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TRIP REPORT

GULF INTERIOR SALT DOMES

September 8-19, 1980

Peter Hart
Robert L. Johnson
Thomas J. Nicholson
Ellen Quinn
Robert J. Wright

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INTRODUCTION

Purpose of Trip

Between September 8 and 19, members of the NRC staff undertook a technical survey of the U.S. Department of Energy (DOE) studies in the Gulf Interior Region (GIR). Within the GIR, seven salt domes are under preliminary investigation as possible sites for storage of high-level nuclear waste. Two domes are in northwest Louisiana, two domes are in east Texas and three are in Mississippi (Figure 1).

The trip is one of several to review DOE investigations for the siting of a high-level waste repository. This work is under way in a variety of rock types at a number of locations within the United States.

The trip was intended to serve several purposes: to provide an opportunity for the NRC staff to become familiar with the salt domes and their geologic setting; to establish contacts and consult with specialists familiar with salt dome geology; to review the nature and thrust of DOE-sponsored investigations; and to develop a basis for refinement of various NRC documents now in preparation. It should be noted that it was not the purpose of the trip to make any evaluation of salt dome suitability for a repository or any comparison of the suitability of any of the seven domes presently under study.

Organization of Trip

A general introduction to the investigation of GIR was provided in Columbus, Ohio on September 9 by the Battelle Memorial Institute's Office of Nuclear

Waste Isolation (ONWI). During the morning, representatives of DOE and ONWI discussed the following topics: the program organization and history, and site screening and decision process. In the afternoon, the geology of salt domes and and of the GIR was presented by Law Engineering and Testing Company (LETCO) and consultants.

During the following ten days, field tours were undertaken of the seven domes, numerous Tertiary exposures, the Winnfield dome caprock quarry, the LETCO Hattiesburg, Mississippi field office, and a hydrologic testing operation underway in Louisiana. These field visits were interspersed with conferences with salt dome and regional specialists in Jackson, Mississippi; Baton Rouge, Louisiana; Alexandria, Louisiana and Austin, Texas. In addition, a tour of the Avery Island salt mine in Louisiana provided a look at salt dome internal structure and the DOE in situ tests. The trip route is shown on Figure 1 and the itinerary is presented in Appendix A.

NRC members who undertook the trip are: Peter Hart (engineering geology), Robert L. Johnson (stratigraphy), Thomas Nicholson (hydrogeology), Ellen Quinn (modelling) and Robert J. Wright (exploration geology). Participating in the first week was F. Larry Doyle (hydrogeology).

Organization of Report

This trip report is a summary of information gained during the trip. It is divided into three major parts: brief topical material, observations, and meeting notes.

The topical material includes stratigraphy, structure, dome growth, internal structure of a dome, hydrology, dissolution, and modelling. These sections give a brief overview of each topic as background for the observations. These sections are not intended to be a comprehensive summary of salt domes, as such information is already available in numerous publications. The observations section discusses the major issues which the group feels should receive attention. The meeting notes (Appendix A) briefly discuss the major topics discussed during each meeting.

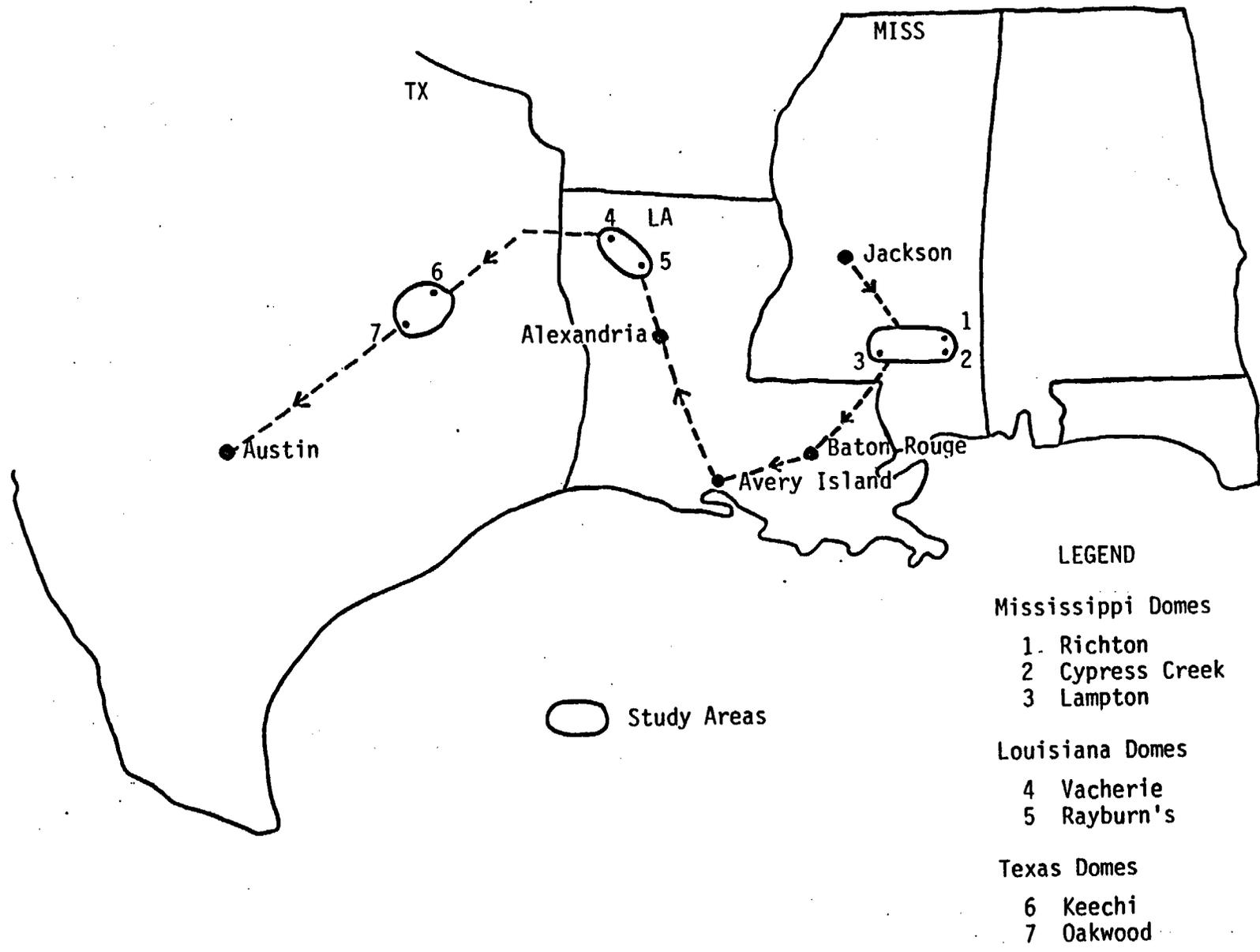


Figure 1 Gulf Interior Region Trip Route

STRATIGRAPHY

This section summarizes the regional stratigraphic framework and identifies some technical problems encountered in Gulf Coast stratigraphy. The focus is on the regional stratigraphy of the sedimentary units surrounding the salt domes, while sections titled Dome Internal Structure and Dome Growth focus on the salt domes themselves.

