UCRL 15250

PO# 6939009

environmental engineers, scientists,
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CDM

CONCEPTUAL MODEL FOR REGIONAL RADIONUCLIDE
TRANSPORT FROM A SALT DOME REPOSITORY

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE LABORATORY

A TECHNICAL MEMORANDUM

for

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE LABORATORY

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May 30, 1980

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FORWARD

This technical memorandum was prepared for the Lawrence Livermore Laboratory of the University of California under Purchase Order Number 6939009 to meet the requirements of Task 1 of that Purchase Order. The technical scope of work is as follows:

Task 1. Develop conceptual model for regional radionuclide transport from a dome salt repository.

Subtask 1. Describe Typical Dome Salt Repository - Describe a typical dome salt repository in order to develop the types of boundary conditions, initial values, and geometric configurations that must be handled by the model. Include a literature review of potential dome salt formations and a site visit to Louisiana and Texas salt dome locations.

Subtask 2. Describe Geologic and Hydrologic Processes - Describe the geologic and hydrologic processes that must be modeled, drawing upon the information presented in the technical memorandum, "Processes and Parameters Involved in Modeling Radionuclide Transport from Bedded Salt Repositories" (UCRL 15095), and focusing attention on those processes unique to salt domes. Interrelationships of processes shall be shown on a general flow chart.

Subtask 3. Define Model Parameters - Develop an annotated list of the parameters necessary to model regional radionuclide transport in ground-water with respect to a dome salt repository site. The parameter list shall include the parameter definition and a qualitative discussion of the importance of each parameter relative to the models. A quantitative discussion of the difficulty of predicting parameter values shall also be included. Seller shall draw heavily upon its expertise and previous work related to bedded salt repositories, focusing this effort on salt dome sites.

Subtask 4. Progress Report - Prepare a progress report on the foregoing three subtasks as described in Part IV - Reports.

A site visit was planned to Avery Island dome (La.). Unfortunately a power failure on the island precluded our entering the mine. We thank the staff of International Salt Company and RESPEC for their efforts in our attempt to visit the mine.

ABSTRACT

Disposal of high-level radioactive wastes is a major environmental problem influencing further development of nuclear energy in this country. Salt domes in the Gulf Coast Basin are being investigated as repository sites. A major concern is geologic and hydrologic stability of candidate domes and potential transport of radionuclides by groundwater to the biosphere prior to their degradation to harmless levels of activity. This report conceptualizes a regional geohydrologic model for transport of radionuclides from a salt dome repository. The model considers transport pathways and the physical and chemical changes that would occur through time prior to the radionuclides reaching the biosphere. Necessary, but unknown inputs to the regional model involve entry and movement of fluids through the repository dome and across the dome-country rock interface and the effect on the dome and surrounding strata of heat generated by the radioactive wastes.

SUMMARY AND RECOMMENDATIONS

SUMMARY

Future use of nuclear energy is highly dependent on capability to dispose of high-level wastes for a sufficiently long period of time to allow the wastes to decay to innocuous levels of radioactivity. Presently, these wastes are being stored in temporary facilities. Because of the time length involved (250,000 years), potential repositories must be geologically secure. Several geologic media are being considered including salt, both bedded and domal. Because all salt domes under consideration--Keechi and Oakwood in East Texas, Vacherie and Rayburns in North Louisiana, and Lampton, Richton, and Cypress Creek in Mississippi penetrate saline and fresh water aquifers, the hydrologic stability of the domes is open to question. This report conceptualizes a hydrologic model for radionuclide transport from a dome repository through the regional hydrologic system, describes the processes which must be included, and presents an annotated list of model parameters.

To be considered a candidate dome, certain geologic criteria must be met (Kreitler, 1979). With respect to structural and hydrologic stability, there must be no evidence of structural movement or dissolution within the last 250,000 years, and little likelihood that they will occur within the next 250,000 years. Should a dome repository be breached possible pathways, length of time, and attenuating affects of radionuclide transport to the biosphere must be considered.

The formation of the basins in which the salt domes occur and the formation of the salt domes themselves are described in the following chapters. The growth history and physio-chemical characteristics of the domes are also described as well as the geohydrology of the basins. The sedimentary column pierced by the domes contains numerous fresh- and saline-water aquifers. Freshwater aquifers are of principal concern. Water movement and quality are a function of the depositional systems of the aquifers, basin structure, recharge/discharge potentials, and head relationships. Geohydrologic conditions in aquifers in the immediate vicinity of the domes are extremely complex.

Major inputs to the regional transport model will likely require construction of additional models in order to accurately determine the rate, concentration, and distribution of radionuclide entry into the regional geohydrologic system. These additional models should address:

1. Entry and movement of fluids through the dome repository.
2. Movement of fluids across the salt dome--caprock/country rock interface.
3. The effect through time on the local hydrology of heat generated by the radioactive wastes.

There are three ways in which the hydrologic integrity of the repository dome can be compromised:

1. Dissolution of the dome by normal circulation of groundwater about the dome,
2. fractures through the salt which would allow water to enter the repository site, and
3. through a manmade hole such as the repository shaft.

Domes under consideration as nuclear waste repository sites do not appear to be dissolving or are dissolving at such a slow rate that it is inconsequential. Major changes in sea/base level would be unlikely to induce enough erosion to uncover the domes. Formation of fractures in the dome of sufficient magnitude to allow groundwater to enter the repository would involve a catastrophic event. Entry of water into the repository through a manmade hole, probably the repository mine shaft, is most likely.

Once the repository is breached, numerous factors remain which could prevent escape of the radionuclides to the biosphere prior to their decay or which

would lead to dilution below harmful concentrations. In particular, the present barrier between the salt dome and the regional hydrologic flow system may prevent or retard escape of radionuclides from the dome repository.

The regional hydrologic flow system serves as the last barrier to the release of radionuclides to the biosphere. Physical processes which must be modeled to determine the performance of the regional flow system are:

- ° Thermal expansion of the salt dome and surrounding strata
- ° Advective transport
- ° Diffusion
- ° Dispersion
- ° Sorption processes
- ° Dissolution and precipitation
- ° Thermal effects
- ° Radioactive decay

The basic conceptual model which should underlie an analytical regional transport of radionuclides from a salt dome repository is presented. The conceptual model fully considers the complex and very important geologic influences and structures.

The manner in which the three barriers to radionuclide transport function are illustrated in Figure 1.

RECOMMENDATIONS

In performing this study and preparing the report, certain research needs have been identified.

1. With respect to the salt domes themselves, probably the least is known about the nature of the salt dome/country rock interface.
 - a. Its physical nature.
 - b. Its chemical nature.

FIG. 1. Path of radionuclides from the repository to the biosphere.

- c. Fluids involved, including their physical and chemical nature.
- d. The interrelationship between the boundary fluids and the salt and surrounding groundwater.

Investigations of salt dome/country rock interface should be carried out on domes similar to the potential repository domes in order not to inadvertently compromise the integrity of a potential repository site. The study should include a comprehensive analysis of why the domes are not dissolving and how easily the dissolution barrier can be destroyed.

- 2. Investigation of the potential effects of major sea level changes should begin. This investigation should include detailed mapping and study of Pleistocene deposits and groundwater history. The approach used in studying uranium deposition is an example.
- 3. Investigations of the thermal behavior of salt domes should be continued. Beginning studies are underway by RESPEC, a South Dakota geotechnical firm being funded by DOE. Further modeling of the anticipated heat load of the repository, its affects on creep, fractures, thermal expansion, and fluids contained in the salt, and on the country rock bounding the dome, including changes in the land surface, aquifers, and surface and groundwater systems is necessary. Construction of time profiles of changes also is necessary.
- 4. Investigations to define and accurately quantify geohydrological parameters that must be included in modeling effects should be continued. The predictive capability of the models will be only as good as the parameters used.
- 5. Detailed geohydrologic analyses of selected domes should be carried out. A major weakness of many hydrologic models is lack of good data on the prototype. The geohydrology of a salt dome is extremely complex. The better it is understood, the better the predictive capabilities of groundwater models will be.

6. Changes in the pH and Eh of the water can drastically affect its ability to transport various ionic species. The chemical evolution taking place in the aquifers surrounding repository domes should be carefully evaluated and assessments of the effects of the chemical changes on radionuclide transport must be made.
7. Many data are available for fresh-water aquifers, but few are available for saline aquifers. Geohydrologists have concentrated on fresh-water aquifers for obvious reasons. Saline aquifers have been studied largely with respect to deep well disposal. The characteristics of saline aquifers in the East Texas, North Louisiana, and Mississippi Basins need to be studied more. The pathway of radionuclide transport to the biosphere is most likely to be through fresh-water aquifers, but dissolution and failure of the repository could occur in saline aquifers.

I. INTRODUCTION

Location and design of a site for permanent disposal of high-level radioactive wastes now stored in temporary facilities is a major environmental problem influencing further development of nuclear energy in this country. Since the National Academy of Science report in 1957, salt deposits have been considered as potentially among the most geologically secure substrates in which to establish a permanent repository. Initial studies focused on bedded salts in Kansas (Bradshaw and McClain, 1971). Because of insurmountable problems associated with the Kansas deposits, other salt provinces are now being studied, including investigation of the suitability of salt domes for disposal of the wastes.

Consideration of salt domes to isolate nuclear wastes for a length of time sufficient to allow the wastes to decay to relatively innocuous levels of activity (approximately one quarter of a million years); raises several questions involving the long-term stability of the selected dome(s). From a purely physical point of view, geologic stability has two interrelated aspects: 1) tectonic stability in terms of driving forces and activation potential, and 2) hydrologic stability. Because salt domes are composed predominantly of the mineral halite (sodium chloride), they are extremely soluble. Should the repository be breached, for whatever reason, allowing groundwater to come in contact with the wastes prior to the presumed safe interval, it is possible that radionuclides could be transported to the biosphere.

It is essential therefore that the mechanisms, pathways, and rates of regional radionuclide transport be explored. Short of actual observations, probably the best way to assess the risks involved is to model groundwater movement within the sedimentary basin(s) containing the candidate dome(s). Such a model must trace radionuclide transport from entry into the regional flow system to potential release to the biosphere. This report describes the processes and parameters that should be included in such a groundwater model, and identifies unknown, but necessary inputs to the regional model. Other aspects of the

stability and ability of salt domes to contain radioactive wastes are discussed briefly because they bear on factors that should be considered in a model of groundwater movement.

From the outset, it must be recognized that the emplacement of salt domes was a very complicated process that is as yet incompletely understood. Furthermore, although there is a certain commonality among salt domes, because of differences between them the geohydrology of each dome must be examined on an individual basis to ascertain the ambient regime in which it occurs.

Finally although not a rationale to ignore or fail to consider potentially catastrophic events within the necessary time frame that the repository must remain intact, it must be borne in mind that all salt domes being considered for disposal of high-level radioactive wastes have existed for a very long time. Salt domes have apparently not moved nor dissolved in the last 30 to 50 million years, that is they have been geologically and hydrologically stable up to 200 times longer than will be necessary for the wastes to decay to innocuous levels. Should no evidence to the contrary arise it is reasonable to anticipate that the domes will remain stable in the geological near term or for more than the next 250,000 years.*

SALT DOMES

Salt domes occur in several provinces throughout the United States, but are most prevalent in the Gulf Coastal Plain. The principal area of interest for disposal of high-level radioactive wastes has been the salt dome province of the Gulf Coastal Plain: Texas, Louisiana, Mississippi, and Alabama. Within this province there are 263 known and suspected onshore domes (Anderson and others, 1973). Nearly an equal number of domes are offshore, principally in the vicinity of the Mississippi River delta, (Hawkins and Jirik, 1966; Jirik and Weaver, 1976).

*This paragraph should not be construed as a position of advocacy for the use of a salt dome(s) as a repository for high level nuclear wastes, but merely a statement that the consideration of the stability of salt domes should include the perspective of geologic time.

The distribution of salt domes by states is as follows: Texas has 78 domes, Louisiana 120, Mississippi 63, and Alabama 2. These domes are associated with several geologic basins: East Texas 20, North Louisiana 19, Mississippi 77, Rio Grande 6, and Texas-Louisiana 141 (Figure 2). The first three basins are considered to be interior basins; the latter two are coastal basins. For various reasons related to depth, probable stability, and prior utilization, all domes in the Coastal Basins have been eliminated from consideration as nuclear waste repositories. Therefore, only the geohydrology of the three interior basins, East Texas, North Louisiana, and Mississippi, is important insofar as modeling radionuclide transport is concerned. Within these basins, only seven domes are still being studied as potential repositories; Keechi and Oakwood in the East Texas Basin (Figure 3; Kreitler, 1978, 1979a; Durham, 1979), Rayburns and Vacharie in the North Louisiana Basin (Figure 4; Durham, 1979) and Cypress Creek, Lampton, and Richton domes in the Mississippi Basin (Figure 5; Durham, 1979; Spiers, 1979). Palestine dome in East Texas was being considered as a potential repository as recently as the Fall of 1979 (Durham, 1979), but studies by the Bureau of Economic Geology at the University of Texas (BEG) indicate that uncertainties related to early brining operations preclude further consideration (Kreitler, 1979a). Studies in the East Texas Basin are much further along than those in Northern Louisiana and Mississippi and provide the principal sources of information in this report.

Salt domes occurring along the Gulf Coast have certain features in common which permit some generalization in constructing a hydrologic model or set of models for potential repositories: composition, basic shape and structure, and intrusion into fresh and/or saline aquifers. Nevertheless, because of considerable variability among the domes--actual shape, amount and kind of impurities contained in the salt, internal structure, and particularly dome-country rock boundary conditions and growth history--individual characteristics of each dome must be examined.

GENERAL GEOHYDROLOGY OF EAST TEXAS, NORTH LOUISIANA AND MISSISSIPPI BASINS

The regional geohydrology of the salt dome basins is obviously important with respect to the hydrologic stability and geologic security of the dome

FIG. 2. Salt basins, salt domes, and uplifts, Northern Gulf Coast Region; modified from Eby, 1956. From Ledbetter and others (1975).

FIG. 3. Location map of piercement salt domes of the East Texas Basin.
From Kreitler (1978).

FIG. 4. Geologic map of North Louisiana Basin; compiled from parish reports by B.J. Guidry; mainly from Fish (1938), Huner (1939), Murray (1948), Martin and others (1954), Anderson (1960, and in preparation), and Echols (1965). From Kupfer and others (1976); above mentioned citations not included in bibliography.

repository. In a very general sense, groundwater in the East Texas, North Louisiana, and Mississippi Basins moves, as expected, downdip in a coastward direction. Three fundamental factors strongly influence and alter the regional groundwater system: major structural highs which bound and separate the basins; structures which developed within the basins and which effectively divide the basins into subbasins; and the depositional systems in which sediments surrounding the domes accumulated. These factors influence not only the occurrence of groundwater and direction of groundwater flow, but the rate of movement, recharge/discharge locations, water quality, and the existence of confined versus unconfined conditions.

MODELING REGIONAL TRANSPORT OF RADIONUCLIDES FROM A SALT DOME REPOSITORY

To ascertain the capability of salt domes and the salt dome basins to contain nuclear wastes for a sufficient length of time to insure that hazardous concentrations of radionuclides do not reach the biosphere, extensive modeling efforts will be required. From a regional point of view, the modeling efforts must first simulate the locations, rates, and concentrations at which radionuclides might escape from a repository and enter the regional groundwater system. Then the potential pathways of regional transports and attenuating effects of the natural geohydrologic system can be modeled.

This report presents a conceptual model for regional transport of radionuclides through the natural geohydrologic system. Chapter II describes the geology and general geohydrology of basins in which domes being considered for nuclear waste repositories occur. Chapter III presents a general description of salt domes--formation and growth history, physio-chemical characteristics, and the dome/country rock interface--and discusses the co-resource problem; brief descriptions of seven salt domes under consideration are provided in Appendix A. Chapter IV contains the general framework of a conceptual model and describes boundary conditions, internal structures, and necessary inputs. Chapter V discusses the geologic and hydrologic processes that must be modeled and Chapter VI is an annotated list of parameters that must be specified to model the required processes.

II. GEOLOGY AND GEOHYDROLOGY OF SALT DOME BASINS

GEOLOGY OF EAST TEXAS, NORTH LOUISIANA AND MISSISSIPPI BASINS

Infilling of the Gulf Coast Basin

Because of the strong influence of the stratigraphy and structure of the East Texas, North Louisiana, and Mississippi Basins on the geohydrology within the basins, it is appropriate to briefly review their development within the context of geologic history of the Gulf Coastal Plain. A general stratigraphic column of the basin is presented in Figure 6. Description of how salt domes form is contained in Section III.

The origin of the Gulf of Mexico and the Gulf Coastal Plain is closely tied to early Mesozoic rifting and separation of the present continents of North America, South America, and Africa, and to major tectonism in the western part of the United States. The configuration of the early Gulf (rift basin) was probably similar to the East African rift valley; red fluvial and alluvial fan gravels and sands were in the initial deposits (Kehle, 1971). With continued separation of the continents, the early Gulf of Mexico probably had a configuration similar to the present Persian Gulf or Red Sea. Marine circulation was undoubtedly restricted, promoting deposition of evaporites, mostly salt.

Deposition of salt, called the Louann Salt, appears to have begun in Late Triassic time and extended into Early Jurassic time (Burke and others, 1969). Salt accumulation was rapid, perhaps as much as 120 cm per year (Ledbetter and others, 1975). Because of subsequent flowage into domes and perhaps because of continued basin subsidence, it is impossible to determine the original thickness of the salt. One to two kilometers is not an unreasonable figure (Dietz, 1973; Kreitler, 1979a). The Louann Salt is inferred to be 2,000 meters thick in eastern Mississippi (Williams, 1969).

