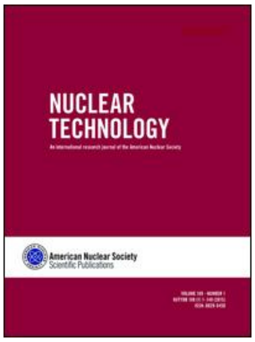

Nuclear Technology

ISSN: 0029-5450 (Print) 1943-7471 (Online) Journal homepage: https://www.tandfonline.com/loi/unct20

Disposal of Radioactive Waste in Bedded Salt Formations

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DISPOSAL OF RADIOACTIVE WASTE IN BEDDED SALT FORMATIONS

RADIOACTIVE WASTE

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KEYWORDS: *New Mexico, radioactive waste disposal, salt deposits, solid wastes, geology*

Received May 24, 1974
Accepted for Publication July 16, 1974

The considerations involved in the evaluation of the suitability of any geological formations for the disposal of radioactive wastes are illustrated by summarizing some of the studies performed in the southeastern New Mexico region on the bedded salt concept. These investigations fall into three main categories:

1. Evaluation of the natural integrity of the formation. In addition to standard geological and hydrological studies, special investigations of the subsurface dissolutioning of the salt formation, the seismic stability of the region, and the possibility of previous mass flowage of the salt have been completed. These results will be confirmed by core drilling and testing currently in progress.

2. Evaluation of the effects of the operation of a waste disposal facility on the geological characteristics of the area over the short term. These studies include prediction of the thermal transient resulting from the radioactive decay heat deposited in the rocks and its effects, such as the migration of brine inclusions up the thermal gradients and the dehydration of moisture-bearing minerals. Other studies in this category are concerned with the possibility and consequences of radiation-induced energy storage in the salt and prediction of the deformations to be expected around the openings excavated in the salt formations.

3. Evaluation of the effects which the operation of a repository and other activities of man may have on the integrity of the geological containment over the long periods that the waste remains hazardous. The principal analyses in this category involve the long-term deformations of the rocks overlying the repository area (including the slow development of a subsidence basin at the ground surface) and the prevention of adverse conditions resulting from penetrations of the salt by exploratory drilling for oil and gas accumulations.

INTRODUCTION

For many years, the Oak Ridge National Laboratory has been engaged in research and development directed toward the disposal of radioactive wastes in geological formations deep underground—especially the disposal of solidified high-level waste from the reprocessing of nuclear power reactor fuels in bedded salt deposits. Some of the investigations that have been performed and are currently in progress relative to the suitability of the southeastern New Mexico area will be summarized here in an effort to illustrate the considerations involved in the evaluation of any geologic formation for the disposal of radioactive waste. In general, the investigations of any geological formation for waste disposal fall into three categories:

1. Definition of the present geological characteristics of the formation and surrounding region and, based upon their development of those characteristics over the geological past, an estimate of future conditions, assuming that the formation remains undisturbed.
2. Evaluation of the relatively short-term effects that the operation of a waste repository itself would have on those geological characteristics. These effects are primarily related to the access excavations required and the intense radiation fields and thermal transients produced by the in-place wastes.

3. Evaluation of any potential long-term effects of the repository operation or other activities of man. Since it is the geological formation itself that provides the long-term containment and isolation of the wastes, these effects are significant.

One concept for the disposal of solidified high-level waste in bedded salt formations that has evolved from our work would consist of the following basic features. First, a series of long narrow rooms and connecting corridors would be excavated in an appropriate section of a thick salt formation (Fig. 1). Individual canisters of waste would be unloaded from a heavily shielded shipping cask, lowered into the mine, and deposited into holes in the floor of the disposal room in a pattern designed to limit maximum temperatures. Shielding of the waste canisters would be provided by backfilling the holes with crushed salt, thereby permitting unlimited access to the rooms except during actual waste transfers. After a room had been filled with waste in this manner, the room itself would be backfilled with salt obtained from the excavation of future rooms. Over a period of several decades, the plastic deformation of the salt, especially as accelerated by the elevated temperatures, would cause closure of the rooms along with compaction and recrystallization of the backfill salt. In this way, the salt formation will be returned to a solid, massive, relatively undisturbed formation containing the wastes.

INTEGRITY OF NATURAL FORMATIONS

The general geology and hydrology of the Delaware Basin portion of the Permian evaporite region of the Southwest have been compiled by the U.S. Geological Survey based on field work, analysis of oil well logs, and other file data.[1,2] In the area of interest (Fig. 2), the three evaporite formations—the Castile, Salado, and Rustler—have a combined thickness of more than 1300 m. Both

