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**RADIOACTIVE WASTE REPOSITORY PROJECT
ANNUAL PROGRESS REPORT FOR
PERIOD ENDING SEPTEMBER 30, 1972**

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OAK RIDGE NATIONAL LABORATORY

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RADIOACTIVE WASTE REPOSITORY PROJECT
ANNUAL PROGRESS REPORT
FOR PERIOD ENDING SEPTEMBER 30, 1972

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DECEMBER 1972

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SUMMARY

Introduction

Concerns about the long-term geologic stability of the salt formation at Lyons, Kansas, resulted in a search for an alternative site for the first radioactive waste repository and in a reassessment of the suitability of other geologic structures than salt for this purpose. We concluded that salt formations continue to offer the best prospects; thus, following experimental confirmation of the suitability of a site, construction of a pilot plant repository in salt is planned for the early 1980s. If the results of operating this pilot plant are uniformly favorable, the facility may eventually be converted into a fully operational, permanent repository.

This report summarizes the results of geological investigations at Lyons and the attendant investigations of alternative sites. Other topics included are: progress on the experimental phases of the program that are concerned with structural analyses of the geologic formation within which the repository may be located; studies of isotope transport by various mechanisms within the repository; considerations of the chemical and radiation effects near the buried wastes; calculations of the thermal conditions to be imposed as a consequence of waste burial; potential ecological effects; conceptual design studies of the pilot plant; and a description of the proposed pilot plant experimental program.

Geological Investigations

The geological investigations reported here were directed toward the following objectives: (1) confirmation of the suitability of the tentatively selected Lyons site, (2) demonstration of the long-term integrity of the containment provided by those salt deposits, (3) identification of suitable alternative sites within Kansas, (4) a more general evaluation of geological alternatives on a national scale, and (5) investigations of physical and mechanical properties of geologic formations vital to the natural containment of wastes.

Lyons Site Investigations. - The basic questions relating to geologic suitability of the Lyons site concern (1) the effect of boreholes and potential dissolution around them, (2) the influence of previous hydraulic mining activities in the area, and (3) the effect of possible future climatic variations.

To date there are five reported instances of salt dissolution and subsequent subsidence of land around boreholes in central Kansas. In all cases, abandoned oil wells serve as conduits carrying fresh water from

shallow aquifers downward into the salt where dissolution occurs. The resulting brine then migrates to a deeper permeable zone below the salt.

Laboratory investigations and mathematical models have been utilized (1) for calculating the rates of salt removal, (2) determining the shapes of ensuing cavities around boreholes, and (3) defining the mechanism of salt transport in boreholes.

Methods and materials for plugging of boreholes have also been studied. The critical factors to be tested in plugging cements are permeability, durability, and the bond between the formation and cement.

Excavations in the salt deposits in the vicinity of the tentatively proposed repository were studied to determine what effect they might have on the integrity of the formation. The nearby American Salt Corporation's underground workings consist of mechanically mined openings in the rock salt deposit as well as solution-mined cavities. The solution or hydraulic mining operations, which consist generally of pumping fresh water into wells that penetrate the salt formation and withdrawing the ensuing brine, extend over an area of about 140 acres and are situated approximately 3 miles south of the proposed location of the high-level portion of the proposed federal repository. It is estimated that only 5 to 7% of the salt has been removed from the area. Furthermore, cavity closure and the resulting land subsidence within the area are expected to proceed at a very slow rate. In an attempt to enhance the removal of salt within the solution extraction area, two wells, 600 ft apart, were connected by hydraulic fracturing. The test was terminated when input fluids were found to greatly exceed fluid recoveries. Although the exact disposition of the unrecoverable fluids is unknown, tests showed that the fractures in the vicinity of the injection and recovery wells were subsequently healed, and that the test apparently did not cause significant changes in the impermeable nature of the salt deposit.

The mechanical mine of the American Salt Corporation extends over an area of about 375 acres and has been developed at the same stratigraphic level as the nearby abandoned Carey mine. Deformation of the rocks in and above the two mines is expected to continue at a very slow rate without the development of throughgoing fractures and faults.

