RADIOACTIVE WASTE MANAGEMENT
BY BURIAL IN SALT DOMES

by

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ABSTRACT

Questions regarding the suitability of salt domes as sites for high level radioactive waste repositories are considered. Since wastes will have to be retained for thousands of years, the principal questions pertain to the geologic stability of the dome, and the possibility of dissolution.

No direct evidence is available to show that movement is positively not occurring in any salt dome. However, it is shown through geologic reasoning that the likelihood of movement of domes in the interior basins is extremely remote and that if movement is occurring, it is taking place at such a slow rate as to present no problems. It is also believed that the likelihood of future movement as a result of geological activity within the storage time span is very remote.

The possibility of dissolution to the point that it might become a threat to containment is found to be slight particularly if the repository is surrounded by shale and below the base of fresh water or actively circulating ground water. Other mechanisms which protect against dissolution are discussed, as well as evidence of dissolution, or non-dissolution in the past. The consequences of dissolution are also examined. Possible flooding of repositories in domes, was found not to be a serious threat.

Temperature rise data from Project Salt Vault are used to estimate temperature rises which might occur in domes, and some simplified calculations are made to determine the temperature rise that would occur under certain hypothetical conditions. These data indicate that heating, of the extent to be expected,
poses no threat to dome stability.

The available data indicate quite definitely that creep or plastic flow around a cavity mined in salt causes the cavity to close, but the rate of closure is so slow as to present no serious problems in the operation of a repository.

Dome and bedded salt are compared as to their suitability for radioactive waste repository sites. Neither is superior to the other in an overall sense. In fact, depending upon the ultimate repository design, dome salt may be the preferred geologic formation. In a survey of all known domes 29 were identified as potentially acceptable candidates for a waste repository. Objections to domes based on their future tectonic stability and hydrologic integrity can be met. Characteristics of the ideal dome for a radioactive waste repository are summarized. At least five domes meet most of the criteria of the ideal dome. Recommendations are made to enable selection of the right dome.
INTRODUCTION

Salt deposits have several characteristics which make them attractive as permanent disposal sites for radioactive wastes, particularly the high-level wastes. These characteristics have been pointed out many times in the literature (Culler, 1971, Parker and others, 1958, Lomenick, 1968) pertaining to waste disposal; so, they need not be repeated here. It should be noted, however, that the basic hypothesis of the suitability of salt deposits as potential disposal sites has been questioned (Hambleton, 1972) and some writers are critical of any scheme that does not provide for retrievability of the radioactive isotopes (Burch, 1973). The preponderance of opinion, however, appears to favor permanent disposal in salt deposits over all other alternatives that have been proposed to date.

Most of the attention up to this time, particularly within the AEC has been focused on bedded salt deposits. (Blanco and Parker, 1967; Boch and others, 1971; Bradshaw and others, 1969). Project Salt Vault which was an extensive field study carried out by the AEC on the problems of disposal in salt has been described as "successful in all respects" (Culler, 1971) and it has led to the conclusion that "burial in salt mines is one of the better, if not the best, methods for ultimate disposal of high-level solidified wastes" (Bradshaw and others, 1970).

Salt found in domes has all of the advantageous physical characteristics of bedded salt. In addition, it has a higher purity than the bedded salt, contains none of the shale lenses and partings found in bedded salt, has great vertical height, and has vertical internal structural elements. The dome salt may
also be slightly stronger than bedded salt. Despite these apparent advantages dome salt has never been given the attention that has been bestowed on bedded salt. However, it has been pointed out that "all considerations on the general advantages of salt failed to reveal any fundamental reason why domes should be excluded from consideration" as repository sites (Culler, 1971).

Nevertheless, a number of questions have been raised regarding the suitability of salt domes. Serious consideration of domes as potential storage sites requires that these questions be addressed and resolved.

Questions most persistently raised are as follows:

1. Where are the candidate domes located?

2. Tectonic Stability: How can it be demonstrated that a candidate dome is not moving, and if it is shown not to be moving, what assurance can be given that it will not start to move when heated by the buried atomic waste, and if it does move, how will the containment be affected?

3. Hydrologic Integrity: How can it be demonstrated that future extensive dissolution of the salt in the dome will be improbable? If ground water movement around the candidate domes must be determined, can this be done at a reasonable cost and in the permissible time span? If the disposal area is surrounded by shale and below the base of actively circulating ground water is the dissolution question pertinent? Is flooding a special hazard for mines in domes?

4. Dome Geometry: Since it is necessary to have some appreciable thickness of salt between the radioactive material and the country rock surrounding the dome, an accurate
determination of the dome geometry is necessary. Can this be done at a reasonable cost, or is the necessary information already available?

5. Residual Stresses: In the process of dome formation the salt within the dome was subjected to very high stresses and underwent severe plastic deformation. Has this process left residual stresses in the salt which will make it impossible to predict what will happen when mines are opened and the salt is heated by the nuclear wastes? What is the nature of the stress distribution in the dome which results from the overburden and the deformation of overlying strata by piercement during dome formation?

In this report these questions will be treated within the proper context of radiation hazards and the necessary containment time of the wastes to be stored.
GEOGRAPHIC DISTRIBUTION OF SALT DOMES

In the northern Gulf Coast area, Texas, Louisiana, Mississippi, and Alabama, there are 263 known and suspected onshore domes (fig. 1; Anderson and others, 1973). Texas has 78 domes, Louisiana 120, Mississippi 63, and Alabama 2. The distribution by geologic basin is: East Texas 20, North Louisiana 19, Mississippi 77, Rio Grande 6, and Texas-Louisiana 141 (Anderson and others, 1973, p. 9). The former three basins are referred to as interior basins; the latter two as coastal basins. Interior basins have 116 domes (44 percent) and coastal basins 147 domes (56 percent).

Anderson and others (1973) in their excellent summary study rejected 227 of the 263 domes as being unsuitable for waste emplacement leaving 36 potentially acceptable domes. They rejected domes more than 610 m below the surface and those used for oil production, LPG storage, and sulfur and brine production. The 610 m cutoff is necessarily arbitrary; its relaxation could increase the number of potentially acceptable or unrejected domes. In this report the 36 unrejected domes are cited for specific illustrative examples (fig. 2). Among these domes 7 are in the East Texas basin, 8 in the North Louisiana basin, 14 in the Mississippi basin (2 in the state of Louisiana), 1 in the Rio Grande basin, and 6 in the Texas-Louisiana basin (all in Texas). Interior basins have 29 unrejected domes (81 percent) and coastal basins 7 domes (19 percent).
Figure 1. Salt basins, salt domes, and uplifts, Northern Gulf Coast region; modified from Eby, 1956.
TECTONIC STABILITY

Concern about tectonic stability revolves around the uncertainty of predicting the future stability of dome salt. It has been stated that the dome must not be currently active and that rejuvenated movement be impossible (Culler, 1971; McClain and others, 1972). The question really becomes one of waste residence time versus the time necessary for unacceptable dome movement to occur. Relevant topics such as triggering mechanisms, regional depositional history, and rates of movement will be discussed.

Salt Diapirism

Triggering Mechanisms. Three probable triggers for salt diapirism or salt movement are density contrast (bouyancy), heat, and faulting. The relative importance of these is difficult to assess; however, no one of them acting alone seems able to trigger movement. Many workers think it takes some combination of these mechanisms to initiate movement (Parker and McDowell, 1955; Gussow, 1968; Tanner and Williams, 1968; Kupfer, 1970a). The factor that causes localized rise at one point and not another may be something as minor as a local basinal irregularity or a facies change in the salt or overburden.

Nettleton (1934) likened salt movement to that of a very viscous fluid under gravitational forces generated by a density contrast between salt and sediment. Later mathematical papers presented a theoretical treatment of salt-dome dynamics
showing that the primary reason for the rise of salt domes is the buoyant force of a light layer of salt overlain by denser sediments (Danes, 1964; Biot and Ode, 1965; Selig, 1965).

Dickinson (1953), using data for Gulf Coast sediments, found that at least 915 m of overburden is required before it exceeds an average salt density of 2.20 gm/cm$^3$. Trusheim (1960) cited 1000 m of overburden; Kupfer (1970a, 1974a) 915 to 1525 m. Other workers have called upon less overburden. Nettleton (1934) implied that 610 m of Gulf Coast sediment was sufficient. Parker and McDowell (1955) suggest that movement began under a relatively thin layer of sediment of approximately 305 m. They indicate that a great thickness of overburden would have prevented the development of domes. Apparently, there seems to be no distinct minimum depth of burial. Perhaps the element that is being overlooked is uneven or differential sediment loading, a much more powerful force in generating salt movement than is a simple density contrast or pure buoyancy (Kehle, 1972). Theoretical work shows that nonuniform loading speeds up instability (Biot and Ode, 1965). Thus the critical factor is the pressure differential to which salt is exposed not simply its depth of burial.

Finally, as there is no agreement on overburden thickness, there is none on minimum salt thickness before movement can begin. Minimum mother salt thicknesses suggested range from 300 to 1525 m. (Trusheim, 1960; Gera, 1972; Kupfer, 1970a, 1974a).

Gussow (1968) and Heroy (1968) are advocates of heat as a critical triggering mechanism for diapirism. Temperature is
the parameter with the largest effect on the physical properties of salt. Creep is a thermally-activated process in which pressure plays a secondary role (LeComte, 1965). Experimental data show that by increasing the temperature of salt from 27° to 410°C the rate of steady state creep is increased 75 times (Heroy, 1968). Gussow (1968, 1970) believes that salt domes are thermally activated and relative density contrast is not a requirement for instability. He discounts the above cited theoretical work because it was based on the invalid assumption that salt and sediment behave as liquids during slow deformation through geologic time. Instability according to Gussow depends entirely on the ability of salt to flow plastically and behave hydrodynamically in response to load differential. Only at elevated temperatures will salt behave plastically and yield by plastic flow. Plastic deformation, in terms of the elastic limit and strength of salt, cannot occur below 200°C. At 300°C plastic flow occurs readily if the stress differential exceeds 44 kg/cm². Once the salt is plastic, the geostatic load is transmitted hydrodynamically to areas of lower pressure where piercing eventually occurs. Tanner and Williams (1968) also make plasticity, and by inference heat, rather than density contrast the prime prerequisite for diapirism. Based on model studies they believe diapirism is the response of a loaded plastic mass to a tensional stress by movement into the nearest available sites of dilation. Flowage folds in coastal-dome salt attest to the importance of heat and plasticity (Kupfer, 1970b) as well as the absence of strain in halite crystals (Balk, 1949).
Basement faulting as a triggering mechanism has been suggested for the salt ridges of Mississippi (Paulson, 1970), salt flow structures of the interior basins (Rosenkrans and Marr, 1967), Bay of Campeche diapirs (Ensminger and Matthews, 1972), and North German domes (Sannemann, 1968).

**Motive Force.** The driving force for salt intrusion is gravitational potential energy generated by buoyancy, caused by a density contrast, and differential loading. The latter is essential to lateral flow, which is critical in keeping a rising dome supplied with salt. If differential loading plays a dominant role, salt structures may coincide with advancing sediment wedges and have an irregular geometry. Buoyancy as a factor is confirmed by the circular shape of the domes and their essentially random distribution pattern. Apparently, buoyancy alone is not sufficient to produce diapirs for salt of considerable extent (German Zechstein) and thickness (1000 m), buried under thick overburden (3000-4000 m) has not produced diapirs. Heat and or secondarily faulting are essential for diapirism. No one of the suggested triggering mechanisms alone seems able to initiate diapirs; two or more must act together.

**Stages of Movement.** Salt diapirism occurs in stages governed by basin position, sedimentation, and time. At the basin edge (e.g. North Louisiana) diapiric structures are simple with short periods of movement while the deeper basin (e.g. Texas-Louisiana) structures are complicated by long spans of movement (Kupfer, 1974a). Stage one is non-diapiric and is
characterized by pillows with 10° to 20° slopes. Modern examples are found on the lower continental slope off Texas and Louisiana (Lehner, 1969). During stage two salt under the influence of increased sedimentation and advancing clastic wedges moves upward into massifs, massive salt structure with great relief and 45° slopes. The advancing sediment may push the salt ahead of it into a salt wall or ridge. An incipient wall is the Sigsbee escarpment (Lehner, 1969). Most of the offshore area today is still in stage two of semi-diapiric massifs. Diapirs appear in stage three rising out of the tops of massifs or independently under the influence of rapid sedimentation from isolated pillows (Kupfer, 1974a). Salt diapirs are uncommon on the modern continental slope.