With continued opening of the Gulf of Mexico, normal marine circulation was possible, and deposition of Upper Jurassic shelf and shelf-edge limestone was

ERA	SYSTEM	SERIES	GROUP	FORMATION
CENOZOIC	QUATERNARY	HOLOCENE		
		PLEISTOCENE	Houston	Bedmont Lissie Wilks
	TERTIARY	PLIOCENE	Citronelle	
		MIOCENE	Fleming	
			Catahoula	
		OLIGOCENE		
			Vicksburg	
		EOCENE	Jackson	Yazoo Clay Meady's Branch
			Claiborne	Cockfield-Vegas Coke Mountain Sparta, Zephia-Wrona Weches Queen City Rexide Corrida
			Wilcox	
		PALEOCENE	Midway	
MESOZOIC	CRETACEOUS	UPPER	Navarro	
			Taylor	
			Austin	
			Eagleford	
			Woodbine	
		LOWER	Washita	
			Fredericksburg	
			Trinity	Poluxy
				Sligo
				Hosston
	JURASSIC	UPPER	Cotton Valley	
			Lovena	
		LOWER		Smackover
	TRIASSIC	UPPER		Lovena
				Eagle Mills
PALEOZOIC	PERMIAN			

FIG. 6. Stratigraphic column, Northern Gulf Coast Region.
Modified from Ledbetter and others (1975).

initiated (Smackover). In Mississippi and Louisiana, later Jurassic terrigenous clastic deltas and barrier islands (Cotton Valley) prograded gulfward over the shelf limestone. For the most part, deposition of marine limestone and shale continued from the Jurassic into the Cretaceous. During the Cretaceous, sea level fluctuated widely. The Cretaceous shoreline shifted from Central Texas to Colorado and Wyoming and back several times producing unconformities and laterally extensive shelf facies.

Cretaceous clastic paralic facies are relatively common in parts of the East Texas and North Louisiana Basins. Major influxes of terrigenous clastics occurred with deposition of the basal Trinity Sands and the Paluxy Sands in the Lower Cretaceous and the Woodbine Formation during the Upper Cretaceous in Texas. The Paluxy and Woodbine were deposited primarily in fluvial-deltaic environments (Caughey, 1977; Oliver, 1971). The North Louisiana Basin apparently received less sand throughout the Cretaceous. Few data on the Cretaceous section are available for the Mississippi Basin.

Basin filling during regressions of the Cretaceous sea, particularly during deposition of the Travis Peak, Paluxy, and Woodbine fluvial-deltaic clastics in Texas was from basin margin on the north toward basin center. Thus, depocenters shifted basinward with time. According to Fisher (1973) and Kehle (1978) this strongly influenced the formation of salt domes in Texas. In addition, during deposition of the Woodbine, the Sabine Uplift was subaerially exposed, and at least in Texas contributed sediment to the basin (Oliver, 1971).

Toward the end of the Cretaceous Period, and extending through the Tertiary Period, marine seas began to recede from Texas, Louisiana, and Mississippi for the final time, and the influx of terrigenous sandstone and mudstone increased considerably. Tectonic activity and uplift of mountains associated with the first phases of the Laramide Orogeny in the western United States provided huge amounts of clastic debris to eastward flowing streams. With the establishment of through-going river systems, much of this sediment was carried to the Gulf of Mexico and deposited in deltas and related strandplain and marine environments. Approximately 4000 meters of Cretaceous sediment accumulated in East Texas (Ledbetter and others, 1975).

At the beginning of the Tertiary, the Gulf shoreline extended from south of San Antonio, east of Austin and Waco, and northeast through Texarkana. Fluvial-deltaic sedimentation was the major kind of deposition in the Tertiary. Four aspects of Tertiary deposition largely determine the distribution of facies within the Tertiary section.

1. Progradation of individual delta lobes, avulsion and construction of new delta lobes, and lateral redistribution of sediments from delta front deposits produced complexly interbedded sands and muds.
2. Rapid subsidence of the basins limited deltaic progradation; vertical accumulation within individual deltaic environments was considerable, and facies representing similar environments are stacked on top of each other.
3. Periodically, the influx of sediments to the whole basin was reduced; continued basin subsidence and compaction of deltaic and prodeltaic sediments allowed the Tertiary sea to transgress across the abandoned delta platform, reworking the older sediments and leaving a veneer of muddy glauconite rich-sediments.
4. With each influx of renewed fluvial-deltaic sedimentation during the Early Tertiary, the major depocenters shifted; depocenter shifts were toward the north and east in Texas and Louisiana.

Lower Tertiary fluvial-deltaic and associated environments are represented by the Wilcox-Carrizo, Queen City, and Sparta Formations in the East Texas and North Louisiana Basins. Times of marine transgression and reworking of previously deposited fluvial-deltaic sediments are represented by the Reklaw, Weches, and Cook Mountain Formations. Cyclic deposition is shown schematically in Figure 7; an example of one progradational cycle is shown in Figure 8. Total thickness of Lower Tertiary sediments in the East Texas and North Louisiana basins is about 600 meters (Ledbetter and others, 1975); the bulk of Tertiary deposition, particularly during the Upper Tertiary occurred downdip toward the Gulf.

FIG. 7. Cyclic deposition in the Texas Eocene. Terminology from Barnes, 1974. From Kaiser (1978a).

FIG. 8. Diagrammatic stratigraphic dip section of a fluvial-deltaic progradational cycle, showing relationship and character of principal component facies. From Fisher and McGowen, 1967.

In the Mississippi Basin, younger Tertiary sediments are preserved. Eocene rocks above Cook Mountain Formation include Cookfield Formation, Moodys Branch Formation, Yazoo Clay, and Vicksburg Group. Miocene rocks also occur (Anderson and others, 1973). Total thickness of the Tertiary sediments in the Mississippi Basin is in excess of 1,000 meters. Downwarping of the Mississippi Basin apparently ceased by mid-Tertiary time and younger Tertiary sediments do not reflect the existence of the basin.

Structural Evolution

The East Texas and North Louisiana basins, and probably the Mississippi Basin, originated during the early Mesozoic. Graben structures developed subparallel to the main Triassic rift valley (Kehle, 1971; Kreitler, 1979). Where the stratigraphy and depositional history of Jurassic and Cretaceous rocks has been investigated in East Texas and North Louisiana, the influence of these sub-basins on depositional environments is obvious. By mid-Cretaceous, uplifts marginal to the basins, such as the Sabine uplift, were already supplying sediment to the basins.

The East Texas Basin resembles a syncline open to the south rather than a true structural basin bounded by uplifts on all sides. Regional warping along a northwest axis has effectively divided the East Texas Basin into two subbasins (Kaiser and others, 1978). Erosion and truncation of strata against the Sabine Uplift produces the apparent deflection of the apex of the syncline to the northeast.

The North Louisiana Basin also resembles a syncline open to the south. Smaller, "second- and third-order" structural features are apparently related to salt kinematics (Kupfer and others, 1976). Closures on these smaller features decrease to the south; the regional structure becomes a broadly warped, south dipping homocline. The apex of this syncline joins the apex of the East Texas syncline on the north side of the Sabine Uplift.

The Mississippi Basin (Salt Dome Basin) is a true structural basin. Anderson and others (1973) described the Mississippi Basin as a deep, west to northwest

trending asymmetrical depression. Displacement of the structural axis south of the topographic center of the basin has produced the basin asymmetry. The basin has little structural expression in younger Tertiary strata.

Three basic kinds of faults occur in the East Texas, North Louisiana, and Mississippi Basins: 1) regional faults associated with subsidence of the basins, 2) growth faults, and 3) faults associated with the salt domes. All faults are normal faults, most are down to the coast. Locally antithetic faults developed along with growth faults.

Of these three kinds of faults, growth faults are probably the most common. Growth faults have three unusual characteristics: 1) they flatten out and disappear at depth, 2) apparent displacement increases stratigraphically upward, and 3) movement, such as it is, occurs during or shortly after deposition. Growth faulting is illustrated in Figure 8. The significance of these faults with respect to the hydrology of the basins is to produce discontinuities in sand trends, the major conduits of groundwater. For the most part, the faults act as barriers to groundwater movement (Kreitler and others, 1977). Locally they provide a passageway for vertical leakage of groundwater between aquifers under different pressure heads.

Two kinds of faults are associated with salt domes; radial and concentric. Radial faults tend to form during piercement. Concentric faults form during collapse resulting from the dissolution of salt. Activation of both kinds of faults during the collapse stage produces local graben structures.

Post Depositional Changes and Present Conditions

Subsequent to deposition of the Lower Tertiary sediments in the East Texas, North Louisiana, and Mississippi Basins, the entire interior of the Gulf Coastal Plain was uplifted somewhat and tilted gulfward. The updip portions of the sediments have been eroded. Considerable amounts of sediment were removed from the Sabine Uplift. Differential erosion has produced a rolling topography in East Texas and the southeastern part of Mississippi where the salt domes being studied occur. Topographic relief is somewhat less in Northern

Louisiana. The northwest part of the Mississippi Basin is overlain by the Mississippi River alluvial floodplain.

Quaternary terraces and alluvium locally veneer the older Tertiary sediments. For the most part, stream development has been independent of the existence of salt domes suggesting cessation of dome movement before development of the stream or at least very slow uplift of the domes. Thus far, although one fault through Trinity River alluvium has been found in East Texas (Kreitler, 1978), no investigation has shown that Quaternary deposits in the interior of Gulf Coastal Plain have been disturbed by upward movement of a salt dome. Tiltmeters placed around selected domes also show no movement. This bears directly on the probable tectonic stability of salt domes and thus potential for alteration of the hydrologic regime around the domes.

The interior basins are presently in an erosive stage. As long as the basins remain erosional, upward movement of the domes cannot occur (Ledbetter and others, 1975; Ad Hoc Panel, 1975; Kreitler, 1979a). Rates of erosion and denudation depend on uplift of the basins with respect to sea level or eustatic changes in sea level. Using an average rate of denudation of 5 cm/1,000 years for the Gulf Coast area (Judson and Ritter, 1964), Ledbetter and others (1975) calculated that only 12.5 meters of overburden would be removed in 250,000 years. Only domes deeper than 155 meters below the present land surface have been considered for waste repositories.

Detailed structural mapping by Kreitler (1979b) shows slight uplift of the center of the East Texas Basin since deposition of the Wilcox. Analysis of depositional environments in the overlying Queen City Formation indicates shoaling of water in the center of the basin (Kreitler, 1979a). There also is some evidence that the sea level is rising, in part due to melting of polar and other glacial ice. Complete melting of the ice caps would raise the sea level approximately 65 meters (Gilluly and others, 1968). In contrast, reoccurrence of continental glaciation on the scale that occurred during the Pleistocene could lower the sea level 130 meters. Whether the effect of lowering of the base level that would occur from either basin uplift or sea level drop would be sufficient to uncover a repository is unknown. Lower sea levels during the

Pleistocene do not appear to have induced significant down cutting of streams crossing the interior basins.

GEOHYDROLOGY OF THE BASINS

Ledbetter and others (1975) present a summary of the general hydrology of the East Texas and North Louisiana Basins. Relying on data presented by Anderson and others (1973) and Payne (1968, 1970, and 1973) they reported transmissivities of Gulf Coast sands reaching $2,100 \text{ m}^2/\text{day}$ in East Texas. Hydraulic conductivities of dip-oriented channel sands varied with thickness; 3.3 m/day to 41 m/day . Regional groundwater flow velocities are reported as 0.3 m/yr to 49 m/yr . Descriptions of the hydrology of each basin is presented below.

Little information is available on the hydrology of the Mississippi Basin. Few data are published and much of what is available is contained in informal reports at the U.S. Geological Survey Office in Jackson, Mississippi (Anderson and others, 1973). C.A. Spiers (U.S.G.S., personal communication, 1980) has completed a report on the general geohydrology of the basin, but this report is still unavailable. Law Engineering Testing Company (LETCo), who is coordinating the U.S. Department of Energy geologic and hydrologic investigation of salt domes in all three states, has just completed the drilling program which is part of their first phase of work (Dave Wheelles, LETCo, personal communication, 1980) but data analyses have just begun. Anderson and others (1973) report permeabilities of 700 to $1,000 \text{ gal/day/ft}^2$ (28.5 m/day to 40.7 m/day) in the basal 30 meters of the Miocene aquifer.

East Texas Basin

In their investigation of the suitability of East Texas salt domes to provide a secure repository for high-level radioactive wastes, Kreitler (1978 and 1979a) and other researchers at the University of Texas Bureau of Economic Geology have been studying the regional hydrology of the East Texas Basin. Primary conclusions based on their first year's work are that the aquifer of principal concern is the Wilcox aquifer; 1) it covers the entire basin, 2) it is in contact with many of the salt domes, 3) it contains fresh groundwater, and 4) it

has relatively rapid rates of circulation. The Queen City also is a fresh-water aquifer, but of more local extent and in contact with fewer domes. The underlying Midway shale separates the Wilcox from saline aquifers in the Cretaceous below (Ledbetter and others, 1975); the base of fresh water is 305 to 610 meters beneath the ground surface.

Wilcox Aquifer. As previously described, the Wilcox was deposited primarily in fluvial-deltaic environments. Fisher (1964, 1969), Fisher and McGowen (1967), Kaiser (1976, 1978) have studied extensively the depositional systems and sand body geometry within the Wilcox (Figures 9 and 10). Major sand thicks deposited in fluvial-distributary channels are dip-oriented, facilitating the movement and flushing of groundwater. Flow and water quality tends to be less in strike-oriented sands and in areas where the percentage of mud is high (Payne, 1968, 1970, 1973, 1975; Kreitler and others, 1977)

Post depositional structural warping along a northwest trending axis in the center of the East Texas basin has increased dip south of the structural divide and a reversed dip north of the divide (Kreitler, 1978). Groundwater recharged at outcrop follows the structural pattern. South of the divide, groundwater flows toward the center of the basin and discharges into throughgoing streams. North of the structural divide, groundwater flow is diverted to the northeast (Figures 11 and 12). Where younger formations overlie the Wilcox, the muddier units act as aquitards, and water table conditions give way to artesian conditions.

Kreitler (1978) indicates that chemical analyses of water from wells drawing from the upper part of the Wilcox aquifer show a predominantly sodium-bicarbonate water. Little is known about the chemistry of water in the lower part of the Wilcox, but analysis of electric logs suggests higher salinities.

Queen City Aquifer. Like the Wilcox, the Queen City was deposited predominantly in fluvial-deltaic environments in the East Texas Basin (Guevera and Garcia, 1972). Erosion has removed much of the Queen City leaving isolated remnants. Recharge is local and groundwater flow is topographically controlled and under water table conditions.

FIG. 9. Net-sand map of the undivided Wilcox Group. Wilcox outcrop from Barnes, 1965, 1966, 1967. From Kaiser and others (1978).

FIG. 10. Sand-percent map of the undivided Wilcox Group. From Kaiser and others (1978).

FIG. 11. Structure map on top of the Wilcox Group, East Texas Basin. From Kaiser, W.R., personal communication, 1978, in Kreidler (1978).

FIG. 12. Potentiometric surface of Wilcox Aquifer, East Texas Basin. Note that groundwater flows north(northeast) in the northern half of the map, whereas in the the southern half flow is to the south. Flow direction is partly controlled by the structural dip of the Wilcox (Figure 11). From Kreitler (1978), parentheses added.

Where the Queen City is more extensive and is overlain by the Weches Formation in the southern part of the basin, artesian conditions prevail. Under these conditions, however, hydraulic heads in the Queen City are higher than in the underlying Wilcox and leakage is downward. Locally the Queen City is a significant recharge source of the Wilcox. Water chemistry of the Queen City is similar to the Wilcox.

The Bureau of Economic Geology at the University of Texas at Austin (BEG) is presently constructing a three-dimensional flow model for Oakwood Dome for groundwater flow through the Wilcox aquifer (C.W. Kreitler and G. Fogg, BEG, personal communications, 1979 and 1980). Results are still preliminary, but one important conclusion has been reached; the effect of salt domes on regional groundwater is minimal (results will be published in Kreitler and others, 1980). Apparently, on a regional basis, salt domes do not provide a significant barrier to the movement of groundwater through the basin. The salt domes function as minor, localized disturbances in the regional flow regime.

North Louisiana Basin

Hosman (1978) has prepared the most recent summary of the North Louisiana Basin. Because of lesser erosion than in East Texas, three major Tertiary aquifer systems are present: Wilcox, Queen City, and Sparta. As in East Texas, Cretaceous sands contain only saline groundwater. Extensive Quaternary alluvial deposits are also water-bearing.

All the strata are saturated below shallow depths. Low permeability muds and shales provide the hydraulic confinement necessary to produce artesian conditions in the permeable sands. Groundwater is under water-table conditions only in the outcrop areas of the aquifers and in some of the Quaternary deposits. Artesian conditions prevail down dip from recharge zones and restricted leakage takes place to overlying and underlying beds. The direction of vertical movement depends upon pressure differences; under natural conditions, movement is mostly upward. In general, the stratigraphically older units crop out at successively higher altitudes. This increase in altitude of recharge areas results in an increase of vertical head with depth of aquifers.

In general, the circulation of water is more rapid in younger aquifers, and they contain fresh water for progressively greater distances downdip. Figure 13 is a summary of aquifer characteristics in the North Louisiana Basin. Salt water in the Tertiary aquifers generally occur downdip from fresh water.

The Sparta Sand is the principal aquifer in the North Louisiana Basin. This is primarily because it is the shallowest and most accessible. The Sparta presently supplies sufficient groundwater to meet the areas demands, precluding the need to tap deeper aquifers. Flow rates are such that under 1975 conditions of recharge and withdrawal, approximately 4,500 years would be required for water in the vicinity of Vacherie dome to reach the City of Monroe, the major pumping center nearby (See Appendix B for basis of determination). The rate of radionuclide transport would be less as shown by Ledbetter and others (1975) and also by Hosman (1978).

Water quality within all three aquifers can vary. Generally fresh water is a sodium-bicarbonate type. Locally iron content is significant. Flow maps for the other aquifers in the North Louisiana Basin cannot be constructed because of lack of data. Other than Payne's work (1968, 1970) detailed analysis of the depositional systems and sand body geometry of Tertiary aquifers has not been made.

