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THE EFFECTS OF RESOURCE ACTIVITIES UPON REPOSITORY SITING AND WASTE CONTAINMENT WITH REFERENCE TO BEDDED SALT

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1.0

INTRODUCTION

The primary consideration for the suitability of a nuclear waste repository site is the overall ability of the repository to safely contain radioactive waste. This report is a discussion of the past, present, and future effects of resource activities on waste containment. Examples of resource activities which could affect containment include the following:

- Drilling
- Production of water, oil, and gas from wells
- Injection of fluids into aquifers
- Underground mining
- Solution mining
- Underground excavation for power plants, tunnels, storage space, etc.
- Surface water diversion and storage (reservoirs).

Past and present resource activities which provide release pathways (i.e., leaky boreholes, adjacent mines) will receive initial evaluation during the early stages of any repository site study. However, other resource activities which may have subtle effects on containment (e.g., long-term pumping causing increased groundwater gradients, invasion of saline water causing lower retardation) and all potential future resource activities must also be considered during the site evaluation process.

Resource activities will affect both the siting and the designing of repositories. Ideally, sites should be located in areas of low resource activity and low potential for future activity, and repository design should seek to eliminate or minimize the adverse effects of any resource activity.

Buffer zones should be created to provide areas in which resource activities that might adversely affect containment can be restricted or curtailed. This could mean removing large areas of land from resource development. The impact of these "frozen assets" should be assessed in terms of their economic value and of their effect upon resource reserves.

Major points to consider in a resource investigation for a potential repository site should include the following:

- The types and quantities (reserves) of resources in the area affected by the repository (i.e., in the buffer zones). This will determine the types of resource activities that have occurred or could occur in the future.
- Past and present resource activity near the repository and within the buffer zones. This will determine the importance of the area from a resource standpoint and will indicate possible effects upon containment due to past and present resource activity.
- The value of frozen assets in terms of their current value (Present Value Index). This will provide a basis for comparing the total resource values of different repository sites.
- Projected future resource activity assuming no repository exists (i.e., no restrictions on activities). This will indicate potential problems which could be caused by resource activities if administrative control is lost.

- The value of frozen assets in terms of their estimated future value (Future Value Index). This will indicate the economic pressures which could be exerted in the future for resource activity. It also will indicate the potential for resource activity if loss of administrative control should occur.

A major step in a resource investigation for a repository is the definition of buffer zones within which certain resource activities are restricted or curtailed because they may adversely affect containment. This step could require a major effort in data acquisition and analysis followed by extensive numerical modeling of regional fluid flow and mass transport. Numerical models should be used to assess the effects of resource activity upon containment and should include the cumulative effects of different resource activities. Analysis by other methods is probably not possible except for relatively simple cases.

2.0

ASSESSMENT OF RESOURCES

2.1 DEFINITION OF RESOURCES

When evaluating the effects of resource activities upon repository containment, it is necessary to assess the following:

- The types of resources occurring at a potential repository site
- The quantity or reserves of these resources both at the site and elsewhere
- The present and future demand for the resources
- The relative importance or value of the resources at the site compared to other potential sites.

An assessment of resources should be an integral part of any site selection and suitability study.

"Natural resources" is used here as a collective term to mean any naturally occurring wealth or asset of an area. Concepts of resources change with time and place, but the general notion is always of something necessary or useful to mankind.

Examples of resources are:

- Land - includes land used for agriculture, settlement, and recreation and products such as food and lumber
- Surface Water - includes rivers, lakes, reservoirs
- Ground Water - includes pumped supplies of fresh water (and, to a limited extent, saline water) and springs

- Minerals - include near-surface and deep deposits of metallic, nonmetallic, or energy minerals
- Petroleum - includes oil and gas.

Resources can be classified as nonrenewable or renewable. Nonrenewable resources include most minerals and petroleum deposits. Once extracted or mined, they are not renewed except over geologic time (i.e., millions of years). Renewable resources include land and water. They are renewed naturally over relatively short time periods. For instance, water resources are renewed annually by precipitation.

It is common to use renewable resources at rates exceeding their ability to be renewed. This results in mining of the resource and reduces the total quantity or reserve of the resource. For example, groundwater withdrawal at a rate exceeding natural recharge will cause water levels to fall. If the withdrawal is stopped, however, the water levels may recover to normal conditions.

2.2 CONCEPT OF RESERVES

The potential for resource activities at a repository site will depend heavily upon the amount of resource present and the economic and technological factors associated with its production. The producible amount of a given resource within a deposit is known as the "reserves" of that deposit. The term "deposits" is generally used to define mineral and petroleum resources, but in a broader sense it can also include areas of land, bodies of surface water, and groundwater aquifers. Although the term "reserves" is most commonly associated with mineral and petroleum resources, it can also be extended to other types of resources.

Different categories of reserves are based upon the amount of reliable data with which the reserve estimate is made. A common classification of reserves is as follows (U.S. Bureau of Mines 1968):

- Proven or measured reserves. These are quantity and quality (or grade) estimates which result from a high sampling density (applicable to the type of deposit). The estimates are normally compiled from sampling data derived from outcrops, trenching, drilling, and surface and underground workings. Estimates for some resources may also be based upon geophysical data.
- Probable or indicated reserves. These are reserve estimates based in part on projections of geologic or other evidence for a reasonable distance. Available data are too widely spaced to outline the reserve completely or to establish its overall grade.
- Possible or inferred reserves. These estimates are normally based on a low density of sampling. Primary inference of this category is from geologic or other interpretation such as a broad knowledge of the geologic character of the deposit, assumed continuity to a known deposit, or comparison with deposits of similar type.

As proven resource reserves are depleted by consumption and as knowledge about the deposits becomes more complete, probable reserves may be recategorized as proven and inferred reserves may be recategorized as probable (or proven). Normally, only that part of the resource which is expected to be developed at a profit is included in the reserve estimates. Whether a particular resource is considered profitable depends on a variety of economic and technological factors, including price, transportation, and mining and extracting technology.

2.2.1 Economic Influences on Reserves

As resources are gradually depleted and demand rises, the price of depleted commodities will naturally rise. The stimulus provided by the price increases will promote more vigorous resource exploration and permit development of lower-quality deposits. Another impetus to development can result from policies designed to decrease dependence upon foreign sources for critical resources. The net result will be the addition of new and lower quality deposits to producible or usable reserves.

The recent rapid increase in domestic exploration for oil and natural gas following the dramatic price rises which emphasized the dependence of the United States upon foreign sources is a prime example of incentives to resource development. Coal development has also received new impetus for economic and political reasons. Problems with the United States' balance of payments for foreign oil will provide great incentive for domestic coal production. Thinner coal seams and lower grades of coal will become workable to greater depths. The steadily increasing value of the precious metals such as gold and silver has resulted in greatly expanded exploration and the development of low-grade disseminated deposits. The world production of some other metals such as tin is falling behind demand, and the resulting rise in prices is expected to stimulate production.

2.2.2 Technological Influences on Reserves

Naturally, the highest grade and most easily accessible deposits are depleted first. In order to meet continuing demands, man must look deeper and develop deposits of lower grade. Technological innovations in exploration and extraction/refinement techniques make this expansion possible. Technology and

economics are complexly interrelated. Technological breakthroughs can lower the cost of a commodity by increasing the supply as clearly as increased costs provide the incentive for technological research and development.

Technological innovations can also create new or greatly expanded markets for a resource. Certainly, the discovery of radioactivity and the development of nuclear fission electrical generating plants created a demand for uranium that was previously nonexistent. Should fusion power become a reality, the demand for lithium will take a similar dramatic jump.

2.3 RESOURCE DEMAND

Resource demand is controlled by two essential factors.

- Many resources are nonrenewable or are renewable at limited rates.
- Resource consumption often grows exponentially.

The first factor indicates that nonrenewable resources, if worked long enough, will eventually be exhausted and that some renewable resources could be depleted to very low levels. As the high-quality resource deposits are consumed, the lower-quality or deeper deposits which are more expensive to produce must be utilized. Eventually, the expense of exploration and extraction becomes so great that the commodity becomes a precious resource with limited applications. The second factor is the exponential growth in population and resource consumption. The world population is currently about 4 billion and is expected to reach 7 billion by the end of this century and 14 billion by the year 2040 (Govett and Govett 1976). The increasing standard of living and industrialization results in growth rates of resource demand several times that of population alone.

2.3.1 Nonrenewable Resources

The exponential growth in consumption of many nonrenewable resources will have dramatic effects on supply (Hubbert 1974). For example, although coal has been mined for about 800 years, one-half of the coal production during that period took place during the last 30 years. About half of the world's cumulative petroleum production has taken place in the past 12 years. Obviously, these rates of growth cannot be sustained for long periods of time.

The production history of a nonrenewable resource should display the following characteristics. The curve of the rate of production plotted against time must begin at zero, rise until it passes over one or more maximums, and finally decline to zero. An ideal curve is given in Figure 2-1. The area beneath the curve represents the total amount of the given resource produced during its use cycle. Naturally, real production curves will have minor fluctuations which result from variations in supply and demand or from technological innovations, but the general trend is clear. Mathematically, the production curve may assume an infinite number of shapes, but the technology of production requires that the early phase be one of positive exponential rate of increase, while finite supply requires a subsequent exponential rate of production decrease.