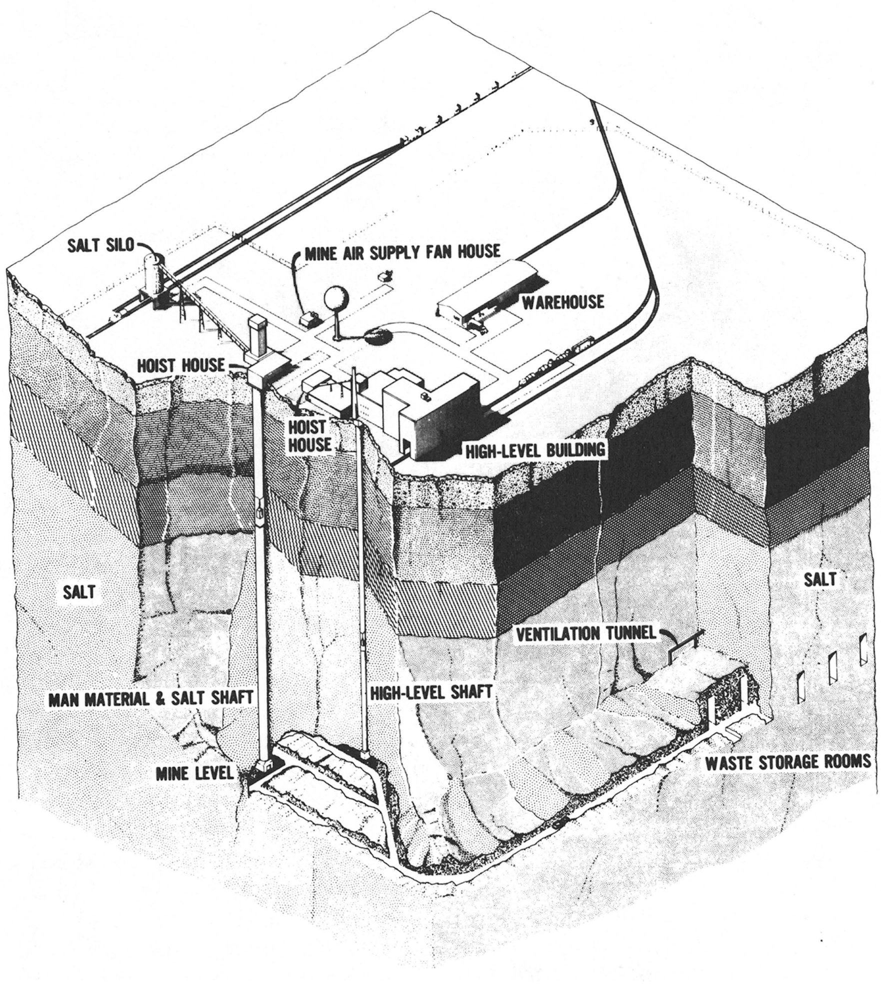

Fig. 1. Schematic view of pilot plant waste repository in bedded salt formation.

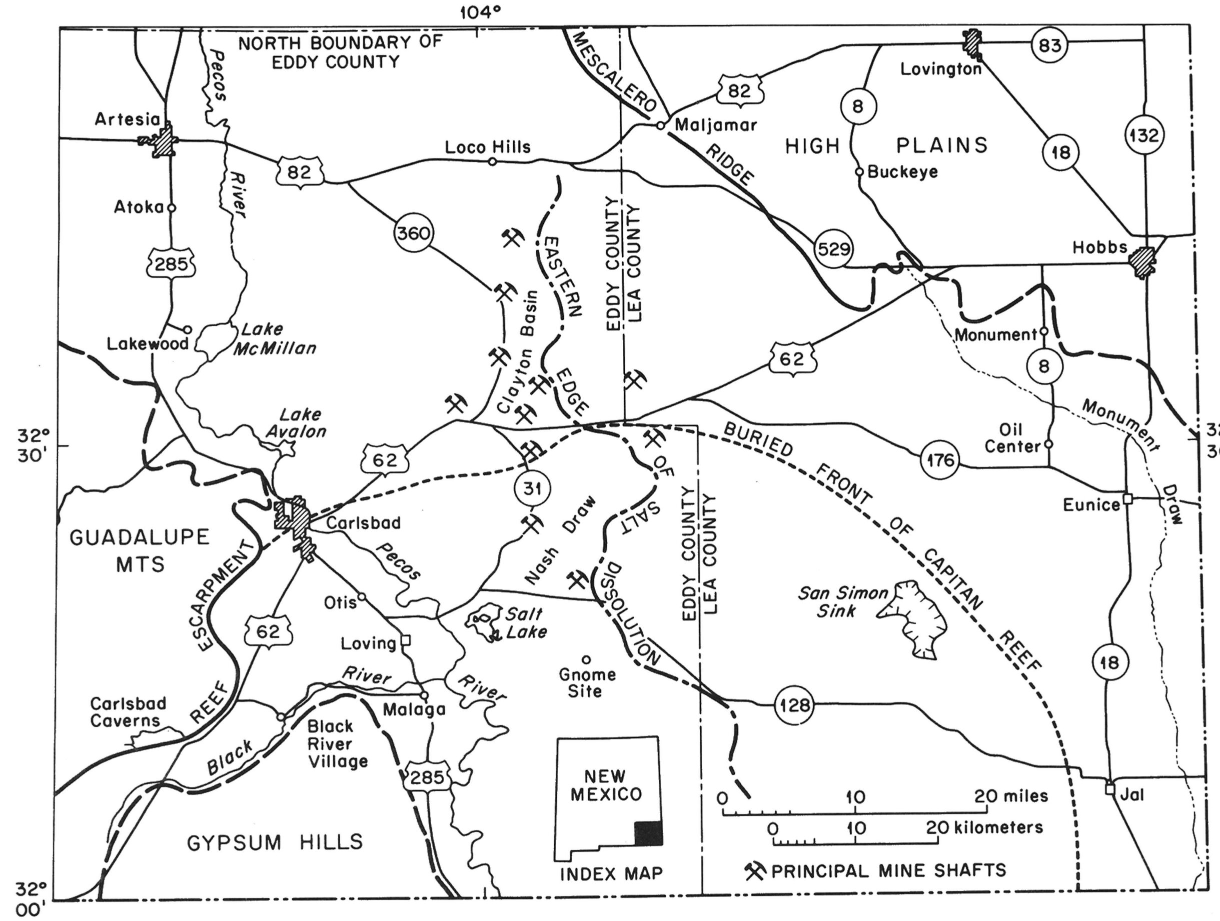

Fig. 2. Location map of the Delaware Basin area in southeastern New Mexico.

the lower Castile and the upper Rustler are richer in anhydrite and poorer in salt than the middle Salado, but they provide this formation with considerable protection from any fluids which might be present.