Salt domes of the GIR pierce through and are surrounded by a thick sequence (15 to 20,000 feet near the domes under study) of generally unlithified sediments of Triassic, Juriassic, and Cretaceous (about 63 to 180 million years before present) and Tertiary and Quaternary (present to 63 million years before present) age. Three units are of primary importance. One, the upper Triassic and lower Juriassic Louann salt is a deeply buried bedded salt deposit which is the source of salt for the domes. Two, the Tertiary sediments (about 2 to 63 million year before present) surrounding the domes at and above repository depth are the most relevant to understanding the hydrogeologic system, dissolution, and reconstructing dome growth. Three, the Quaternary sediments, where they overlie the domes, are useful in detecting any uplift or subsidence.

The sediments thicken towards the Gulf of Mexico and represent the Gulfward migration of ancient depositional environments through time and the downwarping of the Gulf area. These sediments include alternating nonmarine clastics and marine clastics, carbonates, and evaporites. The resulting high vertical and areal lithologic variability is due to repeated episodes of emergence and

submergence causing shifting fluvial, deltaic, barrier island, shelf, and slope depositional environments. This lithologic variability leads to aquifer heterogeneities such as high-permeability sands interbedded with low-permeability muds.

The dome study areas in Texas, Louisiana, and Mississippi are all located within the same complex sequence of sediment; therefore, many of the same formations are being studied in each state. There is, however, some difference that the units in the Mississippi study area are higher in the Tertiary section while those in Louisiana and Texas are lower in this section.

Technical problems exist in identifying, correlating and mapping the complex Tertiary and Quaternary sedimentary units due to a) lack of fossils, b) lack of distinctive lithologic characteristics (c) lack of material for accurate age dating, and d) high degree of vertical and areal variability in lithofacies. Only limited lithologic data exist from continuous cores of aquifer and confining units due to difficulties in recovery core of the generally unlithified Tertiary and Quaternary sediments. Missing or limited extent of Quaternary deposits over the domes limits the ability to detect any uplift or subsidence which might have occurred during the Quaternary.

STRUCTURE

This section focuses on regional and near-dome structure. The three study areas lie with the East Texas Salt basin, Northern Louisiana Salt basin, and the Mississippi Salt basin. These are all contained within the broad gulfward dipping Mississippi Embayment. The regional structures reflect a tectonically stable area. The structures, whether of basement or salt movement origin, are not complex and generally old. The low seismic activity in most of the region also suggests stability.

One of the structures currently being investigated is the Elkhart Graben-Mt. Enterprise fault system. This fault zone has a higher seismic activity than that of the surrounding region. In 1891, an earthquake of about MM 8 was recorded in the vicinity of this fault system. The occurrence of this earthquake is still disputed since the records are not clear. In the last one hundred years several earthquakes of MM 4-5 have also been recorded in this area. The epicenters of these earthquakes have also been placed in the Elkhart Graben-Mt. Enterprise system.

The only Quaternary faults observed in the GIR are in the East Texas Salt basin. These three oblique slip faults, with a maximum throw of 119cm, displace Quaternary deposits along the Trinity River. They dip steeply and strike to the east-northeast. Their location and orientation are consistent with the larger Elkhart Graben-Mt. Enterprise system. Relative movement of 130 mm in another section of this system suggests that the fault system may be active. These determinations were made from a study of Quaternary terrace deposits. Movement on these faults could reflect continued salt movement.

Within the immediate dome area, any faults or changes in dip of units result from the processes of dome growth and dissolution. There are other faults over the domes and along the flanks. Some of these faults have been recognized in the vicinity of the domes under study (ex., Keechi, Rayburn's, and Cypress Creek) but characterization has not been extensive.

These near-dome faults can be either water pathways or flow barriers depending on the level of permeability. Identification of the orientation and characteristics of all such faults would require extensive investigation and impractical levels of drilling adjacent to the dome. Work to date has included surface and subsurface mapping, drilling, and high resolution seismic surveys.

The interface between the dome and surrounding sediments is a fault zone due to the shearing associated with dome growth through the sediments (see anomalous zone discussions in the Dome Internal Structure section). The dip of the beds adjacent to the dome gives information about dome growth and stability (see the Dome Growth section).

DOME GROWTH

According to present theory, the first step in dome formation was horizontal movement in the bedded Louann salt, forming salt ridges or "pillows." One of the mechanisms for this movement was differential loading by overlying sediments, where heavier clastics (sand) pushed the salt towards areas overlain by lighter clay or carbonates. As the overlying sediments consolidated, they became denser than the salt, and this density difference led to further upward movement of the salt and piercement of the overlying sediments. The salt may also have been plastic, due to elevated temperature after burial, and the thermal effects would tend to increase the upward mobility. As upward movement progressed, additional salt moved horizontally toward the dome, providing additional salt for growth, and creating a circular depression ("rim syncline") around the dome. Some domes may have become completely separated from the bedded salt source.

Several basic approaches are being used in assessing future growth potential for the domes.

- a) Regional - The salt domes currently under investigation are in the interior of the Gulf Coastal Plain. These domes are geologically older, and are in a stable geologic environment compared with the coastal domes. There is no currently active erosion or deposition to seriously alter the current equilibrium, and hence no driving forces for additional movement.

- b) Near-dome structure - Studies of stratigraphy and structure of sediments surrounding the domes can indicate the relative age, stage, and rate of movement. In an early stage of development, a dome has a rim syncline that is relatively distant from the dome with thinning and steeply dipping strata near dome. At a later stage the rim syncline is closer to the dome, with strata thickening dipping downward toward the dome. Cylindrical and/or mushroom shaped domes suggest that salt has been withdrawn from around the base and a source is lacking for additional salt movement. Rim syncline analysis has yielded results of less than a meter of growth per 10,000 years for Oakwood dome. Generally, it is believed that the domes under study stopped growing as long as 30 million years ago.
- c) Quaternary Deposits - The best evidence for Quaternary dome stability would be the presence of continuous undisturbed Quaternary sediments or river terraces overlying the domes. Where present, the Quaternary deposits and terraces have been studied and they appear to be generally unaffected by uplift. This approach is, unfortunately, of limited value for several reasons. Many of the Quaternary and pre-Quaternary formations, particularly in Louisiana, can be very similar in appearance and without distinctive fossil or marker zones. Exposures are restricted. Disturbances may be caused by dome solutioning and collapse. Some real and inferred surface faulting of the pre-Quaternary at the domes may be related to dome or caprock collapse. At some of the dome locations, Quaternary formations and terraces may be missing either due to erosion or lack of original deposition.

- d) Precise leveling and tiltmeters - Very sensitive tiltmeters have been used in Louisiana to measure possible current uplift. Results to date indicate that very small movements are taking place, but these may be related to seasonal changes, groundwater withdrawals or earth tides.

From numerous lines of evidence it appears that the domes under study are not growing and are in a stable system. However, it will be difficult to prove lack of present or future growth for each dome, due to lack of direct evidence.

DOME INTERNAL STRUCTURE

The mineralogy of salt domes is very simple, but the process of dome formation has created a very complex internal structure. Generally the rock is composed of about 90 percent halite (salt, NaCl), with small amounts of intermixed and layered anhydrite (Ca SO_4), and trace amounts of shale, silica and carbonate. The salt is generally white, or transparent, and is finely granular to coarsely crystalline. Darker bands result from finely disseminated anhydrite within the salt. These darker bands reveal the nearly vertical orientation of the complex folding. Shearing, recrystallization and discontinuities are also characterized by vertical orientation. These features are all related to the dominantly upward, plastic movement of the salt dome. The problems related to mining have mainly been in what Kupfer refers to as "anomalous zones." The anomalous zones are also referred to in the literature as "shear zones." Each dome is surrounded, on sides and top, by an exterior anomalous zone caused by shearing between the salt and surrounding sediments during dome growth. In addition, a dome may have one or more interior anomalous zones. The interior anomalous zones represent the contact between two "spines" of salt. As dome moves upward to the surface as a heated viscous material it cools down and movement eventually ceases. New source material finds an easier upward path along the edge of the older spine until it, too, stops. The zone between two spines is the "anomalous zone" with sheared materials that include sediments and fluids that were in contact with the salt.