Recently, an apparent plugged oil and gas test borehole of unknown origin was encountered unexpectedly along a working face in the extreme western part of the mine. Since fluids only seeped from it for a short period of time after it was encountered, it is undoubtedly not presently connected with overlying or underlying ground-water aquifers. Furthermore, in the event that the American mine should be inundated with water from this hole or any other perturbation, the underground workings at the proposed repository would remain dry since a 1500-ft-wide barrier of undisturbed rock salt separates the American and Carey mines. Finally, by plugging all boreholes within the American mine area, any intruding waters would stagnate and extensive cavity growth would be precluded.

Climatic variations represent a possible threat to the future integrity of the disposal formation. For example, an ice sheet entering central Kansas in the future would flex the crustal rocks upward a few meters as it approached and would depress the crust by approximately 50 m if the site were overridden by the ice mass. Compressional, tensional, and shear stresses would be introduced into the sedimentary strata. Comparison of estimated stresses with estimated strengths in the bedrock overlying the proposed repository indicates that the approach or overriding of an ice sheet would not cause deep fracturing of the strata; nor should stresses introduced into the bedrock by the glacial loading lead to flowage of the salt.

Alternative Site Reconnaissance in Kansas. - The initial phase of the investigation of Kansas salt deposits for alternative sites was a screening survey performed by the State Geological Survey of Kansas. Eight county-sized areas were evaluated on the basis of (1) geology and hydrology; (2) population centers and densities, transportation facilities, and other cultural features; (3) location and status of oil and gas wells and estimates of potential for future development; and (4) the characteristics of the salt formation inferred from electric logs. Based on the information collected in this study, the eight sites were ranked in order of suitability.

During the latter part of FY 1972, a reconnaissance survey was made of three potential waste repository sites based on the recommendations of the screening survey. In general, the investigations at each of the sites consisted of field surveys to confirm local topographic surface geologic and cultural features and the studies associated with the core hole drilled at each site. These studies were: (1) stratigraphic, using geophysical logs, cuttings analyses, and rig information; (2) hydrologic, based on packer testing within the holes; and (3) lithologic, based on examination of the cores obtained from the salt during drilling. The results of these investigations led to the rejection of one of the sites because of complications from high clay content, lack of lateral continuity of units, and suspected hydrologic problems. The other two investigated sites are suitable for further considerations, although the overall thickness of the salt is not as great as would be desired.

Geological Alternatives Study. - Additional geologic environments were considered as alternatives to the Kansas sites, and preliminary information was accumulated.

Within the Gulf Coast salt-dome province, there are approximately 263 onshore domes. All but 36 of these can be eliminated on the basis of various considerations. Adequate data for evaluation exists for only 4 of the 36 shallow, unused domes.

The Paradox basin contains a series of salt anticlines aligned in a northwest-southeast direction. Flowage is responsible for thickening of the salt in the anticlines; occasionally salt is intrusive through the overlying sediments. Salt has been dissolved from the crests of piercement anticlines.

The Permian salt basin has been relatively stable since Permian time, but shallow salt has been subject to dissolution — as evidenced by some karst development. In the southeastern New Mexico portion of the Permian basin, thick and pure beds of halite exist at the appropriate depth. This is the most promising area among those considered. Potential problems seem to be related to the oil potential of the area and to salt dissolution.

The Supai salt basin is a small area of Permian evaporites on the Colorado Plateau. The principal halite deposits occur as discontinuous units between a limestone below and the overlying Coconino sandstone; this is the principal aquifer of the region, and it is responsible for solution collapse features in the southwest part of the basin.

The Luke salt body in the Basin and Range Province is an irregularly shaped salt mass of late Cenozoic age. It consists of at least 15 cubic miles of halite with shale interbeds underlying an anhydrite cap rock. Ground water in the vicinity is highly saline, indicating some dissolution.

Evaporites of the Salina formation underlie a large area of the Michigan and Appalachian basins and consist of extensive salt deposits at relatively shallow depths in western New York, northwestern Ohio, and the southeast and northern parts of the southern peninsula of Michigan. Strata both above and below the salt are occasionally waterbearing; however, in many areas, the salt beds are overlain by massive anhydrite and dolomite units or shales which are potential hydraulic barriers.