**Internal Structure.** The attitude of all structural elements in domes is steep. Pioneer work on the internal structure of salt domes by Balk (1949, 1953) demonstrated that the limbs and axes of the folded salt are vertical or almost vertical. Salt beds are isoclinally folded around the vertical axes. Since the folds are isoclinal the axial planes are parallel to the limbs of the folds and essentially vertical; therefore, fold axes plunge 80 to 90° (Kupfer, 1963).

As a rule the interior domes are less complex than the coastal domes. Interior domes have simple folds and the folding is typical of solids under high confining pressure. Coastal domes have extremely complex folding, displaying flowage folding, refolding, and attenuation, all reminiscent
of plastic deformation and flow of fluids (Kupfer, 1970a). Because coastal domes have moved through the host sediment for greater piercement distances, they have a more complex history. This greater movement has been cited as a way differentially to purify coastal salt. The less pure salt, because of lesser mobility, was simply left behind (Kupfer, 1970a). Meager data indicate that coastal domes consist of purer salt than interior domes. Interior dome salt is less friable, harder, and less pure than coastal salt and therefore has greater competence.

Depositional and Piercement History

Deposition. The Louann Salt is the mother salt for the northern Gulf Coast salt structures and was deposited in basins initiated by the Early Mesozoic rifting and northward movement of North America from Africa and South America (Kupfer, 1973; Dietz, 1973). Salt deposition was rapid, perhaps as fast as 10 cm/yr or much faster than clastic deposition. Thus the Louann represents a short geologic interval. Prior to diapirism it was very thick but just how thick is uncertain. One to two kilometers does not seem unreasonable with the possibility that it was several kilometers thick (Dietz, 1973). Salt is not continuous across the deep Gulf Basin, but is restricted to the margins of the basin (fig. 1; Antoine and Bryant, 1969). The Louann is overlain by limestones (Smackover) containing definite Upper Jurassic fossils and underlain by
red beds (Eagle Mills) containing probable Upper Triassic fossils (table 1). Most geologists assign a Late Triassic–Early Jurassic age to the Louann Salt (Andrews, 1960; Jax, 1961; Scott and others, 1961; Burk and others, 1969).

Upon full opening of the Gulf of Mexico in the Late Jurassic, evaporite sedimentation ceased and the filling of the Gulf Basin with thousands of meters of terrestrial, paralic, and marine sediments began. Filling has proceeded from the basin rim to the basin center as illustrated by the shifting positions of depocenters and depoaxes in the Gulf Basin (Durham and Murray, 1967, fig. 4). In other words, the greatest thickness of sediment deposited moved progressively toward the basin center with time as a series of offlapping wedges (Hardin, 1962, fig. 7). Older Tertiary and Mesozoic strata are thin or absent on the present continental slope (Lehner, 1969). Thus the interior salt basins received thick sequences of Upper Jurassic and Cretaceous sediment and a markedly thinner Tertiary sequence (table 1).

In the East Texas basin there are over 4,600 m of Cretaceous and Tertiary sediments of which only about 600 m is Tertiary (Coon, 1956). The Mississippi salt basin, by the end of Jurassic time, had received up to 4,575 m of clastic sediment and by the end of Cretaceous time an additional 3,660 m of clastic and carbonate sediment had been deposited for a total of 8,235 m. Thus by the end of the Mesozoic Era the Mississippi salt basin had been filled to geosynclinal proportions. A thinner Cenozoic clastic sequence of 2,440 m is present, but
Table 1. Stratigraphic column, Northern Gulf Coast region.

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does not reflect the older basin. In general clastics (deltaic sediments) dominate the Mesozoic strata of the Mississippi salt basin, while westward in the East Texas basin carbonates characterize the Mesozoic strata.

The coastal salt basins, in contrast to the interior basins, are dominated by extremely thick Cenozoic (Tertiary and Quarternary) sediment sequences of 12,000 to 15,000 m. During the Cenozoic sedimentation was never uniform in the coastal area. Besides shifting gulfward with time, the depocenters and depoaxes shifted northeast. The area of maximum sedimentation for Eocene (table 1) was in South Texas and gradually shifted until the maximum for Miocene was in southern Louisiana (Hardin, 1962, figs. 1 and 5). Today sedimentation is most active in offshore Louisiana.

Clearly the occurrence of salt domes and basins, areas of maximum sediment accumulation, coincide. In view of the very important role of sedimentation (differential loading and density contrast) in triggering and driving salt movement, there is general agreement that sedimentation and salt movement parallel each other (Hanna, 1959; Andrews, 1960; Kehle, 1972; Woodbury and others, 1973). In other words the chronology of diapirism had a history parallel with that of depocenter shifting and shelf out-building. Thus it is concluded that interior domes began and ended their growth before coastal domes.

Piercing. Dome growth may have begun in the Mississippi salt basin coincident with the progradation of the ancient Cotton Valley delta system (Upper Jurassic). Differential
loading due to the advancement of individual delta lobes perhaps initiated growth (Kehle, 1972). To the west in the North Louisiana and East Texas basins it is postulated that growth began later, awaiting deposition of at least a few hundred meters of slowly accumulated Lower Cretaceous marine carbonate and mud. In the interior basins growth continued throughout the Cretaceous with piercing occurring in Late Cretaceous and Early Tertiary time (Clark, 1949, 1960; Thomas, 1950; Coon, 1956; Eaton, 1956; Andrews, 1960; Eargle, 1968; Bornhauser, 1969). Times of rapid growth appear to coincide with the progradation of thick, rapidly deposited clastic sequences. In the Mississippi and East Texas salt basins greatest uplift occurred coincident with rapid and extensive Wilcox and Claiborne sedimentation (table 1; Thomas, 1950; Eaton, 1956). Here again, differential loading appeared to play a significant role in dome growth. Generally, domes in the interior basins were most active from Late Cretaceous to Oligocene time and by lower Miocene they had formed (Kupfer, 1970a, 1973).

Interior domes may now be dormant, buried by post-emplacement strata of Late Tertiary and Quarternary age. Based on theories of caprock origin (Taylor, 1938; Bodenlos, 1970) and assuming the paleo-base of fresh water did not exceed today's maximum depth of 1,068 m, caprock below 1,220 m probably formed earlier under less cover than now. Eighteen of 21 domes in the North Louisiana and East Texas basins whose salt tops are below 1,220 m have caprock (Anderson and others, 1973).
Tertiary sedimentation dominated the coastal area. Growth did not begin until a thick overburden existed to drive it; therefore, the primary age of growth for coastal domes is much later than that of interior domes. Rapid sedimentation in the Miocene rejuvenated salt movement in the coastal area. At the continental margin the Pleistocene sediment wedge "steam rolled" the salt masses southward where salt structures rose through the continental slope sediments (Kupfer, 1973). Coastal domes experienced maximum growth from Miocene to Pleistocene time (table 1) and may still be active today (Kupfer, 1970a). What little evidence there is for present dome growth is restricted to the coastal area, site of currently active sedimentation.

Rates of Movement

Many geologists believe that salt deformation is a slow process, progressing at a rate comparable with that of other geologic processes such as subsidence, mountain building, and sedimentation. Rates of dome growth are difficult to assess. Creep observations in mines are not evidence of salt dome growth. All that is measured is the rate at which a particular pillar is deforming or room or drift is closing. Rates assigned to dome growth, determined by precision leveling and from geologic evidence, range from 0.3 mm/yr to 4 mm/yr (Sheets, 1947; Hanna, 1959; Trusheim, 1960; Ewing and Ewing, 1962; Gera, 1972; Kupfer, 1974a). The 0.3 mm/yr rate is an average rate based on the geologic time scale (Trusheim, 1960). The 4 mm/yr rate seems to be an extreme upper limit. Most
domes on the modern continental shelf and slope are growing at less than 3 mm/yr. Data of Ewing and Ewing (1962) indicate that shallow domes on the Sigsbee abyssal plain rise at 1.12 mm/yr. Trusheim (1960) believes 2 mm/yr is a maximum value. Ewing and Ewing correctly point out that it is impossible to differentiate upward motion of a dome from differential compaction of sediment. Gussow (1968, 1970) believes that differential movement which has been attributed to slow growth of salt domes is really differential compaction of sediment surrounding rigid, competent salt plugs. What have been measured are rates of compaction not rates of dome growth. O'Neil (1973) in a detailed study of the Belle Isle dome concluded that Gulf Coast domes were more affected by changes in sedimentation rates than by changes in rate of salt movement.

Whether the absolute rate of movement is changing or unchanging is not clear. Atwater and Forman (1959) convincingly argue for changing rates believing that domes are not intruded as a constantly upward-moving plug. Stages of movement have been assigned 10 to 40 million year spans (Gera, 1970). Others argue that salt flow is a continuous process and that the rate of flow remains essentially unchanged (Bodenlos, 1973; O'Neil, 1973).

HYDROLOGIC INTEGRITY

Concern over the hydrologic integrity involves possible salt dissolution by circulating ground water and the fear that it may reach stored waste (Culler, 1971; McClain and others, 1972). In other words the possibility of extensive
dissolution must be nil during residence. The problem is one of defining a hydrologic regime that will ensure complete isolation of the stored waste. Anderson and others (1973) found no hydrologic factors of subregional scale that favor either the interior or coastal areas for waste emplacement. Le Grand (1962) makes a choice in favor of the outer coastal plain. In the interior much of the ground water is fresh (< 3,000 ppm TDS or > 10 ohm-m²/m geophysical log resistivity) with appreciable circulation. Ground water beneath the coastal margin is primarily saline (> 3,000 ppm TDS). Though this is true, attention here will focus on the interior basins because they contain 81 percent of the unrejected domes. Relevant topics for discussion are aquifers and aquicludes, ground-water movement, dome geometry, and sorptive phenomena.

Aquifers and Aquicludes

The occurrence of fresh ground water is critical as it has the greatest capacity to dissolve salt because relative to saline water it actively circulates and moves with high velocity. Prolific fresh-water aquifers are present in the interior basins. In the Mississippi salt basin the prime aquifers are sands of the Wilcox, Claiborne, Miocene, and Holocene (table 1); transmissivities may reach 2,100 m³/day/m (169,355 gpd/ft) (Payne, 1968, 1970). Throughout most of the North Louisiana salt basin fresh water is restricted to the Claiborne. Major aquifers in the East Texas salt basin are sands of the Carrizo-Wilcox, Queen City, and Sparta; transmissivities may reach 620 m³/day/m (50,000 gpd/ft) (Myers, 1969). Regionally, the principal aquiclude is the Midway shale and it separates the fresh-water aquifers of the Tertiary from the saline aquifers of the Cretaceous (table 1). Though generalized with difficulty, the base of fresh water in the
Mississippi basin is less than 763 m below the surface; North Louisiana, less than 366 m; and East Texas, 305 to 610 m. The dominant cations are Na$^+$, Ca$^{2+}$, and Mg$^{2+}$ and dominant anions, HCO$_3^-$, Cl$^-$, and SO$_4^{2-}$.

**Ground Water**

**Movement.** Direction of ground-water flow is down the regional dip, south and southeast in East Texas and North Louisiana and south and southwest in Mississippi, except where modified or reversed in areas of large withdrawals. Heavy use of water in Purvis, 9.5 miles east of, and in Hattiesburg, 20 miles northeast of the Tatum dome (Lamar Co., Miss.) has reversed the normal south-southwest regional hydraulic gradient in several of the fresh-water aquifers at Tatum (Anderson and others, 1973). Where the potentiometric surface of an aquifer becomes higher than the surface of overlying aquifers, generally in the deeper fresh-water areas near the limit of fresh water, the dominant movement is upward (Payne, 1970).