Most of the current knowledge on internal dome structure comes from mines, and most of the mining experience has been in the coastal domes. Six domes are

now mined: Avery Island, Weeks Island, Cote Blanche, and Belle Isle on the coast of Louisiana; Grand Saline, and Hockley in east Texas. The Winnfield dome in north Louisiana was mined until it flooded, during the course of one day in November 1965, and was abandoned. Jefferson Island dome was mined until November 1980 when the mine was flooded following a penetration by an oil exploration drill hole. These mines provide most of what is known about internal structures.

Several mining problems are related to the exterior and interior anomalous zones. These include:

- a. leaks into the openings, from internal and external sources, including brines, gases and hydrocarbons;
- b. joints and fractures;
- c. slabbing of the roof and pillars;
- d. gas blowouts and pressure pockets;
- e. shear zones.

Mines where some of the above problems were encountered are at maximum depth of 450 meters. These problems may be greater at the depths anticipated for a repository. Some of the above problems were encountered in the external anomalous zone of a dome and may have been avoided by staying within 300 feet of the dome edge (miner's "rule of thumb").

Since the interior structure of the domes is near-vertical, exploring a dome's interior with vertical borings will provide only limited data. The alternative

of exploring with angle borings may not appear to be acceptable because of the potential for undesirable effects on containment and dissolution. Only limited success has been achieved in testing dome interiors with underground geophysical methods such as radar and sonar. Horizontal borings from mine workings have been used to distances as great as 1000 feet. One possibility for underground repository exploration is to undertake horizontal tunneling in the salt at a level above a proposed repository. Conditions at repository elevation could then be predicted, by downward projection, since the geologic structures are mostly vertical.

HYDROLOGY

The fieldwork for the regional hydrologic studies of Gulf Interior Salt Domes is divided as follows; the U.S. Geological Survey (USGS) in Mississippi, Louisiana State University (LSU), and the USGS in Louisiana, and the Texas Bureau of Economic Geology (BEG) in Texas. Law Engineering and Testing Company (LETCO) is performing the site specific studies that involve flood analysis and subsurface drilling and testing of wells at the domes under study. The various state programs are being synthesized by LETCO for the study area assessment of the various domes.

The surface-water studies, which involve determination of flood histories, flood frequency analysis, and Probable Maximum Floods, are being done by LETCO for all of seven domes. The procedures followed are those outlined in NRC's regulatory guides (RG 1.59 and 1.70) for siting of nuclear power plants. Surface-ground water relationships are also being studied in the vicinity of the domes.

The specific groundwater conditions are highly localized by the topography, structure, and stratigraphy. However, in general the freshwater aquifers are the near-surface Quaternary and Tertiary units. The first confining unit is generally of lower Tertiary age. The character of the confining unit is controlled by its thickness and lithology. The lower Tertiary Midway Clay in northern Louisiana and Texas is the regional aquiclude. Individual overlying units may act as aquitards and affect surface-groundwater relationships and the degree of upward leakage from deeper confined saline units.

Regional groundwater flow directions are generally to the Gulf of Mexico or the Mississippi River with the intermediate and local groundwater flow directions to either the surface drainage network, recharge to the deeper units, or to large-scale pumping operations depending on local conditions.

The location of the fresh (less than 1,000 mg/l total dissolved solids (TDS), brackish (between 1,000 and 3,000 mg/l TDS), and saline (greater than 3,000 mg/l TDS) interfaces are highly dependent upon local groundwater flow conditions especially groundwater and/or petroleum pumping and injection operations, faulting and proximity to the Gulf of Mexico. However, the freshwater-saline boundary is generally in the lower Tertiary units below the regional confining unit. The cretaceous units are generally saline, and the upper Tertiary units can vary markedly from fresh to brackish depending upon local conditions.

The regional groundwater investigations involve identification of the principal freshwater aquifers, confining units, and saline to brackish units adjacent to the domes. In each state, ground-water information is lacking for the units between the near-surface (to 1,000 feet), fresh-water aquifers used for domestic and municipal water wells, and the deep (more than 4,000 feet), saline aquifers encountered in oil and natural gas development.

The identification of the regional flow systems including the recharge discharge and leakage areas and the regional hydraulics, has been defined in Texas, and Louisiana, but not as yet in Mississippi. The restricted study area and lack of historical records and previous ground-water investigations in deep aquifers has limited the work in Mississippi.

Using wells drilled and tested by LETCO, along with groundwater records, hydraulic potentials and gradients were determined in all three study areas. Because of the presence of high TDS in the deeper aquifers, groundwater quality data was also gathered to calculate equivalent hydraulic heads for the more saline units. One irregularity in the preparation of potentiometric surface maps in Mississippi arises from the fact that the USGS uses hydrogeologic units, while LETCO uses various horizons based upon groundwater quality.

The detection and mapping of salt plumes is an important consideration of salt dome stability and is being done in each area. However, hydrochemical facies work is very preliminary. Groundwater quality data is being collected in each area. BEG has been using its ground-water chemistry data in assessing the carbonate dilution factor for carbon-14 dating studies, and validating groundwater recharge, leakage, and discharge delineations.

To ascertain hydraulic properties of the various hydrogeologic units, LETCO has performed single-well pumping tests using the modified Jacob Method to determine the hydraulic conductivities and storage coefficients. Porosities were determined by laboratory tests on side wall cores. Vertical hydraulic conductivities and dispersivity data has not been collected.

For each area, the boundary conditions have been assessed. Regional stresses such as large-scale groundwater withdrawals, waste injection, and oil and natural gas development have been identified and put in the context of the regional groundwater hydraulics. Groundwater residence times have been investigated in Texas using C-14 studies. Groundwater velocities and pathways have been studied in Texas on a limited basis but not in Mississippi or Louisiana.

DISSOLUTION

This section discusses investigations and factors important to understanding salt dome dissolution. Dissolution is obviously one of the most significant processes having the potential for adversely affecting the hydrologic stability of a salt dome. Investigators in each state are studying this problem using various approaches. These studies are far from complete and at this time they seem aimed at: 1) developing better methods of study, 2) obtaining conclusive evidence for or against present and past dissolution, and 3) developing a better understanding of the processes and its controls.

Dissolution is an obvious problem because the existence of several hundreds of feet of caprock is evidence that large amounts of salt dome have dissolved in the past. Furthermore, salt domes at repository depth are now surrounded by a groundwater system which is unsaturated with respect to salt. Nevertheless, salt domes exist today, which indicates some form of protection from external groundwater. Investigators have, to date, observed no solid evidence for active dissolution at any of the seven domes under study.

Two explanations are given for the apparent hydrologic stability. One assumes that active dissolution is at a low rate which, combined with a high groundwater flushing rate, reduces salinities to very low, unobservable levels. The other assumes that some type of barrier exists which precludes of salt to circulating groundwater.