The Williston basin in the north-central plains contains evaporite beds at considerable depths, from 4000 to 12,000 ft below the surface. Local dissolution has taken place in the past, and large-scale removal of salt is thought to be occurring in the Canadian portion of the basin at present.

Argillaceous formations are widely distributed in the United States. Desirable features of some argillaceous sediments are high plasticity, high ion-exchange capacity, and extremely low permeability. A problem related to argillaceous formations is the possible generation of abnormal pore pressures by heating.

Three specific sites — the Gager mine in Tennessee, the Barberton mine in Ohio, and the Demopolis cavern in Alabama — are located in calcareous formations. The first one contains some water; the other two are dry, but the potential permeability of the formation, if fractured, is a serious problem.

Natural Containment Studies. — The natural containment of wastes is dependent on physical and mechanical properties of the geologic formations in the vicinity of the disposal horizon.

A method for measuring thermal conductivity and thermal diffusivity of core samples is being developed, and the required apparatus is being

fabricated. A transient-state plane probe and the required computer program are essentially ready for testing.

The mineralogy and possible dewatering mechanisms in all zones that may experience increased temperatures as the result of waste disposal operations require investigation. Multiple tests have been performed on shale samples from formations overlying the Hutchinson salt member in Kansas. On the basis of these analyses, the quantitative chemical composition and mineralogical composition have been defined. The quantitative mineralogical composition is obtained by means of a computer technique, currently under development, which utilizes a major elements chemical analysis and a semiquantitative mineralogical analysis as input.

Experimental work on evaporites has involved mineralogical determinations from thin sections, x-ray analyses for determination of bulk mineral assemblages, and thermal analyses to define the dewatering characteristics of gypsum and whole rock samples. Results of x-ray analyses indicate that gypsum disappears as a major phase at a depth between 600 and 800 ft. From static heating tests, it can be concluded that gypsum dehydrates rapidly at $102 \pm 3^\circ\text{C}$ at a pressure of 1 atm, more slowly at lower temperatures, and is probably stable at 60°C . The rate of dehydration is, in general, inversely proportional to particle size. In whole rock samples, weight losses decrease with depth, with samples from about 750 ft containing from 5 to 20 wt % water.

Occasionally, water pressures in pores of rocks are higher than hydrostatic. This usually happens in thick sedimentary sequences of Cenozoic age with abundant clay beds. The generally accepted explanation is the progressive loading of water-saturated sediments sealed by very impermeable layers. As the trapped fluids cannot escape, their pressure is increased, and consolidation of the sediments is prevented.

Additional mechanisms, for example, the diagenesis of argillaceous sediments with transformation of smectite to illite and mixed layer clay minerals, have been proposed as causes of abnormal pore pressures. However, at the present time, there is insufficient evidence to determine whether the dewatering of smectite minerals is actually a significant cause of abnormal pore pressures.

Two types of analyses are being carried out to provide an estimate of the magnitude of rock deformation in the strata surrounding the repository. The semiempirical analysis, a computer model simulating in three dimensions the mechanical behavior of the strata and waste through time, yields general outlines and shapes of total deformations and identifies areas where severe conditions may develop. The finite-element model provides details of displacements and strains in areas of interest. Laboratory determinations are made of rock properties (compression and tensile strength, steady-state creep, and static elastic properties) as input to the thermal elastic-plastic and viscoelastic finite-element models. The elastic-plastic analysis has been aimed toward evaluation of variations in values of the elasticity moduli and the tensile and

compressive strengths of rocks with regard to stress behavior for short time periods. A coarse-mesh model has been satisfactory for displacement calculations, but a refined mesh is needed for stress analyses. The visco-elastic analysis has been utilized for evaluation of variations in values of the creep parameter, both transient and steady state, with regard to deformational behavior over long time periods.

Operational Safety

Isotope Migration. - Results of investigations of the transport of water vapor through crushed salt beds indicate little or no alteration of the bed in instances where condensation does not occur, but significant modification of the gas transport characteristics of the bed, including plugging, in regions about and above areas of condensation. While not investigated, effects of hole closure on a crushed salt column contained within a hole in a bedded salt formation are expected to alter the observed behavior of water vapor transport appreciably.