Mississippi Basin

As indicated earlier, few data are available on the hydrology of the Mississippi Basin. Conversations with C.A. Spiers, hydrologist with the USGS in Jackson, Mississippi, and with George Slaughter, hydrologist with Law Engineering Testing Company expanded on information available in Anderson and others (1973), Payne (1968, 1970, 1973, and 1975), and Spiers (1979).

Fresh water is abundant in Mississippi Basin aquifers. Recharge occurs at localized outcrops; surface discharge is into streams and springs. Coastward dip of the aquifers and the presence of numerous aquitards produces confined conditions at shallow depths. Where head relationships permit, discharge is vertically upward. Where there is little or no discharge, flushing of the aquifers has been minimal and groundwater is saline.

Era- them	System	Series	Group	Formation	Description	Water-bearing characteristics
Cenozoic	Tertiary	Quaternary Holocene and Pleistocene			Terrace remnants and alluvial valley fill. Coarse, graveliferous at base grading finer upward to sand, silt, and clay. Thickness about 50 to 150 ft (15 to 45 m).	Freshwater bearing. Used locally for rural supplies and some public supplies. Withdrawals range from small domestic supplies to large irrigation wells. Hydraulic conductivity ranges from 100 to 300 ft/d (30 to 90 m/d).
			Eocene	Cookfield Formation	Fine lignitic sand and carbonaceous clay. Thicker sands in lower part. Thickness about 500 to 800 ft (150 to 180 m).	Freshwater and saltwater bearing. Used mostly for small rural supplies. Hydraulic conductivity ranges from less than 15 ft/d (5 m/d) to more than 40 ft/d (12 m/d).
				Cook Mountain Fm.	Clay, partly sandy and glauconitic. Thickness about 100 ft (30 m).	Generally not water bearing. Local sands yield water to small wells.
				Spate Sand Fm.	Fine to medium sand with clay interbeds; lignitic. Thickness 500 to 700 ft (150 to 230 m).	Freshwater and saltwater bearing. Principal aquifer of north-central Louisiana. Large withdrawals by domestic, municipal, and industrial wells. Hydraulic conductivities range from 30 ft/d (10 m/d) to more than 100 ft/d (30 m/d).
				Gene River Fm.	Mostly clay; some marl. Thickness 200 to 300 ft (60 to 90 m).	Not water bearing.
				Carters Sand Fm.	Fine to medium sand; discontinuous. Thickness 0 to 150 ft (0 to 30 m).	Freshwater and saltwater bearing. Used only by a few shallow wells, mostly in the outcrop. Hydraulic conductivity about 25 ft/d (8 m/d).
			Paleocene	Wilcox Undivided Fm.	Interbedded sand, clay, and silt; lignitic. Thickness 500 to 1,500 ft (150 to 450 m).	Freshwater and saltwater bearing. Used mostly by small rural wells. Larger supplies developed locally where sands are thick. Hydraulic conductivity about 15 ft/d (5 m/d).
				Wilcox Porter Creek Clay Clayon Fm.	Marine clay with thin calcareous basal unit. Thickness about 600 ft (180 m).	Not water bearing.
		Cretaceous	Upper Cretaceous	Atoka Marl	Dark-gray marl, partly chalky. Thickness about 200 ft (60 m).	Do.
				Mcintosh Sand	Shale, sandy, calcareous; sand facies in upper part. Total thickness 250 to 350 ft (75 to 105 m). Sand-unit thickness 100 to 200 ft (30 to 60 m).	Saltwater bearing in sand facies.
				Starbuck Chalk	White fossiliferous chalk; some marl. Thickness about 50 ft (15 m).	Not water bearing.
				Marlbrook Marl	Marl, fossiliferous, chalky. Some glauconitic sand. Thickness 150 to 200 ft (45 to 60 m).	Do.
				Ammonia Chalk	Fossiliferous chalk; marl in lower part. Thickness 200 to 250 ft (60 to 75 m).	Do.
				Brownstown Marl	Calcareous clay and some sand. Thickness about 100 ft (30 m).	Do.
				Tokio Fm.	Poorly sorted sands with silt, ash, shale; lignitic, calcareous. Thickness about 300 ft (90 m).	Saltwater bearing.
				Eagle Ford Shale	Micaceous shale with some micaceous and calcareous sandstone. Thickness about 200 ft (60 m).	Not water bearing.
Mesozoic	Cretaceous			Woodbine Fm.	Interbedded shales and poorly sorted sands; trace of gravel at base. Thickness less than 200 ft (60 m).	Saltwater bearing.

FIG. 13. Generalized post-lower Cretaceous stratigraphic column for Northern Louisiana salt-dome basin. From Hossman (1978).

The relationship of fresh/saline water boundary in the Mississippi Basin aquifers is shown in Figures 14, 15, and 16. As can be seen, the base of fresh water moves upward through the section in one or more steps in a coastward direction. The base of fresh water is approximately 300 meters in the vicinity of the salt domes. The tops of the domes being considered for nuclear waste repositories may be in contact with fresh water, but the sides of the domes are in saline water. For this reason, the geohydrology of saline aquifers in the Mississippi Basin must be investigated.

Available information indicates that saline groundwater in the Mississippi Basin is confined by the structural boundaries of the basin. Discharge can only occur upward through confining layers. Piezometric measurements indicate little potential for saline groundwater movement. Temperature and density differences and natural gas in the saline groundwater may be more important in driving water movement. Temperature and salinity increase linearly with depth. Unless leakage through confining beds proves to be significant, however, radionuclides that escape from potential nuclear waste sites in Mississippi domes would not be transported to the biosphere.

FIG. 14. Contour map showing base of fresh groundwater, in feet below sea level, in the Mississippi salt-dome basin. Long-dashed lines show approximate trace of discontinuities in contoured surface. Modified from Newcome (1965, 1967); Lang (1972); Shows and others (1966); Callahan and others (1964); Newcome and Thomson (1970); and Taylor and others (1968). Contour interval 500 feet. Modified from Anderson and others (1973).

FIG. 15. Geohydrology section across Smith and Scott Counties, Mississippi, showing the relationship between the base of the fresh water and the coastward-dipping aquifers. Modified from Boswell and others (1970) in Anderson and others (1973).

III. DESCRIPTION OF SALT DOMES

Salt domes are commonly circular or elliptical structures in plan view. Downward expansion is also common so that most domes have the form of a truncated cone (Figure 17; Muehlberger and others, 1958). Major deviation from this shape occurs where the top of the dome has taken on a distinct mushroom shape and the top of the dome overhangs the central stock. The tops of some domes are irregular, indicating movement of separate splines of salt; however, this is much more common in coastal than interior domes (Kupfer, 1970).

Knowledge of dome geometry is essential to insure that no part of the repository is too close to the dome margin. Even if dissolution of the selected dome does eventually occur, other things being equal, the more salt that has to be dissolved before the repository is breached, the more the contained wastes will have decayed before entering the groundwater system. All salt domes in the East Texas and North Louisiana Basins occur in the central parts of the basins where subsidence is greatest. This is expected regardless of their origin (see below). Salt domes in the Mississippi Basin also occur in the central part of the Basin; however, basin shape is asymmetrical, with the steeper side on the southwest. Only in the southern part of the basin have salt domes risen close enough to the surface to be considered for disposal of nuclear waste (Anderson and others, 1973)

SALT DIAPIRISM

Salt diapirism is the process by which salt domes are formed. In the following paragraphs the mechanism which drives this process and the growth cycle which is its result are discussed.

Driving Mechanism

Four mechanisms have been advanced to explain why salt domes form and to account for the necessary forces: 1) basement faulting, 2) buoyancy of the salt, 3) heat, and 4) differential loading.

FIG. 17. True-scale cross section of Vacherie Salt Dome showing selected horizons. Double arrow indicates rim syncline for the Lower Austin Group (Crowe, 1975). From Kupfer and others (1976).

Faulting in basement rocks has been suggested by Paulson (1970) as a triggering mechanism for the formation of salt domes. No other geologist has considered this mechanism as essential to the growth of domes.

Buoyancy arising from density differences between the mother salt horizon and overlying sediments is the most commonly advanced explanation. Depending on the amount of impurities, salt attains an average density of 2.2 gm/cm^3 . At deposition, water charged terrigenous sediments deposited over the salt are less dense. With increased burial, the sediments tend to dewater and become more dense than the underlying salt. The depth at which this can be expected to occur is about 1,200 meters (Kehle, 1972).

Kehle (1972, 1978) has shown, however that the hydraulic forces imparted on the salt layer by buoyancy effects alone are insufficient to induce movement in salt. Such forces exist, but are relatively small with respect to other forces.

Gossow (1966, 1968, 1970) has similarly stated that buoyancy forces alone are inadequate to overcome internal resistance to movement within the mother salt layer. He notes, however, that heat will greatly reduce shear strength of the salt promoting flow. Assuming a reasonable geothermal gradient, Gossow calculated that at about 4,000 meters of burial salt becomes plastic and at 8,000 meters it becomes sufficiently hot to flow readily. Intrusion is postulated to be very rapid. Domes which reach the surface form salt mountains up to 1,200 meters high and salt flows; upward and outward movement continues until the salt cools below 200°C and the extruded salt is dissolved. Talbot (1978) expanded on this hypothesis by suggesting that thermal convection takes place in the salt layer and that some salt domes develop as thermal plumes.

The chief problem with hypothesizing that relatively high heat is necessary to form salt domes is the depth required. Analysis of structures associated with salt domes strongly suggests that movement first occurred shortly after burial at relatively shallow depths (Kupfer, 1976; Kreitler, 1979a) and that quite possibly the domes didn't grow upward so much as the mother layer subsided. This is not to say that heat does not have a role in the movement of salt

domes. Heated salt, particularly in the presence of water, flows readily (Ode', 1962). An interesting corollary of this hypothesis, though, is that once the salt stock rose sufficiently high to be hotter than its surroundings, the greater heat conductivity of salt would promote rapid cooling and movement of the salt would not occur again (Gossow, 1968).

Kehle (1972, 1978) and Gera (1972) have suggested that differential loading associated with deltaic progradation is the major force inducing movement of underlying salt. Using relatively a simple model, Kehle shows that the amount of force imparted to the salt by differential loading is 80% more than that of buoyancy forces in that the forces are due to the density difference of sediment and water, not sediment and salt. Moreover the effects of differential loading are independent of the thickness of sediment over the salt. This hypothesis is consistent with observations that salt diapirism began shortly after burial of the Louann salt at shallow depths. Kreitler (1979a) states that salt migration and diapirism began in Late Jurassic to Early Cretaceous. As with Gossow's hypothesis, a significant corollary to Kehle's and Gera's hypothesis is that once active sedimentation ceases in an area, forces capable of initiating or reinducing salt movement no longer exist.

Growth History

Over the last twenty years, geologists have begun to recognize that formation of piercement salt domes is characterized by a definite cycle. Trusheim (1960) was the first to recognize cycles of growth. Kehle (1972), Kupfer and others (1976), and Kreitler (1979a) also have recognized that salt dome growth occurs in stages. Each postulates approximately the same growth cycle.

Kreitler states: "The growth history of a dome and whether a dome has completed the growth cycle is important in determining its geologic stability. The growth history of a salt dome probably follows a generalized pattern: 1) bedded salt, 2) pillow stage, 3) diapir and rim syncline, 4) extrusion and rim syncline collapse (in some cases), 5) postextrusion, low rate of diapiric movement, and 6) end of salt migration." (Figure 18).

FIG. 18. Schematic history of salt dome growth. Salt diapirism follows a pattern of bedded salt, diapirism and rim synclines, extrusion and rim syncline collapse, slow growth that is post-extrusion, and finally, quiescence. Modified from Trusheim (1960) in Kreitler (1979a).

The importance of recognition of salt dome growth cycles is:

- 1) Growth cycles are now recognized in several salt dome provinces.
- 2) Each of the cycles postulated has a definite beginning and end; once a dome has reached the end of its cycle, reactivation of salt movement will not occur.
- 3) Subaerial or subaqueous exposure during the growth cycle, at least in East Texas, is probable. During this exposure considerable amounts of salt and possibly cap rock have been removed.
- 4) The thickness of cap rock is probably an unreliable indicator of the amount of salt dissolved from the top of the dome and the average rate of movement of the dome; the most reliable measurement of salt removed from the dome is based on the volume of salt displaced by the collapse of rim synclines and the amount of salt contained in the salt stock.

It is also increasingly being recognized that initiation of salt migration into pillows and formation of piercement structures occurred soon after burial of the mother salt layer. As mentioned earlier, this observation is consistent with Kehle's (1972) and Gera's (1972) hypothesis that differential loading is driving force in the formation of salt domes. Late Jurassic deltaic deposition in Louisiana and Mississippi and Early Cretaceous fluvial-deltaic deposition on East Texas probably initiated domal growth (Kreitler, 1979a). Growth of domes in all three basins continued through the Early Tertiary.

As clastic depocenters shifted gulfward later in the Tertiary, differential loading of the salt was reduced and salt dome movement ceased, probably by Miocene time. Reloading of the basins on the scale that occurred during the Cretaceous and Early Tertiary would be required to induce reactivation of the salt domes, assuming sufficient salt remains in the mother salt layer to supply further growth of the domes. A major change in eustatic sea level, even greater

than could occur if the polar ice caps were to melt (65 meters) would be required to resubmerge the interior basins.

Estimates of how much salt has been dissolved from the domes are based on the thickness of caprock and on the volume of salt lost as evidence by collapse of rim synclines. The origin and characteristics of caprock are described later in this chapter. A major flaw in using the thickness of caprock to determine how much salt has been lost is that caprock might have also been lost during an extrusive stage.

Estimates of salt lost from domes based on collapse of rim synclines are much more reliable. The Bureau of Economic Geology (Kreitler and others, 1980) has found that for some domes only 10 percent of the amount of salt that has moved up through the dome remain in the salt stock.

Several authors have calculated rates for salt dome growth in interior basins for various periods of time based on assumed depositional rates and measured stratigraphic thinning (Netherland, Sewell, & Associates, 1976; Martinez and others, 1977; Kumar, 1978). Rates vary through time (Table 1) and between basins, but estimated rates during the active growth stages (Early Cretaceous to Early Tertiary) are approximately .001 mm/yr to .04 mm/yr. Netherland, Sewell, & Associates has determined that the average growth rate for East Texas domes since deposition of the Wilcox is only .006 mm/yr. Faster rates of salt dome movement have been estimated for coastal and offshore domes (see Ledbetter and others, 1975).

Applying these rates to the 250,000 years considered necessary for the nuclear wastes to decay to innocuous levels of activity yields a maximum amount of dome uplift of 10 meters and a minimum amount of uplift of slightly over 1 meter. While these amounts of uplift may not be inconsequential in terms of their impact on the hydrologic system surrounding the repository dome, it should be remembered that these are average rates and that there is no evidence that any of the domes under consideration are moving.

Table 1. Range of growth rates (mm/yr) of salt domes of the North Louisiana Basin.

Stratigraphic Interval	Range of Average Growth Rates mm/yr		
	(Minimum)		(Maximum)
Cenozoic	0.001 (Chester)	-	0.027 (Vacherie)
Upper Cretaceous	0.001 (Sikes)	-	0.019 (Winnfield)
Lower Cretaceous	0.009 (Prothro)	-	0.042 (Vacherie)

From Martinez and others, (1977).

CHARACTERISTICS OF SALT DOMES

The characteristics of salt domes described briefly below are general characteristics or are based on studies of domes not presently being considered as a nuclear waste repository. These descriptions provide insight into what can be expected for the dome(s) selected as a repository. Determination of the physical and chemical characteristics of the specific repository dome(s), for the most part, will have to await selection of the dome and initiation of repository construction.

Mineralogy

Salt domes consist predominantly of the mineral halite (NaCl). Impurities within the salt, mostly anhydrite (CaSO_4), range from 1 to 15 percent. The latter figure probably represents a local concentration of anhydrite; 1 to 3 percent impurities can be considered the norm. Interior domes apparently contain more impurities than coastal domes (Ledbetter and others, 1975). The rise of coastal domes from greater depths apparently has a "cleansing affect". Typical chemical composition of domal salt is shown in Table 2.

Structure

Most domes are mined by a solution process which prohibits direct observation of internal structure. Eight domes have been mined by conventional underground methods: Grand Saline and Hockley in Texas and Winnfield, Jefferson, Avery, Weeks, Cote Blanche, and Belle Isle in Louisiana (Figure 19). The last five of these domes and Hockley domes are coastal domes. Mapping of the five domes has been attempted at one time or another (Table 3).

The internal structure of salt domes is very complex (Figure 20). Refolded isoclinal, strongly attenuated folds about vertical axes predominate. Folding is evidenced by light and dark banding within the salt. Local shear zones have been interpreted. Kupfer (1968, 1970, 1974 and 1976) sees faults in domes he has mapped. He infers that the faults separate distinct splines within the

Table 2. Typical chemical composition of domal salt.

Constituent	Percent Abundance
NaCl	99.03
CaSO ₄	0.22
MgCl ₂	0.01
CaCl ₂	0.01
H ₂ O	0.02
H ₂ O Insoluble	<u>0.71</u>
Total	100.00

From Gilbert and Pilcher (1970)

FIG. 19. Index map showing location of Gulf Coast salt domes in which salt has been mined and salt structures can be observed. From Kupfer (1968).

TABLE 3. Status of geologic mapping in subsurface salt mines of the Gulf Coast of the United States.