Four possible barriers are proposed, each affecting a different part of a dome: caprock, clay sheath, upturned clay units, and less permeable lithofacies. One, the caprock exists on the top of the dome and to some extent along the sides of the dome. The anhydrite, gypsum, and limestone making up the caprock is less solvable than salt, and can be several hundreds of feet thick. Two, a clay sheath has been detected at places on the sides of some coastal salt domes. Very little evidence exists for its occurrence in interior domes. However, it is likely that the exterior discontinuity may contain sheared clay material derived from adjoining sediments during upward movement of the salt. Third, the Midway Group (regional clay aquiclude) has been upturned by the growth of Keechi, Rayburn's and Vacherie domes to a position where it appears to separate the salt from the surrounding aquifers. Fourth, permeabilities in aquifers surrounding some domes may decrease toward the dome due to changes in lithofacies.

All of the above potential barriers could protect parts of the salt dome to some degree depending on the extent, continuity, and degree of permeability of the barrier. However, it may not be possible to determine the effectiveness of these barriers using available exploratory methods. Even a number of drill holes would reveal little about the nature and, therefore, the degree of isolation from groundwater provided by the barrier.

Investigations are also focusing on possible indications of both present and paleo dissolution. Salinity anomalies have been detected in the groundwater near some of the seven domes by analyses of water chemistry and interpretation of electric logs. Anomalies are seen as high measured concentrations of

sodium chloride ions, high TDS, low Ca/Na ratios, and a high base of the fresh water. At the present state of knowledge, however, these anomalies could be the result of any of the following: 1) dissolution of the salt dome, 2) dissolution of the anhydrite caprock, 3) upward flow of saline groundwater from underlying units, 4) lack of complete flushing of either saline connate water or water from paleo dissolution from sand units having a higher clay content than surrounding sands. Additional hydrochemical sampling and analyses will be needed before these indications could be taken as conclusive evidence for present dissolution.

Conclusive evidence for present dissolution was only shown for Palestine dome in Texas where high sodium chloride concentrations were measured in a man-made lake over the dome. This salt dissolution was initiated by a solution mining operation during the 1930s and has continued naturally since mining stopped. The dissolution around boreholes is responsible for numerous surface collapses and formation of sink holes. Based on this information and related surface effects and uncertainties, all studies and further consideration of Palestine dome has ended.

It is widely thought that an open contact between the dome and caprock which might contain loose anhydrite sand is also a potential indicator of active dissolution. As with the exploring for potential barriers discussed earlier, one or few cores reveals little about the total extent of this contact or its connection with surrounding aquifers unless pumping tests are also used.

Suggestions of Quaternary or late Tertiary dissolution exist at most of the seven domes under study. These include widening and thickening of late Tertiary and Quaternary deposits in subsidence depressions over the domes, and the existence of subsidence deformation of Quaternary deposits most importantly terraces. However, salt dome dissolution, such as caprock dissolution, or structural readjustment (garben formation) as units were deformed over an uplifting dome. The limited extent or lack of Quaternary deposits around some of the seven domes restricts evidence of Quaternary dissolution of the domes.

It may be possible that by combining indicators, the domes which are relatively more or less susceptible to dissolution can be identified. The model stable dome would have clay gouge, upturned clay units around the flank, no saline plumes in groundwater and no surface salt licks. The model unstable dome would have very thick caprock, loose anhydrite sand at the caprock/salt dome contact, a salt plume downstream in the groundwater and surface salt licks.

Although the studies to date have greatly advanced the understanding of the dissolution process, potential indicators of dissolution, and methods of study, these are not presently sufficient to provide: 1) conclusive evidence for or present active dissolution at any of the seven domes, 2) understanding of the complicated dissolution process from the past into the future, or 3) understanding of the potential adverse effects on a salt dome hosting a repository.

MODELLING

This section summarizes the hydrogeologic and dome movement modelling studies discussed during the trip. This does not represent a comprehensive survey of all modeling studies related to salt domes since the principal modellers at ONWI were not available for consultation at the time of the visit to Columbus.

Hydrogeologic

The primary objective of the modelling studies is to picture the regional groundwater flow in both the fresh and saline aquifers. The amount of data in the states varies greatly because of various levels of prior study in the different states.

In Mississippi the USGS and LETCO will be responsible for modelling the groundwater of the Mississippi study area. Both plan to use the Trescott, Pinder, Larson 3-D Finite Difference Code (USGS Code). The data base consists of 41 aquifer test holes completed during the exploratory drilling phase. Estimates of the permeability of the units will be acquired from tests on sidewall cores.

Modelling of the region (basin) in Louisiana will be done by the USGS using the Trescott Laren 3-D Finite Difference Code. Although the modelling has not yet begun, the study area is defined and a data base has been completed. Much information exists about upper aquifers (30,000 points), but at potential repository depths little is known since the aquifers are saline.

In Texas, work is beginning on modelling water movement around Oakwood dome. The most important parameters to define are the vertical conductivity, the aquifer geometry and the variability in permeability. The 3-D integrated difference model TERZAGI will be used for the evaluation. The mesh will be generated by the OGRE program. Model validation will be done by comparing known heads in the Wilcox against those generated by the program.

The review of modelling efforts shows the need for: 1) more data in many areas, particularly within saline aquifers, and 2) more information about confining units and vertical conductivities. There is also a difference in the level of information available in the different states which impacts modelling attempts.

Dome movement

In Louisiana, modelling is planned to examine dome movement using SIMTRO, a finite element code. A two dimensional analysis of Vacherie dome has begun. The analysis results will be compared to the amount of movement described by tiltmeter data, but several problems remain to be overcome. The movement described by the highly sensitive tiltmeters is not always a reliable indicator of dome growth. Outside disturbances such as local construction, traffic, or soil moisture can distort the results. In addition, the mechanical properties of both the salt and surrounding beds is not well known. The assumption has been made that salt doming is approximated by parabolic movement of a viscous fluid. Laboratory tests are being done to investigate the salt properties. Plans for the Rayburn's dome include modelling in three dimensions, as it's asymmetric geometry does not allow representation in two dimensions.

OBSERVATIONS

To plan and coordinate the GIR program, so as to ensure that it provides results that can be linked with decision points in the national waste isolation effort, is a challenging task indeed. The range of geoscience disciplines is broad. The locations of the investigation are many. The number and variety of contractors and subcontractors--federal, state, university, and private--is considerable.

Much excellent work, by competent investigators, was observed in the three states during the course of the trip. Some of the investigators are leaders in their fields. Nonetheless, some apparent shortcomings in technical planning and coordination were observed. These are summarized in this section of the report.

The observations deal with the thrust and methodology of investigations; they do not concern the program organization and management. As might be expected, the observations reflect special interest in the fields of knowledge represented by numbers of the group. Observations are not attempted in fields where the group has inadequate familiarity--notably geophysics and seimology. It should be said, furthermore, that time did not permit a complete and exhaustive review of all aspects of the geotechnical and earth science work. Also, coverage could not be given to all the references in the truly monumental amount of literature on salt domes.

The observations are summarized under the following headings:

- o Greater emphasis on regional and near-dome groundwater studies.
- o Questions about certain screening criteria.
- o Question: Should the dome flanks be drilled?
- o Need for studies of internal dome structures.
- o Need for integration and coordination of technical studies.

Greater Emphasis on Regional and Near-Dome Groundwater Studies

An understanding of the regional and local groundwater is central to two elements that heavily influence the suitability of a dome: (1) probable release pathways for radionuclides and (2) protection of the salt from external groundwater. To address both of these problems requires satisfactory characterization of the groundwater regime in which the dome is situated.