The formation of interest, the Salado, ranges in thickness generally between 500 and 600 m, with its top ~300 m below the surface (Fig. 3). Rock salt constitutes about 85 to 90% of the formation, with the remainder being anhydrite and potassium-rich rocks which are located solely in the middle portion. Local enrichments of these zones are being mined for potash in a region generally north and west of the area of interest (Fig. 2). For our purposes, the lower rock salt member of the Salado formation, at a depth of about 600 m, appears to be the most attractive. In this area, the sedimentary rocks are, for the most part, only slightly deformed, as represented principally by the gentle homoclinal dip of no more than 2 deg to the southeast. There is no evidence of faulting or interformational folding (Fig. 4).

For waste disposal in nonsalt rocks, hydrology questions are primarily concerned with the quantity of water flowing through the permeability of the formation and, therefore, having access to the radionuclides. Salt is essentially impermeable to liquids and, almost by definition, does not and has never had water circulating through it. However, the high solubility of salt requires an even more thorough understanding of the hydrology to ensure that the salt formation containing the waste will not be dissolved. At the western edge of the Delaware Basin, where the salt formations approach the land surface, extensive dissolution of the salt formations (called subrosion because the salt is removed below the surface) has occurred and produced widespread subsidence structures, especially those known as Nash Draw and Clayton Basin (Fig. 2). This subrosion has been carefully examined from both hydrologic and physiographic points of view.[3] These analyses indicate that the area of interest can be threatened by subrosion chiefly from the west and to a much lesser extent from the east. An area showing evidence of past dissolutioning of the salt, which is now either inactive or is progressing at such a slow rate that it cannot be estimated, is located to the east of the study area. Cessation of dissolution in this area, which is called San Simon Swale, was apparently effected by capture of the headwaters of a tributary drainage. Active dissolutioning is currently taking place to the west of the study area, and its past rates can be determined by geological dating of the resulting collapse structures. These investigations indicate that the average rate of vertical removal of the salt from the Salado formation has been approximately 100 m per million years. Under the most severe climatic conditions of the past, a maximum rate as much as 300 m per million years might have existed. Because of the slight eastward dip of the salt formation, this rate of vertical dissolutioning is translated into a horizontal rate of migration of the dissolutioning zone of 1.2 to 2.5 km per million years. Therefore, the site under investigation, which is several kilometers removed from the active zone, would not be expected to experience any dissolutioning of the salt for several million years; even after it starts, at least another million years would be required before the salt actually containing the wastes was breached.

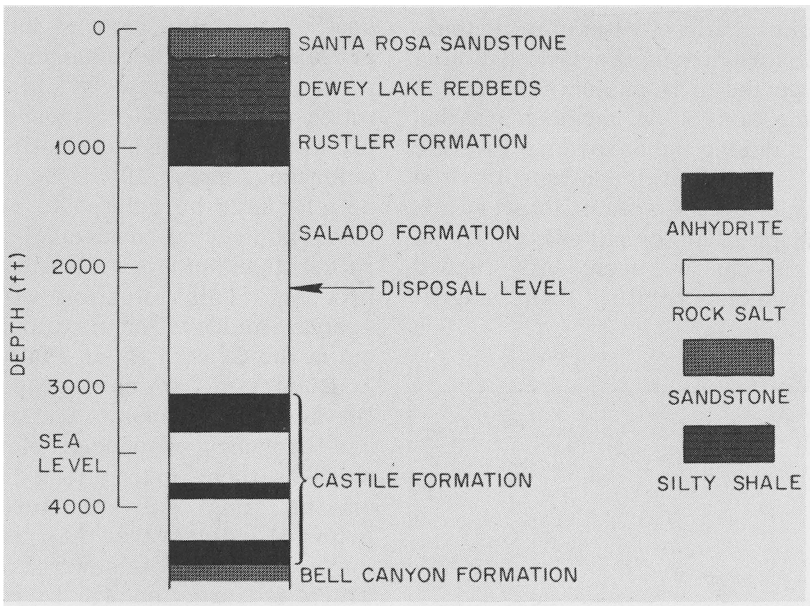

Fig. 3. Generalized geologic section in central Delaware Basin.

