and concluded that because of the negligible variation in potential hazard from the wastes between 100,000 and 10 million years after disposal and the impracticality of predicting geologic events millions of years into the future, the impact of geologic processes on repository containment should not be predicted for more than 100,000 years after disposal.

The following sections of the report will investigate the potential for major episodes of flooding in the United States by examining the geologic history of large-scale flooding during the latter part of the Quaternary Period (about 100,000 years B.P.). Mechanisms leading to recurrence of flooding will be reviewed to estimate when catastrophic flooding can be expected with regard to containment periods required for radioactive waste. Emphasis will be placed on identifying abandoned floodplains by stratigraphic and geomorphic interpretation for the purpose of predicting likely flooding locations and magnitudes in the future.

4.2 Mechanisms of Catastrophic Flooding

4.2.1 Climate

An important mechanism responsible for triggering episodes of catastrophic flooding on the North American continent during the more recent epochs in the Quaternary Period appears to be climate fluctuation. Extended periods of reduced temperature and redistributed precipitation patterns and concentrations have been correlated to expansion of intercontinental inundation during pluvial and glacial ages and to coastal inundation during marine transgressions. Large-scale climate fluctuations have been inferred from geologic evidence to

have begun during the Precambrian (over 2,000 million years ago) and continued at approximately 150 million year intervals (John, 1979). Smaller fluctuations have been shown to occur at much shorter intervals (1,000 years) by paleoecologic studies (Bryson et al., 1970; Webb et al., 1980). Despite these nearly regular fluctuations, periods of extensive flooding have occurred sporadically through geologic history, and it appears that factors other than climate also may regulate the frequency and magnitude of flooding (such as plate tectonics or continental drift - Flint, 1957). The true causative relationship is not known, and, thus, the recurrence of flooding cannot be predicted with certainty.

It is generally recognized that present levels of intercontinental inundation in the United States are nearly at a minimum when compared to levels that have occurred within the past 100,000 years. Average temperature is approximately 8°C higher and annual precipitation is 10 to 18 in. lower than temperature and precipitation rates interpreted to have prevailed during the most recent episode of extensive flooding, which occurred 10,000 to 12,000 years ago (Morrison, 1965). Webb et al. (1980) indicate that hydrologic models estimating future groundwater levels must allow for long-term increases in annual precipitation rates of 20% or more above the present rate. Although flood recurrence cannot be predicted on the basis of climate alone, it is apparent that present climatic conditions indicate a definite potential for renewed flooding in the future.

The formation of lakes during pluvials (periods of increased precipitation and decreased evaporation) in the Pleistocene epoch depended on local physiography in addition to climate. These lakes formed in hydrogeographically closed basins of relatively impermeable strata found at the termination of extensive surface drainage networks collecting runoff from areas with considerable relief (Benson, 1978). Meinzer (1922) and Webb et al. (1980) noted distinct variations in the distribution of extinct pluvial lakes in the southwestern United States that could be correlated with regional topography. Basin and Range topography in Nevada and Utah favored ponding of many large pluvial lakes, but the absence of deep basins and well-developed surface drainage networks in the central plains of Texas prevented the formation of large pluvial lakes.

Most pluvial lake depths were limited by topography rather than precipitation during major pluvials.

Small basins at higher elevations in the Basin and Range Province and the High Plains of New Mexico and Texas overflowed their brims during major pluvials (Wendorf, 1970). In the southern High Plains in Texas, many of these basins formed shallow playas and produced economic deposits of halite and gypsum. The maximum pluvial lake depth interpreted from geologic evidence in this province was approximately 45 m (146 ft) (Reeves, 1976).

Some drainage basins were only partly filled because of outlets located well below basin rims. In Utah, Lake Bonneville, the largest pluvial lake interpreted to have formed in the Basin and Range Province during the most recent major pluvial, filled only 40% of its basin to a depth of 335 m (1090 ft) (Morrison, 1965) and overflowed large volumes of water through its outlet (Meinzer, 1922). Lake Searles and Lake Manly, pluvial lakes that formed in Death Valley, California, overflowed after they reached depths of 195 m (630 ft) and 185 m (600 ft), respectively, (Morrison, 1965).

Other pluvial lake depths were limited by basin geometry. Lake Lahontan, located in the Basin and Range Province in Nevada, filled only 20% of its basin to a maximum depth of 215 m (700 ft) (Morrison, 1965) because extreme widening of the upper portions of the basin permitted evaporation to exceed precipitation and runoff recharge (Embleton and King, 1975). Thus, most pluvial lakes reached their maximum depths before the end of the last pluvial, indicating that precipitation amounts exceeding those experienced during the last pluvial probably would not significantly increase pluvial lake depths.