According to Hubbert (1956), the production period of the first 10 percent of the total reserves is one of implementation and the final 10 percent of production represents a period of drastic conservation. The time required to exhaust the central 80 percent of the total amount of reserves represents the effective lifespan of that resource. In the case of American petroleum production, this time span is estimated to be about 70 years (Hubbert 1974).

Although production must decrease following the apex in the production curve in Figure 2-1, demand will still increase. As production falls appreciably behind demand, increased competition for a limited amount of natural resources will inevitably take place.

2.3.2 Renewable Resources

Renewable resources are subject to a production-demand cycle similar to that for nonrenewable resources. A major difference is that renewable resources are constantly being replenished from some source. This source (e.g., precipitation for water resources) is often fixed and limited in capacity so that reserves of the renewable resource are still being depleted. However, given time and a halt or significant decrease in production, reserves of the resource would again build up.

The production cycle for renewable resources is illustrated in Figure 2-2. It is very similar to the nonrenewable resource cycle shown in Figure 2-1, except that the renewable resource is never completely exhausted. Reserves are first used when production rates of the resource exceed renewal rates. Eventually, the reserves become depleted and the production rate must decrease to a level not exceeding the renewal rate.

Unlike most nonrenewable resources, the supply, demand, and value of renewable resources often fluctuate greatly from region to region. Most renewable resources are relatively abundant in nearly all areas so that local factors such as usage, abundance, production costs, and transportation costs tend to determine local demand and value. For instance, there is no worldwide market for water such as exists for gold, copper, petroleum, and many other nonrenewable resources. Instead, local and regional

factors tend to determine its value. In water-rich areas the value of the resource is generally lower than in water-poor areas. Under extreme conditions, expensive water transportation systems or processes such as desalination become practical because of the high value of the resource.

2.4 VALUE OF REPOSITORY RESOURCES

Resource exploration and development within a designated area around a repository site will be restricted or curtailed (see Section 4.0). Any resources within the area will become "frozen assets." The present and projected future value of these frozen assets could be an important site-selection parameter. For instance, when choosing between two potential repository sites with similar containment characteristics, the site with the lower value in frozen assets might be considered more suitable. A low value indicates low resource potential and, therefore, less chance for resource activities to adversely affect containment.

2.4.1 Present Value Index

For comparison of the resource value of potential repository sites, an index of the current resource value will be useful. Mathematically, the present value (PV) of a particular resource on the site can be expressed as:

$$PV = A \times D \times Q \times E \times (V - C)$$

where:

A = area of restricted activity

D = thickness of recoverable resource (based on current extractive technology)

Q = total quantity of resource per unit volume (i.e., grade, porosity)

- E = extraction efficiency--the proportion of the total resource recoverable using current technology
- V = unit value of resource in current dollars (adjusted for regional location)
- C = unit production cost of resource

The present value index for the repository site can be found by summing the present value of all individual resources

$$PVI = \sum_{i=1}^n PV$$

in which n is the total number of different resources. This index then forms an excellent basis for comparing the relative value of frozen assets between potential repository sites and for estimating the cost of acquiring sites not currently under administrative control.

2.4.2 Future Value

Resource values change according to economic and technological influences. Thus, resources which have little or no present value could have a substantial value at some time in the future. Similarly, resources which have high present value could become worth little or nothing in the future. An attempt should be made to project the future resource value of potential repository sites based upon probable trends in resource use. Trend analysis is discussed in Section 2.5.

Once possible trends are analyzed, a future value index could be calculated in the same way as the present value index in Section 2.4.1. The reliability of such an index would decrease as the length of projection into the future increases. It is impossible to forecast many of the social, economic, and technological changes which could drastically alter resource use

patterns and, therefore, resource value. However, a future value index would provide a useful means of comparison between potential repository sites.

2.5 FUTURE TRENDS IN RESOURCE USE

Future trends in resource use are hard to predict, particularly those projected beyond 10 years into the future. Prediction of resource trends over the containment period of a repository, on the order of thousands to millions of years, will prove highly uncertain and speculative.

Resource trends are often related to other trends in population, gross national product, and technology. Changes in these other trends can result in an accompanying change in the resource trend. A good example of a technological trend is shown in Figure 2-3, which illustrates the increase in drilling depth with time. A significant change in the trend occurred in the late 1920's with the appearance of hard steel alloys and self-cleaning bits. Such a change could be expected to increase the use of resources which are dependent upon deep-drilling technology.

An example of the trend in resource use is shown in Figure 2-4, which plots crude oil production and consumption versus time. The exponential increase in world production reflects the rising worldwide energy demand caused by industrialization and modernization. Various technological advances in oil exploration have been made which have increased the proven reserves of crude oil as production rates have increased (see Figure 2-4).

A final example of trend in resource use is shown in Figure 2-5. Water use is shown in relation to total population increase. The steep slopes of the upper two trend lines (per

PROGRESS IN DRILLING TECHNOLOGY AS A FUNCTION OF DEPTH

(Principally Petroleum Explorations in United States)

Figure 2-3

16

Project No. _____ Date _____ Reviewed _____

UNITED STATES AND WORLD CRUDE OIL PRODUCTION AND PROVED RESERVES IN RELATION TO SELECTED IMPORTANT DEVELOPMENTS IN PETROLEUM EXPLORATION TECHNOLOGY

Figure 2-4

GRAPH SHOWING TRENDS IN POPULATION AND WITHDRAWALS OF WATER IN THE UNITED STATES

Figure 2-5 18

Source: Murrey and Reeves, 1977

capita use and total water withdrawn) illustrate the pattern of resource use increasing at a rate greater than population. These trends in water use could probably be projected with fair-to-good confidence for 10 to 20 years into the future. Projections from 20 to 50 years could be made with much lower confidence. Projections more than 50 years in the future would border on pure speculation.

Once future trends in resource use are estimated, the potential future value of resources at the repository site can be evaluated. Future resource values can be used as one basis of comparison between different repository sites. They can also give an indication of future resource activities which could occur under a partial or complete loss of administrative control.

3.0

RESOURCE ACTIVITIES

3.1 TYPES OF ACTIVITY THAT MIGHT AFFECT CONTAINMENT

Various types of activities for the exploration, development, and use of natural resources can affect repository containment. Examples of such resource activities include the following:

- Drilling for minerals, oil, gas, and water
- Production of oil, gas, and water from wells
- Solution mining by wells
- Underground mining for mineral extraction
- Underground excavation for engineering structures such as powerhouses, tunnels, and storage
- Surface-water diversion, storage, and use.

Generally, resource activities will adversely affect waste containment. However, it is possible that activities such as oil, gas, or water production from wells could alter groundwater flow gradients (magnitude and direction) in a manner which benefits containment.

The effects of a particular resource activity upon repository containment will depend upon a number of factors specific to the repository site. An activity adversely affecting containment at one site could aid containment at another. Generally, the effects (either adverse or beneficial) upon waste containment will increase with the following:

- Increasing sensitivity of the groundwater balance
- Decreasing distance to the repository
- Proximity to the major groundwater flow paths downstream of the repository

- Increasing diameter of the borehole or excavation
- Increasing pumping rates
- Increased salinity along radionuclide flow paths.

3.2 IMPACTS OF RESOURCE ACTIVITIES

Resource activities can impact repository containment in the following general ways:

- (a) Direct disruption of waste - includes drilling or mining into repository
- (b) Formation of new pathways - includes drilling or mining near the repository resulting in new release paths
- (c) Adjustment of gradients - includes gradient changes which increase rate of radionuclide transport or change extent and direction of contaminant plume
- (d) Reduction of barrier effectiveness - includes activities which reduce retardation and increase hydraulic conductivity and porosity
- (e) Improvement of containment - includes reduction of gradients.

Activity types b, c, and d will only be significant if waste radionuclides have been released from engineered containment provided by the waste form, canister, over pack, or any other engineered barrier. The presence of free radionuclides in a repository which is in hydraulic communication with its surroundings will be assumed in these discussions.

3.2.1 Direct Disruption of Waste

This situation can occur only through loss of administrative control. Under such conditions, several types of resource activity could cause radionuclide release.

3.2.1.1 Intersecting Mines

Possibly the most dramatic radionuclide release would occur in the case where a mine intersected a nuclear waste repository. The impact would depend on when the intersection occurred in the life of the waste material. At the worst, the elevated temperature of the repository could trap steam and other gases which could cause an explosive breakthrough into the mine. Loss of life might occur, due both to the breakthrough and the subsequent high radiological exposure of the miners. In any event, the integrity of the repository would be seriously compromised as the mine would make a ready pathway for nuclide escape.

If the breakthrough occurred later in the life of the repository, it is conceivable that repository materials or contaminated rock from near the repository could be transported to the surface as waste rock. This physical transport could create a significant risk to the surrounding population even if the levels of radioactivity were relatively modest.

The possibility of blindly mining into a repository is remote, even with loss of administrative control. Assuming mining methods similar to those currently employed, the repository would most likely be intersected first by exploratory drillholes from the surface. Such holes are used to define the extent and grade of mineral deposits before actual mining is started.