The screening process that has to date yielded seven domes for detailed study has made little use of groundwater hydrology. The reasons are that other considerations have been more important, and the hydrologic data has not been available. However, the understanding of the groundwater picture will become more important during the more advanced stages of screening and selection. This will require collection of certain types of data. Data collection--from borehole testing or from records--takes time, and the analysis takes time.

Therefore, it is important now to identify the nature and form of the hydrologic data needed for input into decisionmaking; then, working back, the timing of contributory activities can be set. We suspect that such an analysis would show that present hydrologic studies may be off to a slow start and may not yield information in time for effective use in decision-making.

Specific comments follow:

1. A regional approach, utilizing hydrologic units, is needed for the various regional, intermediate and local flow systems. The present study area in Mississippi is too limited for this purpose. Some work in Mississippi is by fixed horizons and by hydrogeologic units in determining potentiometric surfaces. This difference in approach needs evaluation.
2. Attention needs to be given to the properties of the confining units. Only the aquifers appear to have been studied to date, yet knowledge of all principal hydrogeologic units is needed for modeling the vertical and horizontal flow components.
3. The methods for developing potentiometric surface maps for various water quality units needs standardization. At least two approaches are now in use.
4. Maximum use has not been made, in all places, of available subsurface data.

5. Consideration should be given to the future use of observation wells to more accurately determine storage coefficients, leakance, and other data not obtainable by single well pumping tests. Also, modified slug tests for confining units should be implemented.
6. More emphasis should be given to water chemistry studies, including isotopic chemical analyses, to determine hydrochemical facies, groundwater residence times, and present dissolution.
7. The approach and selection of computer codes used for groundwater modeling by different investigators needs standardization. Otherwise, comparison of results from different areas will be difficult. At least two approaches are now in use.

Questions About Certain Siting Criteria

Two documents present siting criteria applicable to salt domes: Y/OWI/TM-48,¹ and ONWI 33(2).² We understand that updated criteria are in preparation; however, the impression is that the above documents express the standards used in work to date.

¹G. D. Brunton, R. B. Langhon, and W. C. McClain, Office of Waste Isolation, Union Carbide, "Screening Specifications for Gulf Coast Salt Domes," Y/OWI/TM-48, February 1978.

²Office of Nuclear Waste Isolation, "NWTs Criteria for the Geologic Disposal of Nuclear Wastes: Site-Qualification Criteria," ONWI-33(2), January 1980.

Improved criteria are needed for further screening and site selection. The following imperfections are noted. Criteria numbers are taken from Y/OWI/TM-48.

Shale envelope. Criterion 7 calls for a "shale (mud) envelope" separating the dome and surrounding aquifers. DOE/NE 0007¹ also suggests that the domes are "encapsulated in plastic clays or other impermeable minerals" (pages II-108 and B-5). Most, if not all, domes are probably surrounded by an envelope of sheared sediment. (which may or may not contain clay), that protects, at least to some degree, the salt from dissolution by groundwater (otherwise the salt would not be there). However, a requirement to demonstrate the presence of a shale envelope that seals the sides of a dome presents an impossible task. An irregularity that might provide a path for dissolution can be quite small, and an unrealistic amount of drilling would be required to prove the absence of such an imperfection. Further, such a large amount of drilling might impair the basic integrity of the dome.

Total area. Criterion 3 requires "a minimum total area of 1,000 acres and a 153-m (500 ft) salt barrier around the boundary of a repository." We understand that, at various times since 1978, several figures other than 1,000 acres have been used. Conceptual repository design should now be advanced to the point that a definitive specification for this criterion can be established.

¹U.S. Department of Energy, "Statement of Position of the United States Department of Energy, In the Matter of Proposed Rulemaking on the Storage and Disposal of Nuclear Waste," DOE/NE-007, April 1980.

This point is important because much of the screening done to date has been based on the size of dome area.

Quaternary Uplift and Subsidence. The specification for Criterion 4 calls for a lack of uplift and subsidence during Quaternary time. Whereas this is doubtless a desirable condition, it may be unprovable at a particular dome where very little or no Quaternary deposits are present for observation.

Question: Should the dome flanks be drilled?

Some thought is being given to the possibility of testing the flank of a dome by drilling. The main objective would be to establish the presence of a shale envelope or other barrier between the salt and external groundwaters.

This is a matter for caution and careful judgment. While the presence (or absence) of a hydrologic barrier is clearly a matter of concern and interest, it is doubtful whether drilling can provide a definitive answer. Consider that a suitably-sized dome might have a diameter of two miles and a perimeter length of more than six miles. Even a small imperfection could be a threat to the integrity of the barrier. It is unlikely that any drilling program can prove the absence of an imperfection in the entire perimeter. The other part of the picture is that each borehole penetration could weaken the integrity of the repository. On balance, then, there appears to be greater potential losses than gains in such drilling.

Need for Studies of Internal Dome Structures

From information presented, it was not clear to what extent, or at what point, consideration of the suitability of dome interiors will enter into the screening or selection process. The presence of an interior anomalous zone in a selected dome will present a design problem and, perhaps, a construction and emplacement hazard. Such a zone, if present, will also reduce the area available for use. It appears that evaluation of this feature needs to be considered as a part of site screening and selection. However, present detection methods are inadequate. Studies to understand such features and to develop appropriate geophysical detection methods will be difficult. Long lead times are probably involved. Therefore, these should be started well in advance of future decision milestones.

Need for Integration and Coordination of Technical Studies

The salt dome investigation is a complex technical venture. It represents a wide range of geoscience disciplines, study topics, investigation locations, and types of investigators--corporate, individual and institutional. Furthermore, programmatic needs change with time; e.g., the technical input for decision-making in site screening is somewhat different from that in detailed studies of a particular dome.

It is a challenging task to assure that the right studies are sequenced in the right way to provide the right kind of input at the right time for decision-making.

Some of the preceding paragraphs have touched on areas where better coordination, tighter planning or more standardization are called for. In hydrologic studies,

for example, the approaches to computer modeling and determining potentiometric surface maps differ between states. While various sets of results, by various methods, can no doubt be rationalized, there is a question as to whether different basic concepts may be involved. At the minimum, there needs to be assurance that all sets of results are equally usable and can be compared. Beyond that, some reasonable degree of standardization is expectable within a single program.

Another area needing improvement is represented by the criterion on acceptable area. Establishment of the 1,000 acre minimum provided an important parameter for screening, probably the most important used to date. That figure was first set in early 1978. It is likely that design work since that time has refined ideas on the area needed for a repository, and another figure may be better in the light of present knowledge. If so there appears to be a disconnect between design parameters and site screening standards.

Cross-pollination of ideas between work centers is a normal need of a program of this magnitude. It would be surprising if some improvements along this line were not advisable. One subject which illustrates this involves the wide application of stratigraphy by the Bureau of Economic Geology in Texas to studies of dome growth, regional hydrology, and dome dissolution. Parallel studies in the other states could well be beneficial, particularly when integrated on a regional basis.

The Texas stratigraphic studies also show the potential value to be gained from applying results of regional studies or studies of other than the preferred domes to the preferred domes.

Finally, the mix of study topics needs periodic review from the standpoint of changing current and future needs. As examples, the usefulness of continued caprock and salt petrology studies might be reevaluated with respect to future decisionmaking needs.