Paleontologic studies of pluvial lake fluctuations (for example, Webb et al., 1980) have shown maximum pluvial flood levels approximately 20,000 and 10,000 years B.P. (before present). The interpreted maximum extent of these lakes is illustrated in Fig. 6. Maximum pluvial lake levels coincided with interpreted glacial maxima in the northern United States (Morrison, 1965). Pluvial lakes exist today only as small remnants of past lakes, and many pluvial lake basins are completely dry. If tectonic activity or erosion does not alter existing basin geometries, it is anticipated that inundation levels during the next major pluvial will approach those reached during past pluvials. Climatologic studies indicate that the next major pluvial could occur within the next 5,000 to 10,000 years (John, 1979). However,

smaller pluvials related to shorter-term climate fluctuations can be anticipated to increase pluvial lake levels within the next 2,000 years (John, 1979).

4.2.2 Glaciation

4.2.2.1 Pleistocene Glaciation

Pleistocene glaciation, which began approximately one million years ago (Gilluly et al., 1968), has been characterized by four major glacial advances (Nebraskan, Kansan, Illinoian, Wisconsin) and three major interglacial periods during which the glaciers receded (Aftonian, Yarmouth, Sangamon). The maximum extent of Pleistocene glaciation in the United States is illustrated in Fig. 7. Glacial drift borders indicating the limit of glaciation during each of the four major advances are nearly parallel and are separated by a maximum distance of only 250 miles near Kansas and Missouri (Flint, 1957). Climates existing during the three interglacial periods also have been interpreted to be similar, but the length of the periods varied from 60,000 years (Sangamon) to 150,000 years (Yarmouth) (Clark and Stearn, 1960).

Although evidence allowing detailed interpretation of the characteristics of the early glacial advances was destroyed by later advances, the nature of glaciation during the Wisconsin advances is relatively well understood (Andrews, 1979). The peak of the interglacial period preceding Wisconsin glaciation occurred about 125,000 B.P. and exhibited a climate considerably warmer than the present climate. Nevertheless, the first Wisconsin glaciation reached its maximum extent about 10,000 years later (approximately 115,000 B.P.), indicating that the transition between maximum glacial recession and advance can take place quite rapidly. Three glacial advances (stadials) and recessions (interstadials) occurred during the Wisconsin period, with many minor, local fluctuations. Interstadials

were distinguished by climatic conditions interpreted to be similar to the present climate and averaged about 20,000 years in length (John, 1979). Thus, it is generally believed that present climatic conditions represent an interstadial between advances of Wisconsin glaciation. Because recession of the last glaciation began about 10,000 years ago (Wright, 1971), it may not be unreasonable to predict that the United States will be subjected to severe glaciation with an extent similar to that illustrated in Fig. 6 within the next 10,000 years.

4.2.2.2 The Formation of Glacial Lakes

During Wisconsin glaciation (and probably earlier glaciations) existing drainage networks were altered to produce large lakes (referred to as proglacial lakes) near the glacier margins. Three general proglacial lake types have been identified (Thornbury, 1957):

- a. ice-dammed lakes formed when glacier ice temporarily interrupted the existing drainage,
- b. moraine-dammed lakes formed when drainage was blocked by moraines during ice advance, and
- c. trough lakes formed by glacial erosion producing deep basins that collected surface drainage.

Ice-dammed lakes required the continued presence of glaciers for their existence. Thus, when glaciers receded from the United States, these lakes drained and left only stratigraphic evidence of their previous existence. Observations of modern ice-dammed lakes in Norway (Aitkenhead, 1960) have shown that draining during ice fluctuation can occur spontaneously with great erosive force. Geologic evidence of this process has been preserved in the channeled scablands of Washington (Bretz, 1969). Moraine-dammed and trough lakes were a common result of glaciation in the United States, and parts of these lakes

occasionally remained after glacier recession, as evidenced by the Great Lakes and the Finger Lakes in western New York State. The majority of moraine-dammed and trough lakes are now extinct, though, and the conditions that controlled their sizes and locations also must be interpreted from geologic data.

Geologic evidence and observation of modern glaciers have suggested that modification of drainage patterns by glaciation was quite drastic. Old drainage paths were displaced or totally abandoned so that post-glacial drainage networks were often unrelated to those existing before glaciation (Thornbury, 1957). The character of drainage modification and the corresponding potential for impounding glacial lakes depended on the location and thickness of the ice front and the nature of local topography. A wide variety of conditions could have been responsible for the formation of a glacial lake. Morphologic studies in New England (Koteff, 1974) showed that ice recession resulting in stagnation zones of dead ice was influenced strongly by topography. Muller (1965) presented evidence to indicate that all major northward-opening valleys in New York and New England contained glacial lakes at some time. Some of these lakes achieved depths as great as 125 m (400 ft) (Fairchild, 1912). Differential movement of the lobate ice front on the Laurentide sheet also was responsible for forming glacial lakes in the northeast part of the United States (Wright, 1971). Simultaneous advance and recession of adjacent lobes added to the complexity of glacial lake environments. Such behavior along the ice front of modern glaciers has been monitored (Arnborg, 1955) and, despite lengthy observations, ice front movement and subsequent formation or draining of proglacial lakes have not been predicted accurately even for the short term. Prediction of glacial lake formation in stagnant ice fields during glaciation in the distant future is even less tenable. The relationship between the location of glacial trough lakes and preglacial topography has not been determined. The Great Lakes filled preglacial depressions that were