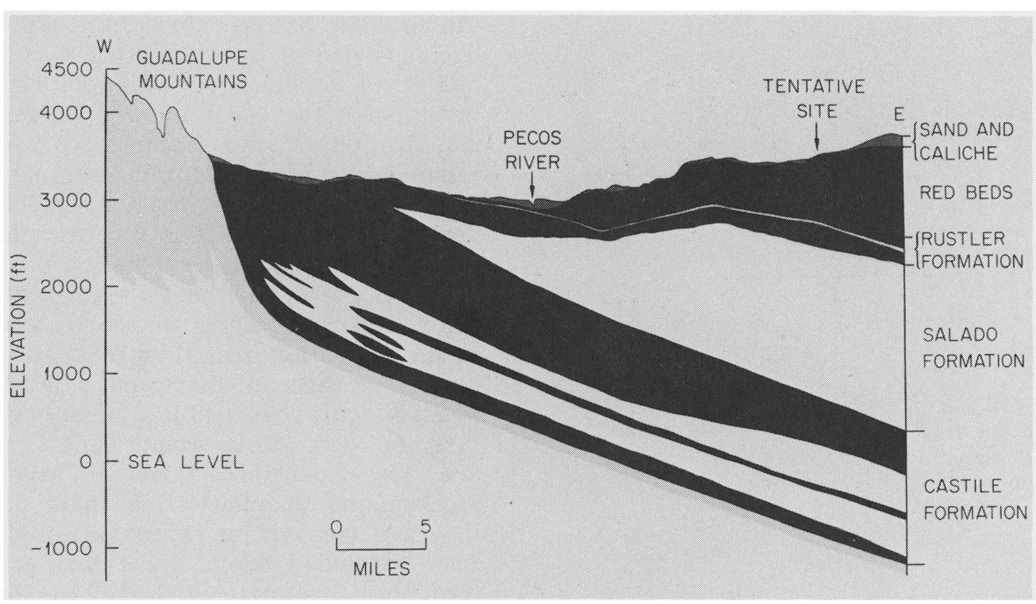

Fig. 4. Geologic cross section of a portion of southeastern New Mexico.

Other natural processes which could lead to exhumation of the waste or, in the case of salt, to a drastic alteration of the groundwater and subrosion regime must also be investigated. These processes include ordinary surface erosion and denudation, and tectonism, especially faulting in the area and mass flowage of the plastic salt (or diapirism). The surface erosion question for the New Mexico area is resolved as an integral part of the hydrology and subrosion investigations. For the last several million years, which includes several pluvial periods, subrosion of the salt has been much more active in modifying the topography than has simple surface erosion.

The entire Permian Basin is within the tectonically stable interior region of the United States and would not be expected to be subjected to major earthquakes, faulting, or other large-scale deformation processes during the hazardous lifetime of the waste. This stability was confirmed by the total absence of faults in the area of interest and by detailed examination of historical seismicity as shown in Fig. 5. As can be seen, this record indicates no earthquakes greater than magnitude 3.5 in the immediate vicinity of the site and suggests that major earthquakes (larger than magnitude 7.8) are not likely to occur closer than 115 km. To further explore the seismicity of the area, a long-term microearthquake monitoring program has been recently initiated at the site. If this program should detect any microseismicity, for example, suggesting a deeply buried and inactive basement fault in the vicinity, further studies would be initiated. To date, the only anomalous feature identified in the seismicity and tectonic investigations is a recent series of minor but nevertheless significant earthquakes on the Central Basin Platform about 50 miles south-southeast of the area of interest. These events are anomalous, because the Central Basin Platform is an extremely old geological structure which shows no other evidence of rejuvenation and for which no earthquake activity had been reported prior to August 1966. It is suspected that this activity may be related to water injection operations at several producing oil fields in the area rather than being a reflection of a natural tectonic process. This situation will be clarified by a special multistation monitoring program carried out at the Central Basin Platform.

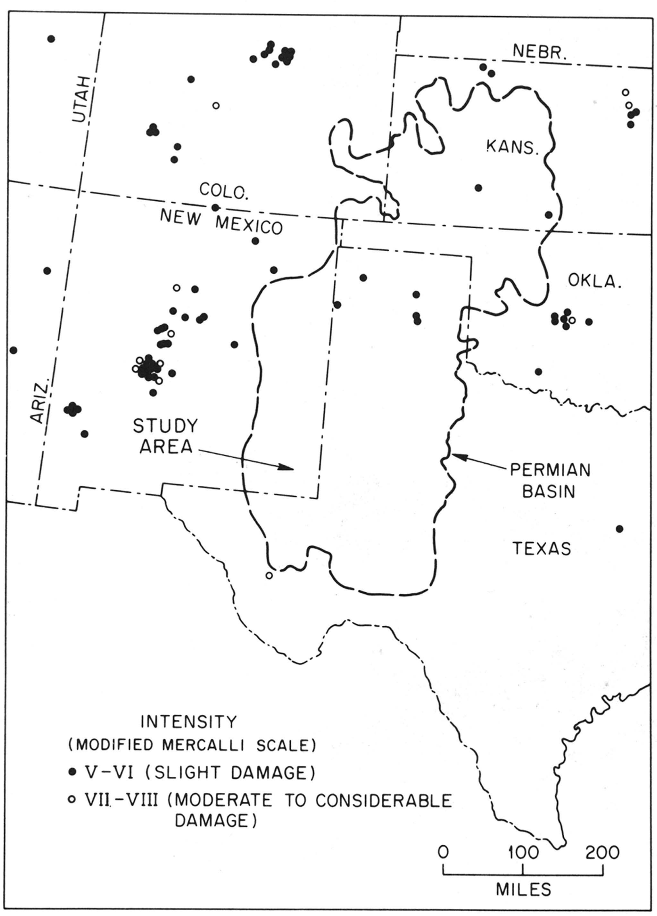

Fig. 5. Major recorded earthquakes.