NAME AND DESCRIPTION	MAPPED BY	COMMENTS
Grand Saline Dome Kleer Mine Morton Salt Co. Van Zandt Co., Tex.	Robert Balk AAPG, 1949	Classic paper Remapped by Muehlberger, Tex. Bur. Ec. Geol., 1959 Int. Geol. Cong., 1960
Jefferson Island Dome Jefferson Mine Diamond Salt Co. Iberia Parish, La.	Robert Balk AAPG, 1953 (Assd. by G.T. Duvall)	Similar to Grand Saline Needs mapping in newer workings.
Winnfield Dome Carey Mine Carey Salt Co. Winn Parish, La.	Hoy, Foose, and O'Neill AAPG, 1962	Stanford Research Inst.
Weeks Island Dome Weeks Mine Morton Salt Co. Iberia Parish, La.	Donald Kupfer AAPG, 1962	Lower level mapped, upper level to be mapped
Avery Island Dome Avery Mine International Salt Co. Iberia Parish, La.	McMullen and Doxey (Unpublished)	Mapped summer 1961
Hockley Dome Hockley Mine United Salt Co. Harris Co., Tex.	Muehlberger and students (1961) (Unpublished)	Reconnaissance map, structure is very simple (personal communication, 1962)
Core Blanche Dome Carey-Monsanto St. Mary Parish, La.	Unmapped	Shaft sinking now in progress
Belle Isle Dome Cargille Corp. St. Mary Parish, La.	Unmapped	Shaft sinking now in progress
Tatum Dome Lamar County, Miss.	?	Atomic Energy Commission
Bruinsburg International Salt Co. Claiborne Co., Miss.	Unmapped	Exploration drilling under lease and option

Taken from Kupfer (1963)

FIG 20. Pattern of layering in salt on 758-ft. level of Morton Salt Company mine at Weeks Island, Louisiana. From Kupfer (1962).

dome which moved somewhat independently. Some coastal domes have blocks of the host sediment entrained in them.

The distribution of impurities within the dome probably mimics original depositional layering (Kreitler, BEG, personal communication, 1979, 1980). Kupfer (1968) has likened the formation of salt domes and the internal fold patterns to drawing layers of wet multicolored tissue through a ring producing a star shaped configuration. While this does display the general types of folding occurring within a salt dome, the analogy should not be extended to suggest that salt and the surrounding country rock are so deeply infolded that the salt-country rock interface occupies a significant amount of the maximum diameter of the salt stock; there is no evidence for this.

One other factor should be born in mind. Because of accessibility, most of the mapping and description of the internal structure of salt domes is based on work in coastal domes. Although they do not elaborate, Kupfer (1970, 1974) and Atwater (1968) have pointed out that coastal domes are probably much more complex than interior domes and information derived from coastal domes should not be applied to interior domes without question. Coastal domes are younger and have pierced through twice as much sediment as interior domes. The Louann salt has been depressed much deeper along the coast (50,000 feet) and subjected to greater heat. In addition, host sediments along the coast are anomalously overpressured. Because of greater heat, greater rise through the sediments, and perhaps faster movement, the internal structure of coastal domes shows evidence of greater flowage, refolding and attenuation (Ledbetter and others, 1975). Folds in interior domes are simpler and more typical of solids deformed under greater confining pressure. Salt crystals in coastal domes appear to have suffered greater recrystallization and are somewhat larger than in interior domes.

Physical Properties

Creep. Mine closure rates are relatively rapid at first, but decline with time, gradually reaching a steady state. At Avery Island, Louisiana (Figure 20) at the 550 feet mine level, closure rates have reached a steady

state of .5 in/yr after 80 years (L. VanSanbeck, RESPEC, personal communication, 1980). Reynolds and Gloyne (1960) reported on mine closure rates at Hutchinson, Kansas, and at Grand Saline in Texas (Figure 4). Their measurements also indicated that creep rates decline within a short time after a new mine is opened.

The long history of mining in salt domes demonstrates that the creep rate at all times is sufficiently slow to be of little or no problem during the life of operations. Heat can increase the rate of creep; however, even with the application of heat, the rate of creep declines with time (Parker and Blanco, 1963).

Permeability/Porosity. Measurements of the natural permeability and porosity of salt domes were made by Serate (1960) and Gloyne and Reynolds (1976). Gloyne and Reynolds measured permeabilities of 0 to 1.5×10^{-9} cm² in domal salt and an effective porosity of 1.71 percent. Measurements were made in the laboratory, and are at the low end of the permeability scale. Gloyne and Reynolds (1975) concluded that in situ permeabilities would be even less. The basic shape of salt crystals (cubic) and lack of intergranular pore space prevents development of significant permeability.

Secondary porosity and permeability via fractures might develop locally in a dome and could cause a dramatic rise in movement of fluids through the salt. Unless the fractures were very wide and long, they would heal themselves, through creep or perhaps by re-precipitation of salt.

Thermal Properties. The thermal properties of salt are of importance in the use of salt domes as repositories for nuclear waste. Three factors must be considered: 1) heat conductivity, 2) effect of heat on the strength and rate of deformation of salt, and 3) thermal expansion. A fourth factor, presence of fluid inclusions, is not a thermal property, but is discussed here because of the effect of heat on the inclusions.

The thermal conductivity of salt is 0.8 to 1.7×10^{-2} cal/in/sec/°C or about two to three times the conductivity of quartzose sedimentary rocks (Table 4; Bear,

TABLE 4. Heat conductivity of various rocks.

Rock	Heat Conductivity [†]	Rock	Heat Conductivity [†]
Basalt	5.2	Graphite	12.0
Chalk	2.0	Gypsum	3.1
Concrete, cinder	0.81	Halite	17.0
Earth's crust, average	4.0	Marble	7.0
Granite, 100°C	4.5-5.0	Dry Sand	0.93
Quartz			
Parallel to axis	30		
Perpendicular to axis	16		
Sandstone	3.5-10.2*		
Shale	2.8-6.9*		
Slate	4.7		

Most values taken from 42nd edition of CRC Handbook.

*From Table 17 Ekren (1974).

+10⁻³ cal/cm/sec/°C

1971; Gera, 1971). The net affect of this higher heat conductivity is to dissipate heat produced during radioactive decay of the nuclear waste much faster than other potential hosts for the wastes. Strata and groundwater bounding the salt will receive this heat much faster than from a repository in other media, other things being equal. The rise in temperature should be slight, however. Salt domes also should transmit normal geothermal heat better than surrounding sediment. If this were occurring it would affect the hydrology around the dome. No heat anomalies have been detected over domes in East Texas, however (Kreitler and others, 1980). It is likely that after 30 million years, salt domes are in thermal equilibrium with their surroundings.

The effect of heat on the strength of salt and its ability to flow has been extensively discussed by Gussow (1966, 1968, 1970). Although his conclusions about salt diapirism can be questioned, Gussow does document that increasing heat decreases the strength of salt and promotes plastic flow. As mentioned previously, Parker and Blanco (1963) show that heat increases the rate of creep in salt, although the rate declines with time.

Like most natural materials, salt expands as its temperature is raised. Therefore, the addition of heat from the radioactive waste may cause some movement of the sediments in the vicinity of the dome. Gussow (1970) states that the maximum expansion that can be expected is six percent. Ledbetter and others (1975) calculated that the maximum amount of upward movement of a dome that can be expected is approximately 20 meters; but that closure in the mine might cancel this out.

RESPEC is conducting heater experiments in the Avery Island salt dome (Figure 26). The mine level where the heaters are emplaced, is at 550-foot level. In the area where the heater experiments are taking place, the rooms are 25 feet high with no support. The floor above the heaters has risen slightly. Above the site with the maximum power output the floor has risen 0.17 inches. Slight expansion stress on the salt has been detected immediately outside the zone of the heaters, but no expansion is measurable (L. VanSanbeck, RESPEC, personal communication, 1980). Modeling based on the heater experiments demonstrates that if the heat source were run for several hundred years, the effects of thermal expansion would migrate through the mine to the surface.

Computer simulations of the expansion of the salt due to the additional heat also have been conducted by Dwyer and Thomas (1974) of Louisiana State University. RESPEC and Dwyer and Thomas models are based on different assumptions and, therefore yield different results. The Dwyer and Thomas model predicts that the salt dome would expand laterally and the top would sink, following the basis approach taken earlier by Dwyer (1973). The RESPEC model, on the other hand, predicts that the expansion would be vertical. Different timespans for heating were used in each model.

In the RESPEC model maximum displacement occurs directly above the repository. The displacement curve is dome-shaped with displacement dropping off sharply with increasing distance from the center. Maximum displacement varies, depending on the type of waste and the size of the dome, from 4 feet to 8 feet (1.2 mm/yr - 2.4 mm/yr) directly above the center of the dome. Between 1,000 and 2,000 years are necessary for the displacement to reach a maximum. After the maximum is reached and the repository cools, the land surface will subside (G. Callihan, RESPEC, personal communication, 1980).

In Dwyer's (1973) model it was assumed that the dome was tear dropped shaped and detached from the mother salt layer. There is no concrete evidence that any of the interior domes are detached from the Louann Salt. Furthermore, it was presumed that the dome could expand laterally. This would require displacing or compressing the sedimentary column around the dome. It would be far easier to displace the top of the dome upward along existing planes of weakness. Both models indicate that some displacement can be expected to result from the heat added to the system by the radioactive wastes. Displacement will be highly localized--a mile from the repository it was predicted to be zero. Whether this will provide significant change in the geohydrology cannot be determined.

Computer models for thermal expansion are useful to indicate that measurable expansion will take place. At this stage in their development, they should not be construed to indicate the real magnitude of the displacement; that will depend on the actual shape and size of the dome, the magnitude and spacing of the heat sources, and the size of the mine opening among other factors.

Furthermore, neither of the models discussed considered the effect of the mine opening. Some of the thermal stresses will be dissipated by closure of the mine opening itself. How much of the thermal stresses can be dissipated by closure within the mine must be determined on a site specific basis. A beneficial effect of the expansion (and flow) of salt at elevated temperatures would be the increased tendency to close or heal fractures through the repository.

It has long been known that salt domes contain small brine-filled inclusions and that elevating the temperature at a point within the dome will promote migration of the inclusions toward the heat source. The amount of brine involved, the rapidity with which the inclusions would migrate toward the heat source, and the affect on the repository are subject to debate. Ledbetter and others (1975) concluded that the fluid inclusions presented little or no problem. In that the inclusions migrate toward a heat source and are not hydraulically connected to groundwater outside the dome, they do not represent a mechanism of radionuclide transport to the biosphere. It is likely that the principal problem associated with the presence of the brine inclusions is corrosion of the waste canisters. Evenson and others (1979) and Bradshaw and others (1968) describe other potential problems associated with brine inclusions. Evenson and others conclude that the problem is local; the problem raised by Bradshaw and others can be eliminated by proper mine design.

Gas and Brine Pockets. In several of the coastal domes and in Winefield Dome, gas and brine pockets have been encountered during mining operations. In the case of Belle Isle, the encounter was explosive. For the most part the problem is minimal and flow of gas or brine ceases in a short time indicating no connection with outside sources. Problems associated with encountering gas or brine pockets in a repository dome would occur during construction of the repository itself before emplacement of nuclear wastes.

Caprock

Caprock composed of various amounts of anhydrite, gypsum, and limestone occurs on many domes. Four theories have been advanced for the formation of caprock.

Two theories--two residual in place accumulation (Taylor, 1938) and re-precipitation (Walker, 1973, 1976)--are the most accepted theories. Both theories involve dissolution of pure salt and accumulation of impurities in the domes. Data are insufficient to determine which, if either theories are correct. Kreitler and others (1980) have studied a core through caprock into salt of Gyp Hill, a salt dome in South Texas. Using a set of photomicrographs, they can demonstrate preservation of anhydrite crystal size from fresh salt into the caprock, lending strong support to the residual-in-place theory.

Caprock is so variable that it is difficult to characterize its hydrologic characteristics accurately. Water, whether it is groundwater or surface water, fresh water or salt water, had to circulate around the salt dome at some time in the past. Continued formation of caprock today would involve the dissolution of salt and, therefore, a distinct saline plume or springs should be evident. No definite saline plumes or springs of sufficient magnitude have been identified. Therefore, it must be concluded that no flowing groundwater or minimal amounts are in contact with the upper part of domes at present. Post depositional alteration of caprock apparently can render it rather tight. Caprock on Oakwood Dome is tight (Kreitler and others, 1980), although petroleum reservoirs in caprock suggest extensive fracturing (Hanna, 1953).

SALT DOME/COUNTRY ROCK INTERFACE

Probably less is known about the interface between the salt dome and adjacent sediments than any other aspect of salt domes. Yet the nature of this boundary is extremely critical to the hydrologic stability of salt domes. Several authors (Hanna, 1953; Hosman, 1978; Kupfer, 1970, 1974; Anderson and others, 1973) report that salt domes are apparently surrounded by a clay sheath or gouge material (which is not described) which either was dragged up with the salt domes or intruded along side of the domes and may be highly fractured and brecciated. Others, such as Guevara and Giles (1979, Figure 6) show that caprock may occur on the sides of a dome as well as the top.

Obviously, faults or permeable material could abut against the outside edge of domes. If the dome is not dissolving and it is surrounded by fresh-water

bearing sediments, something is keeping the water from coming in contact with the soluble salt and protecting the dome from dissolution. The absence of a saline plume in the fresh water aquifer surrounding a dome indicates that some process or structure exists that is protecting the dome from dissolution.

RESOURCE POTENTIAL

Other than the salt itself, salt domes being considered for disposal of nuclear wastes have little resource potential. Commonly associated resources of primary interest are oil and gas, although the potential for uranium, lignite, and clay also must be considered. Description of the resource potential of Oakwood and Keechi Domes are presented in Appendix A; Keechi Dome is not productive, but Oakwood Dome is. Kupfer and others (1976) reported that most oil and gas in the North Louisiana Basin is associated with sediment thicks between the domes. Anderson and others (1975) found no record of oil and gas finds in the Mississippi domes. Oil and gas associated with domes is found in structures adjacent to the domes beneath a salt overhang or in caprock, but never within the dome itself. Furthermore, work at the Bureau of Economic Geology at the University of Texas at Austin (Kreitler and others, 1980) has shown that the potential for petroleum resources associated with a salt dome is related to its growth stage. The Texas Bureau of Economic Geology is presently developing a predictive model based on empirical data which relates the presence of oil and gas to growth stage and position in the basin. Domes which have been exposed some time during their history are extremely unlikely to contain any oil and gas resources.

Potential occurrence of economic resources of uranium, lignite, or clay resources is equally slight. While uranium might have once been present near candidate domes, flushing by oxidizing groundwater has probably removed it all. Lignite occurs in the Wilcox of East Texas, but extraction by either conventional or in situ conversion is profitable only in relatively large, undisturbed areas. To be considered a resource, clay deposits also must be mined in a relatively large undisturbed area. Deformation of strata adjacent to domes reduces the likelihood that either clay or lignite occurring near a dome can be considered a resource.

Essential points to bear in mind when considering the co-resource problem are:

1. The resource potential of any dome(s) selected as a nuclear waste repository will have already been assessed.
2. It is within geologists' capability to predict whether a given salt dome has any resource potential, particularly oil and gas, precluding the necessity of drilling out every dome to determine the likelihood that resources are present.
3. Even if a repository dome were unintentionally drilled into at some time in the future, it is unlikely that drilling would proceed far into the dome. Even early geologists recognized that oil and gas resources are very unlikely to occur within salt.

Wick and Isaac (1978) hypothesized that salt domes should be considered as a vast source of energy developed through dissolution of domes and creation of osmotic pressure differences between two fluids. Even if the method becomes practical, however, withdrawal of a few domes for disposal of nuclear waste should not significantly reduce the total amount of energy available from salt. Furthermore, the environmental consequences of dissolving all domal salt in the Gulf Coast probably exceed considerably the consequences of disposing of nuclear waste in salt domes.

CHAPTER IV. CONCEPTUAL MODEL OF REGIONAL RADIONUCLIDE TRANSPORT WITHIN A SALT DOME BASIN

INTRODUCTION

In this chapter we develop a conceptual model of regional radionuclide transport from a salt dome repository. Because of the clastic nature of the sedimentary basins in which salt domes occur, regional flow and transport systems can be modeled through application of existing geohydrologic data collection and modeling techniques. These techniques must, however, be applied with certain recurring structural features in mind, as well as the types of boundary conditions that might be expected. The processes and parameters which must be modeled are, except in the immediate vicinity of the domes, the same processes and parameters that have been modeled in scores of more conventional regional flow and water quality studies that have been carried out by geohydrologists. These regional processes and parameters as well as the processes and parameters active in the vicinity of the domes, as they effect the regional model, will be discussed at length in Chapters V and VI.

As noted above, in the immediate vicinity of the salt domes the geohydrologist is faced with a less conventional set of processes and parameters which influence radionuclide transport. Although these processes are so localized that they probably will not be included in the regional model, they dictate the rate and concentration at which radionuclides are released to the regional transport system. Thus these processes must be properly understood and their outcome predicted in order to specify realistic, meaningful source terms in the regional model.

BASIC STRUCTURE OF THE REGIONAL MODEL

A regional model of radionuclide transport within a salt dome basin must take into account a number of basic properties of the salt dome basin if meaningful results are to be obtained. Among these are:

- ° the composition of the aquifers, which make up the basin,
- ° the structure of the basin, and
- ° the role of salt domes in the basin.

Each of these factors will be discussed below.

Composition of the Aquifers

The aquifers of principal interest in studies of the regional transport of radionuclides from salt dome repositories are the fresh-water aquifers. These are the aquifers that are most likely to allow discharge of the radionuclides to the biosphere through non-catastrophic means. These fresh-water aquifers are generally the shallowest, the ones from which water is pumped for human use and the most likely to discharge to surface streams and springs. Generally, experience suggests that the water in the saline portions of the aquifers and in the saline aquifers themselves is essentially stagnant. In fact, saline aquifers in all three salt dome basins are used for deep well disposal of wastes because of their lack of contact with either the biosphere or the fresh-water aquifers. Therefore the regional model need include only the fresh-water aquifers at this time.

The aquifers in these basins are clastic sedimentary aquifers (Tertiary age) consisting predominantly of interbedded sand and mud. Porosity and permeability are primarily intergranular throughout the region. Neither fracture flow nor cavernous flow occurs at the regional level. Even at major discontinuities such as faults which might act as conduits, porosity and permeability are primarily intergranular. Thus conventional groundwater models should apply quite well within the aquifers.