Major factors affecting regional flow are the orientation of sands (aquifers) with respect to the direction of regional flow and their thickness and origin. Sands oriented parallel to regional flow are subject to extensive fresh-water flushing. In sands normal to regional flow movement is greatly impeded and there is considerably less flushing by fresh water. The hydraulic conductivity of channel sands, parallel to regional flow, varies directly with thickness; values range from 3.3 (80.5) to over 41 m$^3$/day/m$^2$ (1000 gpd/ft$^2$) (Payne, 1968, 1970). Regionally,
average ground-water velocities, calculated using Darcy's Law divided by porosity, vary from 0.3 (l) to 49 m/yr (160 ft/yr).

Little is known about ground-water movement in the vicinity of salt domes. Except for the Dribble Technical letters (USGS) on the Tatum dome no reports contain specific information on the hydrology of salt domes. Incidentally, nothing extraordinary was detected at Tatum. Hydrologic patterns around domes are complex as indicated by the presence of salines. Domes have a pronounced effect on the depth of occurrence of fresh-water; it is very erratic in the immediate vicinity of domes. In one case the base of fresh water may be lower at the flanks of a dome than in the surrounding area and in another vice versa (Rollo, 1960).

Dissolution. When domes extend above the regional base of fresh water, ground-water movement and the nature of the seal between salt and country rock become especially important to whether or not dissolution will occur. Lack of data makes it impossible even to say if dissolution is or is not occurring. Studies specifically designed to determine dissolved solids content of ground water surrounding domes are unknown.

Anderson and others (1973) concluded that generally a tight hydraulic seal exists between salt and country rock because oil is commonly trapped at the sides of domes. Many of the salt domes in the central part of the North Louisiana salt basin are located where the base of fresh water is locally over steepened south-southeast in the direction of the normal hydraulic gradient (Rollo, 1960). Contribution of significant dissolved solids to the aquifers from the domes
is not indicated and dissolution seems unlikely.

Very limited data suggest that dissolution may be occurring at some coastal domes. In Fort Bend County, Texas the quality of ground water is adversely affected in the vicinity of salt domes. Plumes of anomalously high total dissolved solids (TDS) in sands of one aquifer extend outward from some domes for several miles and are believed to be related to the domes. Aquifers updip from these domes have a TDS content of approximately 1,000 ppm and downdip greater than 3,000 ppm (Wesselman, 1972). Besides dissolution other factors such as incomplete flushing of connate saline water and contamination from oilfield operations may influence TDS content. When sands are oriented normal to the direction of regional flow, flushing is impeded by the shalier areas between massive sands (Payne, 1970, 1972). Near the coast shallower sands have not yet been flushed by fresh water (Hammond, 1969). Finally, flushing may be incomplete on the downflow side of a dome causing a lee-side shadowing effect.

Dome Geometry

Commonly salt domes display a downward enlargement of diameter so that most of the domes have the form of a truncated cone (Muehlberger and others, 1958). Others are nearly cylindrical (e.g. Tatum dome) or a combination of cylindrical and conical with overhang; still others are difficult to characterize; for example, the Minden dome is postulated to be disc-like below its upper cylindrical part (Nettleton, 1943). Tatum dome, based on reflection seismic traverses
radiating about 3050 m in 8 directions from the caprock margins, is roughly cylindrical to at least 1525 m below sea level. At 610 m the diameter is about 1312 m, at 1068 m, in the narrower part of the dome, the diameter is about 1098 m, and below this level the dome expands gradually (Anderson and others, 1973). The upper part of a typical dome has a cross section from circular to oval and an average diameter varying from less than 2000 m to greater than 8000 m (Gera, 1970). Dome height is great and probably approximates 4600 m, the depth to mother salt.

Dome geometry is essential to ensure that waste-emplacement excavations are not too close to the dome edge, risking dissolution and water inflow from surrounding aquifers. To preserve the seal against ground water, salt mining operations are always kept well inside the dome and several tens of meters of unmined, undrilled, and completely untouched salt is left on all sides (Kupfer, 1963). Size and shape are especially important in salt domes whose tops are near the 610 m depth cut-off limit. If the upper surface is irregular, siting in the upper few hundred meters might be precluded and would force siting far below 610 m (ORNL Staff, 1972).

Sorptive Phenomena

Adsorption of radionuclides onto host rocks provides a second-line defense against migration into the biosphere. Should a waste repository be breached by circulating ground water sorption phenomena will prevent or minimize migration and confine the radionuclides to limited areas. Radionuclides are retarded by sorption reactions due primarily to ion exchange. If the clay mineralogy is known, the ion-exchange capacity
of the sediment can be characterized in relative terms as high or low. A sediment rich in montmorillonite would have a high exchange capacity, one rich in kaolinite a low capacity. Maximum adsorption occurs in a pH range of 6 to 9. Above pH 7 ionization increases and ion-exchange capacities increase (Tamura, 1972). Furthermore, at higher pH hydroxides are scavenged by clay minerals. The behavior of Sr-90, Cs-137, and Pu-239, three radioisotopes requiring long term isolation, is discussed. In general Cs-137 is retarded to a much greater degree than Sr-90, though both are significantly retarded. Less is known of the behavior of Pu-239 in the subsurface environment.

**Velocity of Radionuclides.** An approximate expression for the rate of movement of radionuclides within one dimensional ground-water flow (Mayer and Tompkins, 1947; Higgins, 1959) is:

\[
V_i = \frac{V_w}{1 + K_d \rho / \phi}
\]

in which \(V_i\) is the velocity of the ionic species,

\(V_w\) is the velocity of the ground water,

\(\rho\) is the bulk density of the media,

\(\phi\) is the porosity, and

\(K_d\) is the distribution coefficient.

With a known \(K_d\) and reasonable values for porosity and density of sandstones, it can be seen that radionuclides will travel with only a small fraction of the velocity of the ground water. The distribution coefficient \(K_d\) indicates the capacity of the aquifer materials to retard the movement of a particular radionuclide. A large \(K_d\) indicates strong tendency for sorption. \(K_d\) is the ratio of the adsorbate equilibrium concentration on
the solid-mineral phase to its concentration in the solution.\n\n$K_d$ is dimensionless and uniquely determined for only a single set of conditions; for example, $K_d$ is lower for a particular species in brines than in fresh water. For all ionic species the presence of cations reduces exchange capacity by competing for available exchange sites.

**Strontium.** Reliable prediction of $K_d$ Sr even for formations whose clay mineralogy is known is difficult. Hydrous iron and aluminum oxides are not well characterized, though they show high $K_d$ values for Sr (Tamura, 1972). $K_d$ for trace amounts of Sr was found to vary from 0.5 to 50 in sandy aquifers with no clays or organic material saturated with various cations (Schroeder and Jennings, 1963). Robertson and Barraclough (1973) used a $K_d$ Sr-90 of 3.0 for the Snake River basaltic aquifer. Measured $K_d$ values for carrier-free Sr-85 ranged from 0.78 to 77 for five sand samples (Tatum dome, well HT-3) and six simulated aquifer waters (Janzer, 1974). Clearly Sr travels considerably slower than ground water, the higher the $K_d$ the slower it travels. Sr-89 in a sandy California aquifer traveled at a few percent of ground water velocity and Sr-90 in a clean Ontario Pleistocene sand at 3 percent of ground water velocity (Cherry and others, 1973). In southeast Manitoba radionuclides (U, Pu, Sr, and Cs) in a sandy aquifer (grd. wtr. vel. 3-8 m/yr) travel at less than 10 percent of ground water velocity (Cherry and others, 1973). Even the Snake River basaltic aquifer (grd. wtr. vel. 555-2780 m/yr), with only a few interbedded sediment layers and a relatively low ion-exchange capacity significantly retards the migration of Sr-90. Mass balance calculations for Sr-90
indicate that only 3 percent of the Sr-90 discharged down the National Reactor Testing Station (Idaho) chemical processing plant well is in the aquifer; the other 97 percent is apparently adsorbed. Since 1952 Sr-90 has migrated about 2 km from the well; the Sr-90 plume (0.005-0.15 pCi/ml) covers 4 km² of aquifer (Robertson and Barraclough, 1973).

**Cesium.** The distribution coefficient for Cs ranges from 1 to 500 (Schroeder and Jennings, 1963). Measured $K_d$ values for carrier-free Cs-137 ranged from 6.4 to 190 (Janzer, 1974). Minerals with high ion-exchange capacity can adsorb Cs preferentially. Besides montmorillonite, illite is a good adsorber of Cs and Cs is not easily desorbed from it. Also clinoptilolite and mordenite (zeolites) show high selectivity for Cs (Tamura, 1972).

Cs-137 is even more affected by sorption than Sr-90. Though Cs-137 and Sr-90 are produced and discharged at the National Reactor Testing Station (Idaho) in nearly equal quantities, Cs-137 has never been detected in any aquifer near the test reactor area or chemical processing plant (Robertson and Barraclough, 1973).

**Plutonium.** Published data on Pu distribution coefficients are unknown; however, Pu sorption on soil does take place and effects retardation (Smith, 1973). Pu can exist in $3^+, 4^+, 5^+, \text{ and } 6^+$ oxidation states. Even in the $3^+$ state Pu is subject to hydrolysis in the pH range (6-9) normally encountered in natural waters. Sorption of Pu from a water system is not by normal ion-exchange, but more likely by scavenging of Pu hydroxides.
and oxides. Higher pH favors removal because hydroxides are readily scavenged by clay minerals (montmorillonite, etc.) (Tamura, 1972). Pu is likely to be present as Pu$^{4+}$; therefore, its mobility depends on the properties of very insoluble Pu(OH)$_4$. Should Pu(OH)$_4$ form a stable colloid, its solubility is small enough to keep Pu$^{4+}$ within acceptable limits (NAS, 1972).

**IDEAL WASTE REPOSITORY DOME**

**Tectonic Stability**

The facts of regional depositional and salt diapir history favor interior domes over coastal domes. Depocenter shifting and diapirism coincided. Major sediment accumulation long ago ceased in the interior basins and by inference so did diapirism. Today erosion is the rule, providing a stabilizing influence by removing sediment and reducing differential load. Interior domes have probably been inactive or undergoing only slight adjustment since the end of the Oligocene, about 25 million years ago. As long as the interior basins remain areas of negative sedimentation renewed dome growth is unlikely. On the other hand, coastal domes may still be active because they are in areas of active sedimentation. Note that the coastal domes affect younger strata than the interior domes (table 2). Other factors favoring interior domes are a simpler internal structure and salt of greater competence.
Table 2. Geomorphic and geohydrologic data for unrejected domes.