enlarged by glacial erosion (Flint, 1957). However, the Finger Lakes formed in deep basins (greater than 340 m deep) eroded transversely to the preglacial valleys in western New York State (Clayton, 1965). Quantitative analysis of subglacial erosion mechanisms by Boulton (1974) indicate that glacier velocity and thickness determine the erosive energy of a glacier. Massive glaciers advancing at relatively high velocities would exhibit erosion patterns reflecting glacial movement, while less energetic glaciers would tend to exhibit erosion patterns related to the preglacial topography. Consequently, the locations and depths of glacial trough lakes produced by the next glacial advance cannot be predicted by examining only the existing landscape.

Some geologic evidence has been found suggesting recurrent inundation of large glacial lakes related to fluctuation of the ice margin during Wisconsin and possibly even earlier glaciation. In the northwestern part of the United States, the lobate Cordilleran ice sheet interrupted drainage networks to form several large ice-dammed lakes that emptied and refilled periodically during ice recession and advance (Patton and Baker, 1978). Recurrent catastrophic draining of Lake Missoula, (maximum depth equal to 700 m) eroded plateau basalts to form channeled scablands in eastern Washington (Richmond et al., 1965). Lacustrine deposits separated by till sheets beneath extinct lake beds near the Great Lakes and in North Dakota (glacial Lake Agassiz) were described by White (1974) to be additional evidence for recurrent flooding during Wisconsin glaciation.

A map outlining the major areas of flooding attributed to lakes formed as a result of Wisconsin glaciation is given in Fig. 8. Many small extinct lakes can be found outside of the areas indicated in Fig. 8, and methods for identifying the location of extinct glacial lakes are discussed in Section 4.3. Although future impoundment of glacial lakes

formed independently of the preglacial topography is unpredictable, evidence of recurrent flooding in many of the areas shown in Fig. 8 supports the possibility of repeated inundation of these areas during future glaciation.

Studies of glacier physics (Andrews, 1975) have shown that melting of ice under extremely high hydrostatic pressures can produce subglacial lakes. These lakes could connect hydraulically with groundwater beneath the glacier and severely alter groundwater flow gradients. Because glacier thicknesses exceeding 6000 ft occurred at many locations in the United States (Clark and Stearn, 1960), the potential impact of subglacial lakes on groundwater flow could exceed that of proglacial lakes. More studies of subglacial environments are needed before the conditions permitting subglacial lake formation can be identified.

4.2.3 Marine Transgression

During the past 40,000 years, fluctuations of apparent sea level have caused emergence and inundation of extensive coastal areas in the United States. A number of mechanisms have interacted to produce these fluctuations; the most important are listed below:

- a. climate changes producing global eustatic sea level fluctuation,
- b. isostatic crustal movements resulting from glacial loading and unloading, and
- c. orogenic crustal movements along tectonically active shorelines.

Interaction of the above mechanisms has complicated interpretation of past sea levels and prediction of future coastal flooding. Each component contributing to sea level fluctuation must be considered separately for prediction purposes, as recurrence intervals of these processes vary substantially and the relative impact of these processes on flooding is a function of geographical location.

Attempts have been made to distinguish the eustatic component of sea level fluctuation in the United States by examining stratigraphic indicators of previous shorelines along tectonically stable coasts south of the extent of glaciation. Investigations have shown that eustatic sea levels are minimized during major pluvials and coincident glaciations and maximized during interstadials. Apparently, the large volume of water frozen in glaciers and thus removed from the oceans exceeds precipitation increases during a pluvial. Present eustatic sea levels are interpreted to be from 5 m below the maximum eustatic level experienced during the last interstadial (Fairbridge, 1961) to 30 m above the last maximum transgression (Blackwelder et al., 1979). However, if all ice presently existing at the polar ice caps melted completely, the eustatic sea level would rise approximately 60 m above its present level (Bird, 1969). The coastal areas that consequently would be inundated are illustrated in Fig. 9. This is probably an upper-bound estimate of coastal inundation that could be attributed to an increased eustatic sea level.

Estimates of minimum eustatic levels that occurred during the last glacial maximum vary from 90 m (Dillon and Oldale, 1978) to 130 m (Milliman and Emery, 1968) below the present level. This variability results from inability to separate completely the isostatic and tectonic components of sea level fluctuation and errors in interpretation of physiographic and paleontologic evidence of extinct shorelines.

Tectonic activity along the southern California coast and the southern Texas shelf has affected the elevation of strandlines indicating past sea levels. Marine terraces have been elevated up to 400 m above the present sea level in southern California (Flint, 1957), and portions of south Texas may have been uplifted at least 20 m during the past 35,000 years (Milliman and Emery, 1968). At these locations, continental uplift rather than high stands of sea level produced elevated strandlines. Tectonic uplift continues today at these locations and reduces the potential for future coastal inundation.