Basin Structure

The salt dome basins are made up of layers of aquifers, such as described above, separated by more or less extensive aquitards. The aquifers are generally fairly continuous but may pinch out along strike and down dip. Certain of the aquifers, e.g. the Queen City aquifer in the East Texas

Basin, have been eroded and exist primarily as isolated remnants. The aquitards, which may be hundreds of meters thick, pinch out along strike and up dip.

The basin system is therefore basically a layered system with layers (aquifers) that tend to vary considerably in thickness, areal extent and thickness. Although a layered model may be a convenient conceptual model of the basins, there are several important geohydrologic controls generally not considered or included in models of groundwater flow systems that must be included in the conceptual salt dome basin model. These controls suggest that a simple layered model is not sufficient and that a fully three-dimensional model or a very specialized layered model may be required.

Primary geohydrologic factors which must be considered in conceptualizing a groundwater model of radionuclide transport are:

1. the configuration and development of the basin,
2. the kinds of depositional systems which filled the basin and their orientation with respect to structural dip,
3. syn- and post depositional structural modifications, and
4. post depositional erosion and development of surface topography.

The configuration and development of the basin exerts a first order control on the geohydrology of the basin by influencing:

1. the distribution of outcrop and aquifer recharge areas,
2. the occurrence of major hydrologic barriers,
3. the direction and amount of primary structural dip, that is the dip of the major layers, as it was during deposition and as it is now, and
4. the positions through time of major sedimentary depocenters.

Understanding of the kinds of depositional systems which filled the salt dome basins and their spatial and temporal relationships provides key information on:

1. sandy body distribution, geometry, thickness and orientation--an index to permeability,
2. lateral and vertical facies changes and thus further knowledge of permeability distribution, including permeability changes down depositional, structural, and hydrologic dip, and flushing rates and water quality.

Figure 8 schematically illustrates down dip facies changes and thus changes in permeability. Figures 9 and 10 illustrate gross sand body distribution, thickness, and orientation, and by inference, lateral facies changes of one fresh-water aquifer, the Wilcox Formation of East Texas.

Syn- and post depositional structural modifications produce:

1. structural and hydrologic subbasins,
2. dip reversal and realignment of structural, depositional, and hydrologic dip, and
3. hydrologic discontinuities, such as faults.

Lastly, post depositional erosion and development of topography influences head relationships between aquifers, which can be complex, and the locus of groundwater discharge. Comparison with recent analogs and general sedimentary models provides a predictive tool to fill data gaps.

In all three Gulf Coast Salt Basins, there is a major factor that cannot as yet be included in regional transport model applications. This is potential vertical leakage through exploration or production drill holes. Although complete records are kept now, it is quite probable that unrecorded holes occur in the basins. In addition, some holes may be incompletely or improperly cased or plugged, and even properly cased and/or plugged holes may fail within the time frame necessary for the radioactive wastes to decay to harmless levels. Should a dome repository site be selected, a concerted effort must be made to insure that all drill holes in the vicinity have been found and there is no evidence of impending failure.

Effects of Salt Domes in the Regional Flow System

In Chapter II, the preliminary results of a modeling study of groundwater flow through the Wilcox aquifer (C.W. Kreitler and G. Fogg, BEG, personal communications, 1979 and 1980) were mentioned. These results, as yet unpublished, suggest that the disruption of the regional flow field is very minimal. Figure 21 illustrates in plan view the kind of disturbance to the regional flow field that might be expected around a salt dome. The small disturbance raises the question of whether or not the domes need to be included in the regional model.

We suggest that, unless the entire basin is being modeled (that is, hundreds of miles), that domes be included until further studies demonstrate that they are never important. Studies under many different conditions and correlation of regional results to the results of more detailed models are required before this conclusion can be reached. In applications, the primary parameter describing domes in a regional model is dome geometry since they are impermeable and essentially inert sections of the basins. Therefore parameterization should not be a problem.

HYDROLOGIC BOUNDARY CONDITIONS FOR THE REGIONAL MODEL

In Chapter II, the general geohydrology of the salt dome basins in East Texas, North Louisiana, and Mississippi are described. Although each of the basins has a distinctive geohydrology a general set of boundary conditions that feed and deplete the basin-wide hydrologic and transport systems may be suggested on the basis of that discussion. The modeler must be prepared to include any or all of these boundary types in models of the salt dome basins.

The basins generally receive water from one of two sources:

- ° recharge areas at aquifers outcrops, and
- ° leakage from overlying or underlying aquifers.

The areas in which one of the aquifers in the basin outcrops can surround the basin on all or just a few sides and may extend into the areas containing salt

FIG. 21. Exaggerated effect of salt dome on regional flow path.

dome region. The aquifer is unconfined in and near these areas and is capable of receiving a substantial amount of recharge (unless already full). In those areas where the aquifer is overlain by another aquifer, but separated by an aquitard, piezometric head and topographic differences between the aquifers can lead to leakage either to or from the lower aquifer.

There are a number of possible sinks into which the regional flow system can flow. The primary sinks are:

- ° discharge upward into surface streams and springs
- ° pumpage centers
- ° leakage into saline aquifers
- ° mixing with saline water in the down dip portions of the aquifers.

The first two sinks are principal routes for radionuclide transport to the biosphere and thus must be well understood. The last two sinks involve losses of water to the nearly stagnant saline zones in the deepest portions of the aquifers and in the deepest aquifers. There is probably very little flow within these deep aquifers and thus radionuclides and other wastes that reach these aquifers are less likely to reach the biosphere.

Generally, except in outcrop areas, the upper boundary of the aquifers in the basins are aquitards which allow significant hydraulic connections to overlying aquifers. The upper boundary of the basin as a whole is the ground surface or water table. The effective lower boundary of the basins are the deep nearly stagnant saline aquifers.

The edges of the basins may be defined by the outcrops of the oldest fresh-water aquifers, the downdip stagnant saline zones and by outcrops of impermeable materials underlying the basin. The prime example of the latter boundary type is found in the Mississippi basin which lies in a relatively impermeable "cup" of aquicludes. Discharge from this basin is essentially all vertical (Spiers, 1979). The boundary between the East Texas and North Louisiana basins falls in none of the above categories. In fact the basin

boundaries are largely defined in this instance by the political boundary between the states. Thus the hydrologic boundary between the basins would have to be chosen along a water divide, keeping in mind that pumpage changes or other geohydrologic changes might alter the geometry of this boundary.

If the entire basin is not to be included in the regional model then boundaries must be chosen somewhat arbitrarily. Wherever possible true basin or aquifer boundaries should be applied as boundary conditions. Elsewhere either specified head or specified flow boundaries should be applied at the margins of the model depending on the local hydrology. Water divide boundaries may also be used as boundaries, once again keeping in mind that these boundaries are sensitive to significant changes in pumping rates or geohydrology within and outside the study area. Generally in those cases in which true basin or aquifer boundaries are not employed boundaries must be situated far enough from the areas in which changes in geohydrology are occurring so that they do not "feel" the local effects.

SOURCE TERMS FOR THE REGIONAL MODEL

As noted above, radionuclide transport processes in the vicinity of the salt dome repository will determine the rate and concentration at which radionuclides enter the regional transport system. The importance and complexity of these processes can be seen by considering the repository system in terms of the three barriers to radionuclide transport to the biosphere illustrated in Figure 22. The barriers shown are:

- ° the salt dome itself,
- ° the geohydrology in the immediate vicinity of the domes, and
- ° the regional geohydrology.

In this study, we are concerned with the regional geohydrology in its role as barrier to radionuclide transport. Although development of detailed conceptual models of the salt dome and the local geohydrology barriers is outside the scope of work, it should be noted that in order to adequately foresee the conditions

FIG. 22. Three barriers to Radionuclide Transport from a Salt Dome Repository

Future Research: Define release mechanisms and determine the rate, location and concentrations of radionuclide from the salt dome.

Future Research: Determine flow rates that exist at edge of dome. Evaluate existence of two-fluid system and chemical concentration gradient. Determine the rate, geometry and concentrations of radionuclide transfer to the regional flow field.

Regional Model: Find how long it would take for radionuclides from a breach in the repository to reach the biosphere and what level of radioactivity they would have based on regional flow rate and chemical retardation.

under which the regional geohydrology will have to act as a barrier to radionuclide release and in order to determine its effectiveness in this role, the performance of the other two barriers will have to be predicted and, most likely, modeled in some detail.

Salt Dome as a Barrier

The salt dome acts as a major barrier to radionuclide transport because it is virtually impermeable, allowing no through-flow of groundwater which might dissolve and transport radionuclides from the waste canisters. The effectiveness of the dome as a barrier could be compromised by any of several mechanisms including natural and manmade catastrophic events, or dome dissolution. Under such conditions, several processes within the salt could either stop or slow the rate of transport. For example, the self-healing property of salt could close a repository breach. If these processes were not effective in stopping transport within the dome, the end result would be that radionuclides could be transported to the salt dome/country rock interface. If this happens the second barrier, the geohydrology near the salt dome/country interface, would be expected to slow or stop transport of the radionuclides to the regional system.

The effectiveness of the second barrier would depend on the amount of radionuclides reaching the interface, the areal extent and time duration of the release and the location of the breach in the repository and dome. Determination of these factors might for some release scenarios, require a very detailed model of the dome. In other cases, a very simple, gross model could suffice. In either case, the following information would be required concerning the failure of the salt dome to contain the radionuclides:

- ° Definition of the release mechanism, and
- ° The rate, location and concentrations of radionuclides released from the salt dome.

In order to derive this information, calculations and simulations must be performed in much greater detail than is appropriate in a regional model.

Local Geohydrology as a Barrier

We have seen that the salt domes under consideration as repository sites do not appear to be dissolving at any appreciable rate. Among the explanations proposed for this are:

- ° A very low permeability material such as shale sheath or gouge may surround the dome.
- ° Low permeability caprock may extend over a large portion of the dome, including the sides.
- ° Saturated brine which experiences little interaction with the fresh-water regional flow field may surround the dome.

In any case, the same mechanism that protects the dome from dissolution by preventing fresh-water flow in the regional system from dissolving the dome may well serve to slow or prevent transport of radionuclides from the dome to the regional flow field. In addition other processes related to the local geohydrology could serve to stop or slow the transport of radionuclides. An example is the possibility that sorption could be important. Another example is the possibility that extreme dilution and dispersion effects might be induced by rapidly varying flow fields near the dome. These effects would reduce considerably the radionuclide concentrations entering the regional flow field.

The capacity of the local geohydrology to serve as a barrier will of course depend on the manner in which the repository is breached and the rates, concentration and location at which the radionuclides leave the dome. The local geohydrology might fail to stop the radionuclides, for example, as a result of a catastrophic event, or as a result of thermally-induced flow field or structural changes. In fact, it is not likely that the local geohydrology would be able to permanently stop radionuclide transport. If this is the case, this barrier will only be able to slow the rate of transport, and thus at some point, the radionuclides will still reach the regional system.

If the local geohydrology fails to prevent transport of the radionuclides to the regional flow field, the regional model will require the following information:

- ° The rate of radionuclide release
- ° Concentrations at which radionuclides are released
- ° Location and areal extent of release.

As in the case of the first barrier, obtaining the above information could require very detailed analyses.

Regional Geohydrology as a Barrier

Finally, the regional geohydrology would be expected to act as a barrier to radionuclide transport to the biosphere. It is, in fact, the last barrier. We have reported that the travel time of water from Vacherie Dome to the major pumping center nearby is less than 4500 years. This is a rather short time compared to the 250,000 years required for the radionuclides to decay to innocuous levels. Therefore unless the flow path of the radionuclides is very different or unless such processes as sorption and dispersion are very important and very effective in slowing the transport or reducing concentrations, the final barrier is not sufficient. In this case, the earlier barriers must be sufficient to insure that radionuclides have ample chance to decay to harmless levels.

The effectiveness of the regional geohydrology as a barrier depends on the concentrations of the radionuclides being released into the regional system and the site at which the radionuclides are released. These factors are, of course, determined by the performance of the local geohydrology as a barrier which may in turn depend on the effectiveness of the salt dome. Thus derivation of meaningful inputs to the regional model may require a considerable and very detailed analyses of the salt dome and the local geohydrology. The specification of inputs to the regional transport model, therefore, is a very difficult task and raises the problems that are most complex and most unique to the salt dome environment.

The general mechanisms by which radionuclides could be transported or fixed along the path from a breached salt dome repository through the local and regional flow systems to the biosphere are illustrated in the flow chart, Figure 1. This flow chart indicates how the barriers and physical processes interrelate with each other and themselves. The processes are discussed in the next chapter.

V. GEOLOGIC AND HYDROLOGIC PROCESSES TO CONSIDER IN MODELING RADIONUCLIDE TRANSPORT FROM A SALT DOME REPOSITORY

INTRODUCTION

In this chapter the geologic and hydrologic processes that must be modeled in order to predict regional radionuclide transport from a salt dome repository are discussed. Important geologic processes have been presented in Chapters II and III and will not be reviewed extensively here. Instead geologic processes will be discussed only in terms of the extent to which they must be included in a regional model of radionuclide transport from a salt dome repository.

Hydrologic processes of interest and their parameters have been discussed in considerable detail as they apply in models of bedded salt repositories in Camp Dresser & McKee's technical report "Processes and Parameters Involved in Modeling Radionuclide Transport from Bedded Salt Repositories" (UCRL 15095, Evenson and others, 1979). The discussion of hydrologic processes and parameters presented here will cover primarily those aspects of the processes discussed in that memorandum that are especially important in the salt dome environment.

GEOLOGIC PROCESSES

Geologic processes of major importance are:

- 1) sedimentologic processes, their spatial and temporal occurrence, and resultant depositional systems which filled the salt dome basins, and the impact of these systems on the regional geohydrology,
- 2) structural evolution of the basin, including faulting, which occurred during and after deposition, and
- 3) the driving mechanism and growth histories of the salt domes.

The principal conclusion to be drawn is that many of the geologic processes involved in the filling of the Gulf Coast Basin and formation and emplacement

of the salt domes--widespread sedimentation and basin loading, upward growth of the domes, formation of caprock, salt dissolution, and structural readjustment of the basin--are not presently active or are proceeding so slowly that they are unlikely to pose significant problems within the next 250,000 years.

Similarly, surface erosion is proceeding too slowly to be of consequence.

Therefore, although these processes strongly influence the geohydrology of the Gulf Coast basin and the transport of radionuclides from a salt dome repository, they need not be included in models of salt dome repositories as active processes.

Geologic processes that have been active in the past and which could be active in the near future (100,000 years) are earthquakes, faulting and major changes in sea level related to glaciation or melting of the polar ice caps. These processes would have significant impact of the surface and groundwater hydrology around the domes, possibly leading to a breach of the repository. Such occurrences, even those which proceed relatively slowly (glaciation) must be considered as catastrophic and beyond the scope of this study.

Three geologic processes should be considered in modeling a salt dome repository, although not necessarily in a regional transport model. Two of the processes, 1) migration of fluid inclusions and brine toward the waste canisters, and 2) thermal expansion of the dome and the country rock in the immediate vicinity of the dome, are not naturally occurring processes, but are related to generation of heat from radioactive decay of the nuclear wastes in the repository dome. The third process is trapping of fluids in structural and stratigraphic traps in the vicinity of the dome.

As mentioned in Chapter III, the occurrence of fluid inclusions and migration of brine toward waste canisters in the repository is probably not a serious problem, and probably to a large extent can be accommodated in repository design. Thus, fluid migration in the dome is probably a minor consideration and need not be included in the regional transport model.

Potential thermal expansion of the dome and country rock in the immediate vicinity of the dome should be considered, but may prove insignificant in the

regional transport analysis. This is discussed further in the following section on media deformation.

The presence of structural and stratigraphic traps in the aquifer should be ascertained, but included in model as boundary conditions, not as processes. Petroleum industry literature contains extensive descriptions of the types of traps that occur at and near salt dome margins. Halbouty (1967) has illustrated many of the structures. Since the presence of significant oil and gas resources will eliminate a dome from candidacy as a nuclear waste repository, and since the domes under consideration may be at the growth stage where hydrocarbons that once were trapped have already escaped, it is likely that remaining traps in the vicinity of the dome contain only water. These traps would act as impermeable barriers to groundwater movement or possibly as traps for radionuclide contaminated water.

Media Deformation

When the salt dome expands due to the heat of the radioactive wastes, the media immediately surrounding the salt dome will be put under stress. As the heat rises to the surface, the strata above the salt will also expand creating a small topographic rise above the repository for a few thousand years. Displacement at the surface will not just be due to the expansion of the salt and the resulting deformation of overlying sediment, but also will be due to thermally-induced expansion of the overlying sediments. Generally since expansions and deformations will be relatively small and will take place slowly, the strata will probably deflect smoothly without causing the formation of fractures (G. Callihan, RESPEC, personal communication, 1980).

As noted in Chapter III, several modeling efforts have been undertaken to predict the extent of thermally-induced expansion of salt domes under repository conditions. In order to predict the effects of this expansion on surrounding strata the salt dome expansion models will have to be perfected and linked to structural models of local geology. Development of a model to evaluate the effects of thermal expansion is beyond the scope of this report. It may be noted, however, that, from a geohydrologist's point of view, if there is

substantial regional flow of groundwater near the dome, it may be necessary to include the cooling action of the flow system in model calculation.

The effects of media deformation on geohydrology and therefore on radionuclide transport may be expected to be fairly localized. The four to eight feet of deformation predicted by the RESPEC model are not expected to have a significant effect on regional geohydrology (Gary Callihan, RESPEC, personal communication, 1980). The local drainage pattern, perhaps within a half-mile of the greatest deflection, might be changed. The geohydrology of the area immediately over the salt dome itself also may be altered. In general, the permeability can be expected to increase slightly as the strata expands. If a corresponding decrease in hydraulic gradient does not take place, the flow rate above the dome will increase.