<table>
<thead>
<tr>
<th>NAME</th>
<th>Depth to Salt Dome</th>
<th>Geohydrologic</th>
<th>Drainage</th>
<th>Topography</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knoxie</td>
<td>92-133</td>
<td>5.0</td>
<td>Youngest Strata Affected</td>
<td>Lime</td>
<td>X X</td>
</tr>
<tr>
<td>Palestine</td>
<td>37 209-518</td>
<td>6.45</td>
<td>To X</td>
<td>X X X</td>
<td>Flanked by Upper Cretaceous and Midway shales (1); Pleistocene terraces not affected by dome (1); See references 2 and 4.</td>
</tr>
<tr>
<td>Brooks</td>
<td>67 306</td>
<td>2.40</td>
<td>Claystone</td>
<td>Mt. Selman</td>
<td>X</td>
</tr>
<tr>
<td>Bullard</td>
<td>162 3.60</td>
<td>Clays</td>
<td>To X</td>
<td>X</td>
<td>Top of dome is in Wilcox (Esconal) (1).</td>
</tr>
<tr>
<td>Stein</td>
<td>92 153</td>
<td>3.20</td>
<td>Claystone</td>
<td>Mt. Selman</td>
<td>X ?</td>
</tr>
<tr>
<td>Whitehouse</td>
<td>613 366</td>
<td>Claystone</td>
<td>Cook Mtn.</td>
<td></td>
<td>Top of dome is in Midway (Esconal), which completely overlaps the dome (1).</td>
</tr>
<tr>
<td>Gip Hill</td>
<td>254 274</td>
<td>1.60</td>
<td>Gated</td>
<td>X X</td>
<td>No evidence of Pleistocene uplift (1).</td>
</tr>
<tr>
<td>Davis Hill</td>
<td>366 518</td>
<td>Moraine</td>
<td></td>
<td>X X</td>
<td>Surface is low flat Pleistocene terrace which shows little or no rise in elevation (1).</td>
</tr>
<tr>
<td>Hawkinsville</td>
<td>137-188</td>
<td>274</td>
<td>Houston</td>
<td>Lisie</td>
<td>Evidence of uplift in Pleistocene and probably in Holocene time (1); see reference 6 for possible rates of movement.</td>
</tr>
<tr>
<td>Hoskins Mound</td>
<td>336-351</td>
<td>274</td>
<td>Houston</td>
<td>Beaumont</td>
<td>Looping stream south of dome (3).</td>
</tr>
<tr>
<td>Hockley</td>
<td>300-338</td>
<td>610</td>
<td>Houston</td>
<td>Lisie</td>
<td>Looping stream on west and northwest of dome; see references 2.5.</td>
</tr>
<tr>
<td>Long Point</td>
<td>204 540</td>
<td></td>
<td></td>
<td>X</td>
<td>Some evidence of movement since Beaumont time (1); March on east and west sides.</td>
</tr>
<tr>
<td>Gulf</td>
<td>336-408</td>
<td>274</td>
<td>Houston</td>
<td>Beaumont</td>
<td>Partially overlapped by Upper Cretaceous and Midway (Esconal) shales units (5); dome rose post Early Cretaceous (1).</td>
</tr>
<tr>
<td>Vacherie</td>
<td>238-244</td>
<td>214-344</td>
<td>Claystone</td>
<td>Sparta</td>
<td>X</td>
</tr>
<tr>
<td>Kings</td>
<td>52 46</td>
<td>2.40</td>
<td>Claystone</td>
<td>Sparta</td>
<td>X X</td>
</tr>
<tr>
<td>Poston*</td>
<td>214 400</td>
<td>4.80</td>
<td>Claystone</td>
<td>Sparta</td>
<td>X X X</td>
</tr>
<tr>
<td>Price*</td>
<td>396 3.70</td>
<td>0.80</td>
<td>Claystone</td>
<td>Sparta</td>
<td>X X X</td>
</tr>
<tr>
<td>Bayburns</td>
<td>35 386</td>
<td>0.80</td>
<td>Claystone</td>
<td>Sparta</td>
<td>X X X</td>
</tr>
<tr>
<td>Binfield</td>
<td>61-305</td>
<td>76-108</td>
<td>Claystone</td>
<td>St. Maurice or Yegua (Cockfield)</td>
<td>X ?</td>
</tr>
<tr>
<td>Cedar Creek*</td>
<td>228 517-537</td>
<td>4.85</td>
<td>Claystone</td>
<td>Yegua</td>
<td>X X X</td>
</tr>
<tr>
<td>Castle Creek*</td>
<td>46 517</td>
<td></td>
<td></td>
<td>X</td>
<td>No topographic expression; overlapped by Sparta (1); see figure 72, p. 205 of reference 1.</td>
</tr>
<tr>
<td>Broussard</td>
<td>573-383</td>
<td>214-305</td>
<td>Clays</td>
<td>X</td>
<td>No topographic expression; overlapped by Sparta, Zilpha, and Mowina - chalky clay with very little mud (1); Lack of structure indicates stable since Missouri (1).</td>
</tr>
<tr>
<td>McLaurin</td>
<td>588 366</td>
<td></td>
<td>Claystone</td>
<td>Sparta</td>
<td></td>
</tr>
<tr>
<td>Lampton</td>
<td>503 427</td>
<td></td>
<td></td>
<td>X</td>
<td>No topographic expression; salt has penetrated to base of Claborn (1).</td>
</tr>
<tr>
<td>Leedo</td>
<td>631 214-305</td>
<td>1.60</td>
<td>X X</td>
<td>Dome is below drainage divide (the divide may not be due to the dome).</td>
<td></td>
</tr>
<tr>
<td>Arm</td>
<td>588 274</td>
<td>1.60</td>
<td></td>
<td>X</td>
<td>Pearl River bands around southwest edge of dome; dome is located at the center of a 0.45 km wide floodplain (1).</td>
</tr>
<tr>
<td>Crowsville*</td>
<td>&gt;610</td>
<td>1.60</td>
<td></td>
<td>X</td>
<td>No topographic expression; dome appears to be located on floodplain of Turkey Creek.</td>
</tr>
<tr>
<td>Gillis</td>
<td>540</td>
<td></td>
<td></td>
<td>X</td>
<td>No topographic expression.</td>
</tr>
<tr>
<td>Serdi Church*</td>
<td>610</td>
<td>1.60</td>
<td>X X</td>
<td>Overprinted by Claborn (Esconal) clays (1).</td>
<td></td>
</tr>
<tr>
<td>Hazen*</td>
<td>488 610</td>
<td></td>
<td></td>
<td>X X</td>
<td>Overprinted by Claborn (Esconal) clays (1).</td>
</tr>
<tr>
<td>County Line</td>
<td>682 153</td>
<td></td>
<td>X</td>
<td>Overprinted by Cockfield (1).</td>
<td></td>
</tr>
<tr>
<td>Richardson</td>
<td>503 505</td>
<td>186</td>
<td>Claystone</td>
<td></td>
<td>Overprinted by Mowina clays (1); Citronelle was arched and removed in late Pleistocene and Holocene (1).</td>
</tr>
</tbody>
</table>

*Suspected dome

REFERENCES

Geomorphic analysis, an approach largely overlooked, may be the easiest and cheapest way to evaluate dome stability. Basic drainage patterns (dendritic, trellis, etc.) are controlled by regional structure. The regional pattern is regarded as the norm and the deviations are anomalies, which suggest structural or topographic deviations from the regional plan (Howard, 1967). Drainage patterns are very sensitive to any change of gradient and thus are sensitive indicators of movement such as uplift due to a salt or igneous plug. Since adjustment to a new gradient is geologically swift drainage anomalies may reveal recent tectonic activity. Some typical anomalies associated with salt domes are radial-annular enclave in a dendritic pattern, local stream meandering and braiding, and curves and turns (Howard, 1967, fig. 4, p. 2257). A well-developed annular pattern, a sign of mature dissection, may mean movement in the more distant than recent past (e.g. Palestine dome). From the standpoint of stability the most favorable domes are those without drainage anomalies; no movement or only minor movement is postulated in these cases. Table 2 presents geomorphic data collected from USGS topographic maps for the unrejected domes of Anderson and others (1973). Bullard, Whitehouse, Mt. Sylvan, McLaurin, Lampton, Gilbert, and Richmond domes are anomaly free.

Heat flow data may be excellent corroborative data to collect. This statement rests on the idea that young domes are hotter than old domes (Heroy, 1968). Lack of thermal equilibrium or temperature anomaly can arise in two ways from (1) the residual heat of an originally and uniformly hot salt mass and (2) from heat generated by internal friction in a
rising dome (Gera, 1972). Either way the most stable dome would be one whose heat flow measurements most closely approach that of its host rocks, approximately $1.2 \times 10^{-6}$ cal/cm$^2$-sec. (Jacoby and Paul, 1974).

Tectonic stability has relevance only in terms of rate of dome movement versus waste residence time. If a dome is not moving there is no problem. Three radioisotopes, Sr-90, Cs-137, and Pu-239, are of greatest long term concern. Of the three, the most hazardous to humans and animals is Sr-90, the least hazardous is Cs-137. Pu-239 is less of a hazard than its long half-life would suggest. Very small amounts of Pu-239 are to be stored, less than 0.01 percent of the total accumulated activity of Sr-90, Cs-137, and Pu-239 to the year 2000 (Culler and others, 1971). Pu forms highly insoluble compounds in the biosphere. Unequal fractions of Sr-90 and Pu-239 are ingested (Pu-239 four orders of magnitude less than Sr-90) and reach the critical organ, bone. Biological half-life in the critical organ is two years for Pu-239 and 49 years for Sr-90 (NAS, 1972).

Isolation of Sr-90 and Cs-137 for 1000 years will bring their concentrations to less than currently permissible in drinking water (NAS, 1972). If the maximum rate of dome movement were 2 mm/yr the emplaced waste would move 2 m, hardly cause for alarm. As far as Sr-90 and Cs-137 are concerned all domes are tectonically stable. A commonly cited residence time for Pu-239 is 250,000 years (10 Pu-239 half-lives), a long time for man but geologically very short. In this time a hypothetical dome moving at 2mm/yr would move 500 m. Certainly, this is an unacceptable amount of movement. At the average rate of 0.3 mm/yr
there would be 75 m of movement. The adjusted relative hazard concept is another way of fixing required residence time (see p.52). Under the assumptions used high-level waste with actinides need to be stored 8,850 years. Depending on rates the amount of movement in that time would range from 2.7 to 17.7 m. This seems to be an acceptable range. However, even though this movement might be tolerable a moving dome would not knowingly be selected. In the end the problem becomes one of selecting a stable dome. Geomorphic and geologic evidence show that many interior domes have been stable for 8 to 100 times 250,000 years (table 2).

Hydrologic Integrity

Concern over dissolution of salt has been expressed because salt domes intrude overlying sediments and are not protected from circulating ground water by thick impermeable shale (Culler, 1971; McClain and others, 1972). This is true of some domes; for example, Tatum dome, site of the Salmon and Sterling nuclear detonations, but such is not the case for all domes. Data to evaluate all domes are not available, but there are domes that intrude thick Upper Cretaceous and Midway marine shale (Mt. Sylvan, Vacherie, Whitehouse; fig. 2 and table 2). Hydrologically this kind of dome is to be favored as a waste repository site. The dome top is surrounded by shale and below the base of fresh water. Most importantly the intervening shale is a regional aquiclude protecting the salt from circulating ground water, especially actively circulating fresh water, and dissolution. Furthermore,
in the unlikely event a waste repository were breached contamination of ground water by radionuclides would be minimized or even avoided. The repository is well below potable water and surrounded by shaly, fine-grained sediments so that maximum advantage is taken of sorptive phenomena. These Gulf Coast sediments are extremely rich in minerals with high ion-exchange capacities, montmorillonite, hydrous oxides, hydroxides, illite, zeolites, glauconite, etc., and have an enormous volume of pore space which provides opportunity for ion-exchange. Radionuclides are significantly retarded in sandy aquifers; shaly, fine-grained sediments will retard them orders of magnitude more.

Dome geometry affects the probability of dissolution. Obviously waste emplacement must not be too close to the dome edge. Geometry is best evaluated by geophysical methods. Geophysical data for many domes are in oil company files and should be available to the AEC on a company confidential basis as they were for Project Dribble (Tatum dome). In general a piercement or diapiric dome is encircled by relatively impermeable shale and fault gouge which provides a hydraulic seal (Muehlberger and others, 1958). Steep dome flanks imply piercement (Smith and Reeve, 1970). Erosion poses no threat of breaching overlying strata. Rates of denudation for the Gulf Coast area are about 5 cm/1000 years or 12.5 m in 250,000 years (Judson and Ritter, 1964). Reportedly Winnfield and Belle Isle domes are the only Gulf Coast salt mines ever breached by floodwaters. In both cases flooding was attributed to shaft problems, either a subsequent loss of seal or a poor initial seal (Kupfer, 1974b). At Winnfield the hydrologic setting is optimum for flooding.
There are cavities at the salt-caprock contact open to the surface. The shaft passes through caprock at the surface, containing sinkholes and large, active solution channels, and in hydraulic communication with adjacent fresh-water aquifers (Anderson and others, 1973).
Summary

The ideal dome for a high-level waste repository has the highest probability for tectonic stability and hydrologic integrity. Such a dome has the following characteristics:

1. Large interior piercement dome of regular geometry, salt top below base of regional fresh water, and intruded into and enclosed in Upper Cretaceous or Midway shaly, fine-grained rocks,

2. No drainage or thermal anomaly,

3. Site over 60 m above sea level, located off flood plains with gentle relief, and away from population centers,

4. No or very little potential for hydrocarbons, sulfur, etc., and

5. Few boreholes, shafts, etc.

Under these criteria the Whitehouse dome is suitable for a pilot waste repository facility; additional domes can be identified. Mt. Sylvan, Vacherie, McLaurin, and Lampton domes are excellent candidates for more study (fig. 2, table 2).
RESIDUAL STRESS AND OTHER STRUCTURAL PROBLEMS

The residual stress, if any, in a salt dome is the stress that remains in the salt as a result of its previous deformation history. Concern about the possible existence of these stresses stems mostly from the effects these stresses may have on closure rates of cavities mined in the salt dome, and the effects these stresses, when combined with a temperature rise, will have on overall movement of the salt mass.