Isostatic compensation of crustal loading by glaciers may have exceeded the effects of eustatic sea level fluctuation along glaciated shorelines. Isostatic movements are believed to originate from disturbance of flotation balance in the lithosphere. The litho-

sphere (or earth's crust) apparently "floats" on the easily deformable stratum. When a glacier overrides a section of the crust, a volume of the deformable stratum equal in weight to the weight of the superposed glacier is displaced, and the crust "sinks." Because of the relative densities of glacial ice and the earth's crust, full isostatic compensation of glacial loads would involve crustal movements equaling 25% to 30% of glacier thickness. Sinking of coastal areas under glacial loads has been indicated by marine strandlines elevated 500 to 700 ft above present sea level in Arctic Canada (Farrand, 1962). Farrand (1962) also reported isostatic movements of less than 1000 ft at locations in Canada where glaciers were believed to reach a thickness of 10,000 ft. Apparently, full isostatic compensation did not occur during the most recent glaciation, and it has been concluded that the duration of glaciation probably was insufficient to allow full, time-dependent compensation (Farrand, 1962).

If the geometry of the next Wisconsin ice sheet is similar to the existing continental glacier in Greenland (Flint, 1957), ice near coastal glacier margins in the United States could be nearly 1 km thick. Full isostatic compensation of future glaciation with equal thickness could cause coastal areas to sink 250 to 300 m below their existing elevations. Combined with a eustatic sea level decrease of 120 m during maximum glaciation, the apparent sea level in areas within the influence of glacial isostasy would be approximately 150 m above the present sea level. The coastal areas that would be inundated are illustrated in Fig. 9.

4.3 Identification of Extinct Flood Plains

4.3.1 Marine

Estimates of eustatic sea level fluctuations during the past 40,000 years have varied as much as 40 m partly because of the difficulty in separating eustatic, isostatic and tectonic components. For the purpose of predicting the impact of coastal inundation on a high-level-waste repository, the maximum transgression resulting from a combination of these components should be computed. In Section 4.2.3 it was estimated that large transgressions (on the order of 150 m) could occur along glaciated coasts subjected to isostatic compensation. This estimate resulted from geomorphic and

stratigraphic identification of abandoned shorelines presently elevated above sea level. Establishing potential sea level changes by these means involves margins of error inherent to the identification methods.

Interpretation of past sea levels from geomorphic data is possible if the abandoned shoreline features are relatively uneroded. Erosion (especially glacial erosion) usually destroys morphologic details indicating extinct water levels. Transgressions also tend to destroy strandlines marking previously low stands of sea level. However, shore features formed since the most recent Wisconsin glacial advance remain relatively intact and provide useful morphologic evidence to establish postglacial sea levels.

The truest morphologic measure of sea level is afforded by wave-cut notches at the base of old sea cliffs, which define the upper limit of wave action (Miller, 1939). The uncertainties regarding orientation of the upper limit of wave action and mean sea level, though, provide sources of error. Potential variations in tidal range and wave energy make it impossible to fix mean sea level, but it can be approximated with greater accuracy than is allowed by other landforms, because the position of this feature in the shore environment can be confidently established, and the tidal range at a given location is more restricted than the potential range of other nearshore environments (Bird, 1969). For example, bar, spits, and other offshore constructional forms are morphologically distinctive but can be deposited within a wide range of water depths. Consequently, they are weak indicators of past sea levels (Flint, 1957).

Coarse, conglomeratic shingle beaches can be accurate indicators of extinct intertidal zones. The high-energy depositional environment necessary to winnow out all but the coarsest sediments can be provided by unsheltered shorelines subjected to violent wave action. However, not all intertidal zones can sustain shingle beaches, and imbricated conglomerates also can be placed in high energy fluvial (terrestrial) environments (Miller, 1939). Because fossils reflecting the depositional environment are usually winnowed out with finer sediments, assemblages of landforms accompanying the shingle beach are usually needed to determine the origin of the deposit.

Identification of extinct marine environments leading to interpretation of past sea level on the basis of sediment size alone is not reliable (Guilcher, 1958). Classification of these environments, according to absolute energy levels that allow sorting of sediment grain sizes, is not valid generally, although sand-sized sediments tend to be deposited in near-shore deposits and clay-sized sediments are typical of relatively deep, offshore deposits. Exceptions to such classification are numerous and can produce large errors in interpreted sea levels. For example, fine-grained muds can accumulate locally in intertidal zones as well as in deep water, and ice rafting of gravel and cobbles can supply coarse sediments to low energy, deep water environments (Dunbar and Rodgers, 1957).