A search of the literature for data concerning the establishment of flammability limits for hydrogen-air mixtures in unconsolidated porous media, such as beds of crushed salt, has yielded no information having direct application. However, if several reasonable approximations are made, it appears that the use of crushed salt backfill of suitable size characteristics would completely exclude the possibility of hydrogen-air explosions. On the other hand, conclusions regarding flammability limits in backfill comprised of very coarse, as-mined crushed salt cannot be established on the basis of currently available data.

Surface diffusion studies of La_2O_3 on polished NaCl surfaces indicate that the mechanism proceeds only on the submonolayer scale and, at 420°C , is characterized by a diffusion coefficient of about $3 \times 10^{-10} \text{ cm}^2/\text{sec}$.

A series of experiments designed for studying the conditions to which solid wastes containing fission products or actinides would be subjected during exposure to crushed salt backfill is being performed. In the initial experiments, waste containing ^{137}Cs , ^{106}Ru , or plutonium was placed at about the midplane of a column of crushed salt. The transport of isotopes up or down a given column is monitored by scanning each column at about 1-month intervals. The columns containing ^{137}Cs and ^{106}Ru are held at 340°C , while the column containing plutonium (which is now being dismantled) was maintained at ambient temperatures. The results show that, after about 6 months of exposure, no transport of cesium, ruthenium, or plutonium has occurred.

Radiation Effects. - We analyzed experimental and theoretical information on radiation damage and energy storage in oxides and silicates, and concluded that any energy storage in typical calcined waste oxides and glassy solids will result predominantly from displacements or "spikes" caused by elastic collisions of the heavy recoiling nuclei that are formed in the alpha-disintegration of the transuranic elements within the wastes.

Energy storage in the radioactive wastes is likely to be less than 200 cal/g, but the possibility that it will be higher in some systems cannot be excluded. Temperatures greater than 1000°C may be needed to effect the release of all stored energy from some wastes. The release will not be spontaneous unless there is a stepwise increase in temperature to a high level at which rapid release is initiated. Radiation damage in radioactive wastes can be investigated experimentally with synthetic wastes, using fast-neutron irradiation under conditions which can be achieved in the Oak Ridge Research Reactor.

We designed and constructed a Roux-type drop (to high temperature) calorimeter for use in our experimental work with synthetic wastes. The accuracy and the sample size requirements of this device at the high temperatures (~1000°C) that may be required with the wastes are being investigated in calibration runs. Results to date indicate that the calorimeter will be satisfactory for measurements at 1000 to 1200°C with samples weighing about 100 mg. It should be possible to determine the stored energy with an accuracy greater than ± 1 cal/g, which will be adequate for our needs.

We initiated a program of experimental studies aimed at establishing the amounts of stored energy in rock salt under repository conditions (maximum gamma-ray doses and intensities of $\sim 2 \times 10^{11}$ rads and $\sim 5 \times 10^5$ rads/hr at temperatures ranging up to about 330°C). We have designed and are constructing equipment for making experimental gamma irradiations of salt within the target region of spent HFIR fuel elements. Using the drop calorimeter at 500°C, we determined the stored energy in samples of synthetic crystals of NaCl which had been gamma-irradiated to 1.5×10^{10} rads at 10^7 rads/hr and at 95°C. Our average value of 14.6 cal/g exceeded, by factors of 1.7 to 2, those reported by other investigators who used heat-of-solution calorimeters. It is also much higher than the values, approximately 1 cal/g, previously reported by Sonder and Lindenbaum for synthetic salt crystals that had been irradiated at $\leq 80^\circ\text{C}$ to comparable doses, but at higher dose rates ($> 10^9$ rads/hr), with van de Graaff electrons. The explanation for the latter discrepancy remains to be established. However, it is conceivable that a dose-rate effect exists, in which migration and clustering of defects into relatively stable aggregates (colloids) become important at the longer exposure times prevailing at the lower dose rates. The difference between the results of the two calorimetric methods can be reasonably explained by assuming that aqueous dissolution of radiation defects in NaCl results in the formation of certain species in addition to Na^+ and Cl^- . The heat of formation of these is less than that of Na^+ plus Cl^- so that some of the energy associated with the defects is not measured in a heat-of-solution measurement. The possible products of the dissolution of the radiation defects which are consistent with available information include H_2 , ClO_3^- , and H_2O_2 .