The terms creep and plastic flow have both been used to describe the tendency of rock salt, or halite to deform continuously under load over a wide range of temperatures. For metals plastic flow is distinguished from creep by the fact that it occurs at stresses above the yield strength. For materials such as salt which have no clearly defined yield strength there is no clear distinction between plastic flow and creep. Usually, however, plastic flow refers to large deformations which occur in a relatively short time. Under nominal stress conditions this would require the salt to be at a temperature in excess of 100°C. Creep refers to deformations which may, in the aggregate, be large but which occur at very slow rates. Thompson, (1965) has shown that salt exhibits a time-deformation relationship similar to the typical creep curve for many other materials. In this relationship the strain increases rapidly for a short time after load is applied (primary phase). This period is then followed by a relatively long period in which strain increases at essentially a constant rate (secondary phase). For unconfined specimens a third phase is sometimes seen in which the deformation rate increases rapidly and failure
occurs (tertiary phase). The secondary creep phase is the most important phase in the consideration of the movement of salt domes and of stress relief in the salt. Thompson (1965) in laboratory creep testing of salt samples from the Grand Saline and Hockley domes found that for a constant temperature and constant triaxial loading the secondary creep rate could be expressed as

\[ \dot{\varepsilon} = C\left(\frac{\sigma}{\sigma_u}\right)^n \]

where \( \dot{\varepsilon} \) is the creep rate
\( C \) is the constant
\( \sigma \) is the deviatoric component of the stress tensor
\( \sigma_u \) is the ultimate strength of salt in axial loading
\( n \) is an exponent of the order of 5.

The constant \( C \) is a strong function of temperature and a weak function of the hydrostatic component of the stress tensor. It also depends on the source of the salt sample. For example, there is an appreciable difference in the value of \( C \) for the Grand Saline salt and the value for the Hockley salt. As the temperature decreases the creep rate also decreases, and presumably at very low temperatures creep could conceivably not occur at all. However, Lomenick (1968) has shown that significant creep occurs at temperatures as low as 22.5°C. Thompson's creep equation implies that creep will occur no matter how small the deviatoric stress component may be. However, the lowest deviatoric stress at which his tests were conducted was 1400 psi (98.5 kg/cm²). An extrapolation of those results to zero stress would be questionable. Balk (1949) states that...
salt flows at shear stresses as low as 437 psi (30.8 kg/cm\(^2\)). This suggests that the Thompson creep equation might reasonably be expected to apply at stresses as low as 500 psi (35.2 kg/cm\(^2\)). Thompson (1965) found that \(C=11.14 \times 10^{-7}\), \(n=5.24\) and \(\sigma_u=2500\) psi (175.9 kg/cm\(^2\)) for the salt samples used. For these values and \(\sigma=500\) psi (35.2 kg/cm\(^2\))

\[
\dot{\varepsilon} = 11.14 \times 10^{-7} \frac{500}{2500}^{5.24}
\]

\[
= 2.4 \times 10^{-10} \text{ units/min}
\]

\[
= 1.27 \times 10^{-4} \text{ units/yr}
\]

This rate could be in error by two orders of magnitude and still it would represent a large deformation over a geologic time span. Such a large deformation at a stress as low as 500 psi (35.2 kg/cm\(^2\)) supports Nettleton's (1934) assertion that both the salt and the surrounding sediments behave as highly viscous liquids. Thus it may be concluded that salt formations will be unable to sustain appreciable stress states, other than hydrostatic, over geologic periods of time. Quiescent salt domes have therefore reached a state of equilibrium in which the weight of the dome is balanced by the buoyant force of the surrounding sediments and stresses within the dome are not a factor. This does not, however, mean there are no stresses within the dome. As indicated above, the salt can sustain a hydrostatic stress state and such a stress state will exist everywhere in the dome. The question is, will the hydrostatic stress be simply a function of depth below the surface or can it be significantly greater than the pressure at a corresponding depth in the surrounding sediments? For some insight on this point the process of dome formation must be reexamined. In that process the salt moved upward under the weight of the overlying sediments. Those sediments that lay in the path
of the diapir were forced out of the way either by being shoved aside or by being pushed upward. This upward movement eventually would deform the overlying strata. For a rapid upward movement the competent rock formations would, no doubt, have offered great resistance to the movement and this would have resulted in the development, temporarily, of stresses in the salt higher than those that would have resulted simply from the weight of the overburden. However, the upward movement was a slow process as indicated previously, with rates estimated at 0.3 mm to 4 mm per year. These slow rates allowed the stresses in the overlying rocks to be relieved by creep or flow in the rock. Also the stress in the salt gradually became, or was from the beginning hydrostatic. This stress state could not be sustained unless the surrounding sediments were capable of containing the salt. If the stress in the salt were higher than the ambient stress in the surrounding sediments the salt would move toward the sediments until an equilibrium state was reached. Only if the surrounding sediments are capable of sustaining indefinitely a stress state higher than the stress due to the weight of the overlying sediments can the stress in the salt be something more than just a function of depth. The relief by creep of stresses in the overlying rock strata makes it impossible for the surrounding sediments to maintain a stress state other than hydrostatic and proportional to depth over geologic periods of time.

If the early stages of dome formation involved piercement of soft clastic deposits and then the dome was buried by post emplacement strata (as was suggested previously regarding some of the interior domes), no appreciable residual stresses would be expected. First, because of the lack of resistance to the
upward movement, and second, because of the slowness of the deposition of the overlying strata. Time and the ability of the salt to slowly deform under load would relieve any stresses in the salt other than those produced by the weight of the overburden.

Mine Closure Measurements

Some presently available mine closure data for both bedded salt and dome salt are pertinent to this question. Reynolds and Gloyna (1960) have reported on creep, or closure, measurements made in bedded salt at Hutchinson, and in dome salt at Grand Saline. Both mines are approximately 1000 feet (305 m) below the ground surface. At Grand Saline measurements were made at two locations, one in a section of the mine that was over 10 years old, and the other in a section that was 6 years old. It was found that closure was taking place at both locations, but the rate of closure in the 10 year old section was much lower. The creep rate was found to be changing with time, an indication that the creep was still in the primary phase. Creep in the Hutchinson mine was measured in a room 30 years old. Thus none of the measurements are directly comparable. These test results do show that creep is slow enough at the temperatures encountered in these mines for it to be eliminated as a major problem in disposal operations unless there is a significant increase in the creep rate as the temperature rises. Measurements made of the rate of closure in a rectangular room cut in a heated pillar in the Hutchinson mine did show a substantial increase in the creep rate initially, but after 115 days of heating the rate had decreased to about $20 \times 10^{-6}$ units/day or $73 \times 10^{-4}$ units/year (Parker and Blanco, 1963).
At this rate the walls of a 50 ft (15.24 m) room would approach each other 0.36 ft (0.11 m) in one year. It does not appear that this rate of closure would cause any significant operational problems in a pilot repository. McClain (1973) has concluded that even in the heated pillar experiment deformations resulting from thermal stresses were much larger and more dominant than deformations resulting from increased creep properties. As he points out, however, "the heating of the pillar took place over a much shorter period of time than would be the case in a typical waste disposal operation". This does not imply that slower heating would have a different effect on creep properties, but rather that the relationship between creep deformations and thermal stress deformations might be different.

Stress in a Salt Dome Due to Overburden Pressure

As indicated previously the stress state in a salt dome should be essentially hydrostatic and a direct function of the depth below the ground surface. There is no direct evidence to suggest anything different. The moderate closure rates observed in the Grand Saline mine indicate that if any unusual stress distribution exists in the dome as a result of the way the dome formed, or of the way it is loaded by the overburden, that distribution has no extraordinary effect on closure rates. Further evidence bearing on this question could be collected by making extensive closure measurements in other mines in salt domes. Such measurements are not likely to do anything more than confirm what is now known; namely, some flow does occur around mine openings in salt whether it is bedded or dome salt. If no unusual stress
distribution exists in a salt dome; then temperature effects should be essentially the same as those observed in Project Salt Vault, with one exception. There would be no roof sag like that reported for Salt Vault, (Blanco and Parker, 1967; Bradshaw and McClain, 1971).
TEMPERATURE RISE

The temperature conditions in a salt dome with one exception present no problems that are not also presented in connection with repositories in bedded salt. That one exception is the question of whether the rise in temperature will trigger upward dome movement.

If the stress state in a dome is hydrostatic an increase in the temperature alone will have no tendency to produce renewed overall movement of the dome. The effect of temperature is to stimulate plastic flow or creep in the salt, but temperature change can have no effect on creep if there is not also a deviatoric stress component present. Localized heating such as would occur in the presence of radioactive wastes could produce some localized movement. How localized will the heating be? Some results presented by Culler (1971) based on estimated temperature distributions in the demonstrational salt bed repository indicate that the temperature rise in shale beds 2500 feet (762 m) below the ground surface and 1500 ft (457 m) below the repository was imperceptible until 400 years after burial and by 2000 years after burial the rise was no more than 3.3°C. For salt domes, with a repository located far from the boundaries, temperature calculations are simplified since the problem can be treated for order of magnitude computations, as a point source in an infinite homogeneous medium.

It has been shown by Ingersoll and others (1948) that for a constant point source of heat in an infinite medium the temperature at any distance, r, from the source and at
anytime, $t$, is given by

$$T = \frac{Q'}{4\pi kr} \text{erfc}(r\eta)$$

where

$T$ = the temperature, zero everywhere except at $r=0$, when $t=0$

$r$ = distance to point where temperature is to be computed

$k$ = conductivity of the medium

$\eta = \frac{1}{\sqrt{4\pi at}}$

$\alpha$ = diffusivity of the medium

$t$ = time

$Q'$ = units of heat released per unit of time

The heat generating capacity of radioactive waste decays exponentially (NAS, 1972). However, to make some simple calculations for upper limit values of temperature it will be assumed that the heat input is constant for a specified number of years and then is suddenly cut off. As an example it will be assumed that the heat input $Q'$ continues for 100 years. The temperature rise at a point 1500 ft (457 m) from the heat source is calculated using the following thermal properties of salt.

$$k = 2.6 \text{ in fph units} \quad (\text{Bradshaw and McClain, 1971})$$

$$\alpha = 0.1$$

At time $t = 100$ years and $r = 1500$ ft the temperature rise is

$$T = 6.8 \times 10^{-9} Q'$$

Assuming a source intensity of 15,000 kW, which is equivalent
to 150 kW per acre in a 100 acre repository

\[ T = 0.35^\circ F \ (0.2^\circ C) \]

With this same heat source the temperature rise 1500 ft from the repository after 2000 years will be

\[ 2.45 \times 10^{-7} Q' \]

or

\[ 12.6^\circ F \ (7.0^\circ C) \]

At a distance of 3000 ft from the repository the temperature rise after 2000 years will be

\[ 5.62 \times 10^{-9} Q' \]

or

\[ 0.3^\circ F \ (0.2^\circ C) \]

and after 10,000 years it will be

\[ 1.39 \times 10^{-8} Q' \]

or

\[ 0.7^\circ F \ (0.4^\circ C) \]

These are extreme temperatures because the heat is injected into the salt much more rapidly than it would be in an active repository. Also, a 100 acre repository site would not look like a point source of heat from a spot only 1500 ft away. Consequently these numbers are meant to be only an indication of the order of magnitude of the temperature changes to be expected. These computations also indicate that for a dome with a vertical dimension of 15,000 ft (4572 m) and a repository 1500 ft (457 m) below the top of the dome the temperature rise near the root of the dome, 13,500 ft (4115 m) from the heat source, will be completely negligible. It is in this region that one would expect a temperature rise would be needed if upward movement of the dome, as a result of further extrusion from the mother salt, is to be triggered.
It might be noted here that the time during which a dome would be heated by a radioactive waste repository is essentially no time at all in comparison to the geologic times required for the formation of the dome. Consequently even if the rise in temperature did trigger some upward dome movement the total movement that could occur before the dome cools down will be of the order of 65 ft. (20 m) if it is assumed that 10,000 years are required for the dome to heat up and cool down, and that a movement of 2 mm per year results from the heating.