Some efforts have been made to establish extinct sea levels by examining rejuvenated and buried stream channels, fluvial terraces or other indicators of changed base levels in streams emptying into the oceans. Polynomial curve-fitting to representative portions of stream thalwegs (longitudinal profiles) has allowed extrapolation to old base levels indicating previous sea level elevations. However, sensitivity analyses (Miller, 1939) have shown that even slight variations in polynomial expressions representing the thalweg curve can lead to very large differences in extrapolated base levels. Logic data input into these analyses are not sufficiently refined to permit accurate curve fitting and can lead to errors in interpreted sea levels as large as 60 m (Miller, 1939). Fluvial terraces can mark changed sea level only if they grade directly into marine terraces (Guilcher, 1958). Many other phenomena can change the flow regime of a stream independently of sea level fluctuation and can thus cause gross misinterpretations.

The concept that stationary sea levels determine the grading of coastal margins is probably misleading and may produce substantial error in estimates of sea level fluctuation even after correct interpretation of landforms and their environments of deposition. It is likely that sea level changed gradually during the Pleistocene and, rather than producing the perfectly horizontal, planar grades assumed in geomorphic analyses, coastal processes formed surfaces with gradual slopes

making recognition of distinct, intermediate sea levels difficult (Miller, 1939). However, this uncertainty is less important for estimating maximum marine transgression and regression, which is the primary concern in repository site studies. Recent estimates of sea level fluctuation have used stratigraphic shoreline indicators to improve precision. Salt-marsh peat and shallow lagoon assemblages formed in intertidal zones have been used to compute new Pleistocene sea-level curves for the U. S. Atlantic Coastal shelf (Blackwelder et al., 1979). Sea levels interpreted from oolite deposits formed only in agitated, shallow warm water have shown good agreement with these curves (Milliman and Emery, 1968) when isostatic movements are considered, but attempts to distinguish carbonate cements precipitated in intertidal and subtidal environments have not been successful (MacIntyre et al., 1975).

Identification of in-place fossil assemblages indigenous to narrow marine depth-ranges is a reliable method for establishing and dating past sea levels if the stratigraphic investigator considers several factors that can lead to interpretation errors. Depth-range limits for the supposed fossil habitat must be confidently determined. Corals have been used as indicators of shallow marine conditions, but certain species have been found at depths greater than 20 m (Milliman and Emery, 1968). Some depth-range limits for key fossils used for sea-level interpretations are given by Emery and Merrill (1979), and substantial interpretation errors resulting from arbitrarily chosen limits are cited. Depth-limit errors occasionally originate from failing to discriminate between in-place specimens and specimens transported to hostile environments after death. Detailed paleontologic examination of fossil evidence is often required to make this distinction (Emery and Merrill, 1979). The fossils most widely used for identifying and dating past sea levels are oysters confined to intertidal and beach environments (*Crassostrea virginica*) and other mollusks with less restricted, but well established, depth limits (*Mesodesma arctatum*). Unfortunately, *Crassostrea virginica* can be used to interpret sea levels only since the most recent glaciation because of this species' poor tolerance for low temperatures (Emery and Merrill, 1979).

Even the best estimates of Pleistocene sea levels incorporating both physiographic and stratigraphic evidence must include margins of error. The most accurate estimates reported in the literature have resulted from identifying extinct intertidal environments, but the potential range of mean sea level within the intertidal zone depends on the tidal range, which is a function of coastal geometry and exposure to storms. Bird (1969) concluded that extinct Pleistocene sea levels can rarely be determined within ± 1.5 m of true sea level and the expected error range should be closer to ± 5 m. This small error range may be insignificant when determining the potential impact of marine inundation on a deep repository.

4.3.2 Lacustrine

Many useful criteria have been established for identifying abandoned lacustrine plains. Because unique relationships between geologic products and their formative processes generally do not exist (Kitts, 1976), positive recognition of lake deposits must result from observations of assemblages of the criteria discussed below rather than observation of a single criterion. Presence of these geologic features at a proposed radioactive waste repository site suggests that the site may have been flooded previously, and prediction of repository containment characteristics should consider the consequences of reinundation. However, it is important to note that the absence of these criteria is not sufficient to disprove the existence of an abandoned lacustrine plain.

Identification of abandoned shore features often demonstrates the former presence of a lake. These features can range from morphologically well-defined terraces, beaches, bars or spits as described by Gilbert (1890) to remnant belts of coarse sand and gravel surrounding deposits of finer-grained silt or clay. The development and continuity of abandoned shore features depend on the available supply of unconsolidated sediment, the size and duration of the lake, and exposure to erosive processes after the lake has drained (Feth, 1964). Studies of modern lakes have shown that strandlines and shore features can develop rapidly (in less than 40 years - Emberton and King, 1975) if conditions are favorable. Many early Pleistocene shore features have

been destroyed by late Pleistocene glacial erosion, but those formed in conjunction with late Wisconsin lakes (less than 20,000 years B.P.) remain mostly intact and readily identifiable. Studies of lake level fluctuations incorporating ^{14}C dating of strandlines have allowed more precise interpretation of the varying extent and depth of pluvial lakes in the past (Webb et al., 1980).