3.2.1.2 Intersecting Drillholes

A more likely scenario, although somewhat less serious, is the case of the intersection of an existing repository by a drillhole. In this situation, a small quantity of solid transport (drill cuttings or core from the radioactive waste) is possible and might cause limited impact on the biosphere. Drilling fluid may also be contaminated and might present a threat to the environment. If the intersection occurred relatively early (during the first hundred years) in the repository life and the hole is not full of water (as would be a hole drilled by air rotary), the conduit created might allow venting of steam and radioactive gas at high pressure and high velocity. This, however, is unlikely. In this worst-case scenario, the prospect of material and fluid transport in this venting gas suggests that a risk of radioactive contamination of the biosphere is possible.

Even if venting of steam and gas did not occur, the drillhole would offer the prospect of a direct conduit from the repository to the surface or, more likely, to overlying and underlying aquifers. This would also be true of an undetected existing borehole or well which intersected the repository site. Such a connection would allow accelerated resaturation of the repository and could substantially reduce the containment capability of the entire system. Once the resaturation of the repository was complete, the borehole or well could act as a conduit for escape of contaminated groundwater and dissolved gases to aquifers above and below the repository or directly to the biosphere.

It is extremely unlikely that a water well would penetrate a bedded salt repository. Intersecting drillholes would probably be either for mineral exploration (e.g., potash) or for oil and gas exploration.

3.2.2 Formation of New Pathways

Formation of new pathways could occur if resource development is allowed too near the repository, either through error in defining the buffer zone around the repository in which resource activity should be restricted or through loss of administrative control.

3.2.2.1 Nearby Wells

Perhaps the next most significant manmade feature in terms of radionuclide release would be a nearby water well. The pumping of water from near the repository could cause contaminated water to be drawn toward the well. The danger comes not only from the shortening of the path for contaminants to reach the biosphere, but also from direct human use of the water.

3.2.2.2 Nearby Mines

Nearby mines located beneath the water table act as a sink for regional groundwater; thus, the potential exists for more rapid movement of radionuclides to the mine. The influxing water is pumped from the mine to the surface and would in most instances be discharged. In mines located within the bedded salt, any influx of water would probably evaporate and be carried to the surface by the ventilation air. The inflow water might discharge dissolved radioactive gases, including radon, and could conceivably expose the mine workers and contaminate the discharge ventilation air. Salt which precipitates as water enters the mine and evaporates could subsequently be mined along with other ore. Use of the contaminated salt could cause an unacceptable radionuclide release.

3.2.2.3 Nearby Drillholes

Possibly the least significant of the direct manmade influences is from nearby drillholes other than water wells. Although most boreholes are backfilled with allegedly impervious material ("sealed"), the final condition of such holes is highly variable and the effective life of the backfill is often relatively short. These drillholes might create connections between aquifers and between the repository layer and aquifers. This would allow a pathway for escape of contaminated ground water to the biosphere. This connection could be significant in sedimentary strata in which the horizontal hydraulic conductivity of the repository rock may exceed its vertical hydraulic conductivity by several orders of magnitude. Under these conditions, the significance of a vertical conduit to the biosphere, even at some distance from the repository, may be important.

3.2.2.4 Brine Wells

A final manmade subsurface feature which may create or alter pathways for radionuclide escape is the brine or solution well. Water may be injected into a subsurface formation to dissolve salt for subsequent transportation to the surface via brine wells. This creates a transport medium for contaminated ground water and potentially reduces the thickness of the salt layer which protects the repository. Under the worst case, brine wells could intersect the repository directly.

3.2.3 Adjustment of Gradients

Resource activity can cause changes in natural groundwater flow gradients. These changes on a large enough scale could

increase the rate or alter the direction of contaminant transport. Estimation of the effects of resource activity at some distance from the repository will require projections of maximum development and calculation of the development's effects upon gradients. Following are some of the more significant possible changes, along with case histories.

3.2.3.1 Increase in Vertical Head Gradient

In certain cases, the vertical flow of ground water which would carry radionuclides vertically away from the repository is proportional to the vertical hydraulic gradient in the repository layer (other parameters being constant). The vertical hydraulic gradient can be increased by a number of human activities.

- (a) Depletion of overlying aquifers. Groundwater usage in many areas is depleting resources and lowering pressures in near-surface aquifers. Examples are common and include shallow aquifers in Arizona, California, Nebraska, and Colorado. Aquifer depletion can increase the upward head gradients in the underlying materials and could speed transport of radionuclides to the near-surface aquifers. As these aquifers are often being utilized for human consumption, the effect could be serious.
- (b) Mine dewatering. Mine dewatering has been observed to have effects similar to (a) above. However, the water extraction is more localized, and the drawdown is frequently less severe as a result. With respect to mines in bedded salt, dewatering will probably not cause significant changes in the vertical gradient across the repository layer because of the apparent lack of

through-flowing fluid in bedded salt. Mines in underlying and overlying aquifers could cause gradient changes due to dewatering. Good examples of regional groundwater depletion due to mine dewatering are observed in Morwell, Australia (lignite); Fort McMurray, Canada (tar sand); and Bancroft, Zambia (copper).

- (c) Oil field and geothermal exploitation. Fluid-pressure reductions due to oil field depletion or geothermal energy extraction are another potential method of increasing hydraulic gradients in deep repositories. When resource activities are located deeper than the potential repository site, the downward flow gradient would be increased due to reduction of pressure. Reduction of pressure in shallow oil fields (i.e., those less than 3000 feet deep) could increase the upward flow gradient. Examples of major pressure reductions in oil fields include Willmington, California, and the gulf coast of Texas; a geothermal depletion example is Aukland, New Zealand.
- (d) Fluid injection. The vertical head gradient in the repository layer can also be increased by fluid injection into layers below the repository. Fluids could be injected for the disposal of waste and for water-drive stimulation in deep oil fields.
- (e) Changes in current resource use activities. Currently, the regional groundwater regime could be altered by ongoing pumping (oil, gas, water) and/or fluid injection. Conditions which may presently be advantageous could be altered by termination of these activities. Thus, an existing man-induced, downward gradient could change to an upward gradient in the future.

All of the above activities increase the potential for greater vertical flow through the repository layer rather than create new paths for transport.

3.2.3.2 Increase in Horizontal Head Gradient

Horizontal head gradients within aquifers can be significantly changed by resource activity such as large-scale extraction of fluids.

- (a) Localized aquifer use. Many towns and cities draw domestic and municipal water from near-surface aquifers. The producing wells are usually located close to the use points and thus create a gradient in the regional groundwater system toward the town. This could cause radionuclide movement toward the population centers and into the drinking-water system.
- (b) Mine dewatering. Large-scale mine dewatering has a similar effect on aquifer use. The impact is somewhat smaller, as the water is not generally used for human consumption. However, direct discharge is a common disposal technique and contaminated water could easily enter the biosphere.

3.2.4 Reduction of Barrier Effectiveness

Resource activity can result in a reduction of the effectiveness with which geologic or hydrological barriers prevent radionuclide transport. Several examples are given below.

- (a) Brine invasion. Withdrawal of fresh water from an aquifer may lead to brine water replacing the fresh water, either from another brine aquifer or from seawater. There are numerous examples of this phenomenon, especially on islands (Hawaii, Long Island, New York) and in coastal regions (Florida). Apart from the degradation of the water resource, the brine may increase the speed of radionuclide release by reducing the degree of retardation which radionuclides experience in the aquifers.
- (b) Solution of rock. Changes in head gradients may result in fresh water being drawn into previously brine-saturated areas of rock. The subsurface dissolution of material may vastly increase hydraulic conductivity, leading to more rapid nuclide transport. In a salt repository, dissolution of the repository rock itself could occur.
- (c) Temperature effects. Some mining and drilling activities (e.g., in situ shale-oil extraction and coal gasification, fire and steam flooding, geothermal energy extraction) change the thermal balance of large volumes of rock. The changes in temperature may cause an increase in hydraulic conductivity, induce water circulation, and/or increase rock fracturing.
- (d) Deformation effects. Nearby mines could induce significant subsidence and deformation in overlying or adjacent strata which could adversely alter the overall waste containment. Although it is dependent upon a number of factors, the area of subsidence generally spreads upward at an angle of 20 to 40 degrees from the

vertical (Brauner 1973). A more detailed discussion of subsidence effects is given in Obert and Duvall (1967). It is important to realize that, under normal mining operations (high extraction ratios and minimal back-filling), little attempt may be made to control long-term subsidence.

3.2.5 Improved Containment

Some resource activities can improve upon repository containment, primarily by changing gradients. (For example, fluid withdrawal from wells can reduce both vertical and horizontal gradients; consequently, the rate of radionuclide migration is decreased.) The advantages to such improvements should be compared carefully with disadvantages such as creation of new pathways. Improved containment may result from allowing new resource activities to be started or by allowing current activities to continue.

3.3 Specific Resource Activities Associated With Bedded-Salt Deposits

Bedded-salt deposits occur in sedimentary basins. Generally, salt beds from different basins have similar characteristics because of their similar depositional environments. Rock types making up sedimentary basins include sandstone, siltstone, shale, conglomerate, limestone, dolomite, anhydrite, and halite.

3.3.1 Mineral Resources

Mineral resources associated with sedimentary basins include salt (halite), potash, gypsum, sulfur, petroleum, natural gas,

coal, uranium, copper, vanadium, stone (ornamental and industrial), limestone, sand, and gravel. Table 3-1 is a comparison of supply between 1964 and 1974 and of estimated reserves of salt, potash, petroleum, natural gas, and uranium. Table 3-2 is a comparison of demand between 1964 and 1974 for the same mineral resources and includes a projected demand for the year 2000. Each of these mineral resources is discussed below.