Another approach to this question taken by Dwyer (1973) indicates that instead of rising as a result of heating, the top of the dome recedes from the surface of the ground. The general trend was for the dome with stored hot wastes to mushroom at the top. This brought the storage sites a little nearer the surface of the domes but further from the ground surface. In this analysis, which was based on a finite element approach, it was assumed that the dome was detached from the mother salt and had assumed a tear drop shape. There is no direct evidence that such domes exist and many geologists doubt that they exist. Consequently, the results, although interesting, can not be considered significant at this time.

Other Temperature Effects

It is expected that some elevation of the ground surface will occur as a result of the heating of the salt, and that it will be of the same order of magnitude as that computed for Project Salt Vault, (Culler, 1971; Bradshaw and McClain, 1971) and that the rise will eventually be cancelled by subsidence due to closure of the mined openings as a result of creep in the salt. Further analytical study of this expected thermal expansion
is recommended after a dome has been selected as a site for a pilot repository. Possible rises in aquifer temperatures near the dome should also be investigated, in connection with the analytical studies of thermal expansion.

It should be noted here that in some thermal calculations involving crushed salt (Gera, 1973), a thermal conductivity of 1/16 that of rock salt has been assumed. This seems to be an unduly conservative assumption. It would be more logical to use a figure of 1/5 to 1/3 that of rock salt in view of the rapid reconsolidation of the salt.

Most of the calculations of the expected temperature rise in the salt formation, in adjacent geological formations and in aquifers are subject to significant modification by (1) the age of the waste when it is buried, and (2) by the spacing of the buried canisters (the thermal power per acre). At 10 years after processing the thermal power of fuel charged to the reactor is 1080 (W/Mton) and at 30 years it is 595 (Culler, 1971). Thus the density of the storage of 30 years old wastes could be increased significantly from that required for 10 year old wastes. Some writers have recommended that the wastes be kept in retrievable storage for 30 years before permanent disposal just in case a use should be found for the wastes and also to allow further time for working out the best means of final disposal (Hammond, 1974). This does not imply that wastes stored in salt, dome or bedded, is not retrievable. It can be retrieved but obviously the process would be more difficult and more expensive than it would be for wastes stored in a retrievable surface storage facility.
Migration of Water

It has been shown that small brine filled cavities in salt at temperatures below the decrepitation point will migrate toward a heat source (Anthony and Cline, 1971). It has been estimated that in a 50 X 300 foot room with about 200 container holes the total integrated inflow of brine would be less than 2,000 liters (Culler, 1971). For a two or three tiered disposal arrangement the total amount of brine released would be roughly two or three times the volume released in a single tiered arrangement. Since this water is released over a 20 to 30 year period and is removed by the ventilating air it presents no problem other than the effect it has on container corrosion and this effect is controllable.

RADIOLYSIS OF ROCK SALT AND BRINE INCLUSIONS

Ionizing radiation creates electron-hole pairs in an absorbing crystal. The pairs are trapped in the solid, but will, upon dissolution, cause reactions—the electrons oxidizing and the holes reducing (Heal, 1955).

In the absence of general dissolution of a salt repository, the only dissolution which may occur is that caused by migrating brine referred to above.

Furthermore, the brine itself undergoes radiolysis. The principal concerns have been directed at the gases liberated by radiolysis. Jenks (Boch and others, 1971) presents estimates of the types of and maximum rates of release for gases around
a waste canister. He shows about 5 moles/year of hydrogen, 20 moles/year of hydrogen chloride and 0.5 moles/year of nitric acid. All of the radiolytic releases are dwarfed by the 400 moles/year of hydrogen from the corrosion of the canister. Smaller amounts of chlorates, chlorine, oxygen, ozone, and other species are formed.

The large release rates occur within a short time after burial. The gases will either be vented through the crushed salt backfill or trapped in the salt as it reconsolidates. Either happening seems easily tolerable.

ENERGY STORAGE AND RELEASE

When crystalline materials are irradiated, energy is stored in the crystals as a result of the lattice defects introduced. The stored energy is released upon heating, the so-called Wigner effect (Dienes and Vineyard, 1957). The possible effects of this phenomenon in a waste repository have been rather thoroughly evaluated (Boch and others, 1972).

The amount of energy that may be stored varies with the type of crystalline material and the temperature at irradiation. This amount ranges from practically zero for copper to several hundred calories per gram for materials with covalent bonds such as graphite (Boch and others, 1971).

In salt the experimental values for energy storage have not been in total agreement; however, the probable energy storage is about 2 cal/gm and the maximum is almost certainly less than 20 cal/gm. In calcined waste the maximum energy storage is probably about 200 cal/gm (Boch and others, 1972).
Calculations made on the effects of releasing the maximum stored energy have shown that no "serious implications" result (Boch and others, 1971).

**ACTIVATION PRODUCTS**

The activation products of sodium are generally of negligible significance because of either or both short half-lives and low formation cross sections. The most significant product seems to be Na-22 with its 2.62-year half-life, being formed by Na-23 (n,2N).

The (n, r) reaction for Cl-35 has a high cross section (44 b) and produces Cl-36 with a half-life of 3(10^5) years; however, Cl-36 is a beta emitter, which mitigates any possible hazard (Radiological Health Handbook, 1970).

The activation products certainly seem to be of little significance, but the overall safety report for the repository needs to point this out.
RETENTION TIMES AND RELEASE HAZARDS

Introduction

There is no way to set an exact requirement on the retention times for high-level radioactive wastes to reach "safe" conditions. The word safe necessitates judgments of probabilities on both the occurrence of and the effects of release, and neither of these probabilities can be precise. The dissolution of the salt repository and the entrained wastes is certainly a very remote possibility, and the injection of large quantities of radioactive particles into the atmosphere is even much less probable.

Rules of thumb for required retention times are often stated as 1000 years for fission products (Sr-90 and Cs-137 decay) or 250,000 years for the actinides (approximately 10 half-lives for Pu-239). These periods should be acceptable when considered in the geological time frame; however, it seems preferable to estimate the relative hazards at various times after processing the wastes and to decide what hazard level is within tolerable limits. Five methods of evaluating the relative hazards for various retention times are described here.

Hazards as Dilutions Required

Simple calculations of the dilutions required, in air and in water, to reach the Radiation Concentration Guides (RCG's) values deemed permissible, have been used to quantify the
relative hazards of wastes (Blomeke and others, 1974). The hazard rating is simply calculated by

\[ H_j = \sum_i \frac{A_i}{RCG_{ij}}, \quad j = a \text{ for air} = w \text{ for water} \quad (1) \]

where \( H_j \) = the relative hazard \((\text{m}^3/\text{MT}, \text{MT} = \text{metric ton of fuel used})\), \( A_i \) = the activity of the \( i \)th radionuclide \((\text{Ci/MT})\), and \( RCG_{ij} \) = the RCG for the \( i \)th radionuclide in air or in water \((\text{Ci/m}^3) = 1/3 \) of the concentration listed in table 2, Appendix B of 10 CFR 20, adjusted to \( \text{Ci/m}^3 \). Values of \( H_a \) and \( H_w \) for various times after processing the wastes are shown in table 3 for PWR-U waste.

**Times for Salt-Limiting Dilutions**

One logical approach to the interpretation of the relative hazard at a given retention time is the use of dilutions which make the concentration of salt limiting rather than the concentration of the radioactivity (Boch and others, 1971).

The U. S. Public Health Service standard for maximum allowable salt in drinking water is 500 ppm \((500 \text{ mg/l} \text{ or } 500 \text{ gm/m}^3)\). Based on 10 year old wastes stored 150 kW/acre and a 15 foot thickness of salt going with the wastes, the salt volume is about 125 m\(^3\)/MT for fission products or 133 m\(^3\)/MT with the actinides included. The corresponding weights of salt are 2.70\((10^8)\) gm/MT and 2.87\((10^8)\) gm/MT. At 500 gm/m\(^3\), the dilutions are 5.4\((10^5)\) m\(^3\)/MT and 5.75\((10^5)\) m\(^3\)/MT. If interpolations are made on the basis of exponential (first-order) decay of the dilution requirements between any two times shown in Table 3, the hazard for water \((H_w)\) reaches these levels in about 865 years.
Table 3

Hazards for PWR-U Solidified Fuel Wastes
(per metric ton, MT, basis)

<table>
<thead>
<tr>
<th>Time (yr)</th>
<th>Activity (Ci)</th>
<th>Hazard (\text{(m}^3))</th>
<th>Adjusted Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Air (H_a)</td>
<td>Water (H_w)</td>
</tr>
<tr>
<td>Fission Products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3.01(+6)(^d)</td>
<td>1.01(+16)</td>
<td>4.49(+11)</td>
</tr>
<tr>
<td>3</td>
<td>6.76(+5)</td>
<td>3.39(+15)</td>
<td>2.66(+11)</td>
</tr>
<tr>
<td>(10^1)</td>
<td>3.06(+5)</td>
<td>2.26(+15)</td>
<td>2.08(+11)</td>
</tr>
<tr>
<td>(10^2)</td>
<td>3.42(+4)</td>
<td>2.42(+14)</td>
<td>2.26(+10)</td>
</tr>
<tr>
<td>(10^3)</td>
<td>2.09(+1)</td>
<td>8.40(+9)</td>
<td>8.34(+4)</td>
</tr>
<tr>
<td>(10^4)</td>
<td>1.99(+1)</td>
<td>7.98(+9)</td>
<td>8.02(+4)</td>
</tr>
<tr>
<td>(10^5)</td>
<td>1.5(+1)</td>
<td>6.0(+9)</td>
<td>6.0(+4)</td>
</tr>
<tr>
<td>(10^{6/4})</td>
<td>1.0(+1)</td>
<td>4.0(+9)</td>
<td>4.0(+4)</td>
</tr>
<tr>
<td>(10^6)</td>
<td>2.4(+1)</td>
<td>1.0(+9)</td>
<td>1.0(+4)</td>
</tr>
<tr>
<td>Fission Products plus Actinides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3.03(+6)</td>
<td>2.38(+16)</td>
<td>4.50(+11)</td>
</tr>
<tr>
<td>3</td>
<td>6.79(+5)</td>
<td>1.31(+16)</td>
<td>2.66(+11)</td>
</tr>
<tr>
<td>(10^1)</td>
<td>3.08(+5)</td>
<td>1.02(+16)</td>
<td>2.08(+11)</td>
</tr>
<tr>
<td>(10^2)</td>
<td>3.45(+4)</td>
<td>2.17(+15)</td>
<td>2.26(+10)</td>
</tr>
<tr>
<td>(10^3)</td>
<td>1.02(+2)</td>
<td>4.39(+14)</td>
<td>1.56(+7)</td>
</tr>
<tr>
<td>(10^4)</td>
<td>4.31(+1)</td>
<td>1.64(+14)</td>
<td>3.73(+6)</td>
</tr>
<tr>
<td>(10^5)</td>
<td>1.64(+1)</td>
<td>1.4(+13)</td>
<td>2.3(+5)</td>
</tr>
<tr>
<td>(10^{6/4})</td>
<td>1.07(+1)</td>
<td>3.6(+12)</td>
<td>1.1(+5)</td>
</tr>
<tr>
<td>(10^6)</td>
<td>2.95(0)</td>
<td>2.7(+12)</td>
<td>9.0(+4)</td>
</tr>
</tbody>
</table>

\(^a\)After reprocessing; reprocessing 150 days after shutdown.