Deltas are formed from sediments deposited by a stream flowing into standing water and are reliable evidence for lacustrine environments. Deltas usually contain steeply dipping frontal (foreset) beds truncated by overlying topset beds dipping gently toward the lake. The elevation of the truncation surface at the front of the delta approximates the surface elevation of the extinct lake (Embleton and King, 1975). Deltas are more resistant to erosion because of their massive forms, and they have been used successfully to identify extinct lakes formed during early Wisconsin glaciation.

The morphology of lacustrine plains is quite distinctive, allowing identification by aerial photography and quantitative morphometry (King, 1974). Lacustrine plains have little or no relief, poor drainage and dark color in black and white aerial photographs. Highways constructed on lacustrine plains commonly form rectangular grid systems because of the lack of obstructions. Outwash plains with unusually low relief occasionally have been misinterpreted as lacustrine plains during aerial reconnaissance, and stratigraphic analyses are sometimes needed in glaciated areas to distinguish these landforms (King, 1974).

Lacustrine deposits cannot be characterized by a distinctive grain size, although they are typically fine-grained. The nature of lacustrine soils depends on the sediment supply and the depth of the lake. Deposits in deep lakes usually grade from coarse to fine sand near the shore to clay in deeper sections, while deposits in shallow lakes may consist of uniform, fine sand (Feth, 1964). Despite grain-size variations, lacustrine deposits consistently exhibit parallel laminations, which can be distinguished from cross-bedding characteristic of tributary streams with relatively high velocity. Fining-upward sequences attributed to lake succession are especially evident in ice-marginal lakes (Shaw, 1975). Other depositional structures, such as mudcracks and symmetrical ripple marks, are not unique to lacustrine environments but provide valuable supportive evidence (Feth, 1964).

Mineralogy of sedimentary deposits can indicate lacustrine origin with some certainty. Tabular or lenticular bodies of saline deposits (especially borates) are limited in the western United States to lacustrine deposits. Gypsum and saline deposits grading outward from halite to less soluble salts also can be found in extinct lake beds (Feth, 1964). Limestone with fresh-water mollusks or ostracods and fresh-water diatomite also are definitive of lacustrine deposition.

Some geologic features formed in glacio-lacustrine environments indicate the location of extinct glacial lakes. Ice action on glacial lakes modifies typical lake strandlines by forming ramparts of rocks and soil pushed into ridges paralleling the shore and usually ranging in height from 0.5 m to 1.5 m (Goldthwait, 1957). Glacial lake sediments often include varves, couplets of finer- and coarser-grained sediment reflecting repeated fluctuation of tributary stream flow velocities typical of glacial margin environments. The most distinguishing criteria for identifying glacio-lacustrine environments are morphologic sequences of ice-contact landforms and meltwater deposits. These sequences are described in detail by Koteff (1974), and consist of typical assemblages of ice-contact, fluvial and lacustrine landforms and deposits that indicate ice-margin environments of deposition.

Inundation depth estimates for extinct proglacial lakes can be made by mapping probable spillway thresholds, ice-margin features indicating the nature of the ice front, and lacustrine deposits marking the lake bottom. However, disturbance by erosion and differential isostatic rebound adds considerable uncertainty to these estimates.

5. IMPACT OF FLOODING ON GROUNDWATER FLOW AT TWO HYPOTHETICAL REPOSITORY SITES

In this section the results of rudimentary analyses illustrating quantitatively the impact catastrophic flooding could have on groundwater flow are reported. Hydrology and geology of the hypothetical repository sites examined below are described only briefly to identify dominant groundwater flow patterns and calculate conservative groundwater migration rates.

5.1 Flood Basalts - Columbia River Plateau

Extensive geologic and hydrologic studies of the Columbia River Plateau at the Hanford Reservation have been conducted (National Academy of Sciences (NAS), 1978) to evaluate the management of radioactive wastes produced during plutonium re-finement at the federally-operated facility. The Hanford site is located in the Pasco Basin section of the Columbia River Plateau basalts in south central Washington (see Fig. 10). At the site, basalt flows separated by horizontal sedimentary interbeds of clay, silt and gravel achieve a composite thickness exceeding 3000 m. The basalt sequence is overlain by the Ringold formation, consisting of a lower clay member and upper members of gravel and sand-silt with a typical thickness of 230 m. Above the Ringold formation glaciofluvial sands and gravels up to 120 m thick deposited during glacial meltwater flows extend to the ground surface (NAS, 1978).

Groundwater occurs in an unconfined aquifer extending upward from the lower clay member of the Ringold formation into the glaciofluvial sediments and in confined aquifers interbedded between basalt flows. The water table is generally 100 m below ground surface at the Hanford site (Geotechnical Engineers Inc., 1978a). The piezometric head in the confined aquifer located at a depth of about 950 m exceeds the head of the unconfined aquifer within the Ringold formation and produces upward groundwater flow with a velocity of 0.002 m/day (Geotechnical Engineers Inc., 1978a). The Columbia River is recharged by the unconfined aquifer by horizontal flow that may reach velocities as large as 0.7 m/day (NAS, 1978).