The above geohydrologic changes can be included in regional models in the areas near the dome or in local analyses to determine radionuclide inputs to the regional system if the proper relationships between the expansion of the salt dome, resulting stresses in the surrounding strata, and changes in physical properties (such as permeability or porosity) can be determined. The deformations and expansions themselves could be modeled as time-varying boundary conditions. Such boundary conditions would add considerably to the computational burden of a modeling effort, but can be handled (Sa' DaCosta and others, 1979). Changes in the physical properties of the media through which transport occurs as a result of media deformation can be modeled as time-varying parameters; however, the exact relationships between stress and properties such as permeability are not known at present. This is an area of considerable importance in the prediction of repository performance in any medium and is one to which a considerable research effort should be applied.

HYDROLOGIC PROCESSES

Hydrologic processes to be modeled are basically the same for flow within the dome, at the dome boundary, and in the regional system. For instance, no matter what type of system is being evaluated hydrologically, advective flow

and dispersion will have to be considered. The relative importance of the various processes depends on what type of system is being evaluated and what types of information are of interest. For instance, the importance of diffusion is severely limited in regional analyses while it may be very important near the dome boundary.

As noted above, the various hydrologic processes are discussed in detail in our July 1979 technical memorandum to LLL, "Processes and Parameters Involved in Modeling Radionuclide Transport from Bedded Salt Repositories (Evenson and others, 1979). The reader is directed to that report for further more general discussions. In this report, the relative importance of each process with respect to radioactive waste disposal in a Gulf Coast salt dome is discussed as well as the special problems associated with a salt dome.

As discussed in Chapter IV, to evaluate a salt dome as a repository site and regional transport of radionuclides from such a repository, considerations must range from very detailed analyses to regional models. A detailed evaluation of the mine itself will have to be made to determine how the salt will react to the heat load and to predict how water might enter and move through the dome. The salt dome/country rock interface must also be considered. These considerations may be developed separately or as part of a regional flow model. Finally, the regional flow model must be developed. Information developed in each model may be used to develop boundary conditions of the other models. The hydrologic processes of importance to both the salt dome model(s) and the regional model are discussed in this section with emphasis on processes that should be considered in developing a regional model. Since the boundary between the dome itself and the regional flow system is of importance, this also will be discussed.

Advective Flow

In 1856, Henry Darcy described the relationship between pressure head and flow rate through porous media:

$$Q = KA \frac{dh}{dx},$$

where

Q = flow rate (cm^3/day)

K = hydraulic conductivity (cm/day)

A = cross-sectional area (cm^2)

h = pressure (cm)

x = distance (cm).

"This statement, that the flow rate through porous media is proportional to the head loss and inversely proportional to the length of the flow path, is known universally as Darcy's Law. It, more than any other contribution, serves as the basis for present-day knowledge of groundwater flow." (Todd, 1959).

Hydraulic conductivity, K , depends on both the particular medium and the particular fluid. The fluid is normally considered to be water, although the equation also applies to brine or oil. Hydraulic conductivity is calculated by:

$$K = k \frac{\gamma}{\mu}$$

where

k = specific permeability (cm^2)

γ = specific weight (grams/cm^3)

μ = viscosity (poises).

Specific permeability is a property of the medium that reflects the ability of the medium to transmit any fluid.

The effective velocity of the flow rate is:

$$v = \frac{Q}{A},$$

where

V = effective velocity (cm/day)

Q = flow rate (cm³/day)

A = cross-sectional area (cm²).

With respect to radioactive waste disposal in salt domes this flow rate is important because it indicates:

1. the volume of water per unit time potentially available to dissolve salt dome salt, and
2. the volume of water per unit time available to dilute radioactive waste should a breach of the repository take place.

For reasons that will become apparent later both of the above uses of the effective velocity yield very conservative results.

The seepage velocity is:

$$u = V/n,$$

where

n = porosity,

and is the rate at which radionuclides in solution would be transported in the absence of sorption, dispersion or diffusion.

Darcy's Law applies very well in granular porous sediments such as occur in the Gulf Coast region. Its applicability is less certain within the salt dome. Generally the permeability of salt in situ is expected to be so low that flow will only occur at significant rates through fractures or boreholes. Flow through fractures or boreholes will also dominate in low permeability caprock material.

In fracture flow systems, adjustments to Darcy's Law must be made. These adjustments are highly dependent on 1) fracture density, 2) number of fracture sets, 3) gap between fracture faces, and 4) inter-connection between fracture sets. In soluble materials such as salt, temperature and dissolution are important. As seen in Chapter III, fractures in salt tend to heal themselves, and so for fractures and flow through fractures to be a significant problem in a salt dome repository, some catastrophic event would have to occur. Fracture flow is discussed in the companion report on radionuclide transport from basalt repository sites, and the discussion is not repeated here. Regionally, fractures should not be important except under catastrophic circumstances.

Unlike bedded salt, basalt, shale, or granite, the other media being considered for repository sites, salt domes, do not occur as a layer in the geologic strata and they are not an integral part of the regional flow system. Instead, salt domes are highly localized disturbances within the regional system. Figure 23 helps to illustrate the difference. The other media being considered serve as aquicludes in the regional geohydrologic system, separating water-bearing strata that lie above and/or below. Salt domes appear as vertically impermeable vertical spikes around which groundwater must flow (Kreitman and others, 1980).

The geohydrology of the Gulf Coast has already been described. The fluvial-deltaic and marine sediments were deposited in several on-and-off lapping sequences. Groundwater moves down dip from the recharge zone so that artesian conditions prevail at shallow depths. Discharge to surface springs and streams takes place through faults or windows in the confining layers. The extent of flushing action determines water quality. Zones with high flow rates tend to have good quality water and vice versa. In this relatively well understood, well understood system, salt domes do not alter the regional flow pattern, but only deflect it slightly.

Finally, it should be noted that in areas where the salt content of groundwater is varying rapidly or wherever the density of the water is varying significantly, the above equations describing advection may have to be modified to include buoyance/density effects. These modifications already have been

FIG. 23. Other repository medium as part of regional geohydrologic system vs. salt dome as disturbance in the regional geohydrologic system.

accomplished in models describing several geohydrologic situations such as seawater intrusion (Sa' DaCosta and others, 1979) and geothermal studies (Faust and Mercer, 1979). The modifications, therefore, would not be difficult to make. They do, however, significantly increase computational burden.

Dispersion

While Darcy's Law describes the flow rate of the general mass of water, dispersion refers to the transport of individual particles of water or solute. When water flows through a porous medium, no single particle flows in a straight path. Instead, each particle flows over, under, and around the individual grains of the aquifer. The difference in the travel times of various particles results in mixing referred to as dispersion.

A technical memorandum was prepared by the contractor for Lawrence Livermore Laboratory to review how dispersive processes must be incorporated into regional models, and, the reader is referred to that technical memorandum, (Evenson and Dettinger, 1980) for a detailed discussion of this process. In that memorandum it was reported that dispersion generally plays an increasingly important role in regional transport as the distance scale of interest and the seepage velocity increase.

At the regional scale the dispersion process will result in extensive mixing and is caused by inhomogeneities within or between the aquifers. When very long times and distances are considered, the geologic inhomogeneities (stratigraphy) may be expected to dominate mixing, and the dispersion process will appear to be extreme important unless the regional model incorporates considerable geologic detail. At more local scales the dispersion processes will tend to be less influential in diluting and dispersing radionuclides. Therefore, it may prove negligible within the salt dome under certain breaching scenarios.

Diffusion

Mixing that takes place as a result of molecular motion is called diffusion. This mixing is discussed in our recent technical memorandum on dispersion processes. (Evenson and Dettinger, 1980).

At very low flow rates where dispersion is negligible diffusion may be significant. In the regional salt dome system, diffusion might be important at the interface between the salt and the surrounding strata, particularly within the very low permeability caprock zone. Elsewhere in the caprock or other no-flow zones, unless information to the contrary is found, diffusion effects should probably be neglected in the salt dome repository and regional models. The decision to include or neglect diffusion effects should be based on the Peclet number, the ratio of convection effects to diffusion effects. A high Peclet number would indicate that convection effects overpowered diffusion effects. A low Peclet number would indicate diffusion effects were quite significant.

In the actual regional model, in comparison to the other hydrologic processes discussed so far, diffusion effects are insignificant.

Sorption

In evaluating the regional geohydrology of a potential repository site, the ultimate question is "Can the radioisotopes travel through the groundwater fast enough to reach the biosphere before they have decayed to innocuous levels of activity?" As noted above, the seepage velocity is the rate of transport of radionuclides in the absence of other effects. Among these "other effects" are the sorption processes which tend to slow the rate of transport.

Sorption processes are primarily chemical in nature and include adsorption, ion exchange, colloid filtration, reversible precipitation, and irreversible mineralization (Burkholder and others, 1976). In most transport models the processes are quantified in terms of a dimensionless coefficient called the

retardation coefficient (K) which is calculated from the selectivity coefficient (K_d), a characteristic of the particular solid fluid system. The retardation factor is used to calculate the rate of transport of the radionuclides as follows:

$$u^* = u/K,$$

where

u^* = rate of transport of radionuclide (cm/s)

u = seepage velocity (cm/s), and

K = retardation factor.

Some of the factors known to affect the sorption rates are:

- ° mineral composition of sediments
- ° extent of sediment packing
- ° chemical composition and concentration of the water
- ° groundwater velocity
- ° temperature
- ° pressure
- ° pH
- ° Eh.

Compacted clay layers commonly function as semipermeable membranes letting water through, but not dissolved chemicals. This osmotic property of clay layers can cause zones of pressurized concentrated saline water to form (Freeze and Cherry, 1979). In the Gulf Coast sedimentary sequence, the hydrology of interest is generally not deep enough to obtain these pressures so chemical concentration would not take place, although there are undoubtedly pockets of chemical concentration scattered throughout the deltaic sediments. With the statistical information that the Texas Bureau of Economic Geology has developed on the sedimentary composition surrounding the salt domes they are evaluating as potential repository sites (Kreitler and others, 1980), it may be possible to estimate the magnitude of these osmotic effects.

Freeze and Cherry, 1979, present a comprehensive discussion of the chemistry of groundwater. The interested reader is referred to their work, to our technical memorandum on bedded salt (Evenson and others, 1979), and to Borg and others (1976).

Sorption processes have the potential to greatly decrease the capacity of the regional flow system to transport radionuclides released from a repository. The natural reactor at Oklo (Africa) demonstrates the power of various sorption processes. After two billion years most of the daughter products are still in place (Cowan, 1976). Thus, it is very important to include sorption processes in regional transport models.

On the other hand, within the salt dome, sorption processes will be practically non-existent and are very ineffective at attenuating radionuclide transport. Therefore in very localized models of the repository the sorption processes might be negligible.

Dissolution and Precipitation

Dissolution of salt domes, as was discussed earlier, has occurred during the extrusion growth stage of some domes and during formation of caprock. As also discussed, there is no evidence that salt domes under consideration as nuclear waste repositories are being dissolved today. Nevertheless, dissolution of salt could be involved in the escape of radionuclides from a dome repository. It also may affect regional flow and transport of radionuclides.

The dissolution rate of salt is proportional to the area of the salt exposed to dissolution. To be exposed to dissolution, water unsaturated with respect to the salt must move past the salt. If the water in contact with the salt is not moving, then no appreciable amount of salt will be dissolved. Enough salt will dissolve to saturate the volume of water that is in contact with the salt. As this dissolution occurs concentration gradients will arise, and diffusion will carry the salt out into the unsaturated fluid; however, diffusion is a very slow process. Therefore, unless moving unsaturated water is in contact with the salt, dissolution will be a very slow process.

The area of salt that actually is exposed to moving water will be very difficult to estimate. Some of the factors involved are:

- ° fractures and overhangs
- ° gaps between surrounding strata and salt dome
- ° open joints or fractures around dome periphery.

The rate of dissolution also depends on both the velocity of flow of the water and the solubility of the salt in the water. Solubility is a function of:

- ° concentration of other chemicals in the water
- ° temperature
- ° pressure
- ° concentration of NaCl in water.

Based on regional flow rates and on the difference in chloride concentration between the upstream and downstream water, the rate at which the dome is dissolving can be calculated. Assuming that the regional geohydrology will not change significantly during the life of the repository, the expected dissolution can then be estimated. For domes under consideration in Texas, however, no chloride concentration change that can be positively associated with salt dome dissolution has been identified. No data are available for Louisiana and Mississippi domes.

It is possible that a two-fluid system exists around the periphery of the domes, with highly saturated brine directly in contact with the salt and fresh-water elsewhere. Little salt would be dissolved by the brine layer in such a situation. If the major mixing mechanism with the regional flow system is diffusion, very little salt would be removed from the brine layer. Effectively then, almost no dissolution could occur.

In the salt dome system, it is unlikely that groundwater flow takes place flush against the salt. When flow splits to go around a smooth obstacle, a narrow no-flow zone develops that encircles the obstacle. Salt domes are probably not smooth obstacles. Crenulations around the outside edge of a salt dome could

inhibit fluid movement, effectively widening the no-flow zone. Thus a brine layer may exist around the domes which places a severe limit on the amount of dissolution. Shale or breccia surrounding the dome may have the same effect.

To evaluate a salt dome as a repository, dissolution inside the mine and around the edge of the dome will have to be carefully considered. A ground-water model should be used to discern what change in chloride concentration would be found in the surrounding strata if dome dissolution was taking place. If dissolution is to be modeled, then a study of the mechanisms of caprock formation--either residual-in-place accumulation (Taylor, 1938) or re-precipitation (Walker, 1973,1976)--probably should be included in the model development process.

Precipitation, the opposite of dissolution, is the process where solute comes out of solution forming a solid. In the salt dome itself, halite precipitating out of solution may tend to heal fractures that might develop. Solubility is highly temperature dependent, the higher the temperature the greater the solubility. Therefore, as water flows away from the heat source and cools, its saturation level will decline and salt may precipitate.

Dissolution and precipitation are not likely to be important in the strata surrounding the salt dome. The clastic materials in these strata will be much less soluble than the salt dome. By the time the fluid has flowed into the strata it may be expected that the fluid temperature will have returned to nearly the ambient level and precipitation will have ceased. Thus, in the regional flow model, these processes can safely be neglected.

Dissolution of salt dome may still have a very important effect on regional transport. Radionuclides would most likely be transported through and out of the dome in a briny solution as a result of dissolution along the entry and escape paths. Brines are more dense than fresh-water and will tend to sink, affecting the flow path of radionuclide transport through the region (Hosman, 1978). In addition, the natural brininess of water in various parts of the salt dome basins may well play a role in determining regional flow patterns. Therefore, dissolution which affects the chemical composition and density of

the water near the salt domes and the solution containing the radionuclides may have regional impacts which must be considered.

Thermal Effects

Temperature influences the rates at which all of the geologic and hydrologic processes take place. In the salt dome itself, the effect of the heat load of the canisters will be substantial. The U.S. Department of Energy is spending a great deal of money to determine how the salt will behave under the heat load (for example Avery Island experiments by RESPEC). The results of these investigations should add greatly to our understanding of repository performance.

Regionally, temperature should have very little effect. The heat load of the waste should not significantly change the ambient temperature of the region, except in the small portion around the salt dome. The major effect of temperature on regional flow would be indirect through the expansion of the strata above the dome.

Locally, if the temperature increases, many other changes would also take place. Generally speaking, the whole system would be speeded up. The most obvious temperature induced changes are:

1. The advective flow rate would increase as the temperature rises. Viscosity is inversely related to temperature. As the temperature rises the viscosity is reduced and flow rates increase.
2. Dispersion is an increasing function of seepage velocity. A temperature-induced increase in water velocity would also increase the rate of dispersion of radionuclides.
3. Diffusion rates increase with increasing temperature (Evenson and others, 1979).

4. The amount of sorption occurring would also increase as a greater amount of dissolved chemicals are exposed to the sorption sites through the increased flowrate and as the rate of the chemical reactions increase.
5. Solubility rates generally would increase with increasing temperature. The amount of dissolution occurring would be increased as a result of both the solubility change and the increase in flowrate since:

$$(\text{volume dissolved}) = (\text{solubility}) \cdot (\text{flowrate}).$$

It should be noted that temperature and fluid flow may be related in a very complicated manner. If the temperature rises, we have seen that the rate of flow will also rise. This increased flow carried away part of the heat, and thus, under some conditions may tend to lower the temperature at the heat source. To model this sort of feedback between temperature and flow, very complicated methods may be required. This topic is discussed in some detail in some detail by Faust and Mercer (1979) and Fried and Combarous (1971).

Radioactive Decay

Radioactive decay of radionuclide is a natural mechanism for the attenuation of radionuclide transport. The process is irreversible but may lead to the generation of new radionuclides which are also hazardous.

Radioactive decay proceeds at a very well defined rate for each radionuclide and results in an exponential decrease in radionuclide concentration. Different lengths of time are required to reduce the concentration by half, for example, from 13.2 years for Pu241 to 1.7×10^7 years for I129. It is estimated that the time required to reduce the activity of radionuclides released in a repository accident to acceptable levels is 250,000 years.

Radioactive decay should be considered at the salt dome scale only as an indicator of the strength of the radionuclide source. At the regional scale the

process should be considered as a very important attenuation process and should definitely be included in all transport models.

Summary

In the evaluation of a salt dome for a radioactive waste repository, the hydrologic and geologic regime of the dome and the surrounding region must be carefully studied. If a breach of the repository were to take place, groundwater would be the most likely mechanism to transport radioactive isotopes from the dome to the biosphere and into human contact.

The only geologic process that must be incorporated in repository modeling efforts is media deformation due to heat loading.

All other geologic processes are believed to be either (1) inactive now and in the future lifetime of the repository, (2) active but too slow to be of consequence during the lifetime of the repository, or (3) rare and catastrophic occurrence which are too unlikely to be included at this time.

The hydrologic processes which might be included are:

- ° Advection
- ° Dispersion
- ° Diffusion
- ° Sorption
- ° Dissolution/Precipitation
- ° Thermal Effects
- ° Radioactive Decay

Because salt domes are found in the type of clastic sedimentary sequence that geohydrologists have worked in for many years, the regional flow characteristics are well understood and the speed of the flow can be evaluated relatively accurately. Through the use of existing numerical models, many breach scenarios can begin to be evaluated. Further developments will be needed but a good start can be had through use of these conventional aquifer models.