\(^b\)Tables 5.7 and 5.8, ORNL-3965 for time to \(10^4\) years; calculated decay of radionuclides to \(10^6\) years.

\(^c\)Table B-1, ORNL-3965 to \(10^4\) years; extrapolated on curie basis to \(10^6\) years.

\(^d\)Numbers in parentheses are power of ten exponents.
for fission product wastes or 70,400 years for the fission products with the actinides.

The Federal secondary ambient air standard is 60 \( \mu g/m^3 \) (annual average). The dilutions for \( 2.70 \times 10^8 \) gm/MT and \( 2.87 \times 10^8 \) gm/MT to reach this concentration are \( 4.50 \times 10^{12} \) m\(^3\)/MT and \( 4.79 \times 10^{12} \) m\(^3\)/MT, respectively. The hazard (\( H_a \)) from fission product waste would reach this level in about 450 years or with the actinides included, in about 218,000 years.

According to these calculation, the hazard of release would be acceptable after 900 years for the fission products or after 218,000 years for the waste with the actinides included.

Retention time is controlled by the water concentration hazard (\( H_w \)) for the fission products; whereas, the very low levels of the RCG's for insoluble particles (\( H_a \)) in the lungs control the retention times for the actinides. The total wastes are treated as being insoluble for the air calculations and, subsequently, as soluble for the water calculations.

**Probable Dilution Basis**

Another logical method for fixing retention time requirements could be based on the probable dilution that the waste would receive if it should be released to the air or water environment. Note that the release is not probable; it would be the maximum credible accident. The analysis that follows is presented to sort out the effects in case the "what if" actually occurred.

The hazard as expressed by the dilution values to the RCG's, the \( H_a \) and \( H_w \) values, could be adjusted by the release rate and the environmental mobility that would probably prevail; i.e.,

\[
H_{ja} = H_j \frac{R_j}{D_j} = \frac{R_j}{D_j} \sum_i \frac{A_i}{RCG_{ij}}, \quad j=a \text{ for air} = w \text{ for water (2)}
\]
where $H_{ja} = \text{adjusted relative hazard (dimensionless)}$,  
$R_j = \text{maximum release rate (MT/hr for air and MT/yr for water)}$,  
and $D_j = \text{dilution for time base (m}^3/\text{hr for air and m}^3/\text{yr for water)}$. The time basis for air should be one hour because  
any problems would occur within an hour of wind distance from  
the point of release; the time for water should be much longer,  
probably one year, because of the slow movement of ground water.  
The $R_a$ and $R_w$ values could include not only the possible release  
rates but also a relative probability factor.

**Assumed Dilution Parameters.** The $R_w$ and $D_w$ values are  
calculated here on the following assumptions:

i. Salt dome diameter is 5 km;

ii. Repository covers 900 acres ($1908 \text{ m}^2$) with effective  
thickness of 15 ft (worst case);

iii. Ground water velocity = 50 m/yr = $1.59 \times 10^{-4} \text{ cm/sec}$;

iv. Gaussian distribution of salt concentration prevails  
across plume (saturated at centerline; 265,600 ppm$_w$ at  
$30^\circ \text{C}$); and

v. Horizontal plume spread velocity = $1.1 \times 10^{-5} \text{ cm/sec}$  
for iii (Baetsle, 1967).

vi. Vertical plume spread to reach water wells of 100 m  
deepth is 500 m from the 600 m repository depth and the  
vertical spread is one-fifth of the horizontal spread.

The plume spread ($\sigma_y$) is calculated to be 425 m in the time for  
the water to move from upstream to downstream of the dome.  
Under these assumptions, the time for the water to reach the  
repository would be 18,400 years, the minimum probable retention  
time. The release rate ($R_w$) is found to be 8.35 MT/yr from a  
leach rate of 0.064 m/yr on two sides of the repository. The
probable dilution \( \left( D_w \right) \) is calculated as \( 1.96(10^8) \text{ m}^3/\text{yr} \) (50 m/yr \( \times \pi \times 2500 \text{ m} \times 500 \text{ m} \)) before the plume spread \( (\sigma_z) \) would reach the deepest water wells (\( \sim 100 \text{ m} \)) based on the assumptions above. Therefore, the adjusted hazard is \( H_{wa} = 4.26(10^{-8}) H_w \). The tabulated values of \( H_{wa} \) versus time are shown in table 3.

The dilution for air \( (D_a) \) is calculated according to the plume spread predicted by current atmospheric dispersion methods (Turner, 1967). The stability is taken to be moderately unstable (B-C) and the wind speed is assumed to be 3.8 m/sec. The plume spread dimensions are \( \sigma_y = 1250 \text{ m} \) and \( \sigma_z = 1100 \text{ m} \). The area of the ellipse with these radii is multiplied by the wind velocity to obtain the dilution of \( 5.91(10^{10}) \text{ m}^3/\text{hr} \). Only 68 percent of the diluted material would be included in \( \pm \sigma \); however, the maximum would be greater than the average by a compensating amount. Therefore, all material should be assumed to stay within these limits. The release rate for air is taken to be one-third that for water or 2.78 MT/yr, which should be conservative. The adjusted hazard for air is

\[
H_{aa} = 5.37(10^{-15})H_a
\]

When the adjusted hazard values reach unity, the RCG criteria have probably been satisfied. For the fission product wastes, the times are calculated to be 123 years for \( H_{aa} \) and 595 years for \( H_{wa} \). The wastes that include the actinides decay to the RCG values in 8850 years for \( H_{aa} \) and 949 years for \( H_{wa} \). Since all of the required retention times are less than the minimum probable retention time, 18,400 yr, the dome safety should be adequate. Also, there are two mitigating circumstances that add further to the indicated safety on dissolution; namely (1) the base of fresh
water is above the repository which is assumed to be at 600 m and (2) the ion-exchange would increase the holdup time for the wastes (see p. 23).

Field Test Parameters. The probable rate of dissolution of the salt dome should be investigated with hydrologic test wells. Such wells need to be drilled up and down gradient from the salt dome.

If the dome is to be considered for a repository, it is almost certain that the downstream salinity will not differ significantly from the upstream value. In this case, the maximum error of analysis in the salinity for the ground water can be used to replace the assumed values above and the calculation process repeated.

The dissolution rate should certainly be less than the assumed rates used above since they represent a probable worst case. Evidence in support of this statement is that the domes have lasted much longer than the 18,000 years calculated from the assumptions. Wesselman (1972) cites a dome in Fort Bend County, Texas that shows only 3000 ppm downflow versus 1000 ppm upflow salt concentrations--far from the saturation value of over 200,000 ppm used in assumptions.

Hazards Relative to Earth's Crust

The relative hazards of radioactive wastes versus decay times have been quantified by expressing the risk as a multiple of the hazard from the earth's crust because of its uranium (6 ppm$_w$) and thorium (12 ppm$_w$) contents (Boch and others, 1971, table 12.4). For a repository volume of $1.35(10^4)$ acre-feet (900 ac X 15 ft), the hazards from high-level waste range from $3.8(10^6)$ at zero time
(by Sr-90) to 10 at $10^7$ years (by I-129). If an acceptable value of this hazard indicator is taken as 100 times the radioactivity in the earth's crust the containment time required could be estimated as 8500 years (because of daughters of AM-241 and Am-243).

Fault Tree Probabilities Approach

The probability of each event in the required sequence of events essential for release is estimated, then the product of the individual probabilities is used as the probability of the release (Wash-1297, 1974). The probability of release ($P$) by dissolution in time ($t$, years) is calculated within two orders of magnitude by

$$P = 10^{-12} t^{4/3}$$

The probability of release within 250,000 years (approximately 10 half-lives of Pu-239) is less than $1.57(10^{-3})$ and may be as low as $1.57(10^{-7})$.

Summary

Probable containment times for high level radioactive wastes in a salt dome repository are far in excess of the estimated times for the hazards to reach acceptable levels. Quite conservative estimates show that the margin of safety for public protection is more than adequate.
COMPARISON OF BEDDED VERSUS DOME SALT

Bedded salt's favored status as the geologic formation for radioactive waste repository sites is due to concern over the future tectonic stability, potential for dissolution, and limited lateral extent of dome salt (Boch and others, 1971, p. 23; Culler, 1971; McClain and others, 1972). These fears can be put to rest by selecting the right dome.

Potential bedded-salt sites are in areas that have been tectonically stable for over 200 million years, while interior domes have been stable for at the most 25 million years. However, both are equally stable in terms of the length of time it takes for waste to decay to safe levels (approximately 250,000 years). In our opinion the predictability of the future stability of interior domes, that have completed their evolutionary cycle and are undergoing negative sedimentation, equals that of bedded salt.

The fact that domes are still intact today is convincing evidence that dissolution, when it occurs at all, occurs at an extremely slow rate. From the standpoint of dissolution probability, neither bedded nor dome salt is to be preferred if the site is protected from actively circulating ground water by a few 100 meters of impermeable rock. There is no reason to prefer bedded salt over dome salt that intrudes and is encased in thick Midway-Upper Cretaceous shaly strata.

The lateral extent of dome salt is not relevant until the thickness of the buffer zone surrounding the repository is established. Lomenick (1971, p. 61) implied that 0.75 mi of intact salt was sufficient. Evaluation of dome geometry for proper emplacement
of waste must be done by geophysical methods. On the other hand, due to the complexities of depositional environment, vertical and horizontal persistence of pure bedded salt is also difficult to assess (Lomenick, 1971, p. 31). Determining the geometry of bedded-salt seams suitable for storage will require extensive exploratory drilling.

Dome salt is 95 to 98 percent halite, occurring as truncated cones and cylinders of 2 to 4 km diameter and over 4.5 km high. There is no question that its purity and homogeneity is superior to that of bedded salt. Even the purest halite beds in bedded salt contain countless clay and shale lamina. The Salado Formation of southeast New Mexico, Los Medaños area, is a 500-m thick cyclic sequence composed of evaporite cycles 1 to 9 m thick (Brokaw and others, 1972; Jones and others, 1973). Thus an approximately 9-m bed of high purity halite is the thickest to be expected. At Lyons, Kansas the thickest bed of high purity halite is 2.74 m (Lomenick, 1971, p. 41).

Dome salt and bedded salt, as potential repository sites for high level radioactive waste, are qualitatively compared in table 4. A check mark (✓) in the dome salt column indicates that it would be preferred so far as the particular characteristic checked is concerned and vice versa for the bedded salt column. A check mark in both columns indicates no preference.

In most cases the advantage that one formation has over the other is not great. For example, geographic location, all other things being equal, should provide no advantage either way. However, bedded salt has been checked because suitable sites in bedded salt are available in arid, remote, sparsely settled regions, whereas the potential dome sites are in areas of 40 to 50 in of annual rainfall with much greater population densities.
<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>DOME SALT</th>
<th>BEDDED SALT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Extent</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Vertical Extent</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Purity &amp; Homogeneity</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Geographic Location (dry climate, population density, public vs. private domain)</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Tectonic Stability (predictability of future stability)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hydrologic Integrity (dissolution probability)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Possibility of Accidental Mine Flooding</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Stability of Mine Openings (possibility of rapid closure, roof sag, etc.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External Temperature Effects (heating of adjacent aquifers, and of ground surface above the repository)</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Secondary Lines of Defense (sorptive phenomena, vertical structural elements)</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Abandoned Wells</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Economic Potential (oil, gas, sulfur, etc.)</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>R and D Costs</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
SOLID VERSUS LIQUID WASTE DISPOSAL

Early studies of the waste disposal problem were concerned with liquid wastes since the high level wastes being produced in the 1950's were in liquid form (Parker and others, 1958). However, there was a great deal of uneasiness over storing wastes in such a mobile form. It was postulated that if a liquid waste were stored in a salt deposit the heating of the waste would form steam which would rise to the top of the storage cavity, condense there and drop back into the heated pool below. The condensate would tend to dissolve the salt in the ceiling and carry the dissolved salt back down into the pool. Eventually the dissolved salt would deposit on the bottom of the pool as the liquid in the pool reached supersaturation. Thus the storage cavity would tend to migrate upward and as a result containment might eventually be lost. Laboratory experiments produced results which seem to confirm this hypothesis (Parker and others, 1958, 1959). As a consequence of this and other considerations, technologies were developed for solidifying wastes and the disposal problem studies were shifted to dry solid wastes (Bradshaw and others, 1969).