APPENDIX AITINERARY^a

<u>Date</u>	<u>AM</u>	<u>PM</u>
Tuesday September 9	U.S. Department of Energy, NWTs Program Office-Columbus and Office of Nuclear Waste Isolation (ONWI), 505 King Avenue, Columbus, Ohio 43201	
Wednesday September 10	Alvin Bicker Mississippi Bureau of Geology P.O. Box 5348 Jackson, Mississippi 39216 (601) 354-6228	Charles A. Spiers U.S. Geological Survey Water Resources Division 100 W. Capital Street Jackson, Mississippi 39201 (601) 960-4600
Thursday September 11	Tour of Mississippi study area and LETCO field office in Hattiesburg.	
Friday September 12	Joseph Martinez, Institute for Environmental Studies, Louisiana State University, Baton Rouge, Louisiana 70803 - (504) 388-8521.	
	Donald H. Kupfer Department of Geology Louisiana State University Baton Rouge, Louisiana 70803 (504) 388-2975	Chip Groat Louisiana State Geological Survey Box G, University Station Baton Rouge, Louisiana 70893 (504) 342-6754
Monday September 15	Tour of Avery Island Mine International Salt Company Avery Island, Louisiana	Gary Ryals U.S. Geological Survey Water Resources Division P.O. Box 5402 Alexandria, Louisiana 71301 FTS 8-497-7992
Tuesday September 16	Tour of Louisiana study area and Winnfield dome caprock quarry.	

^aFigure 1 is a map of the Gulf Coast showing the seven domes and their three study areas, the cities where meetings were held and the general route taken on the trip.

Wednesday
September 17 Tour of Texas study area.

Thursday
September 18 William Fisher and Charles Kreidler, Texas Bureau of
Economic Geology, 1300 Lavaca, University Station, Box X,
Austin, Texas 78712 - (512) 471-7721.

APPENDIX B

LIST OF MEETINGS HELD DURING
THE GULF INTERIOR SALT DOME TRIP

State Organizations

Mississippi Bureau of Geology, Jackson, Mississippi
Louisiana State Geological Survey, Baton Rouge, Louisiana
Bureau of Economic Geology, Austin, Texas

Federal Organizations

Department of Energy and Office of Nuclear Waste Isolation, Columbus, Ohio
U.S. Geological Survey, Jackson, Mississippi
U.S. Geological Survey, Alexandria, Louisiana

University

Department of Geology, Louisiana State University, Baton Rouge, Louisiana
Institute of Environmental Studies, Louisiana State University, Baton Rouge,
Louisiana

APPENDIX C

MEETING NOTES

There follows, in chronological order, a brief summary of each meeting with groups other than DOE/ONWI.

Mississippi Bureau of Geology

Jackson, Mississippi--September 10, 1980

Attendees: Alvin R. Bicker (State Geologist), Mark Smith, Curtis Stover (Bureau of Geology); John W. Green, Robert J. Forsythe (Energy and Transportation Board); L. Doyle, P. Hart, B. Johnson, T. Nicholson, E. Quinn, R. Wright (NRC).

Discussion

Mr. Bicker asked if repository construction control by NRC would be similar to that used on nuclear power plants, which he had seen in action at Yellow Creek, Mississippi. He noted that not much had been seen of the work done by DOE. John Green mentioned that following recent decisions of the State Planning Council, Congress will soon be asked to include state participation in NRC licensing decisions on repositories.

A discussion followed, led by John Green, of the monitoring and studies being done at Tatum Dome, where nuclear weapons were detonated in 1964 and 1966. Tritium is now being found in near-surface and deeper (Cook Mt. Formation) aquifers, and (perhaps) surface soils. The measured tritium concentrations and releases appear to be increasing. Mr. Bicker feels monitoring of the Tatum Dome tests was not adequate. A bibliography was provided.

In Mississippi, four state agencies have responsibilities in connection with waste management: Bureau of Geology (Jackson); State Board of Health-- Radiological Division (Jackson); Research and Development Center (Jackson); and Mineral Resources Institute (Oxford).

U.S. Geological Survey, Water Resources Division

Jackson, Mississippi--September 10, 1980

Attendees: P. Dooley, C. Spiers (USGS); O. Swanson (ONWI), L. Doyle,
P. Hart, B. Johnson, T. Nicholson, E. Quinn, R. Wright (NRC).

Discussion

The function of the USGS in the area studies in Mississippi is to act as a consultant to Law Engineering. The USGS advises on techniques used for hydrologic testing, assists on aquifer tests and observes on-site drilling and testing.

The USGS also conducts an independent analyses of the data for DOE to determine the regional flow system within the study area. Forty-one pump tests had been completed. The data from twelve are considered invalid because of gas pressure and density changes; these are not used in regional analyses. The head values are corrected from brine to fresh water and potentiometric protection surfaces are drawn for the various hydrologic units.

Two gradients are seen in the area. There is regional flow to the south. There is also a vertical component of flow into areas between Richton and Cypress Creek domes. A head level difference of 75 feet exists, but the amount of flow and the point of discharge is not known. These values will be affected by the vertical conductivity of the confining units, which was not studied. The area is referred to as a "source sink" for the flow system.

Chemical analysis are also being conducted and Ca/Na ratio determined. The highest level of total dissolved solids was seen down-dip of the Richton dome in the Catahoola Formation. The anomalous concentration does not appear to be the result of vertical gradients since it is centered in one formation. The amount of data does not allow a complete evaluation. A similar study needs to be done at Cypress Creek Dome.

Institute for Environment Studies, Louisiana State University

Baton Rouge, Louisiana--September 12, 1980

Attendees: Joseph Martinez (Director, Institute Environmental Studies), Charles Kolb, Betty Lee, Edward Newchurch, John Sterling, Robert Thoms, Ronald Wilcox, (LSU); Owen Swanson (ONWI); L. Doyle, P. Hart, R. Johnson, T. Nicholson, E. Quinn, R. Wright (NRC).

Discussion

After a cursory review of Gulf Coast Salt Domes, Dr. Martinez outlined the various theories as to the origin and growth of both interior and coastal salt domes. The geology of Louisiana was then outlined, placing the salt domes in a regional perspective. Although it would appear that the geologic aspect of salt domes is well understood, the interior structure of salt domes has been barely studied.

Hydrologic dome stability was illustrated by two extremes. The unstable model has a thick caprock above the dome, unconsolidated anhydrite sand along the dome, and an aquifer in connection with the salt indicated by a salt plume down-gradient from the dome and salt springs above the dome. The stable model has a clay sheath around the dome, the dome is overlain by marine sediments and the aquifer is not in direct connection with the salt, as indicated by absence of salt plumes or springs. All domes fall somewhere between these extremes.

In geomechanics the principal objective is investigation of the tectonic instability of domes. Tiltmeters have been located on the flanks of the salt dome, with precise leveling studies to determine the rate of movement. The tiltmeters and leveling studies are extremely accurate and sensitive to everyday meteorological events and groundwater movement. One tiltmeter location was abandoned on Vacherie Dome because of the local disturbances. To assess these local perturbations, soil and air temperatures and rainfall data are also collected.

The Quaternary geologic studies focus on Quaternary deposits over and near the dome to detect any movement during Quaternary time due to dome growth or dissolution. So far no movement has been indicated.

A large storage room, kept at very low humidity, houses salt cores collected during the studies. With a light box, cores of salt were examined to show the various crystal textures, coloring, and inclusions. A tight contact between the caprock and salt was exhibited by one core.