Salt. Sedimentary basins provide one-fourth of the yearly production of salt in the United States, approximately to 24 million tons (Pierce and Rich 1975). Total salt reserves in the United States are estimated to be 61 trillion (61×10^{12}) tons (U.S. Bureau of Mines 1975). Although much salt is produced from the evaporation of seawater, the relative ease and low cost of mining plus the location of many mines near local markets maintains the economic interest in bedded salt deposits. Because of the vast reserves of bedded salt and its availability from seawater (making it essentially a renewable resource), it is unlikely that withdrawal of areas of bedded salt for a repository would seriously affect the supply of this resource except on a local basis.

Potash. Approximately 42 percent of the annual demand for potash (K_2O) in the United States is supplied domestically (U.S. Bureau of Mines 1975). Mines in the Permian Basin (Delaware Sub-Basin) provide 85 percent of that production. Domestic production of potash has fallen behind demand. The reason for the decline in domestic production is attributed to high production costs relative to foreign supply and not to shortages in U.S. reserves, which total about 200 million short tons of K_2O , recoverable at 1973 prices. Other resources include another 200 million tons of K_2O , half of which is in the Paradox Basin, with the remainder attributed to the Michigan Basin in Michigan and Williston Basin in

TABLE 3-1
COMPARISON OF SUPPLY 1964-1974 AND ESTIMATED RESOURCES
(from USBM 1977)

	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	Estimated Resources
SALT (Thousand short tons)	34,734	38,037	39,927	42,839	45,915	48,732	51,570	51,095	40,013	50,455	52,751	61 Trillion (10^{12}) Tons
POTASH (Thousand short tons K_2O)	4,112	4,543	5,513	5,697	5,751	5,812	5,726	5,807	6,048	6,645	7m084	74,000 x 10^6 short tons K_2O
PETROLEUM (Million 42-gallon barrels)	4,947.3	5,106.6	5,357.6	5,640.7	5,986.6	6,224.5	6,476.6	6,678.2	7,030.6	7,390.0	7,226.9	72 Billion Barrels at 95% probability level
NATURAL GAS (Billion cubic feet)	17,320	18,056	19,405	20,457	21,795	23,305	24,687	25,752	26,166	26,287	25,578	Between 322 and 655 Trillion cubic feet
URANIUM (short tons U)	14,253	13,373	13,789	14,083	17,778	14,444	26,698	20,646	21,375	29,491	32,467	2,450,000 Tons U at \$30 per pound U_3O_8

TABLE 3-2
COMPARISON OF DEMAND 1964-1974 AND 2000
(From USBM 1979)

	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	2000
SALT (Thousand short tons)	33,200	36,364	38,215	40,976	44,002	46,746	48,607	47,885	46,174	46,876	49,296	136,400
POTASH (Thousand short tons of K_2O)	3,199	3,391	4,004	4,141	4,340	4,720	4,728	4,815	4,816	5,550	6,086	12,000
PETROLEUM (million barrels)	4,034	4,202	4,411	4,585	4,902	5,160	5,365	5,553	5,990	6,288	6,078	11,400
NATURAL GAS (billion cubic feet)	14,725	15,279	16,452	17,388	18,632	20,056	21,139	21,793	22,101	22,049	21,224	27,000
URANIUM (short tons U)	500	500	500	1,000	1,000	3,400	4,000	4,900	6,400	6,900	8,000	69,000

North Dakota (U.S. Bureau of Mines 1975). Potash resources in the United States are not presently being extensively developed. However, should any constriction of foreign sources occur, domestic production would be increased.

Petroleum and natural gas. Sedimentary basins contain some of the most prolific oil and natural gas fields of all geologic environments. Exploration and development of petroleum resources will continue to intensify with sedimentary basins as a major target. Besides new exploration, older petroleum resources will be subjected to techniques for higher recovery. Many of the reservoir stimulation techniques incorporate underground mining methodologies as well as improved pumping methods. Most (or all) areas containing bedded salt have the potential for containing petroleum resources somewhere within the stratigraphic section. Removal of large areas from exploration and development (i.e., for a repository) could remove substantial petroleum resources from the public domain.

Uranium. Substantial uranium resources exist in sedimentary basins, generally in localized deposits. Current uranium production in the United States is adequate to meet demands. The future demand depends upon the reliance the United States places on nuclear power. Should nuclear power be given a high priority, it is expected that exploration and development of uranium resources will greatly intensify.

3.3.2 Other Resources

Other resources occurring in sedimentary basins include land (agricultural, recreational, industrial, etc.) and water (surface and underground).

Land. Bedded salts underlie large areas in sedimentary basins. Land use in these areas is varied, ranging from agricultural, recreational, and municipal to essentially none at all.

Water. Water resources in sedimentary basins are variable in quantity, quality, and value. Current use is a function of local or regional factors. In dry areas of the western United States, surface water is generally being used to its maximum capacity and ground water is an extremely important and valuable resource. In wetter areas, surface water is often not being used to maximum capacity and demand for ground water is less. Future water demand will depend upon factors such as population growth, land use, new water treatment technologies, and ultimately the quantity of the available resource. Table 3-3 summarizes water used by each state in 1975. Use is broken down according to surface water, ground water, fresh water, and saline water. Table 3-4 summarizes water use in the regions of the United States shown in Figure 3-1.

A more detailed description of resource activities associated with bedded-salt basins is given by Geotechnical Engineers, Inc. (1978). It includes discussions of problems caused by leaky wells and boreholes, solution cavities, subsidence, and other resource-related impacts.

TABLE 3-3
SUMMARY OF WATER WITHDRAWN, EXCEPT FOR HYDROELECTRIC POWER
In Million Gallons Per Day, by States, 1975
(From Murray and Reeves, 1977)

State	Popu- lation (thou- sands)	Fresh- water per capita use (gpd)	Water withdrawn including irrigation conveyance losses										Convey- ance losses	Fresh- water con- sumed
			Ground water			Surface water			Re- claimed sewage	All sources				
			Fresh	Saline	Fresh and saline	Fresh	Saline	Fresh and saline		Fresh	Saline	Fresh and saline		
Alabama	3,577	2,500	370	5.0	370	8,600	200	8,800	0	8,900	210	9,100	0	260
Alaska	404	500	44	0	44	160	1.0	160	0	200	1.0	200	0	5.6
Arizona	2,245	3,500	4,800	0	4,800	3,000	0	3,000	54	7,800	0	7,800	250	5,900
Arkansas	2,116	2,400	2,600	0	2,600	2,500	0	2,500	0	5,100	0	5,100	170	2,200
California	21,113	1,900	19,000	240	19,000	21,000	9,700	31,000	160	41,000	9,900	51,000	5,300	23,000
Colorado	2,534	4,000	2,700	7.3	2,700	7,300	9.4	7,300	80	10,000	17	10,000	1,000	5,300
Connecticut	3,111	460	120	1.0	120	1,300	1,200	2,500	0	1,400	1,200	2,700	0	160
Delaware	575	450	110	0	110	150	1,800	1,900	0	260	1,800	2,100	0	39
Florida	8,485	810	3,300	48	3,300	3,600	11,000	15,000	0	6,900	11,000	18,000	220	2,300
Georgia	5,023	1,100	810	0	810	4,600	520	5,100	0	5,400	520	5,900	0	590
Hawaii	809	1,900	850	15	870	650	980	1,600	0	1,500	990	2,500	450	560
Idaho	824	21,000	5,600	0	5,600	12,000	0	12,000	5.6	17,000	0	17,000	4,300	4,900
Illinois	10,692	1,200	1,000	31	1,100	12,000	0	12,000	0	13,000	31	13,000	0	200
Indiana	5,367	2,100	530	2.5	530	11,000	0	11,000	0	11,000	2.5	11,000	0	370
Iowa	2,824	1,200	560	0	560	3,000	0	3,000	0	3,500	0	3,500	0	220
Kansas	2,319	2,500	5,000	0	5,000	810	0	810	0	5,800	0	5,800	110	4,100
Kentucky	3,391	860	150	0	150	2,800	0	2,800	0	2,900	0	2,900	0	180
Louisiana	3,790	3,000	1,500	36	1,600	9,900	260	10,000	0	11,000	300	12,000	610	3,200
Maine	1,059	550	47	0	47	540	610	1,200	0	590	610	1,200	0	41
Maryland	4,106	360	140	0	140	1,200	6,000	7,100	150	1,500	6,000	7,400	0	110
Massachusetts	5,785	390	350	0	350	1,900	6,500	8,400	0	2,200	6,500	8,800	0	110
Michigan	9,141	1,600	300	400	900	14,000	0	14,000	0	15,000	400	15,000	0	310
Minnesota	3,890	1,000	610	0	610	3,400	0	3,400	0	4,000	0	4,000	0	270
Mississippi	2,315	680	1,100	0	1,100	470	540	1,000	0	1,600	540	2,100	67	530
Missouri	4,806	860	470	0	470	3,600	0	3,600	0	4,100	0	4,100	2.3	400

TABLE 3-3 (continued)

SUMMARY OF WATER WITHDRAWN, EXCEPT FOR HYDROELECTRIC POWER
In Million Gallons Per Day, by States, 1975 (From Murray and Reeves, 1977)