The clastic nature of salt dome basins, although an advantage to the modeler, may be a disadvantage because the clastic regional aquifer systems may allow relatively rapid transport of radionuclides to the biosphere compared to other proposed repository systems which include vast aquicludes. Containment of the radionuclides within the salt itself becomes particularly critical unless it can be shown that the regional system can in fact dissipate or slow transport of radionuclides. Thus, other processes besides advection are critical in modeling regional transport of radionuclides.

The current state-of-the-art in evaluating attenuation of chemicals in groundwater flow is not as advanced as the state-of-the-art of evaluating physical flow processes. Retardation of radionuclides carried in groundwater by sorption processes should significantly reduce their speed of flow. Radioactive decay will also reduce the concentration of radioactive isotopes as they flow through the system. More research is needed to quantify these effects.

VI. ANNOTATED LIST OF MODELING PARAMETERS

INTRODUCTION

In Chapter V, we conclude that only one geologic process may have to be modeled in a regional model. The process is:

- ° thermal expansion of the salt dome due to heat loading.

A number of hydrologic processes have to be included or at least considered in putting together a regional model. The processes identified in Chapter V are:

- ° advection
- ° dispersion
- ° diffusion
- ° sorption
- ° dissolution/precipitation
- ° thermal effects
- ° radioactive decay.

In this chapter, we will list parameters necessary to model these processes. Because the individual processes are of different importance at different locations within the region and at different distance scales, this chapter is organized so that the parameters necessary to model processes in and near a salt dome that are also important in the regional model and the parameters of the regional processes are listed and discussed separately. The parameters to be listed have all been discussed in detail and defined in an earlier report, "Processes and Parameters Involved in Modeling Radionuclide Transport From Bedded Salt Repositories" (Evenson and others, 1979). This chapter will therefore deal with the parameters and their values only briefly, and as they apply to the salt dome basin model. The reader interested in a more general discussion of the parameters is referred to the above report.

PARAMETERS FOR THE PROCESSES LOCAL TO SALT DOMES

Processes which we have identified as being important in the regional model and in the vicinity of a salt dome are:

- ° thermal expansion of the salt dome due to heat loading
- ° thermal effects
- ° advection
- ° dispersion
- ° diffusion
- ° sorption
- ° dissolution/precipitation.

Advection and sorption are essentially inactive within the salt dome, but are discussed here in order to demonstrate that fact. The rest of the processes are of only marginal importance in most regional studies since they affect only a rather small part of the regional flow field local to the dome. As we have seen, in a regional model which considers a significant portion of a salt dome basin, the domes apparently have a negligible effect on the groundwater hydrology. However, since all regional studies may not be so ambitious and the processes above may have a greater effect in more detail studies, we discuss the parameters of the above processes in this section.

The area immediately surrounding the domes is not well understood. We have seen that although salt is extremely soluble the salt domes under consideration do not seem to be dissolving. The nature of the protecting mechanisms are not known. We suggested earlier that these same mechanisms may tend to inhibit release of radionuclides to the regional system. Before we can test this hypothesis, the exact mechanisms must be determined through further research. Similarly, our ability to parameterize this environment is at present extremely limited.

Parameters of the Salt Dome Thermal Expansion Process

We have seen that as the radioactive wastes heat the dome and the overlying strata, the salt and possibly the surrounding strata will expand, raising the

topographic surface slightly. These changes probably can be predicted with a thermomechanical model of the salt dome and surrounding strata. The predicted changes in the dome geometries and surrounding strata might then be incorporated into the regional transport models as time-varying boundary conditions if the effect on regional transport is expected to be significant.

Thermal expansion of the salt dome and overlying strata will depend on the temperature distribution within the dome and at least the following parameters:

Thermal Expansion Coefficient, $1/^{\circ}\text{C}$
Thermal Conductivity, $\text{cal/cm-sec-}^{\circ}\text{C}$
Rock Strength.

Typical values for these parameters in halite are given in Evenson and others (1979). See Table 4 of this report for conductivity values for various rocks. The thermal expansion coefficient has a typical value of $0.001/^{\circ}\text{C}$ (Talbot, 1978) for salt domes. Morgan (1979) gives a good discussion of this parameter for salt domes, too. Rock strength depends on a number of factors and is measured in terms of a variety of other parameters such as yield strength, compressive strength, and modulus of elasticity.

The thermal expansion of the surrounding strata is probably negligible and values of the rock strength parameters are available in many rock mechanics texts. However, the immediate interface between the dome and surrounding strata is not yet a well understood structure. Any of a number of materials might occur. Until the composition and structure is known, parameterization is essentially impossible.

Parameters of the Thermal Effects in Salt Domes

The temperature distribution needed above will have to be determined experimentally through analog experiments or through application of thermal models. The temperature distribution depends on the following parameters:

Specific Heat of Salt Dome (cal/g-°C)

Density of Salt Dome Material (g/cm³)

Coefficient of Thermal Diffusion

Coefficient of Thermal Dispersion.

Typical values of the specific heat of halite range from 0.19 to 0.47 cal/g-°C, and reported density values range from 2.108-2.44 g/cm³. Generally, thermal diffusion is small and is either negligible compared to the thermal conductivity or thermal dispersion, depending on whether or not Darcian fluid flow is present. In salt, Darcian fluid flow generally does not occur and, therefore, thermal conduction dominates. Outside the dome thermal dispersion will dominate, and temperature changes induced by heat loading should be negligible.

The capacity of the groundwater surrounding the salt dome to accept heat from the dome and the temperature changes induced are parameterized in terms of specific heat of fluid (cal/f-°C). Values that this parameters assumes can be determined in the laboratory and are known quite accurately. Typical values for fresh-water range between 0.99802 and 1.00738 cal/g-°C.

All the above parameters except the coefficient of thermal dispersion can be determined to laboratory accuracies through laboratory or in situ studies of borings in salt domes. These borings might most conveniently be made into shallow domes, exposed domes or domes which already have been mined. The coefficient of thermal dispersion is generally equivalent to the hydrodynamic dispersion coefficient to be discussed below.

Since no regional flow is expected through the domes, regionally the temperature distribution is the only thermal effect of interest.

Parameters of the Advection Process In and Near Salt Domes

In the regional model, the capacity of salt domes to allow through-flow is the most important concern regarding advection in salt domes. Assuming that more detailed studies have been performed to determine radionuclide release mechanism and input rates, we are concerned only with how the regional flow and transport is affected by the salt dome.

Parameters of the advection process in the salt dome are:

Permeability

Porosity

Spacing and length of fractures.

The capacity of dome salt to transmit fluid, its permeability, is extremely low. Gloyna and Reynolds (1961), report non-reactive fluid permeability values ranging from $6.28 \cdot 10^{-5}$ darcies to $2.63 \cdot 10^{-3}$ darcies for samples of halite from the Grand Saline Dome. Flow did not take place through the crystals themselves, but instead through relaxation cracks that formed when the samples were extracted. In situ, the permeability of the salt dome would be even lower. Dome salt is essentially impervious.

Porosity is generally very important in determining the rate of advective transfer. However, the effective porosity of dome salts may be expected to be at least as small as those found in bedded salts (0.5% - 2%). See Evenson and others (1979) for a more detailed discussion of this parameter.

In actuality, the permeability and porosity are only of importance in indicating that no flow will pass through the crystalline salt. Flow and transport within the domes will be primarily through fractures or mined areas. It seems unlikely, given the plastic behavior of salt, that fractures would extend far enough into the dome to connect the repository with the surrounding strata. In a regional model, therefore, the repository dome will appear as a point or line source of radionuclides from an otherwise almost impermeable structure. Other domes in the regional flow field will appear also in the regional model as impermeable structures.

Advection in the area immediately surrounding the salt dome is important primarily as it affects input of radionuclides to the regional flow system. Porosity and permeability parameters should, except in the caprock, depend on the geologic composition of the area and be comparable to regional values. Further discussion will be delayed until we address the regional values.

Since the surrounding strata are primarily composed of clastic materials, fractures should be relatively unimportant except in the caprock or in any consolidated shield that might be protecting the dome from dissolution.

Permeability of the intact caprock is very low with respect to the permeability of the surrounding strata. Fractures through caprock might allow significant secondary permeabilities and porosities to develop. Permeability tests should be run on samples collected from the exploratory drilling for each dome under consideration. Should fractures be found, it is likely fracture flow will dominate over porous flow in the caprock. Particular care should be taken to characterize the fracture pattern through borings. Later fracture mapping may be conducted during repository construction. Regionally, however, these fractures are probably minor effects.

Two additional parameters may be important if significant temperature or chemical changes occur within the study area. These parameters are:

Viscosity (poise)

Specific weight (dynes/cm³).

As noted in Chapter V, hydraulic conductivity is a function of these parameters. The two parameters describe physical properties of the fluid for any given temperature or chemical composition. These parameters may be determined in the laboratory for a variety of conditions. The difficulty, from the modeling standpoint, lies in deciding what specific temperature and chemical conditions will be encountered at depth. Typical values are reported under a wide variety of conditions in Evenson and others (1979).

Parameters of the Dispersion and Diffusion Processes In and Near Salt Domes

The dispersion process is parameterized in terms of the:

Dispersion coefficient (cm²/s), or

Dispersivity (cm),

where the dispersion coefficient is equal to the dispersivity multiplied by the seepage velocity. The diffusion process is parameterized in terms of the:

Diffusion coefficient (cm^2/s).

Dispersive and diffusive transport are modeled in the simplest case by including the dispersive flux term:

$$\frac{\partial}{\partial x} D \frac{\partial C}{\partial x}$$

in the advective transport equation, where D is some additive combination of the dispersion and diffusion coefficients.

Because salt is not a porous medium and allows little or no flow, we would not expect either dispersion or diffusion to be important within the salt domes. From a regional perspective, the processes are negligible even if they do operate within the domes.

The diffusion coefficient, important only in the no-flow zones near the salt dome boundaries, depends on the medium through which diffusion occurs. Typical diffusion coefficients in porous media range from 10^{-5} to $10^{-8} \text{ cm}^2/\text{s}$ and can be determined in the laboratory very accurately, given undisturbed samples of the porous media involved.

Dispersion coefficients in the interface zone would be much more difficult to determine and would be much more variable. Where no-flow conditions do not dominate in the interface zone, very complex flow patterns may be expected. Measurements to determine the dispersion coefficients in this zone would be difficult to design and very difficult to perform.

Typical values of dispersivity (the more commonly specified parameter) range from 0.034m to 150m, within our distance scale of interest and depending on the flow field being studied and method of measurement. In the salt dome/country rock interface, depending on the detail of the model, any value in the range

0.01m to 50m might reasonably be expected. A very detailed discussion of these processes and parameters is presented in our report "Dispersive Processes in Models of Regional Radionuclide Migration" (Evenson and Dettinger, 1980).

Parameters of the Sorption Processes In and Near Salt Domes

As noted in Chapter V, sorption processes tend to slow the rate of radionuclide transport through a medium to rates that may be considerably less than the seepage velocity. These processes are generally parameterized in terms of the:

Retardation coefficient,

which may be calculated in terms of:

Porosity,

Bulk density of the medium, and

K_d , the selectivity coefficient (ml/g).

A detailed discussion of these parameters is available in Evenson and others (1979) and indicates that the sorption capacity of salt relative to most other rock types with respect to radioactive isotopes is extremely low. Borg and others (1976) reported values of the selectivity coefficient of 0.19 mg/l for sorption of Sr to domal salt and 0.027 for Cs. From the regional point of view, the sorption capacity of the salt dome is probably negligible.

Density and porosity were both discussed above.

Sorption properties of the interface between the salt dome and regional flow system depend on the materials encountered there. As noted above, this interface is not well understood.

It can, however, be assumed that the caprock and the rest of the interface around the dome will act very differently. The caprock is composed primarily of evaporites whereas the rest of the interface is likely to be some altered form of the sands and muds that make up the basin aquifers through which the

salt domes intruded. The amount of sorption that takes place in the caprock will be low, since very little flow will occur there. We did not find sorption capacity values for anhydrite or gypsum with respect to radionuclides in the literature, so these remain to be determined. As evaporites, however, the sorption capacity of these minerals is probably quite low. Sorption properties of the sands are rather well understood and will be discussed below in connection with the regional processes.

Parameters of the Dissolution/Precipitation Process in and Near Salt Domes

Dissolution and precipitation may be parameterized in terms of:

- Surface area of salt exposed to water (m^2)
- Solubility of the salt in the fluid (mg/l), and
- Volume of water available to dissolve the salt (l).

As discussed earlier, all evidence from the salt domes under investigation as potential repository sites indicates that no significant dissolution is taking place. Unfortunately, it is not clear what protects the domes from dissolution.

The surface area exposed to dissolution must be estimated based on the geometry of the dome and the tightness of the strata that abut the dome. If an impervious shale sheath surrounds a large portion of the dome for instance, the surface area of salt exposed to regional flow may be quite small. The presence of fractures may greatly increase the contact area available.

Solubility values for salt were reported by Evenson and others (1979). Dome salt should be represented by these values. The solubility of the salt at the edge of the dome can be determined easily in the laboratory for any given fluid. The difficulty is determining the chemical characteristics of the water to be used in the test. If a dead zone exists against the salt, where no flow takes place so that a two-fluid system exists, the salt concentration of the water in contact with the salt will be very different from the concentration of the water in the regional aquifer. Since no salt can dissolve in a NaCl saturated solution, but a great deal of salt can be dissolved in fresh water,

the chemical characteristics of the water in contact with the salt have a great deal to do with how much salt actually dissolves. Such chemical parameters as Eh and mineralogy also may be expected to effect solubility.

Another difficulty lies in determining the effects of the radioactive wastes on solubility. Irradiated salt is weaker than un-irradiated salt (Holdaway, 1974), and it is also more soluble (Chapman, 1979); however, the Lyons, Kansas, experiment demonstrated that irradiation effects do not penetrate far into the salt (Holdaway, 1974). Therefore, this effect is probably negligible in a regional model. Typical values range from 356,484 mg/l in cold water to 391,200 mg/l in hot.

The volume of water available to dissolve the salt will depend on the regional flow rate and what fraction of this flow contacts the dome while unsaturated. As noted above, evidence indicates that no significant dissolution is taking place, suggesting that there is little contact between the regional flow field and the domes.

Dissolution should certainly be included in local models of the repository salt dome, but it is evidently less important in the regional model under natural conditions. Construction of the repository could disrupt some of the natural barriers and result in dissolution playing an important role. If so, at the regional scale dissolution should be modeled as a changing boundary condition based either on detailed model results or on the simple, gross parameters listed above. Gross calculations may also be employed if the brine-fresh water density effects are deemed significant regionally.

Finally, little dissolution of the caprock or surrounding strata should be expected. Both have rather low solubilities. Thus, the process can safely be neglected there. Regionally, precipitation can also be neglected in the interface zone since most will have occurred within the dome or immediately upon existing from it. Therefore, the parameters need not be determined to any great accuracy in the interface zone.

PARAMETERS FOR THE REGIONAL PROCESSES

Processes which we have identified as being important in the regional model are:

- ° advection
- ° dispersion
- ° sorption
- ° radioactive decay.

Certain of these parameters have already been discussed in the previous section; only differences with respect to the regional transport model are presented here.

Parameters of the Regional Advection Process

The parameters of the regional advection process are:

Permeability (m^2), or hydraulic conductivity (m/yr), or
transmissivity (m^2/yr)

Porosity.

Both of these parameters will vary from aquifer to aquifer, from aquifer to aquitard, and within each member. Typical hydraulic conductivity values within the sandy parts of some East Texas aquifers may range from 0.3 m/yr to 49 m/yr as one progresses up-dip. The aquitards may have hydraulic conductivities of between 1.6×10^{-4} and 0.003 m/yr. Porosities will range between 10-30 percent in the sandy zones and between 1-10 percent in the clay and mud sections of the basin.

Accurate hydraulic conductivity and porosity values are probably the most difficult information to obtain about the existing flow regime. Even within a single formation, it is not unusual for permeability to vary over three orders of magnitude.

In the East Texas and North Louisiana Basins, a great deal of information from well logs is available. Using statistical methods, it may be possible to accurately determine permeability distribution. Techniques, such as kriging (Delhomme, 1979) to correlate data from one place to another should be refined as much as possible both from the view point of the radioactive waste disposal program and advancing the state-of-the-art.

In bedded deposits, where the grains tend to align themselves along the bedding planes, permeability becomes directional and may be greater in one direction than in any other. Generally, permeability is greatest parallel to the bedding plane and least perpendicular to the bedding plane. Obviously directional permeability must be taken into account in order to predict the flow path of a point source of pollution from a radioactive waste repository. Measurements of this phenomena in a repository siting situation will be very limited unless many very good undisturbed sediment samples can be obtained for laboratory analysis.

Generally geohydrologists are able to develop much more meaningful parameterization of regional flow properties through well tests, essentially measuring the average flow properties of the entire volume of sediment influenced by pumping a well. The resulting parameter is generally transmissivity, a "vertically integrated" flow property. Transmissivity is the vertically averaged hydraulic conductivity within an aquifer multiplied by the vertical extent of the aquifer. This property is much more representative of regional flow and covers more area per measurement than any laboratory analysis could. Well tests can also be designed to yield information about the aquitards and hydraulic connection to other aquifers. Walton (1962, 1970) presents excellent discussions of well tests, well test design, and the advantages and disadvantages of the tests.

Taken together, permeability and well test measurements can result in a fair understanding of the structure and flow properties of the regional system.

Parameters of the Regional Dispersion Process

The parameters of the regional dispersion process are:

Dispersion coefficient (m^2/s), or
Dispersivity (m).

As noted above, we have presented a very detailed discussion of regional dispersion processes in a recent report to Lawrence Livermore Laboratory (Evenson and Dettinger, 1980). In that report, regional values of dispersivity were found to range between 10m and 150m. There is even a large scale (hundreds of kilometers on a side) study which led to suggestions of a 50km dispersivity value. Thus the dispersivity is extremely variable.