Preliminary subsurface investigations have found a relatively unfractured basalt flow 55 m thick at a depth of 900 m. Existing upward seepage from the confined aquifer below this basalt flow could permit migration of groundwater from a repository in this basalt flow to the water table in approximately 1000 years (NAS, 1978). Subsequent migration to the Columbia River could then occur within an additional 10 to 20 years.

The Hanford site is located on the floodplain of the extinct glacial Lake Lewis, which inundated the site to a level 250 m above the existing Columbia River during its maximum stage (NAS, 1978). Impoundment of Lake Lewis during future glaciation could drastically alter the existing groundwater flow. Recharge of the unconfined aquifer would induce seepage downward toward the confined aquifer beneath the hypothetical repository (Lake Lewis would not recharge the confined aquifer) with a velocity approaching 0.2 m/day, and groundwater at the repository would probably migrate to the confined aquifer in less than ten years. Subsequent flow within the aquifer would be controlled by permeability and horizontal gradients. If the properties of the aquifer were not affected by flooding, flow velocities between 0.0006 and 0.003 m/day could be achieved. Depending on the location of discharge into the biosphere from the aquifer, it appears that flooding would not pose a serious threat to this hypothetical repository because downward (rather than upward) seepage would be enhanced. However, little is known regarding groundwater flow within these deep, confined aquifers, and more studies of confined aquifer characteristics and locations of recharge and discharge near the Hanford site would be needed for a complete impact analysis.

5.2 Vadose Zone - Nevada Test Site

The Nevada Test Site (NTS) is located in southern Nevada in the Basin and Range Province (see Fig. 11). The site is characterized by parallel mountain ranges and valleys with regional groundwater flow between enclosed valley basins occurring within a confined aquifer of fractured carbonate rock approximately 2000 m below the basin floors (Winograd and Thordarson, 1975). Groundwater seepage velocities between 0.6 m/day and 60 m/day have been interpreted to occur within the aquifer, which discharges at the ground surface at Ash Meadows about 35 km from NTS (Geotechnical Engineers Inc., 1978a). Above the carbonate aquifer, volcanic tuff deposits form an aquitard with variable thickness (typically 1400 m thick), extending upward to within a depth of 600 m below ground surface in some valleys (Golder Associates Inc., 1977). The upper portion of this aquitard is locally fractured and forms an aquifer with limited lateral extent. Overlying the volcanic tuff and extending to the ground surface in the valleys at NTS are sediments eroded from the adjacent mountains. The water table in these sediments is found at a depth of 500 m in several valleys (Geotechnical Engineers Inc., 1978a). Leakage from the water table to the lower carbonate aquifer occurs at a rate between 4×10^{-7} m/day and 2×10^{-4} m/day, depending on the fractured nature of the volcanic tuff (Winograd and Thordarson, 1975).

Because of the present arid climate and high rate of evapotranspiration, infiltration from precipitation in the valleys is limited to only the upper few meters in the valley-fill sediments. Thus, there is essentially no groundwater circulation within the vadose zone at NTS, and this condition combined with an extremely deep water table could provide a hydrologically isolated environment for a radioactive waste repository.

Flooding resulting from the formation of pluvial lakes known to have existed in basins in southern Nevada (see Fig. 6) could permit circulation of groundwater in the vadose zone and encourage migration of radionuclides. It has been estimated (Geotechnical Engineers Inc., 1978a) that the extremely large discharge capacity of faults at the Ash Meadows area would not permit the water table elevation to increase appreciably during a pluvial unless tectonic activity changed the discharge capacity or elevation. No stratigraphic evidence has been found to support the existence of higher water table elevations, although aquifer discharge volumes in the past have exceeded those presently observed at Ash Meadows (Winoograd and Thordarson, 1975). Therefore, a vadose zone repository located well above the existing water table probably would not become saturated during a pluvial. However, if the ground surface became inundated for a sufficient period of time (which depends on the depth of inundation and the moisture content of the vadose zone soil, among other factors), water could infiltrate downward under a hydraulic gradient of one with a seepage velocity approaching the saturated hydraulic conductivity (Geotechnical Engineers Inc., 1978a), which has been measured to range from 1×10^{-4} cm/sec to 8×10^{-6} cm/sec on the porous sediments (Winoograd and Thordarson, 1975). Estimates of the velocity of downward percolation of water in fractured rock within the vadose zone have ranged from 0.07 m/day to 1.1 m/day (Geotechnical Engineers Inc., 1978a) and downward percolation through porous sediments could approach a velocity of 0.09 m/day. At these rates, infiltration from the hypothetical repository to the water table could occur in one to four years; leakage through the saturated aquitard to the confined carbonate aquifer could occur within 10,000 years, and migration through the carbonate aquifer to the Ash Meadows discharge area could occur within 2 to 200 years. Thus, under these conditions of pluvial flooding, groundwater could migrate from the hypothetical repository to discharge areas in less than 21,000 years, whereas, if flooding did not occur, the repository probably would remain completely isolated from the biosphere during the required waste containment period. Moreover, it is possible that during flooding, local changes in the groundwater flow system could supersede regional trends and permit even shorter migration paths and times for waste discharge. The potential for repository saturation by a perched water table would also have to be investigated at a repository site proposed in the vadose zone.