Department of Geology, Louisiana State University

Baton Rouge, Louisiana--September 12, 1980

Attendees: Donald H. Kupfer (LSU); P. Hart and R. Wright (NRC).

Discussion

Dr. Kupfer's primary interest in salt has been study of the interior of the domes, and much of his work had been related to mining of salt.

The problems related to mining have mainly been in what Kupfer refers to as "anomalous zones." The anomalous zones are also referred to in the literature as "shear zones." Each dome is surrounded, on sides and top, by an exterior anomalous zone caused by shearing between the salt and surrounding sediments during dome growth. In addition, a dome may have one or more interior anomalous zones. The interior anomalous zones represent the contact between two "spines" of salt. As dome moves upward to the surface as a heated viscous material it cools down and movement eventually ceases. New source material finds an easier upward path along the edge of the older spine until it, too, stops. The zone between two spines is the "anomalous zone" with sheared materials that include sediments and fluids that were in contact with the salt.

Mining problems, where encountered, are generally related to the anomalous zones:

- 1) leaks (internal and external) of fluids, such as brine, gas, oil;
- 2) joints, which can extend up to 100' away from openings;

- 3) slabbing of salt from the roof;
- 4) gas blowouts (methane, carbon dioxide, hydrogen sulphide); and
- 5) weak salt in shear zones from 20' to 200' wide.

The growth history of salt domes can be illustrated by examples from various areas. Ranked according to increasing extent of upward growth, these are: Spain, Germany, interior Louisiana domes, Mississippi domes, shoreline Louisiana domes, and offshore Louisiana domes.

Other specific points of interest are:

- a) salt is only "self healing" in depth, say, over 2,500' deep;
- b) shales in the anomalous zone can contain water under pressure;
- c) since salt dome geologic structures are aligned vertically, features in a repository can be predicted by observations in excavations at higher levels;
- d) two "experts" on design of openings in salt have opposite opinions--one says make the opening as large as possible to create a wide stress envelope, the other says keep them as small as possible to minimize the stress;
- e) in Germany, tunnel headings are pre-drilled in advance of excavation.

Louisiana State Geological Survey

Baton Rouge, Louisiana--September 12, 1980

Attendees:

Chip Groat (State Geologist), Judy Bond, Lori Eversull, John E. Johnston, III, Harry L. Roland, Jr., (LGS); P. Hart, R. Wright (NRC).

Discussion

The state has initiated a new program for monitoring and regulating disposal of wastes by injection, the Underground Injection Control (U.I.C.) program. The state considers groundwater with salinity of less than 10,000 ppm as fresh water. Fresh water is as deep as 3,000' in the northern part of the state and becomes shallower to the south.

In northern Louisiana the Wilcox, Jackson, and Claiburn Formations contain lignite which is now being considered as a potential economic resource. Maps of the lignite have been prepared by the State. Clay is also considered a resource in northern Louisiana. The Cook Mt. Formation contains iron but is not now a resource due to the high phosphorous content.

The state Survey has available numerous publications, geologic maps and deep well logs including computerized data on 133,000 wells. Some of the items available are: surface map of lignite, clay resources map, oil and gas well map, groundwater recharge map, surface water supply, Quaternary map, palynologic map, bulletins on origin of caprock.

It should be noted that there is a gap in the data coverage between depths of water wells (generally less than 1,000 feet deep) and oil and gas wells (generally more than 4,000 feet deep).

Avery Island Mine, International Salt Company,

Avery Island, Louisiana--September 15, 1980

Attendees: Michael Gibbons, William Ubbes (ONWI); Donald Kupfer (LSU);
P. Hart, R. Johnson, T. Nicholson, E. Quinn, and R. Wright
(NRC).

Discussion

The tour of the Avery Island salt mine consisted of two parts: 1) observation of the in-situ tests being conducted for DOE and 2) observation of the internal structure of the Avery Island salt dome.

The test location is in a mine room on the 500 foot level. Electrical heater tests, accelerated borehole closure tests and brine migration tests are being conducted by RE/SPEC, Inc. for DOE/ONWI.

The three heater tests which have been underway for about three years are presently in a steady state condition and will be shut down in October. The results concerning the near-field response of dome salt to a heat source will be compared to Project Salt Vault test results in bedded salt to determine if the bedded salt thermomechanical models are applicable to dome salt.

Four accelerated borehole closure tests, or flat jack tests, are presently measuring the rates of closure in test boreholes for four different pressure and temperature conditions.

The brine migration tests consist of 1) natural brine movement under ambient-temperature conditions, 2) natural brine movement under elevated-temperature conditions, and 3) synthetic brine (deuterium-tagged) movement under elevated temperature conditions. The synthetic brine test resulted in the collection of 17 ml. of brine in 300 days with an elevated temperature gradient of $1.5^{\circ}\text{C}/\text{cm}$. No deuterium was detected, indicating that the brine collected is natural brine from within about two inches of the heater. Some problems with these tests were noted. One of the synthetic brine boreholes lost all of its brine overnight with no explanation yet known. Also, it is uncertain how much of the brine collected is old mine water trapped in microfractures during a period of mine flooding.

Dr. Kupfer noted a variety of banding structures exposed in the ceilings and walls of the test facility room and adjacent rooms. The near-vertical orientation of the banding allows for excellent correlation of major structures from one depth to another. In another part of the mine a sandy salt zone was observed; it has been the source of brine leaks and may be the edge of an internal anomalous zone. The development of the mine is strongly influenced by mining problems associated with these anomalous zones.

U.S. Geological Survey, Water Resources Division

Alexandria, Louisiana--September 15, 1980

Attendees: G. Riles (USGS); M. Gibbons (ONWI); P. Hart, R. Johnson,
T. Nicholson, E. Quinn, R. Wright (NRC),

Discussion

The USGS is conducting a regional study of the hydrogeology in northwest Louisiana. The area studied is 125 x 130 miles and contains Vacherie and Rayburn's domes. The stratigraphic units are grouped into hydrogeologic units. Much information (30,000 data points) exist for the Sparta Sand unit, since it is the principal fresh water aquifer in the area. The flow in the Sparta Sand has been greatly affected by commercial pumping at Monroe and Jonesboro. Historically the Sparta Sand had southeast flow, but the pumping has induced a northeast flow direction. The time required for the flow to return to the predevelopment state, if the stress ceased, has not been determined.

Less information exists for the deeper saline units in the area, and potentiometric maps have not yet been drawn. The USGS recommends more drilling in these formations since they occur at the proposed repository level near the domes. The USGS also recommends that information be obtained about the vertical conductivity of the confining units. Discharge appears to occur outside the study area but this can not be verified until more information is obtained.

Modelling of the system using the USGS finite difference model is planned. Before modelling occurs, determination of head gradients in the Nacatoch Sand is recommended. An additional element in the system is the presence of an inferred fault, 65 miles long with a 200 foot displacement, which cuts the top of the Sparta Sand. The inferred fault, middle Eocene in age, occurs 4-5 miles from Vacherie dome and 2 miles from Rayburn's dome. It is not known if this fault acts as a vertical pathway for leakage.

BUREAU OF ECONOMIC GEOLOGY

Austin, Texas--September 18, 1980

Attendees: L. F. Brown, Jr., Eddie Collins, Owen Dix, E. Dow Davidson, Shirley Dutton, W. L. Fisher, Alice Giles, Tom Gustavson, Martin Jackson, Charles Kreitler, Mary McGowen, Alice Seni, Steve Seni, E. G. Wermund, Debra H. Wood, BEG; Wayne Pennington (UT Department of Geology); Michael Gibbons (ONWI); P. Hart, R. Johnson, T. Nicholson, E. Quinn, R. Wright (NRC).