Methods of determining regional dispersivity values are discussed at length in our recent report and will not be reiterated here. Suffice it to say, that regional dispersivity values are most properly obtained through model studies of the transport of environmental tracers through the study area. This is a very difficult and expensive task.

Parameters of the Regional Sorption Processes

The parameter of sorption processes, as contained in the regional model, is the:

Retardation coefficient

which may be calculated in terms of the:

Porosity

Bulk density (g/cm^3)

K_d The selectivity coefficient.

Typical values of the selectivity coefficient, how it is measured, and how it can be used to calculate the retardation coefficient are all discussed in detail in Evenson and others (1979). It should be noted that each chemical and adsorption site combination will have a distinct K_d which will also depend on the chemistry and temperature of the water.

Among the materials encountered in salt dome basins, sands are reported to have selectivity coefficients of 1.37 ml/g for Sr and 102 ml/g for Cs. Clay and mud will have much higher adsorption capabilities than the sands, perhaps three orders of magnitude. This suggests very high retardation coefficients within the aquitards and fairly high values in the aquifers.

Bulk density and selectivity coefficients can be determined in the laboratory if relatively undisturbed samples are obtained. Quite often laboratory tests to determine selectivity coefficients involve grinding the porous medium sample; this should be discouraged since it changes the surface area available for chemical interaction. Perhaps the most difficult problem with the current technologies lies in determining the relationships between the chemistry witnessed in the laboratory, which deals with small disturbed samples, and the average or large scale trends which must be modeled in the regional study. A concerted statistical effort should be mounted to determine this relationship in the vicinity of proposed repository sites.

Parameters of the Radioactive Decay Process

The parameters of the radioactive decay process are either:

Radio-isotope half lives, or
Radioactive decay rates.

The radioactive decay rate, λ , can be calculated in terms of the half life according to

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

Each isotope has a unique half-life, so the rate of radionuclide loss or production caused by radioactive decay is much greater for some isotopes than for others. Characteristics half-lives are presented in Evenson and others (1979).

CONCLUSIONS

Table 5 presents the list of parameters discussed above. A rating for each parameter of the ease with which accurate measurements can be obtained to determine the parameter value and the amount of value variation that might be expected within the study area is also presented. The discussions above indicate that we are most uncertain about parameter values in the immediate vicinity of the domes and least uncertain concerning parameter values within the domes. Regional values lie somewhere in between.

Very often in discussions of radionuclide transport the overwhelming uncertainties concerning parameter values take precedence over the problem of describing the system structure. The clastic nature of salt dome basins makes parameter uncertainty somewhat less pressing. The parameters of the regional model are expected, because of the clastic nature of the media, to be obtained through rather conventional means and are not expected to take on exotic values. On the other hand, salt dome basins are tremendously complex layered systems composed of numerous aquifers and aquitards. Thus, determination of the structure of the basin is perhaps the more pressing concern in development of a regional model of radionuclide transport through a salt dome basin.

TABLE 5. Regional model parameters.

Parameter	Ease of Measurement*	Value Variation†
Thermal Expansion Coefficient		
Salt Dome	High	Lowest
Thermal Conductivity		
Salt Dome	High	Lowest
Rock Strength		
Salt Dome	High	Medium
Surroundings	Low	Medium
Specific Heat		
Water	High	Low
Salt Dome	High	Low
Bulk Density		
Salt Dome	High	Low
Surroundings	Low	High
Regional	Low	High
Coefficient of Thermal Diffusion		
Salt Dome	Medium	Low
Coefficient of Thermal Dispersivity		
Surroundings	Low	Highest
Permeability		
Salt Dome	Low	Medium
Surroundings	Low	High
Regional	Medium	Highest
Porosity		
Salt Dome	High	Low
Surroundings	Low	High
Regional	Low	High
Viscosity	High	Low
Specific Weight	High	Low
Dispersion Coefficient		
Surroundings	Low	Highest
Regional	Low	High
Diffusion Coefficient		
Surroundings	Medium	Low
Selectivity Coefficient		
Salt Dome	Medium	Low
Surroundings	Low	High
Regional	Low	High
Surface Area		
Salt Dome	High	High
Solubility		
Salt Dome	High	Low
Radioactive Decay Rates	High	Lowest

*Rated as high, medium, and low

†Rated as highest, higher, high, medium, low, lower, and lowest

APPENDIX A

DESCRIPTION OF CANDIDATE DOMES

EAST TEXAS

Kreitler and others (1978) have described the two domes in East Texas, Keechi and Oakwood, still being considered as potential repositories for nuclear waste. Description of these domes has been taken from their report and others by Kreitler (Figure numbers have been changed). In addition to the references cited in the text and their own observations, Kreitler and others drew heavily on a report by Netherland, Seawell and Associates (1976).

Keechi Dome

Geography. Keechi dome is located on the divide between the Neches River and Trinity River drainage systems (Figure 3). Elevations in the vicinity of the dome range from about 290 feet in the valley where Keechi Creek flows to the southwest to over 600 feet in the southeastern portion of the area. In general, the topography is gently rolling, with a ring of hills surrounding the center of the dome. Keechi dome is expressed as a low valley and is almost completely surrounded by a rim of interior low hills with elevations on the order of 400 feet. The topography is more extensively discussed by Powers (1926), and Ebanks (1965).

Shape of the Dome. The salt mass is elliptical in shape with the long axis trending north-south (Figures 24 and 25). It becomes more egg-shaped below 5,000 feet (Figure 26) and has an overhang on the south end at about 2,000 feet. The dimensions of the dome are 6,000 feet x 10,000 feet (1,100 acres) at 3,000 feet (below land surface). It is capped on the north and central portion with material variously described as gyp, hard rock, and cap. The caprock is probably a composition of gypsum and anhydrite and reaches a maximum thickness of 300 feet near the apex of the salt mass. The caprock at present does not cover the entire salt stock. The caprock is confined to the northern portion of the salt dome and drapes over the salt mass down to 3,500 feet in the north and 2,500 feet in the south (Ebanks, 1965).

FIG. 24. Structural section, Keechi Dome. Stratigraphic markers dip away from the dome. Dome shape modified from Netherland, Sewell and Associates (1976). From Guevara and Giles (1979).

FIG. 25. Isochore map. Top of Pecan Gap Chalk to base of Austin Chalk, Keechi Dome. Note thinning of unit toward dome. From Guevara and Giles (1979).

KEECHI DOME: MAXIMUM TOTAL DISSOLVED SOLIDS IN WILCOX AQUIFER

FIG. 26. Estimated groundwater-salinity distribution in Wilcox Aquifer around Keechi Dome. From Kreitler and others (1978). Recent data suggests that salinity maxima are associated with muddy facies in the Wilcox and are evidence of lack of flushing, not dissolution of the dome.

Geology. Keechi Dome has a central fault of considerable magnitude which brings Cretaceous Pecan Gap on the south in contact with Wilcox beds on the north. Strata overlying and surrounding the salt core have been arched into a steeply-dipping, probably highly-faulted quaquaversal fold. It is assumed that faults are normal and form a radial pattern. An expression of the central fault can be observed from the surface. The Wilcox covers the entire domal uplift with the exception of the Cretaceous and Midway outcrops. The Cretaceous exposures appear to be an expression of uplift by the salt and caprock on the southeast side of the dome (Ebanks, 1965).

Drilling around the periphery of the dome has disclosed a complete geological section from the Wilcox to the Pettet, with all formations thinning in a domeward direction (Ebanks, 1965).

Hydrology. Evidence suggests a possible surface saline and a saline plume associated with Keechi salt dome. Powers (1926) reported salty patches along the Salt Fork of Keechi Creek as it crosses the dome. Figure 26 shows a possible saline plume to be hydrologically downdip from the dome in the lower Wilcox aquifer. The source of the apparent saline water is questionable. The salinity may result from salt dissolution or nonsolution origins. This apparent increase in salinity which occurs only at the base of the Wilcox may result from (1) poor circulation and lack of flushing of saline waters, (2) possible leakage of saline water from deeper formations, or (3) dome dissolution.[†]

Oil and Gas Potential. It appears that Keechi Dome is not an attractive hydrocarbon exploratory target. With the exception of a heavy oil show in the Woodbine in the first well drilled on this dome, no other oil and gas indications have been reported.

Oakwood Dome

Geography. Oakwood Dome is located approximately on the Freestone-Leon County line 2 miles northwest of the town of Keechi (Figure 3). Subsurface

[†]More recent data suggests there is no saline plume associated with Keechi, (Graham Fogg, BEG, personal communication, 1980). Rather, salinity highs are associated with muddy Wilcox facies and indicate lack of flushing, not dome dissolution.

geologic work along with seismograph work indicated the presence of the salt dome structure in 1927. Seven test wells were drilled on or near the structure before Oakwood Dome field was brought in. Topography shows some evidence of the presence of the dome. A central depression with centripetal drainage occurs over the dome. No saline springs or saline prairies have been reported in the literature.

Geology. The salt core is cylindrical in shape with a diameter of approximately 11,500 feet (1,800 acres) at a depth of 2,000 feet (Figures 27 and 28). A salt overhang occurs on both the east and west sides of the domes to depths of 5,000 feet. Anhydrite caprock covers the dome and was drilled at 705 feet below land surface. The surficial geologic unit over the dome is the Queen City formation. Drilling has penetrated geologic units as old as the Glen Rose Formation (Lower Cretaceous) at a depth of 9,000 feet. Radial faults in the subsurface Woodbine Formation have been mapped around the dome (Nance, 1964).

Hydrology. Oakwood Dome is in contact with the Wilcox group and therefore has the potential for salt dome dissolution. Salinity estimates for groundwater in the Wilcox around Oakwood (Figure 29) indicate a saline plume. No surface salines over the Oakwood Dome have been identified.

Oil and Gas Potential. Hydrocarbons have been produced from the Oakwood dome field since 1958. Production has come from Woodbine and Georgetown formations beneath the salt overhang. Total cumulative production (1958-1977) has been 2,110,100 bbls. Annual production in 1977, however, was only 6,556 bbls from 5 wells.

NORTH LOUISIANA

Martinez and others (1975) presented descriptions of domes in the North Louisiana Basin. The description of Vacherie Dome was prepared for that report by C. Crowe, a graduate student at Louisiana State University who studied the dome. Anderson and others (1973) presented a geologic and hydrologic summary of salt domes in the Gulf Coast region. The description of Rayburns Dome was taken from their report.

FIG. 27. Northwest-southeast structure section through Oakwood Dome, Freestone and Leon Counties, Texas. From Kreitler (1978).

FIG. 28. Southwest-northeast structure section through Oakwood Dome, Freestone and Leon Counties, Texas. From Kreftler (1978).

OAKWOOD DOME: MAXIMUM TOTAL DISSOLVED SOLIDS IN WILCOX AQUIFER

FIG. 29. Groundwater salinity distribution around Oakwood Dome in Wilcox Aquifer. From Kreitler and others (1978). See comment on figure 26.

Vacherie Dome

Vacherie salt dome is centered in the southern half of section 16, T17N, R8W, near the Webster-Bienville parish line (Figure 4). It is located 3.6 miles east of Heflin (pop. 360), 3.8 miles northeast of Fryeberg (pop. 100), and 9.8 miles southwest of Gibsland (pop. 1,400). There are several dirt and gravel roads crossing the dome, but some have been abandoned and are now impassable. Part of the land over the dome is agricultural fields, but much is wooded terrain.

The area above the salt stock itself is a central low formed by the floodplain of Bashaway Creek; low hills rise ten to twenty feet in a few places. Surrounding the depression is a ridge of Sparta sand (cuesta) as much as 200 feet higher and only open on the southeast end.

Vacherie Dome has a northwest to southeast elongation. At a depth of 100 feet the long axis is 17,000 feet (3.2 miles) and the short axis is 4,000 feet (0.8 miles). The width of the stock increases with depth (Figure 17) so that at 6,000 feet the long axis is 21,000 feet (4 miles) and the short axis is 7,500 feet (1.4 miles).

Eight wells have encountered caprock or salt and fourteen others were drilled within a two mile radius of the center of the dome. The shallowest depth at which salt has been located is -581 feet (MSL) or 777 feet beneath the surface. There is no description of the salt on either the driller's logs or in the literature. The shallowest depth to caprock is -462 feet (MSL) or 658 feet beneath the surface. Caprock is found over the top and along the sides of the stock to a depth of as much as -4,821 feet (MSL). Its thickness ranges between 80 and 140 feet. Spooner (1926) described the caprock as white and dark gray anhydrite, with irregular dark gray and blue banding. A driller's log from the 1923 Standard Oil Company of Louisiana Stephens well shows pyrite above 114 feet of gypsum.

Vacherie Dome is located in the normal Sparta sand outcrop belt, but Cane River and Wilcox beds occur in the center (Martin and others, 1954). One strike and

dip of N52E, 14SE was taken on a Cane River outcrop near the middle of the line dividing sections 21 and 22; this dip is thought to be abnormally high for the area.

The whole of the Vacherie area, ridges and lowland, is covered by a blanket of Pleistocene terrace deposits, which are essentially undifferentiated.

Exposures in a small pit (sand quarry) over the center of the dome and in a railroad cut six miles to the north suggests that the lower surface of the terrace is cut by stream channels and may have a local relief of several feet. Discontinuous gravel beds occur at or near the base of the unit.

Rayburns Dome

Rayburns Dome is located in Bienville Parish (Figure 4). Radial (centripetal) streams and springs feed into salines located over the dome. Depth to salt is 115 feet. Caprock, consisting of calcite, gypsum, and anhydrite is up to 130 feet thick and may be exposed at the surface. The dome is approximately 2,300 feet across about 500 feet below sea level and expands to 3,500 feet across at 2,000 feet below sea level. Fresh groundwater is not present over the dome, but extends to a depth of 1,000 feet on the sides of the dome much like a cone of depression around a well.

No oil and gas resources are associated with Rayburns dome. The nearest field is six kilometers away in reservoirs unrelated to the dome. Limestone is quarried from Cretaceous strata dragged up on top of the salt. Only three wells have been drilled into the salt.

MISSISSIPPI

Descriptions of Cypress Creek and Lampton Domes were taken from Anderson and others (1973). Sparse data are available for Richton Dome in Jirek and Weaver (1976); this dome had been rejected for consideration by Anderson and others (1973). See Figure 5 for locations.

Cypress Creek Dome

Cypress Creek was only suspected to be a dome in 1978, and little published information is available. The dome is apparently slightly smaller than Tatum Dome (approximately 1.6 kilometers); no figures on depth to salt are available, but Anderson and others (1973) estimate the depth to salt to be about 600 meters. The dome is overlain by a poorly drained swamp on Cypress Creek which is surrounded by hills about 16 meters high.

Lampton Dome

Lampton Dome is located in Marion County. Depth to caprock is 421 meters and depth to salt is 515 meters. No published data are available on the size of the dome. Fresh groundwater is present over the dome. The dome is apparently surrounded entirely by shale.

Sixteen wells have been drilled into and around the structure. Only two wells reached salt, and oil and gas exploration has been unsuccessful. The caprock was drilled in search of sulfur, but no significant showings were found.

Richton Dome

Richton Dome is located in Perry County. Depth to caprock is 155 meters; depth to salt is 226 meters. No published data on the size of the dome are available. There is no known hydrocarbon production near the dome.

APPENDIX B

EXCERPT FROM HOSMAN (1978) DESCRIBING DETERMINATION OF GROUNDWATER FLOW TIME FROM VACHERIE DOME TO THE CITY OF MONROE, LOUISIANA

The Sparta Sand is the most widely used aquifer in the area and is the only aquifer for which sufficient potentiometric, hydraulic, and physical data are available to enable determination of regional flow paths. The flow paths on plate 10 (Figure 30) were produced by digital-modeling techniques to show the course taken by water passing several selected domes. Fluid flow from one of these domes would follow more or less the path indicated. However, the time required for a fluid to travel the path might be substantially longer than the time taken by the native aquifer water to travel the same route. This is because any fluid escaping a dome likely would be a brine. A brine entering a freshwater aquifer will settle to the bottom of the aquifer because it has a much higher density than freshwater. Thus, the brine will follow the lowest part of the aquifer as it moves toward a discharge point, a much longer path than considered for average conditions by the computer program.

Movement of solutes in a brine would be affected by forces that probably are more significant than the density of the brine. Sorptive properties of some or all of the solutes and materials in the aquifers and confining beds, as well as dispersion and diffusion of the brine, could have an effect on solute transport that would outweigh hydraulic influences. Conceivably, solute transport might be limited to a relatively small area by natural controls.

Flow through the Sparta Sand is greatly influenced by the fact that the formation is composed of interbedded sands and clays of variable extent that were deposited by a system of constantly shifting stream channels (Payne, 1968). The sands generally are considered interconnected to varying degrees, and a path following the lowermost sands would necessarily be circuitous. Low zones would have to "fill up," so to speak, before the denser water could proceed beyond them. For these reasons the travel times shown for the flow paths on plate 10 are conservative and probably represent the minimum time required for freshwater to travel the indicated distance under prevailing head conditions.

FIG. 30. Map showing flow paths in the Sparta Sand from Vacherie Dome in North Louisiana. Modified from Hosman (1978).

The traveltimes of water shown on plate 10 were computed using a two-dimensional model of the Sparta sand. Adsorption and dispersion were not considered in the computations. The flow paths shown on plate 10 are based on limited potentiometric data for May 1975 and apply only so long as the general pumping patterns and gradients remain unchanged. Development of new pumping centers or change in old ones will alter the potentiometric surface and the flow net accordingly. Plate 10 should be considered preliminary, as the potentiometric data it is based on are locally inadequate. The results will be refined as additional data are collected and incorporated into the model. If one of the domes is used as a repository the flow map should be updated periodically.

Regional maps of flow in and between the remaining aquifers cannot be constructed with available data. Test-drilling plans at a prospective dome should include a sufficient number of test wells at some distance from the dome to provide hydrologic data for all major aquifers. These data would be used to establish hydrologic properties of the aquifers and confining beds and to construct flow maps and determine hydraulic gradients and flow rates.

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