Montana	694	17,000	220	0	220	11,000	0	11,000	0	12,000	0	12,000	2,500	2,800
Nebraska	1,528	5,700	5,900	0	5,900	2,800	0	2,800	0	8,700	0	8,700	1,600	6,000
Nevada	610	5,800	670	13	690	2,800	0	2,800	11	3,500	13	3,500	720	1,600
New Hampshire	826	460	59	0	59	320	620	940	0	380	620	1,000	0	21
New Jersey	7,436	370	790	0	790	2,000	3,800	5,800	0	2,800	3,800	6,600	0	440
New Mexico	1,147	2,800	1,600	10	1,600	1,600	0	1,600	0	3,200	10	3,200	21	1,600
New York	19,530	610	1,000	3.4	1,000	11,000	12,000	23,000	0	12,000	12,000	24,000	0	740
North Carolina	5,367	940	540	0	540	4,500	950	5,500	0	5,100	950	6,000	0	490
North Dakota	617	1,400	100	2.7	110	780	0	780	0	880	2.7	880	16	240
Ohio	10,751	1,500	1,100	0	1,100	15,000	0	15,000	0	16,000	0	16,000	0	510
Oklahoma	3,260	650	1,200	140	1,400	880	0	880	0	2,100	140	2,300	14	1,200
Oregon	2,091	3,300	1,200	0	1,200	5,700	0	5,700	3.6	6,900	0	6,900	1,700	3,200
Pennsylvania	11,828	1,300	880	0	880	17,000	200	17,000	0	18,000	200	18,000	0	830
Rhode Island	930	160	27	.3	28	120	330	460	0	150	330	480	0	14
South Carolina	2,818	2,100	200	0	200	5,600	41	5,600	0	5,800	41	5,800	0	280
South Dakota	680	800	220	4.5	220	330	0	330	0	540	4.5	550	150	300
Tennessee	4,170	1,800	370	0	370	7,300	0	7,300	0	7,600	0	7,600	.6	270
Texas	12,236	1,900	11,000	0	11,000	13,000	5,100	18,000	62	23,000	5,100	29,000	430	13,000
Utah	1,197	3,400	790	4.0	790	3,300	49	3,300	.9	4,000	53	4,100	390	2,400
Vermont	476	700	43	0	43	290	0	290	0	330	0	330	0	110
Virginia	4,920	990	210	0	210	4,600	2,600	7,200	0	4,900	2,600	7,500	3.0	71
Washington	3,497	2,100	670	0	670	6,500	41	6,500	0	7,200	41	7,200	1,000	2,500
West Virginia	1,800	3,400	80	0	80	6,100	0	6,100	0	6,200	0	6,200	0	66
Wisconsin	4,418	710	460	0	460	2,700	0	2,700	0	3,200	0	3,200	0	240
Wyoming	414	17,000	420	24	440	6,800	0	6,800	0	7,200	24	7,200	1,600	2,100
District of Columbia	716	400	.8	0	.8	280	0	280	0	290	0	290	0	18
Puerto Rico-Virgin Islands ¹	3,220	210	180	0	180	500	3,500	4,000	0	680	3,500	4,100	54	240
United States ²	217,482	1,600	82,000	980	83,000	260,000	69,000	330,000	530	350,000	70,000	420,000	23,000	96,000

¹ Preliminary data subject to revision.² Including Puerto Rico and Virgin Islands.

TABLE 3-4
SUMMARY OF WATER WITHDRAWN, EXCEPT FOR HYDROELECTRIC POWER
In Million Gallons Per Day, by Regions, 1975
(From Murray and Reeves, 1977)

[Partial figures may not add to totals because of independent rounding]

State	Popu- lation (thou- sands)	Fresh- water per capita use (gpd)	Water withdrawn including irrigation conveyance losses										Convey- ance losses	Fresh- water con- sumed
			Ground water			Surface water			Re- claimed sewage	All sources				
			Fresh	Saline	Fresh and saline	Fresh	Saline	Fresh and saline		Fresh	Saline	Fresh and saline		
New England	11,803	420	600	1.3	610	4,400	9,300	14,000	0	5,000	9,300	14,000	0	440
Mid-Atlantic	40,169	620	2,700	3.4	2,700	22,000	27,000	49,000	150	22,000	27,000	52,000	2.1	1,600
South Atlantic-Gulf	26,405	1,100	5,400	53	5,500	24,000	14,000	38,000	0	29,000	14,000	43,000	220	3,700
Great Lakes	22,311	1,600	1,200	400	1,600	35,000	0	35,000	0	36,000	400	36,000	0	1,100
Ohio	21,131	1,700	1,800	20	1,900	34,000	0	34,000	0	36,000	20	36,000	.2	1,200
Tennessee	3,319	3,200	270	0	270	10,000	0	10,000	0	11,000	0	11,000	.4	280
Upper Mississippi	19,455	970	2,400	15	2,400	16,000	0	16,000	0	19,000	15	19,000	.1	800
Lower Mississippi	6,458	2,500	4,800	34	4,900	11,000	260	11,000	0	16,000	300	16,000	840	5,500
Souris-Red-Rainy	681	520	86	1.2	87	270	0	270	0	350	1.2	360	.2	94
Missouri Basin	8,907	3,900	10,000	30	10,000	25,000	5.8	25,000	80	35,000	36	35,000	5,700	15,000
Arkansas-White-Red	7,758	1,900	8,800	140	9,000	6,200	3.6	6,200	6.5	15,000	140	15,000	260	9,000
Texas-Gulf	10,449	1,600	7,200	.9	7,200	9,700	5,100	15,000	35	17,000	5,100	22,000	160	8,000
Rio Grande	1,991	2,700	2,300	9.4	2,300	3,000	0	3,000	20	5,400	9.4	5,400	400	3,500
Upper Colorado	449	9,000	130	5.1	130	3,900	0	3,900	0	4,100	5.1	4,100	560	170
Lower Colorado	2,640	3,200	5,000	.2	5,000	3,500	0	3,500	64	8,500	.2	8,500	300	6,300
Great Basin	1,434	4,800	1,400	17	1,400	5,400	49	5,500	5.5	6,800	66	6,900	1,000	3,600
Pacific Northwest	6,572	5,000	7,300	0	7,300	26,000	41	26,000	9.2	33,000	41	33,000	7,400	11,000
California	21,117	2,000	19,000	240	19,000	22,000	9,700	32,000	160	41,000	9,900	51,000	5,500	23,000
Alaska	404	500	44	0	44	160	1.0	160	0	200	1.0	200	0	5.6
Hawaii	809	1,900	850	15	870	650	980	1,600	0	1,500	990	2,500	450	560
Caribbean ¹	3,220	210	180	0	180	500	3,500	4,000	0	680	3,500	4,100	54	240
United States ²	217,482	1,600	82,000	980	83,000	260,000	69,000	330,000	530	350,000	70,000	420,000	23,000	96,000

¹ Preliminary data subject to revision.

² Including Caribbean region.

WATER RESOURCE REGIONS OF THE UNITED STATES

Figure 3-1

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Source: Murray and Reeves, 1977

4.0

REPOSITORY BOUNDARIES

4.1 TYPES OF CONTROLLED AREAS

Two types of controlled areas are recommended around repository sites (Nuclear Regulatory Commission 1979).

- Exclusion area: fenced, secured area
- Buffer zone(s): area(s) of restricted resource activity.

The exclusion area should include the area directly overlying the repository and probably will extend several times the repository radius. It should be secured against any unauthorized access, including terrorist activities.

The buffer zone(s) should define the area(s) of restricted resource activity. Buffer zones should specifically address a particular resource activity. A buffer zone adequate to control one type of resource activity may be inadequate for another type because of the different effects such activities can have upon containment. Alternatively, a single buffer zone could be defined based upon the worst-case resource activity and all resource activities within the zone could be restricted. This would be easier to administer but could result in the removal of resources from the public domain over unnecessarily large areas.

4.2 EXCLUSION AREA

The area which is to be excluded from all resource activity and from public access can be defined in terms of a specific distance from the repository. Its boundaries are not defined by resource considerations but are based on the area needed for surface-handling facilities and for security. The exclusion area should be well protected against any unauthorized access (such as entrance by terrorists).

The exclusion area can be easily isolated in case of an accidental contaminant release. Such a release would most likely result in groundwater contamination, which could be controlled and cleaned up before the surrounding buffer zone(s) are affected.

4.3 BUFFER ZONES

The physical characteristics (size, depth, shape, etc.) of buffer zones vary depending upon the regional geologic and hydrologic conditions and the particular resource activity or activities being restricted. Some general characteristics of buffer zones are proposed below.

- Buffer zones may be large, depending upon the impact of the resource activity. They could exclude hundreds or thousands of square miles of land from some types of resource development.
- Buffer zones will have variable geometry. The size, depth, and shape of a buffer zone should be specified after considering the impacts of resource activity upon containment.
- Buffer zones should specifically address a particular resource activity or activities. A buffer zone defined for one resource activity may have a different geometry and extent than a buffer zone defined for another resource activity.
- Within a buffer zone, the degree of restriction placed upon a particular resource activity could vary. For instance, small domestic water wells may be allowed in

areas within a buffer zone where large municipal well fields are excluded (because large wells alter gradients by a greater amount). Also, the number of activities could be restricted within a buffer zone.