Discussion

BEG's function in the high-level waste program is to provide LETCO with basic data for characterizations. While accomplishing that task, the study will look at the East Texas basin overall and determine the adequacy of using salt domes in a generic sense. This regional approach will look at the variety of domes. The studies fall into four categories:

1. Tectonic or geologic stability;
2. Hydrologic stability;
3. Human intrusion; and
4. Quaternary studies.

A number of detailed presentations were made by BEG staff covering the scope and results of their various regional and specialized studies. Major points are summarized as follows:

Theories of salt dome growth - Mechanisms of salt mobilization were discussed. For initiation of salt movement the salt must behave plastically (in response to either moisture, heat or pressure) and have a lateral variation in thickness. The driving force may result from bouyancy, differential loading, or thermal convection. Differential loading from sediments seems to be the major factor with bouyancy contributing to growth at depth. The stages in dome development from Trueheim's model were discussed. Studies in Texas are trying to refine this model and fit various domes to it. Dome shape and the thickness and dip of surrounding units are used. Gravity mapping of the Louann salt shows anticlines separated by snyclines from which domes originated.

Geologic framework - Sursurface areas around fifteen domes were studied. Only three of these are below the freshwater Tertiary aquifers. Studies of dome tectonic stability use the sedimentary/stratigraphic framework around the domes and dome shape to determine growth histories of domes and the stage of development. Domes along the margin of the East Texas basin appear to have advanced to a later stage of development than those in the basin center.

Oakwood salt core studies - Salt core studies were made of samples from Oakwood dome. Conclusions are: pure salt is coaser grained than impure salt; non-foliated salt probably has been recrystallized; there is a sharp caprock to salt contact, but the caprock has salt-filled fractures; study of fluid inclusions in salt crystals may give clues to the depth and origin of the salt.

Salt strain analysis - Petrofabric studies were made of salt core samples to determine crystal shape, deformation, orientation, and strain history.

Basin formation - Before the opening of the Atlantic the Gulf basin opened by rifting. The Louann salt was deposited at this time during restricted marine conditions. Subsidence due to a tectonics rather than sediment loading was active during this time. Continued Gulf widening resulted in more open marine conditions and deposition of carbonates. As the Gulf continued to subside progradation of deltas began and continued.

Basin sedimentation - The upper Triassic and low cretaceous is characterized by alternating clastic (regressive) and carbonate (transgressive) sequences. Stratigraphic studies are used to understand initial dome growth. It is believed that depocenters controlled the initial salt mobilization which then control subsequent delta locations. A thick carbonate unit only in the center of the basin may have limited salt movement by distributing the loading. This resulted in domes now in the center of the basin appearing to have reached only an early stage of development while domes near the basin margin have reached a late stage.

Sand deposition and salt movement - The control of sediment loading on dome growth was illustrated by sand lobes surrounding Hainesville dome and its rim syncline. Other domes without rim synclines are not surrounded by sand lobes.

Basin faulting - The Mexia-Talco fault zone is crescentric in shape and a peripheral graben system to the north and west of the East Texas basin. It

corresponds with the limits of the Louann salt at depth, and was active from early Triassic to early Tertiary. The Quaternary was not affected. The Elkhart-off enterprise system may be part of the same system. Studies are being made to check on the current activity of this system.

Quaternary faulting - Quaternary faulting was observed in outcrop along the Trinity River following the Elkhart-Graben trend. The faults are oblique slip faults with normal displacement and 80° dip. Leveling surveys in another area at the edge of the Mt. Enterprise showed changes in surface elevation of 130 mm (5 in.). Earthquakes have been recorded along the same trend.

Seismicity studies - The GIR is characterized by a low seismicity. Due to the higher historical earthquake activity near the alt. Enterprise fault system, a seismometer has been established. Many small events have been recorded, but the sources have not been defined.

Lineament mapping - Mapping surface lineaments detailed the regional trends and relation to domes. The southern portion of the basin showed differences from the northern area. Lineaments do not show the Mt. Enterprise fault system.

Dissolution of Palestine dome - Palestine dome was solution mined from 1930-1937. Subsequently, dissolution continued around wells causing numerous sink holes. The man-made lake over the dome has 2500 TDS with a high NaCl content.

Hydrology and domes - The only Texas dome being studied that has water containing NaCl is Palestine. Data for other domes is from electric logs from which TDS is calculated. Other domes show TDS increasing away from domes and higher in lower portions of the Wilcox. This may indicate higher mud content in sands near the dome resulting in poorer flushing of old saline water rather than dissolution. The upturned Midway clay separates Heechi dome from high TDS zones. A high TDS plume has been detected around Oakwood dome. The lack of solid evidence for dissolution might be explained by 1) dilution from a low dissolution rate combined with a high flushing rate 2) the caprock acting as a barrier to dissolution.

Caprock studies - Cores of caprock from Oakwood and Gyp Hill domes were described and compared. Gyp Hill caprock displayed an anhydrite zone overlain by a gypsum cone. Oakwood has an anhydrite zone overlain by a banded calcite zone but no gypsum zone. The interpretation is that the Gyp Hill caprock form at shallow depth in a low temperature, low salinity environment.

Hydrology of the meteoric section - Studies are focusing on the Wilcox and Carizzo formations which act as a unit, and is confined to semi-confined. Potentiometric maps showing flow lines were used to compare to topography, water shed features, and lithofacies (percent sand maps). It appears that topography and rivers strongly influence the flow system. At the scale of present study, little correlation is seen between lithofacies and the flow system.

Groundwater chemistry - Groundwater chemistry studies are used to evaluate groundwater flow paths, zones of recharge, the evolution of water chemistry, and to identify potential nuclide changes during transport. Deeper groundwater chemistry is predominantly sodium bicarbonate, whereas near the outcrop it is calcium carbonate. The pH rises with depth. The chemistry is important to correct C_{14} dating procedures, since "dead" carbon (mostly from calcite caprock dissolution) is being added to the system. Carbon 14 dating of water in the Gulf Coast will be ver difficult.

Hydrology of the saline section - Studies in the Woodbine formation (saline unit at repository depth) have just started. Pressure declines in the Woodbine have been high and rapid due to fluid withdrawal by oil and gas production. The decline has spread indicating a lack of recharge to the system. Presently, the Woodbine head is lower than that of the overlying Wilcox. Leakage from saline units around domes or along fault zones such as the Mt. Enterprise is possible. "Clay sheaths" have not been seen surrounding Texas domes.

Hydrologic transport modeling - Modeling of water movement around oakwood dome is being done using the 3-D integrated finite difference code TERZAGI. The mesh will be generated by the OGRE program. Studies are being conducted on transport models regarding: 1) location of releases, 2) paths of releases, 3) dilution due to convective dispersion and sorption, and 4) thermal affects on flow. Model boundaries are: 1) lateral flow in and out of the system, 2) vertical leakage, 3) aquifer geometry, and 4) variations in permeability. At present permeability of the aquitards is not known, but samples are being taken from cores. Permeabilities are also being estimated by feest correlating

grain size analysis results of lithofacies to pump tests and then to electric log interpretation. Sediment samples have been sent to Battelle (PNL) for transport retardation studies. Solute transport modelling is planned.