There are some advantages, however, to storage of wastes in liquid or semiliquid form. The cavity in the salt in which the waste is to be stored can be formed by solution mining, and the wastes pumped into this cavity. This would result in a considerable saving in costs since solution mining is cheaper than conventional mining, particularly at depths of 1000 m or more. Moving liquid waste into a cavity would be quicker and probably safer than moving solid waste into a storage site, and
then finally no containers would be required for the storage. These cost advantages not withstanding, storage in liquid form presents too many risks to make that mode of storage a viable option at present. However, further study of the problems involved might show that the method is feasible. If so, the salt dome would gain a significant advantage over bedded salt as a storage site.

It might be possible to utilize most of the advantages of liquid storage and to mitigate the disadvantages. For example, (Gera, 1973) has suggested the possibility of forming a cavity by solution mining at a depth of 2500 m or more, carefully drying out the cavity and then introducing the waste as a mixture of granulated waste and crushed salt by pneumatic transport. By controlling the ratio of waste to salt the temperature rise in the mixture could be limited to a value which would not liquefy the salt. Thus the waste would remain dispersed in the salt, and eventually the salt formation would close in around the granular mixture which would solidify and become a part of the formation. Preliminary calculations by Gera, with the thermal conductivity of crushed salt assumed to be about one-sixteenth that of solid salt, indicate that a very high dilution will be required, and a result the economic advantages resulting from solution mining would be lost because of the large number of cavities required. However, the conductivity assumed by Gera for crushed salt appears to be much too low, particularly if the crushed salt-waste mixture is rather quickly transformed by heat and pressure into a solid. The method appears to have a sufficient number of advantages for storage in salt domes to warrant further investigation. Retrievability, if this form of
disposal is used, becomes extremely difficult, however. Hence, if retrievability is to be a major consideration, study of this method of disposal would have to be relegated to a very low priority.

There are, of course, possibly other materials which would be suitable for mixing with the radioactive wastes for transport into the cavity. Consideration of these other materials should be included in any further study of Gera's concept.
CONCLUSIONS

1. During the past decade exhaustive investigations (primarily by Oak Ridge National Laboratory) of the use of salt deposits for radioactive waste disposal have been conducted, and reported in the open literature. There is also a large volume of literature pertaining to the geology of salt domes. A careful review of the pertinent publications has revealed no valid technical reasons that would disqualify salt domes as repository sites for high level radioactive wastes.

2. There are no data to prove that salt domes are, or are not, moving. From geologic reasoning interior domes are believed to be tectonically stable. They have completed their evolutionary cycle and are undergoing negative sedimentation. Only in areas of active, rapid sedimentation is dome movement likely. Furthermore, the dynamics of the dome formation process indicate that it is a very slow process, similar to other geologic processes such as mountain building. Hence, if there is movement occurring, it takes place at such a slow rate as to pose no threat to the security of a repository.

3. The possibility that movement of a quiescent dome might be triggered by the heating produced by stored radioactive wastes is extremely remote. The significant heating produced by the wastes is very localized in comparison with the bulk of the dome. Furthermore, a quiescent dome is one in which only a hydrostatic stress state exists because over geologic periods of time salt cannot sustain a deviatoric stress component. Heating of the salt while it might increase the mobility of the salt, could not trigger movement because no driving stress is present. Geological evidence
also suggests that something more than high temperature was needed for dome formation. Finally, if movement is triggered because the mobility of the salt is increased by heating, when the mobility returns to its original value (when the "before storage" temperature state is regained), motion would stop. The time required for the rise and fall of the temperature is very short on a geologic time scale. Therefore, the total movement would be quite limited. A total movement of 20 m has been calculated assuming a rate of 2 mm/yr could be generated and sustained for 10,000 years.

4. A repository surrounded by shale and below the base of fresh water (actively circulating ground water) would be safe from dissolution. Should ground water reach the dome, there are two lines of defense between the radioactive material and the biosphere. For reasonable assumptions of a ground water flow rate and dome dimensions, calculations show that 18,400 years will be required for the water to reach the repository by dissolution; required retention times on an adjusted hazard basis are much less. The second line of defense is provided by the adsorption of radionuclides onto host rocks. In the event the waste disposal site is breached by ground water, sorption will confine the radionuclides to limited areas.

5. Flooding of a repository site in a salt dome presents no unacceptable risks provided the dome is carefully selected and sound mining procedures are followed. Reportedly Winnfield and Belle Isle are the only Gulf Coast salt mines ever breached by flood waters. That flooding was attributed to shaft problems. Furthermore, the hydrologic setting of the Winnfield dome is optimum for flooding.
6. Of the 263 known salt domes there are 36 potentially acceptable domes as repository sites. If the choice of a dome is restricted to domes in interior basins the number of potentially acceptable domes is reduced to 29. Five domes, Whitehouse, Mt. Sylvan, Vacherie, Lampton, and McLaurin meet most of the criteria of the ideal dome and are recommended for further study.

7. Very little information on the geometry of the recommended domes is publicly available. Some general information is available, but extensive geophysical data may be available from oil companies on a confidential basis.

8. Residual stresses in salt domes as a result of the formation process would have been relieved long ago by creep or flow of the salt since salt will creep under very low stresses even at low temperatures.

9. If a cavity is mined in dome salt, the deviatoric stress developed around the cavity will result in creep which eventually will close the cavity. The rate of deformation is so low that closure presents no problems to storage operations. Creep will speed up as the temperature of the salt is raised, but it will be no more of a problem in dome salt than it is in bedded salt. Since the shale and mud lenses found in bedded salt are not found in dome salt, cavity closure should be more predictable for dome salt than it is for bedded salt.

10. Measurements of closure rates in mines in both dome and bedded salt indicate that no unusual stress conditions are found in dome salt.

11. Neither bedded nor dome salt is superior overall to the other for radioactive waste repository sites. In fact, depending upon the ultimate repository design, dome salt may be the preferred
12. One of the advantages of a dome as opposed to a salt bed, as a repository, is the great vertical height of the dome. The design of a disposal facility should take advantage of this height. For example, canisters of radioactive material could be stacked in deep boreholes, separated vertically by crushed salt or a solution-mined cavity at great depth could be pneumatically filled with solidified waste.
RECOMMENDATIONS

Research necessary to the selection of a dome for a repository site is recommended in the following areas:

1. Geomorphology
2. Heat flow
3. Geophysics
4. Geohydrology
5. Caprock evolution
6. Precision leveling
7. Land acquisition

Geomorphology

Geomorphologic analysis is a way to evaluate dome stability in terms of geologic time in contrast to the contemporary micro-earthquake or leveling studies. Stereo air photos (1:10,000-20,000) should be used to prepare a detailed drainage pattern map showing ridge crests in the vicinity of each of the unrejected domes (table 2). Stream patterns should be mapped in the immediate vicinity of the domes. A candidate dome in terms of tectonic stability is one with no drainage anomaly (see p.29). On each of the candidate domes a more detailed analysis is suggested evaluating stream density (mi of total channel/mi²), hill slope equilibrium, etc. For this phase of the analysis low-altitude infrared photos may be useful.

Heat Flow

Heat flow data (see p.29) should be collected on candidate domes selected from the geomorphic analysis. Comparative data should be collected from coastal domes (Hoskins Mound and Jefferson Island) where recent movement is suspected. Important
references describing instrumentation, collection, reduction, and precision and accuracy of basic heat-flow data are found in Sass and Munroe (1974).

**Geophysics**

Reflection seismologic and gravity studies are necessary for the determination of dome geometry. Gravity maps may be best for geometry. Micro-earthquake data, because they are collected over the short term (5 yr. or less), have little value for predicting future dome stability. However, they can supplement geomorphic analysis, heat flow data, and leveling measurements. A candidate dome must at the moment be tectonically quiet. Supersensitive seismographic equipment can be installed in a dome in boreholes. This equipment would provide means for "listening" to the dome. From the information thus gained some inferences regarding possible current dome movement can be drawn.

**Geohydrology**

Evaluation of the hydrologic regime for each candidate dome requires knowledge of aquifers, aquicludes, ground-water hydraulics, and water chemistry. For each aquifer the following should be established: total dissolved solids, lithology, geometry, orientation relative to the direction of ground-water flow, extent of communication with other aquifers, and productivity. In addition for each aquiclude data on clay mineralogy, ion-exchange capacity, and position relative to the caprock should be collected. A good understanding of aquifer-aquiclude stratigraphy and structure should extend to the depth of waste emplacement. Cross-sections, isolith maps, and structure maps should be prepared to determine the extent of aquifers, orientation relative to ground-water flow
direction, and regional dip. Much geologic data will come from existing geophysical logs.

Hydrologic test wells will be required to obtain hydraulic parameters and modern, high quality geophysical logs (SP, natural gamma-ray, electric, induction, neutron, and density). The three most critical hydraulic parameters are hydraulic conductivity (permeability), hydraulic gradient, and effective porosity. Knowing these parameters allows calculation of average ground-water velocity. The parameters are obtained from pump tests, slug, injection or swab tests, laboratory tests, water level measurements, and geophysical logs (Walton, 1962; Lohman, 1972). Average velocity should be calculated for each aquifer.

Water chemistry data are needed to establish predisposal base lines. Analyses should include the common ionic species, silica, total dissolved solids, specific conductance, temperature, pH, and radiochemistry (at least gross alpha, beta, gamma). Semi-quantitative values for total dissolved solids and stratal natural radioactivity can be obtained from geophysical logs. Chloride content up and down hydraulic gradient from candidate domes should be determined to make inferences about possible dissolution. Some plume information will also be needed for dissolution computations. However, unless there is a measurable difference in chloride content between updip and downdip wells there is no need for plume determination. Maps of chloride isohalines, at domes like Hockley where nearby heavy withdrawal has steepened the hydraulic gradient and presumably accelerated coastward movement of ground water past the dome, are essential to the evaluation of dissolution rates. From the chloride halo limiting rate values can be calculated using the best time estimates of dome intrusion.
Caprock Evolution

The presence or absence of caprock has been used to make inferences about dome stability (see p.16) and susceptibility to dissolution. The residual accumulation theory of Taylor (1938) has been recently questioned by Walker (1973). Walker proposed that direct precipitation accounts for the bulk of the caprock overlying shallow salt domes. The whole question of caprock evolution should be reviewed. If the residual accumulation theory is favored, the manner in which ground water can dissolve salt uniformly over the wide extent of a salt table should be investigated.

Precision Leveling

To supplement the other studies aimed at evaluating dome stability after some domes have been selected from geomorphic analysis a precision leveling program should be initiated. For this program an established organization skilled in precision leveling should be contracted for a long term study. This organization would provide a detailed plan for accomplishing the objective of the program. In this plan a network of benchmarks would be laid out so as to minimize the possibility of a shift in reference marks being mistaken for dome movement. Benchmark construction would be such as to eliminate or minimize the effects of superficial earth movements. Level measurements need be made only once per year but should span a period of at least 5 years. The errors of these measurements should be no greater than $\pm 0.1 \text{ mm}$ if they are to be of any use.
Land Acquisition

Before any on-site studies can begin steps must be taken to acquire purchase options and exploratory rights on land over the candidate domes. When the studies recommended above have progressed to the point where a decision can be made as to which of the candidate domes would be most suitable for a repository location, a study of ancillary features of that dome should be initiated. These features would include accessibility to transportation facilities, proximity to large population centers, local laws, public attitude, and cost of land. With this information the list of candidate domes should be narrowed down to no more than two. At this point purchases of the necessary land rights for use of the domes as repository sites should be negotiated as quickly as possible.
REFERENCES