- The cumulative effect of different resource activities should be examined and incorporated into the buffer zone restrictions. Cases could arise in which two different resource activities are by themselves acceptable, but when examined in combination produce unacceptable impacts. Such combinations of resource activities should be considered during buffer zone definition.

4.4 METHODOLOGY FOR DEFINING BUFFER ZONES

The restrictions placed upon the buffer zones will have various social and economic impacts (primarily loss of resources). The assessment of these impacts will be an important factor in determining site suitability.

For the purpose of defining the extent of buffer zones, two study areas should be considered.

- Regional area: defined by the regional groundwater flow system, including regional recharge and discharge areas.
- Buffer zone area: defined by the probable extent (in three dimensions) of the area in which past, present, or future resource activities could reasonably be expected to adversely affect repository containment. Consideration should be given to natural and manmade effects which control the extent of the contaminant plume.

A methodology for defining the study areas and repository buffer zones is outlined below.

4.4.1 Regional Studies

4.4.1.1 Regional Flow

The major purpose of regional studies should be to define the general groundwater flow system in a regional framework. This should include definition of recharge areas, discharge areas, aquifers, aquitards, aquifer interconnections, and gross hydrologic characteristics of the media. The area of investigation is defined by the extent of the regional flow system within a sedimentary basin. The regional flow system should be defined sufficiently to determine its total extent, directions of flow, recharge and discharge regions, and the overall relationship between the various aquifers and confining layers. Depending upon the potential location(s) of the repository, important intermediate and local flow systems should also be defined. Intermediate and local flow systems usually extend only to relatively shallow depths. They are directly connected to springs, creeks, lakes, and some rivers. Major rivers may serve as discharge areas for the regional systems.

The results of the regional studies should be formulated into a basin model. Because of the complexity of regional flow systems, a computer model will probably be necessary, although in some cases simple pipe models or analytical models may be sufficient for preliminary evaluations.

Existing data sources such as oil wells, mines, water wells, water quality samples, and surface flows may be sufficient in many sedimentary basins to develop a preliminary model of

regional flow. Additional data, primarily from new boreholes, could be gathered if existing data are not sufficient. Optimum locations for obtaining new data can be chosen after careful examination of existing data and possibly some preliminary regional modeling.

4.4.1.2 Regional Contaminant Transport

The approximate direction of contaminant transport should be apparent from the regional flow model. Further studies of regional contaminant transport should be made utilizing a mass transport model. The model will give a general indication of the feasibility of the chosen repository location and may lead to the choice of a better location. It may also be used to give a preliminary indication of the extent of possible buffer zones. The effects of various manmade disturbances (e.g., wells, mines) can also be determined on a preliminary basis.

The regional transport model will have large uncertainties associated with it because existing data on retardation, effective porosity, and dispersion are either poor or nonexistent in almost all areas. Qualitative or semiquantitative results will be useful in the definition of a buffer zone.

4.4.2 Buffer-Zone Studies

Based upon the regional flow and transport models, one or more apparently suitable repository sites should be chosen. A detailed program of data acquisition should be undertaken within the area of the probable contaminant plume as defined by the regional models. These data could be incorporated into a detailed site model (buffer-zone model) of the area reasonably expected to contain unacceptable contaminant levels under existing

conditions, both natural and manmade. The area included in the buffer-zone model may be adjusted as more data are acquired and the contaminant plume becomes more confidently defined.

The extent of the buffer zones should include all regions (defined in terms of areal extent and depth) in which potential radionuclide levels would be unacceptable (according to regulatory standards) given the existing geologic and hydrologic conditions.

The buffer zones should also extend to regions in which future manmade features would affect the contaminant plume in a way that would result in unacceptable radionuclide levels. Assessment of future manmade features should be based upon a reasonable maximum development. Reasonable maximum development can be evaluated by considering the potential resources available (e.g., fresh water, minerals, oil, gas), the future potential for use based on projected long-term trends, and the availability of alternative sources of natural resources which could be substituted for those existing within the buffer zones.

The buffer zones may not be the same for all types of resource development. The definition of a buffer zone for a particular resource activity does not necessarily mean that all development of the resource should be excluded. It means that development should be controlled in a manner which will not cause unacceptable contamination. For example, small domestic water-supply wells may be allowed within a particular area of the buffer zone, whereas large withdrawal for municipal, agricultural, or industrial use would be restricted.

In many areas, the framework for controlled resource development is in existence. Many states currently regulate various resource developments such as mines and water supplies. Where the existing regulatory framework is not sufficient to assure control within the buffer zone, new regulations should be made. All regulatory activities within the buffer zones should be consolidated under one authority such as the Nuclear Regulatory Commission, so that the cumulative effects of development can be easily and accurately assessed.

5.0

LOSS OF ADMINISTRATIVE CONTROL

Two degrees of loss of administrative control could occur: a partial loss of administrative control over buffer zones or portions of buffer zones or a complete loss of administrative control over the entire repository area.

5.1 PARTIAL LOSS OF CONTROL

A change in governmental policy combined with economic and social pressures for vital resources within the buffer zones could result in the loss of control over the buffer zones or parts of the buffer zones. This would allow resource activities to resume in the former buffer zones which could lead to contaminant release.

Even under a partial loss of administrative control, the actual repository and portions of the buffer zones would remain under control. Thus, nuclide releases would probably be relatively minor compared to possible releases under a complete loss of administrative control.

Economic and social pressures for the restricted resources contained within the buffer zones could be greatly reduced or eliminated by locating the repository in an area of low resource potential.

5.2 TOTAL LOSS OF CONTROL

A catastrophic change in government and society could result in a total loss of administrative control. There would be a significant time period before all records and memory of the repository site would be lost, however.

Because a catastrophic change implies a loss of civilization and technology, it would probably require hundreds of years for civilization to advance to the point that it would have both the technology to mine and drill into the repository and its surrounding area and the need (resource demand) to do so.

The best way to prevent contaminant release under a complete loss of administrative control is to locate the repository in an area of low resource potential. This would reduce or eliminate the chance of any future civilization conducting resource activities that would result in a contaminant release.

6.0

CONCLUSIONS

A resource study should be included as an integral part of any repository siting study. Such a study should include evaluations of the following:

- The type and quantity of resources in the area affected by the repository, including buffer zones
- Past and present resource activity in the repository area, including buffer zones
- The value of frozen assets in terms of a Present Value Index
- Projected future resource activity in the repository area, including buffer zones, assuming no repository exists
- The projected future value of frozen assets in terms of a Future Value Index.

Buffer zones in which certain resource activities that threaten waste containment are restricted or curtailed should be defined around a repository. Definition of buffer zones will require a good understanding of fluid flow and solute transport on a regional scale. Relatively complex numerical models (performance models) will probably be necessary for this task.

Buffer zones should incorporate areas in which the nuclide concentration (or dose) determined by the performance model is unacceptable. They should also include areas in which resource activities could cause nuclide release by the following:

- Direct disruption of waste
- Creation of new pathways
- Alteration of flow gradients
- Reduction in barrier effectiveness.

There are two alternatives for defining buffer zones.

- Different buffer zones could be defined for specific resource activities
- A single, integrated buffer zone could be defined on the basis of a worst-case resource activity.

The integrated buffer zone may restrict certain resource activities unnecessarily, but it would be easier to administer. In any case, the buffer zone(s) should also be defined to prevent adverse impacts from the cumulative effects of resource activities.

In addition to the buffer zone(s), an exclusion area around the repository should be defined to provide an area secured against unauthorized access (such as entrance by terrorists). The exclusion area should not be based upon resource considerations.

A flow diagram of the suggested method for the determination of resource effects and buffer zones is shown in Figure 6-1. First, a performance model (i.e., a numerical model of fluid flow and solute transport) is developed. Next, past and present resource activities are documented and their effects are analyzed by the performance model. If the repository performance is acceptable, the buffer zones can then be defined based upon potential resource activities (evaluated from present resource potential, trends in resource activity, and possible future

**SUGGESTED METHOD FOR THE DETERMINATION
OF RESOURCE EFFECTS AND BUFFER ZONES**

Figure 6-1

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resource activity). If the repository performance is not acceptable due to past or present resource activity, corrective action should be considered. Situations which are not correctable will result in rejection of the site. Situations which are correctable will require the definition of buffer zones to restrict or curtail resource activity. The resulting situation (e.g., abandonment and sealing of mines and/or boreholes, cessation of pumping) must be re-evaluated by the repository performance model. Once tentative buffer zones for past and present resource activity are defined, future resource activity should be considered. This may require some readjustment of buffer-zone boundaries. Once the buffer zones (or integrated buffer zones) are shown to be adequate, they can be secured and the repository design can proceed.