Diapirism, which is the process of mass flowage of salt deposits under the forces of gravity and buoyancy, produces piercement salt domes such as those found along the Gulf Coast region and anticlinal salt structures. Several lines of evidence indicate that the rates of these processes may be as much as several millimeters per year, which is large enough to result in considerable disturbance of wastes over the long times involved. Since it is not possible to precisely specify the necessary and sufficient conditions for the initiation of mass flow of the salt, the problem becomes one of demonstrating that the formation has never experienced even the first stages of diapirism. For the Delaware Basin, this means examination of two features. The first is the minor intraformational folding or, more exactly, a local thickening and thinning, especially of the upper portion of the Castile formation, which is inferred from the interpretation of oil field logs. This folding is viewed as a gravitational sliding which occurred during or shortly after deposition of the formation and, therefore, is not related to diapirism. Second, there are a number of small, symmetrical, rounded hills in the region, particularly in Nash Draw, whose genesis and structure are not understood. One of several possible mechanisms postulated for their origin is that they are the surface expression of salt domes. It was concluded from a detailed gravity survey performed over one of these hills that, although their structure and mode of formation still cannot be exactly defined, salt domes can be excluded from the list of possibilities. Investigation of these two features will continue.

Specific subsurface structural, stratigraphic, and hydrologic data for the area under investigation will be obtained by drilling geological exploration holes. One of these holes was recently completed, and another is now in progress. Preliminary interpretation of the results indicates that the structure and stratigraphy are almost exactly as predicted. Available groundwater is much less than anticipated, with apparent yields from only the Santa Rosa formation (at a depth of ~30 m) of 10 to 30 liter/min. Coring in and below the Salado formation has identified at least two zones of extremely pure salt which would be suitable for waste disposal at depths of ~600 and 900 m.

SHORT-TERM EFFECTS OF REPOSITORY OPERATIONS

The principal points to be discussed in this section concern the effects that the operation of a waste repository itself would have on the geologic character of the area, especially the integrity of the containment provided by the geological formations. However, it should be recognized that the usual operational safety analyses will be performed, including evaluation of the environmental consequences of waste handling incidents involving the potential release of radionuclides.

For a high-level waste repository, the first effect of concern is the thermal transient resulting from the heat deposited in the salt and other formations due to radioactive decay of the waste. The spacing of the waste canister in the mine will be designed to limit peak temperatures in the waste to some value safely below its solidification or processing temperature and in the salt to 200°C except for a small region immediately adjacent to the waste canisters. For waste that is aged 10 years at the time of disposal and has a heat generation rate of 2000 W per canister, these requirements result in an areal spacing of about 65 kW/hectare. Under these conditions, the temperature distributions[4] along the vertical centerline of the repository located at a depth of 1000 ft at various times are shown in Fig. 6. As can be seen, the thermal transient persists for quite a long time, whereas the peak temperatures are reached fairly early. Predictions of thermal histories of this type are necessary both for evaluation of the direct consequences of the elevated temperatures and for use as input into other analyses. As an example of the former consideration, it is apparent that the mining level becomes uninhabitable under normal conditions within 20 to 30 years after deposition of the waste and remains so for several hundred years. The

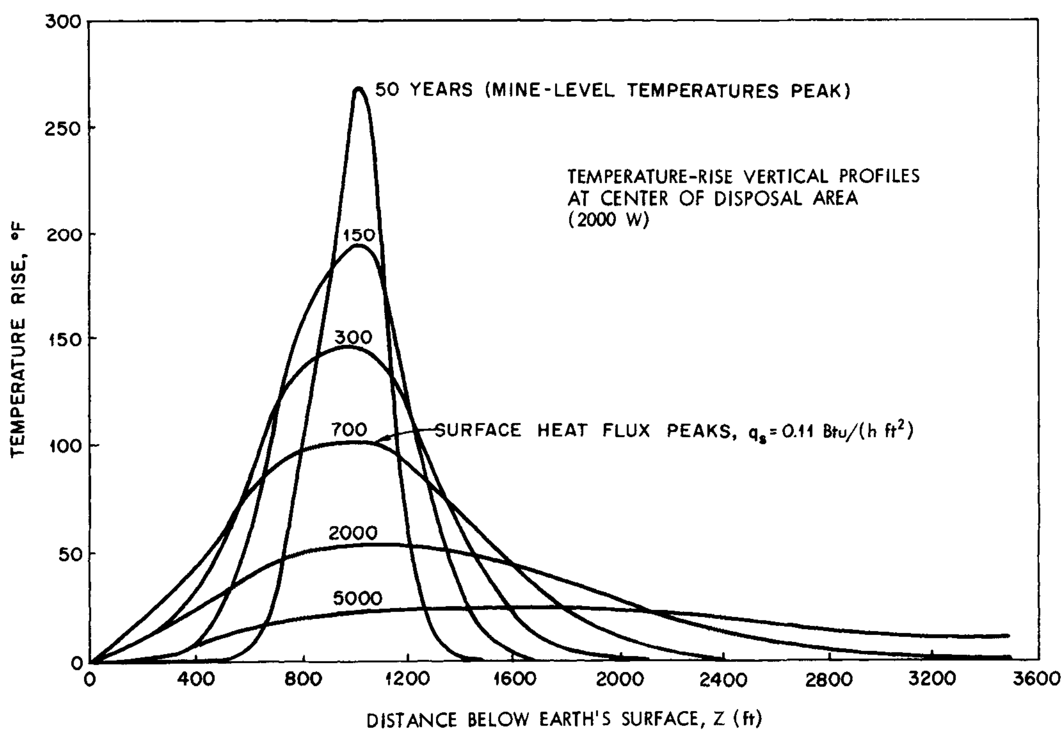

Fig. 6. Temperature-rise vertical profiles at center of disposal area.

maximum thermal flux near the surface is approximately seven times the natural geothermal flux but nevertheless is still only about one-thousandth of the incoming solar heat flux. Therefore, no surface expression of the heat would be expected.