6. CONCLUSIONS

It has been shown that surface flooding can have a detrimental impact on the containment capability of a deep geologic repository. Seepage gradients and velocities through a repository can be increased, characteristics of the repository's hydrologic environment influencing the rate of waste migration can be appreciably altered, and the ability of the repository medium itself to resist waste leakage can be impaired. The magnitude of the impact of repository flooding depends on the depth and duration of inundation and the depth of the repository, and major episodes of flooding are necessary to damage significantly the containment characteristics of a deep (greater than 200 m below ground surface) geologic repository.

Prediction of flooding with return intervals substantially exceeding the length of historical records is made difficult by the incompleteness of the geologic record. It is beyond the present state-of-the-art to predict probabilistically the long-term recurrence of geologic events. Consequently, it should be assumed that geologic events exhibiting return intervals of the same order of magnitude as the required waste containment period will recur during the life of the repository, and their potential impact should be considered. Geologic and climatologic studies indicate that the next period of extensive glaciation and pluviation in the United States may occur within 10,000 years; consequently, proglacial and pluvial lakes represent potential hazards to repositories.

Fluctuation of apparent sea level during the past 20,000 years has been interpreted with generally good accuracy. These studies indicate that repositories in coastal areas may be subjected to inundation in the future. On the basis of the above considerations, extinct floodplains in the United States within which major episodes of flooding could affect the containment characteristics of a deep repository are outlined in Fig. 12. Potential repository sites in these areas should not be automatically declared unsafe; however, site evaluation studies in these areas should be sufficiently complete to address all of the potential impacts of flooding (see Section 5).

Interpretation of flooding depth and duration in these areas, as well as the location of smaller extinct floodplains, must be determined by geologic reconnaissance during repository site investigation. Uncertainties inherent in geologically identifying extinct floodplains and flood depths that are discussed in Section 4 must be considered during these investigations, and more studies to reduce these uncertainties are needed.

Throughout this report, sorption of radionuclides by repository media and the corresponding effect on waste migration has been neglected. During interstitial groundwater flow (as opposed to fracture flow) the time lag of radionuclide migration behind groundwater seepage rate can be substantial, and final analysis of flood impact should consider sorptivity. Lack of precision in measuring this and other repository properties may outweigh the potential effects of flooding. The impact of flooding must be considered in the context of all uncertainties involved in repository site selection to allow rational decision making.

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$$i_1 = \frac{\Delta h_1}{s} \text{ (before flooding)}$$

$$i_2 = \frac{\Delta h_1 + \Delta h_2}{s} \text{ (after flooding)}$$

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Impact of Flooding on
a Radioactive Waste
Repository

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IMPACT OF FLOODING ON
UNCONFINED FLOW GRADIENT
THROUGH A REPOSITORY

Fig. 1

<p>Lawrence Livermore Laboratory Livermore, CA</p> <p>GEOTECHNICAL ENGINEERS INC WINCHESTER • MASSACHUSETTS</p>	<p>Impact of Flooding on a Radioactive Waste Repository</p>	<p>AQUIFER LEAKAGE THROUGH A REPOSITORY</p>
	<p>Project 80654</p>	<p>Fig. 2</p>

Lawrence Livermore Laboratory Livermore, CA	Impact of Flooding on a Radioactive Waste Repository	FIELD PERMEABILITY DATA (from Morgenstern and Guthrie, 1972)
GEOTECHNICAL ENGINEERS INC. WINCHESTER • MASSACHUSETTS	Project 80654	Fig. 4

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LABORATORY PERMEABILITY
DATA
(from Brace et al., 1968)

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Fig. 5

Explanation

Major Pluvial Lakes

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EXTENT OF MAJOR PLUVIAL
LAKES DURING WISCONSIN
GLACIATION
(after Feth, 1964)

Fig. 6

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MAXIMUM EXTENT OF
PLEISTOCENE GLACIATION
(after Flint, 1957)

Fig. 7

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EXTENT OF MAJOR WISCONSIN
PROGLACIAL LAKES
(after Flint, 1945)

Fig. 8

Explanation

0-60 m Flood Contour

60-150 m Flood Contour
(in Areas Affected by
Glacial Isostasy)

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AREAS THAT WOULD BE
FLOODED BY SEA-LEVEL RISE
(after Ekren et al., 1974)

Fig. 9

DEPTH IN
METERS

VERTICAL EXAGGERATION = 20X

Hanford Reservation

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**GEOLOGIC SECTION OF THE
HANFORD RESERVATION**
Modified from NAS (1978)

Fig. 10

DEPTH IN
METERS

YUCCA FLATS (Playa)

DEPTH IN
METERS

NEVADA

NEVADA
TEST SITE

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GEOLOGIC SECTION THROUGH
YUCCA FLATS (NTS)
(from Winograd and Thor-
derson, 1975)

Fig. 11