BIBLIOGRAPHY

- Adams, J.E. 1965. Stratigraphic-Tectonic Development of Delaware Basin. AAPG Bull., V. 49, No. 11, pp. 2140-2148.
- Angino, E.E. and W.W. Hambleton. 1971. Geology and Hydrology of the Proposed Lyons, Kansas, Radioactive Waste Repository Site. Final Report. Lawrence, Kansas: Kansas Geological Survey.
- Arnold, R. and W.J. Kemnitzner. 1931. Petroleum in the United States and its Possessions. New York: Harper and Brothers.
- Baars, D.L. 1962. Permian System of Colorado Plateau. AAPG Bull., V. 46, No. 2, pp. 149-218.
- Bachman, G.O. and R.B. Johnson. 1973. Stability of Salt in the Permian Salt Basin of Kansas, Oklahoma, Texas and New Mexico. U.S. Geological Survey Open-File Report.
- Baecher, G.B. 1975. Subjective Sampling Approaches to Resource Estimations. Schloss Lakenburg, Austria: International Institute for Applied Systems Analysis, Research Memorandum 75-29.
- Baker, A.A., C.H. Dane and J.B. Reeside, Jr. 1933. Paradox Formation of Eastern Utah and Western Colorado. AAPG Bull., V. 17, No. 8, pp. 963-980.
- Ball, M.W. et al., eds. 1951. Possible Future Petroleum Provinces of North America. Tulsa, Okla: American Association of Petroleum Geologists.
- Bayley, R.W. and W.R. Muehlberger, comps. 1968. Basement Rock Map of the United States. U.S. Geological Survey.
- Bayne, C.K. and C. Brinkley, eds. 1972. Geology, Hydrology, Thickness and Quality of Salt at Three Alternative Sites for Disposal of Radioactive Wastes in Kansas. Kansas Univ. Center for Research, Inc.; available from TIC, ORNL/SUB/3484-2.
- Bleimeister, W.C. 1961. Rock Salt Mining Operations in Michigan, Ohio, and Ontario. Mining Engineering, V. 13, No. 5, pp. 467-471.
- 1964. New Cleveland Mine was Designed for Mass Recovery of Salt. E/MJ, V. 165, No. 8, pp. 86-93.

- Brauner, Gerhard. 1973. Subsidence Due to Underground Mining (in two parts), 2: Ground Movements and Mining Damage. United States Department of the Interior, Bureau of Mines Information Circular 8572.
- Brokaw, A. et al. 1972. Geology and Hydrology of the Carlsbad Potash Area, Eddy and Lea Counties, New Mexico. U.S. Geological Survey Open-File Report 4339-1.
- Case, J.E., H.R. Joesting and P. Byerly. 1963. Regional Geophysical Investigations in the La Sal Mountains Area, Utah and Colorado. U.S. Geological Survey Prof. Paper 316-F, pp. 91-116.
- Cater, F.W. and D.P. Elston. 1963. Structural Development of Salt Anticlines of Colorado and Utah. In Backbone of the Americas: Tectonic History from Pole to Pole. AAPG Memoir 2, pp. 152-159.
- Chute, A.E. 1968. Sulfur from Petroleum Gases and Liquids. Trans. Society of Mining Engineers of AIME, V. 241, September, pp. 314-318.
- Coffman, J.L. and C.A. Von Hakke, eds. 1977. Earthquake History of the United States. Boulder, Colo.: Environmental Data Service.
- Cohee, G.V. 1965. Geologic History of the Michigan Basin. Washington Academy of Sciences J., V. 55, No. 9, pp. 211-223.
- Cole, V.B. et al. 1961. Wells Drilled into Precambrian Rock in Kansas. Kansas Geological Survey Bull. 150.
- Cole, V.B. and D.F. Merriam. 1962. Progress Report of the Kansas Basement Rocks Committee and Additional Precambrian Well. Kansas Geological Survey Bull. 157.
- Cooper, J. 1960. Cambrian, Devonian and Mississippian Rocks of the Four Corners Area. In Geology of the Paradox Basin Fold and Fault Belt. Four Corners Geological Society Third Field Conference Guidebook, pp. 59-65.
- Craig, L.C. and R.A. Cadigan. 1958. The Morrison and Adjacent Formations in the Four Corners Area. In Guidebook to the Geology of the Paradox Basin. Intermountain Association of the Petroleum Geologists Ninth Annual Field Conference Guidebook, pp. 182-192.
- Crow, P. 1979. Higher Gas Prices Seen as Deep Andarko Spark. The Oil and Gas J., V. 77, No. 17, pp. 19-21.

- Dellwig, L.F. 1968. Significant Features of Deposition in the Hutchinson Salt, Kansas, and Their Interpretation. In Saline Deposits. Geological Society of America Special Paper 88, pp. 421-426.
- Dellwig, L.F. and R. Evans. 1969. Depositional Processes in Saline Salt of Michigan, Ohio and New York. AAPG Bull., V. 53. No. 4, pp. 949-956.
- Docekal, J. 1970. Earthquakes of the Stable Interior with Emphasis on the Mid-Continent. Ph.D. Dissertation, University of Nebraska.
- Dutton, S.P. et al. 1978. Geology and Geohydrology of the Palo Duro Basin, Texas Panhandle. Texas Bureau of Economic Geology Circular 79-1.
- Edwards, J., Jr. 1966. The Petrology and Structure of the Buried Precambrian Basement of Colorado. Colorado School of Mines Quarterly, V. 61, No. 4.
- Ells, G.D. 1967. Michigan's Silurian Oil and Gas Pools. Michigan Geological Survey Report of Investigations 2.
- Elston, D.P. et al. 1962. Uncompahgre Front and Salt Anticlines Region of Paradox Basin, Colorado and Utah. AAPG Bull., V. 46, No. 10, pp. 1857-1878.
- Evans, C.S. 1950. Underground Hunting in the Silurian of South-Southwestern Ontario. Geological Association of Canada Proceedings, V. 3, pp. 55-85.
- Fisher, J.H. 1969. Early Paleozoic History in the Michigan Basin. In Studies of the Precambrian of the Michigan Basin. Michigan Basin Geological Society Annual Field Excursion Guidebook, pp. 89-93.
- Foster, R.W. and T.F. Stipp. 1961. Preliminary Geologic and Relief Map of the Precambrian Rocks of New Mexico. New Mexico Bureau of Mines and Mineral Resources Circular 57.
- Frye, J.C. 1942. Geology and Ground-Water Resources of Meade County, Kansas, with analysis by R.H. Hess and E.O. Holmes, Jr. Kansas Geological Survey Division of Ground Water Bull. 45.
- Gardner, W.C. 1974. Middle Devonian Stratigraphy and Depositional Environments in the Michigan Basin. Michigan Basin Geological Society Special Papers No. 1.

- Geotechnical Engineers, Inc. 1978. Final Report on the Uncertainties in the Detection, Measurement, and Analysis of Selected Features Pertinent to Deep Geologic Repositories. Prepared for the Lawrence Livermore Laboratory, Livermore, Calif., UCRL 13912.
- Geraghty, J.J. et al. 1973. Water Atlas of the United States. Port Washington, New York: Water Information Center, Inc.
- Gill, D. 1977. Salina A-1 Sabkha Cycles and the Later Silurian Paleogeography of the Michigan Basin. *J. of Sedimentary Petrology*, V. 47, No. 3, pp. 979-1017.
- Govett, G.J.S. and M.H. Govett. 1976. World Mineral Supplies: Assessment and Perspectives. New York: Elsevier Scientific Publishing Co.
- Harris, R.L. and H.A. Larsh. 1979. Kansas: Its Geology, Economics and Current Drilling Activity. *The Oil and Gas J.*, V. 77, No. 18, pp. 323-347.
- Haun, J.D. 1976. Oil and Gas Reserves of Colorado. *Mineral Industries Bull.*, V. 19, No. 5.
- Herman, G. and C.A. Barkell. 1957. Pennsylvanian Stratigraphy and Productive Zones, Paradox Salt Basin. *AAPG Bull.*, V. 41, No. 5, pp. 861-881.
- Hill, J.M. 1968. Permian Basin Field Area, West Texas and Southeastern New Mexico. *In Saline Deposits. Geological Society of America Special Paper 88*, pp. 17-28.
- Hite, R.J. 1960. Stratigraphy of the Saline Facies of the Paradox Member of the Hermosa Formation of Southeastern Utah and Southwestern Colorado. *In Geology of the Paradox Basin Fold and Fault Belt. Four Corners Geological Society Third Field Conference Guidebook*, pp. 86-89.
- 1968. Salt Deposits of the Paradox Basin, Southeast Utah and Southwest Colorado. *In Saline Deposits. Geological Society of America Special Paper 88*, pp. 319-330.
- 1969. Shelf Carbonate Sedimentation Controlled by Salinity in the Paradox Basin, Southeast Utah. *In Third Symposium on Salt. Cleveland: Northern Ohio Geological Society*, V. 1, pp. 48-66.
- Hite, R.J. and S.W. Lohman. 1973. Geologic Appraisal of Paradox Basin Salt Deposits for Waste Emplacement. U.S. Geological Survey Open-File Report 73-114.

Hubbert, M.K. 1956. Nuclear Energy and the Fossil Fuels. American Petroleum Institute, Drilling and Production Practice.

— 1974. U.S. Energy Resources, A Review as of 1972. A background paper prepared at the request of Henry M. Jackson, Chairman, Committee on Interior and Insular Affairs, United States Senate, Serial No. 93-40 (92-75).

Jacoby, C.H. 1969. Correlation, Faulting, and Metamorphism of Michigan and Appalachian Basin Salt. AAPG Bull., V. 53, No. 1, pp. 136-154.

Jewett, J.M. and D.F. Merriam. 1959. Geologic Framework of Kansas--A Review for Geophysicists. In Symposium on Geophysics in Kansas. Kansas Geological Survey Bull. 137, pp. 9-52.

Johnson, K.S. 1972. Gypsum and Salt Resources in Oklahoma. Industrial Minerals, No. 62, November, pp. 33-39.