The effects of the thermal transient are also of direct relevance in a number of other analyses. One of these concerns the migration of small inclusions of brine trapped in the salt formation when it was originally deposited. These brine inclusions are apparently present in all bedded salt deposits. On a volumetric basis, they typically comprise a small fraction of a percent and are usually smaller than 0.1 mm in cross section. Because of the temperature dependence of the solubility of salt, these small inclusions will migrate up any thermal gradient, that is, toward the heat source. For waste disposal, this moisture, and especially the rate at which it arrives at the hole containing the waste canister, will have a significant effect upon the rate of corrosion of the canister material. Because of the many variables involved (e.g., chemical constitution of the brine, impurities in the salt and their distribution, geometrical distribution of the brine inclusions with respect to the heat sources, corrosion mechanisms of the canister metal, etc.), only the limits of these processes can be predicted. Determination of these rates will require field tests in the actual disposal formation and configuration. However, it should be pointed out that the brine migration into the waste hole will terminate within 30 to 50 years because the thermal gradients will no longer be steep enough.

Moisture is also contained in salt formations as water of crystallization of certain accessory evaporite minerals (especially calcium and magnesium sulfates) and within the crystal lattices of clay minerals making up shale impurities and partings. This moisture is released as the temperature is raised, in some cases at temperatures as low as about 125°C. Because this water is driven out of the minerals into the formation pore space, even relatively small quantities can, under certain circumstances, significantly affect the geological and structural character of those formations by drastically elevating the pore pressure. The problems of analyzing the consequence of such an event are largely avoided by selecting a disposal horizon such that there are no appreciable quantities of these moisture-bearing minerals within the heated zone. Of course, this selection requires careful mineralogical analysis of specimens obtained from core drilling.

Another of the analyses of short-term effects of the repository operation concerns the question of whether any stored energy which might be accumulated in the salt immediately surrounding (within a few centimeters) the waste canister as a result of gamma radiation could be released in such a manner as to cause serious thermal excursions or other undesirable effects. The thermal calculations are again of importance in this analysis, because the quantity of energy that can be stored is highly dependent upon the temperature of the salt during irradiation as well as upon the dose rate and total dose. For example, results obtained with a specially constructed calorimeter indicate that at temperatures above 150°C, the energy stored in salt will be negligible since it is annealed as rapidly as it can accumulate; between 120 and 150°C, the amount of energy stored will saturate at 18 to 20 cal/g; below 120°C, extrapolation of the few available data[5] suggests that saturation will be reached at ~60 cal/g. In practice, the temperature of the salt immediately around a waste container will be >150°C except perhaps around isolated, low-temperature waste canisters and, accordingly, only negligible amounts of energy will be stored. However, a preliminary analysis of the effects of a sudden release even of 60 cal/g indicates that no serious consequences would ensue; the salt would not melt, and both thermal and mechanical perturbations would be relatively small and brief.

The design of the underground workings, the size and shape of the disposal rooms and intervening support pillars, and the subsequent analysis of the deformations to be expected around these openings constitute other important short-term effects which are also particularly complex problems: first, because of the conflicting objectives of maximum stability during operation of a repository followed by closure of the rooms as rapidly as possible after cessation of operation in order to provide geological containment at an early date; and second, because the underground deformations are the result of the time-dependent creep properties of salt (a highly plastic rock), that are very temperature sensitive, and the stresses produced by the overburden load, induced mining stresses, and thermal stresses which again vary as a function of time. These deformations are illustrated in Fig. 7, which shows the accelerated vertical shortening of the support pillars when heating was applied in holes in the floors of the rooms in the Project Salt Vault experiment.[6,7] Figure 8 summarizes the total deformations measured in and around one of the pillars during the 19-month heating period of that experiment.

Analyses of the deformations in a hypothetical waste repository are currently in progress along two separate lines. The first is a standard finite-element analysis where the salt is modeled either as a thermo-viscoelastic or a thermoelastic plas-

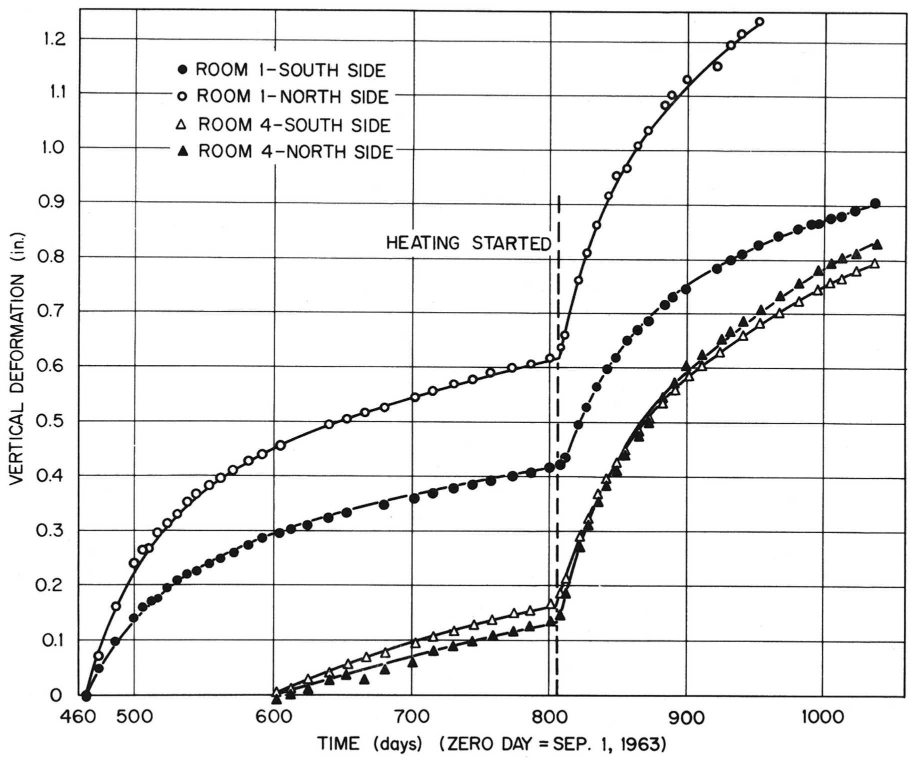

Fig. 7. Vertical convergence in Project Salt Vault experimental area.