— 1976. Evaluation of Permian Salt Deposits in the Texas Panhandle and Western Oklahoma for Underground Storage of Radioactive Wastes. Prepared for Union Carbide Corporation, Office of Waste Isolation, Oak Ridge, Tenn.; available from NTIS, Y/OWI/SUB-4494/1.

Johnson, K.S. and S. Gonzales. 1976. Geology and Salt Deposits of the Michigan Basin. Athens, Georgia: Earth Resources Associates, Inc.; available from Batelle Columbus, Y/OWI/SUB-4494/2.

— 1978. Salt Deposits in the United States and their Regional Characteristics Important for the Storage of Radioactive Waste. Athens, Georgia: Earth Resources Associates, Inc.; available from Batelle Columbus, Y/OWI/SUB-7414/1.

JOIDES (Joint Oceanographic Institutions: Deep Earth Sampling Program). 1965. Ocean Drilling on the Continental Margin.

Jones, C.L. 1965. Petrography of Evaporites from the Wellington Formation Near Hutchinson, Kansas. U.S. Geological Survey Bull. 1201-A.

— 1972. Permian Basin Potash Deposits, South-Western United States. In Geology of Saline Deposits. Paris: UNESCO Earth Science Series No. 7, pp. 191-201.

— 1974. Salt Deposits of the Clovis-Portales Area, East-Central Mexico. U.S. Geological Survey Open-File Report 74-60.

- Jones, C.L. 1975. Potash Resources in Part of Los Medanos Area of Eddy and Lea Counties, New Mexico. U.S. Geological Survey Open-File Report 75-407.
- Jordan, L. and D.L. Vosburg. 1963. Permian Salt in the Anadarko Basin, Oklahoma and Texas. Oklahoma Geological Survey Bull. 102.
- Katich, P.J. 1958. Cretaceous of Southeastern Utah and Adjacent Areas. In Guidebook to the Geology of the Paradox Basin. Intermountain Association of Petroleum Geologists Ninth Annual Field Conference Guidebook.
- Kulstad, R.O. 1959. Thickness and Salt Percentage of the Hutchinson Salt. In Symposium on Geophysics in Kansas. Kansas Geological Survey Bull. 137, pp. 241-247.
- Lambert, I.B. and T. Sato. 1945. Kuroko and Associated Ore Deposits of Japan: A Review of Their Features and Metallogenesis. Economic Geology, V. 69, pp. 1215-1236.
- Landes, K.K. 1945. The Saline and Bass Islands Rocks in the Michigan Basin. U.S. Geological Survey Oil and Gas Preliminary Investigational Map 40.
- _____. 1951. Detroit River Group in the Michigan Basin. U.S. Geological Survey Circular 133.
- Landes, K.K. and H.L. Bourne. 1976. Possibilities for Nuclear Waste Disposal in Michigan Salt Beds; available from Battelle Columbus, ORNL/SUB-7010/2.
- Lee, W. 1956. Stratigraphy and Structural Development of the Salina Basin Area. Kansas Geological Survey Bull. 121.
- Lefond, S.J. 1969. Handbook of World Salt Resources. New York: Plenum Press.
- Mattox, R.B. 1968. Salt Anticline Field Area, Paradox Basin, Colorado and Utah. In Saline Deposits. Geological Society of America Special Paper 88, pp. 5-16.
- McAllister, A.L. 1976. Price; Technology, and Ore Reserves. In World Mineral Supplies: Assessment and Perspective. New York: Elsevier Scientific Publishing Co.
- McCaslin, J.C. 1979. Chevron Goes for Delaware Basin Depth Record. The Oil and Gas J., V. 77, No. 16, p. 99.
- McCulloh, T.H. 1973. Oil and Gas. In United States Mineral Resources, U.S. Geological Survey Prof. Paper 820, pp. 477-496.

- McGregor, K. 1967. The Drilling of Rock. London, England: C. R. Books, Ltd.
- McKee, E.D. et al. 1967. Paleotectonic Maps of the Permian System. U.S. Geological Survey Miscellaneous Geological Investigation Map I-450.
- Merriam, D.F. 1963. The Geologic History of Kansas. Kansas Geological Survey Bull. 162.
- Mesolella, K.J. et al. 1974. Cyclic Deposition of Silurian Carbonates and Evaporites in Michigan Basin. AAPG Bull., V. 58, No. 1, pp. 34-62.
- Moore, W.D. 1977. Ingenuity Sparks Drilling History. Petroleum/200.
- Murray, C.R. and E.B. Reeves. 1977. Estimated Use of Water in the United States in 1975. U.S. Geological Survey Circ. 765.
- Netherland, Sewell & Associates. 1975. Preliminary Regional Study of the Present and Possible Future Oil and Gas Development in the Areas of Thick Rock Salt and Shale Deposits of Michigan, Ohio, Pennsylvania and Western New York. Prepared for Union Carbide Corporation, Office of Waste Isolation; available from TIC, ORNL/SUB-75/87989.
- Nuclear Regulatory Commission. 1979. Disposal of High-Level Radioactive Wastes in Geologic Repositories, 10 CFR Part 60, Draft 7.
- Ohlen, H.R. and L.B. McIntyre. 1965. Stratigraphy and Tectonic Features of Paradox Basin, Four Corners Area. AAPG Bull., V. 49, No. 11, pp. 2020-2040.
- Parker, F.L. et al. 1960. Disposal of Radioactive Wastes in Natural Salt. In Geology of the Paradox Basin Fold and Fault Belt. Four Corners Geological Society Third Field Conference.
- Picard, D.M. 1960. Lithologic Zone Boundaries in Pennsylvanian Paradox Member, Paradox Basin. AAPG Bull., V. 44, No. 9, pp. 1574-1578.
- Pierce, W.G. and E.I. Rich. 1962. Summary of Rock Salt Deposits in the United States as Possible Sites for Radioactive Waste Minerals. U.S. Geological Survey Bull. 1148.
- Rocky Mountain Association of Geologists. 1972. Geologic Atlas of the Rocky Mountain Region, United States of America. Denver, Colo.: RMAG.

- Sanborn, A.F., ed. 1958. Guidebook to the Geology of the Paradox Basin. Intermountain Association of Petroleum Geologists Ninth Annual Field Conference.
- Scott, M.R. et al. 1973. Hydrothermal Manganese in the Median Valley of the Mid-Atlantic Ridge (abs.). Trans. American Geophysical Union, V. 54, p. 244.
- Shoemaker, E.M. 1954. Structural Features of Southeastern Utah and Adjacent Parts of Colorado, New Mexico and Arizona. In Geology of Utah. Utah Geological Society Guidebook 9, pp. 48-69.
- Skinner, B.J. 1969. Earth Resources. New York: Prentice-Hall.
- Smith, J.W. 1975. Permian Basin as a Radioactive Waste Repository. Union Carbide Corporation, Office of Waste Isolation; available from NTIS, Y/OWI/SUB-4495/1.
- Stewart, J.H. and R.F. Wilson. 1960. Triassic Strata of the Salt Anticline Region, Utah and Colorado. In Geology of the Paradox Basin Fold and Fault Belt. Four Corners Geological Society Third Field Conference, pp. 98-106.
- Titley, S.R. 1975. Geologic Character and Environment of Some Porphyry Copper Occurrences in the Southwestern Pacific. Economic Geology, V. 70, pp. 499-514.
- U.S. Bureau of Mines. 1968. A Dictionary of Mining, Mineral, and Related Terms. U.S. Department of the Interior.
- _____. 1975. Minerals Facts and Problems, Bureau of Mines Bull. 667.
- U.S. Department of Energy. 1979. Program for Identifying Sites for Nuclear Waste Repositories. Briefing prepared for Nuclear Regulatory Commission; April 11, Silver Springs, Md.
- U.S. Geological Survey. 1964a. Mineral and Water Resources of New Mexico. New Mexico State Bureau of Mines and Mineral Resources Bull. 87.
- _____. 1964b. Mineral and Water Resources of Colorado. Denver: Colorado Geological Survey.
- Vokes, F.M. 1976. The Abundance and Availability of Mineral Resources. In World Mineral Supplies: Assessment and Perspective. New York: Elsevier Scientific Publishing Co.
- Waldschmidt, W.A. 1966. Geologic Framework of the Permian Basin. In Oil and Gas Fields in West Texas. West Texas Geological Society Publ. 66-52, pp. 7-9.

Walters, R.F. 1946. Buried Precambrian Hills in Northeastern Burton County, Central Kansas. AAPG Bull., V. 30, pp. 660-710.

Wengerd, S.A. 1958. Pennsylvanian Stratigraphy, Southwest Shelf, Paradox Basin. In Guidebook to the Geology of the Paradox Basin. Intermountain Association of Petroleum Geologists Ninth Annual Field Conference Guidebook, pp. 109-134.

Wengerd, S.A. and J.W. Strickland. 1954. Pennsylvanian Stratigraphy of Paradox Salt Basin, Four Corners Region, Colorado and Utah. AAPG Bull., V. 30, No. 10, pp. 2157-2199.

Wright, J.C. and D.D. Dickey. 1958. Pre-Morrison Jurassic Strata of Southeastern Utah. In Guidebook to the Geology of the Paradox Basin. Intermountain Association of Petroleum Geologists Ninth Annual Field Conference Guidebook, pp. 172-181.