tic material. In each approach, the constitutive equations for the salt will be determined from extensive laboratory tests conducted on specimens of the core obtained from the selected disposal horizon. The emphasis in this portion of the analysis is directed primarily toward the question of stability during the operational period.

The second line of analysis involves the development of a model simulating the deformational behavior of the entire repository area based upon a method of averaging displacement discontinuities.[8] The model is a refinement and adaptation (by adding the time- and temperature-dependent properties of salt) of recent mine modeling techniques developed principally in South Africa. The basis of the model is a theoretical derivation which assumes that the rocks over and under the excavated horizon will behave elastically while the salt in the underground pillars will deform in the same way as model pillars in laboratory experiments. The numerical parameters defining that deformation, which differ from the analogous parameters of the model pillars by some unknown scale factor, are then determined by "calibrating" the model against field data. In this case, the only suitable field data are those obtained from the Project Salt Vault experiment. Since this model tends to smear out the details of the deformations immediately around the mine openings, it will be used primarily to investigate the overall rate of closure of the mine rooms after the operational period and the effect which various mine geometries and operating sequences will have on that closure.

LONG-TERM EFFECTS

In addition to the effects of the operation of a waste repository over the short term (i.e., up to perhaps 200 years), which were discussed in the previous section, both the repository and other works of man may have long-term consequences with regard to the containment provided by the geological formations. The first of these is the long-term deformation of the rocks surrounding and especially overlying the repository. In practice, it is not possible to backfill the repository rooms with the same quantity of salt that was originally removed. Over the long term, this missing volume will be taken up by the closure of the rooms and will eventually appear as a broad, shallow subsidence basin on the surface. A similar, but greater, surface subsidence occurs much more rapidly over the potash mining operations in the southeastern New Mexico region without significantly affecting either the integrity of the overlying formations or the hydrologic patterns in the area. In addition to this mining subsidence, the overlying rocks will also be subjected to the effects of volume changes resulting from the bulk thermal expansion of the heated rocks. These two effects work in opposition, and judicious selection of the mine geometry will serve to limit the rates of deformation and subsidence. The amount and rate of these deformations, including those at the ground surface, will be estimated by extending the rock mechanics analyses described previously. The effects of these deformations will be analyzed for any possible consequences, such as through-going fracturing resulting from the induced stresses and disturbance of the overlying groundwater regime.

Another long-term effect of the operation of a repository which is being examined concerns the behavior of the waste itself. Over the very long times involved (thousands of years), all possible mechanisms for the transport of the nuclides through the salt must be investigated. These transport mechanisms include solid diffusion, grain boundary and surface diffusion, and gas diffusion through the salt. Our analysis indicates that, although grain boundary diffusion is several orders of magnitude more rapid than solid diffusion, migration of the radionuclides will still be limited to a few tens of centimeters per million years. Gas diffusion appears to be unimportant because there are no identifiable chemical reactions which lead to the formation of gaseous products, and the quantity of gaseous daughters in the radioactive decay chains of the waste nuclides is insignificant.

In addition to the effects of the repository itself, the long-term effects of other activities by man must be considered. Since we are concerned with the integrity of the geological containment, the activities of interest are those which penetrate or otherwise disrupt the subsurface geological environment. At the depths being considered for waste disposal, penetration of formations for reasons other than exploration for and removal of natural resources seems highly improbable. The common salt of the disposal formations is a mineral of nominal value, but it is so abundant, widespread, and more easily produced in other areas (including by solar evaporation of sea

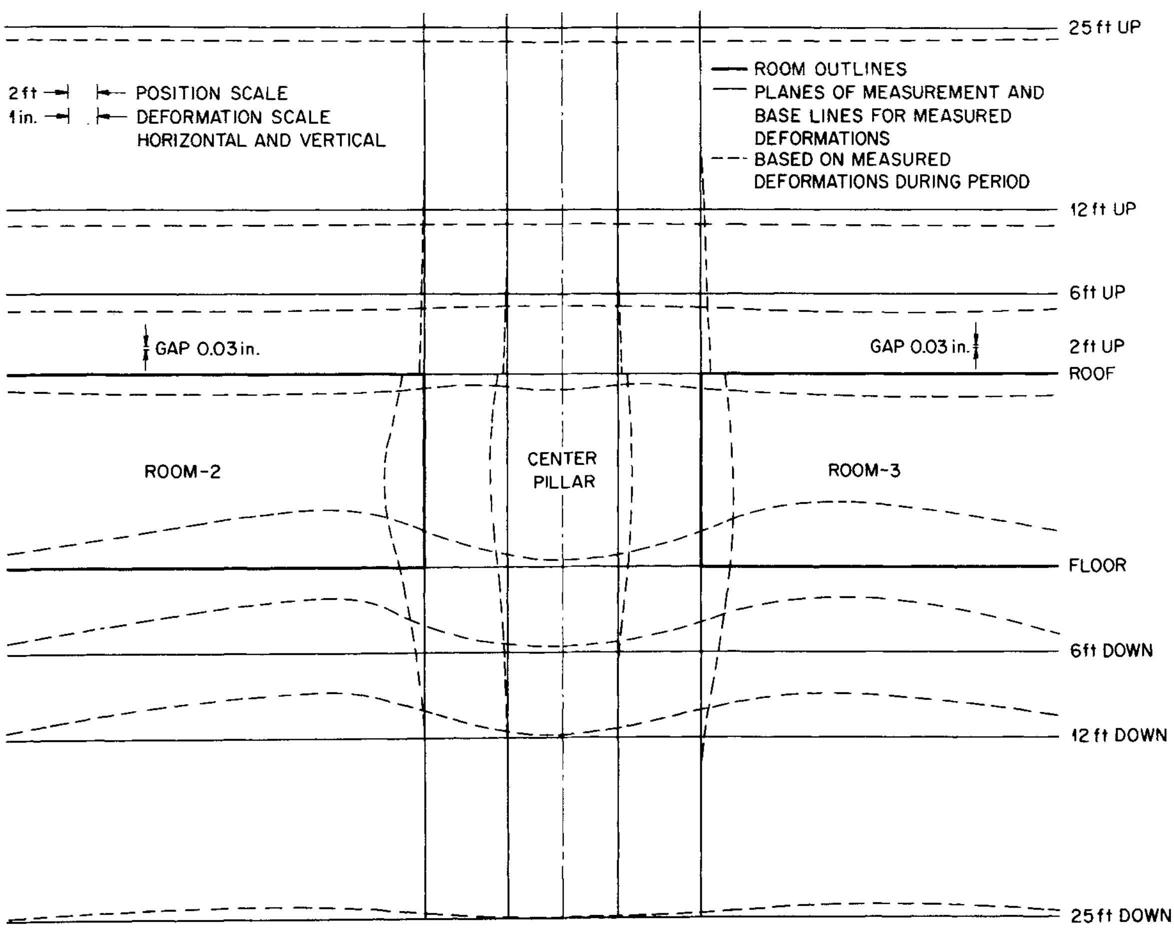

Fig. 8. Summary of deformations in and around center pillar of Project Salt Vault experimental area.

water) that the possibility of future production from a repository area can be disregarded. Potash salts are evaporite minerals of much greater value and importance which are found in association with a few, but by no means all, salt deposits. Potash has been mined from the middle member of the Salado formation in the central Delaware Basin for several decades, and the area of particular interest for a waste repository is located at what appears to be the edge of mineralized zones. Therefore, some potash mineralization is expected at the study area, and this mineralization will be very carefully analyzed and evaluated in the cores. However, no particular problems are anticipated at this time because the mineralization is expected to be so minor that it would never represent an economically attractive ore deposit. Furthermore, the portion of the formation postulated for waste disposal underlies the potash mineral zone by a considerable distance, and it may be possible to extract even this very low-grade material at some time in the future without disturbing either the waste or its containment.

Exploratory drilling for oil and gas accumulations is the principal activity of man which may result in penetration or disruption of the salt formation and any waste contained within it. In general, salt deposits are always found in the same type of geologic environment as oil and gas deposits, i.e., sedimentary basins. It is practically impossible to find a salt formation where the potential for finding oil and gas can be totally precluded.

Petroleum exploration holes represent a potential threat to the salt formation because they can serve as a hydraulic connection through the salt between any overlying and underlying aquifers. Under certain conditions, it is possible to develop a gravity-driven, circulating fresh water system which rapidly dissolves the salt. This has actually happened in five known cases out of an estimated 50 000 wells drilled through the salt formation in central Kansas and has resulted in localized surface subsidence and collapse. These cases are currently being investigated in an effort to identify the conditions necessary for the development of this type of circulation. Detailed theoretical analyses of the dissolutioning and salt transport mechanisms are also in progress to establish both the natural limits of the process and the best methods of intervention. The one obvious method of intervention would be to plug all nearby existing and any future holes in such a way that the properties of the natural formations are completely restored. Toward this end, a program for developing hole-plug materials of very high quality and durability, and techniques for their emplacement, has also been established.

Although there are no known cases of dissolutioning of the salt formations around boreholes in the Delaware Basin, the required conditions are not sufficiently well known (and probably never will be) to preclude the possibility for the long periods of time involved. Therefore, the site was especially selected for detailed investigation to be as remote as possible from all existing exploration holes. Furthermore, it is planned that, when a waste disposal facility is established, all future oil and gas exploration would be excluded in the area of that repository and would be restricted in a surrounding buffer zone perhaps as wide as two miles. These types of restrictions require a very careful selection of the repository site, taking into consideration the potential of any underlying undiscovered oil and gas deposits.

CONCLUSIONS

In this paper, the breadth and range of investigations that would be required in support of any proposal for radioactive waste disposal in geological formations have been illustrated by briefly describing some of the studies in progress on the bedded salt concept. Unfortunately, it was not possible at the same time to illustrate the depth to which each of these investigations is being carried. Furthermore, this use of real examples drawn from study of the southeastern New Mexico area tends to create the impression that there are many problems associated with the proposed use of salt formations for waste disposal and with the Delaware Basin area as a possible site. This is certainly not the case. Salt deposits offer numerous very important advantages over other rocks, and the more we learn of the southeastern New Mexico area, the more suitable this particular deposit appears.

ACKNOWLEDGMENT

This research was sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

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