Two different samples of brine from the Lyons salt were analyzed for Na, Mg, and Ca by emission spectroscopy. The results were in agreement within the precision of the analytical method, $\pm 5\%$. Also, these results

were consistent with information on the solubility of NaCl in solutions of MgCl_2 and with previous information on the composition of brine inclusions in a mine at Hutchinson, Kansas. However, it is notable that the magnesium concentration is 2.1 M rather than the maximum of 3 M, which we previously estimated. Accordingly, the maximum rate of formation of HCl from the hydrolysis of MgCl_2 is about two-thirds of the previous value. Several experiments were made on Lyons salt to obtain estimates of the pressure of gas within the gas-phase bubble, which is generally part of a brine inclusion. These experiments consisted of tapping an inclusion with a 20-mil drill and observing the effects on the behavior of the gas bubble. We concluded that the gas pressure within a cavity is 1 atm or less. Also, we concluded that the maximum concentration of air within the brine will be about 0.002 M, and accordingly, that the effects of this air on radiolysis will be negligible relative to the concentrations of radiolytic products (>0.01 M at the least) with which we are likely to be concerned.

It is necessary to establish the combined effects of the thermal and nuclear environment on the materials surrounding the waste containers. We have completed measurements of the thermal conductivity, λ , of both "fine" and "medium" salt powders in a radial heat flow apparatus. The results showed that λ is sensitive to the gas phase and to imposed stresses. This latter effect will be further investigated in a not-press apparatus to determine the time-temperature-pressure dependence of λ as salt powder is restructured. Another experimental program will determine the effects of dose, dose rate, and temperature on the λ of solid salt.

We employed an instrumented probe in a salt block to simulate the short-time behavior of a waste can in the repository as the hole is back-filled. From a reference temperature of 500°C in air, the waste container will experience a temperature rise to about 560°C in an empty hole, decreasing to about 260°C after the salt powder is added. If a molten salt eutectic mixture is poured around the container, the container experiences a momentary rise to about 560°C and then a rapid decrease to about 210°C .

Thermal Analyses. - Parametric studies of the high-level facility were conducted for a 1000-ft depth and the stratigraphy at the Lyons site, with room and pillar width, waste container array and spacing, and waste age and composition as variables. Preceding this effort, thermal conductivity--temperature dependence was included in the three-dimensional conduction code, and criteria associated with limiting temperatures were modified to achieve greater consistency. Room widths of 15 to 50 ft and corresponding pillar widths of 25 to 50 ft were considered. The results of the analysis indicate a preference for the 18-ft-room, 30-ft-pillar combination (smallest permissible based on other considerations) because of a significantly higher maximum permissible net loading surface density. The corresponding gross loading surface density for 10-year-old waste is about 6 metric tons of waste nuclides per acre (158 kW/acre). The permissible power per waste package is dependent on the age and thermal properties of the waste, the diameter of the container, the time dependence of the backfill thermal properties, and handling considerations. A reasonable upper limit appears to be 5 kW for 10-year-old waste.

A parametric analysis for a 2000-ft depth and a stratigraphy representative of southeast New Mexico was initiated. An 18-ft-room, 60-ft-pillar combination with 10-year-old waste has thus far been considered. The maximum permissible gross and net surface densities are about 8% lower and 50% higher, respectively, than corresponding values for the 18-ft-room, 30-ft-pillar combination at a depth of 1000 ft.

Numerous other miscellaneous calculations were made, all of which tend to substantiate the technical feasibility of the high-level waste repository.

Conceptual Design Studies

Following the completion of a draft conceptual design report for a repository located at Lyons, Kansas, a decision was made to withhold temporarily the selection of a site and pursue the conceptual design of a pilot plant repository (PPR). The objectives of the PPR are to resolve major concerns with regard to long-term storage of wastes in geologic formations by in-situ demonstration and to develop design and operating information applicable to the design of a full-scale repository. The PPR is assumed to have a life of 10 to 15 years, and the estimated number of waste packages to be buried (all in sleeved holes) in the salt formation is about 400.

The PPR will include all facilities necessary to handle safely waste casks and packages, lower the packages into the mine, and dispose of them in sleeved burial holes. These facilities will include a waste receiving building and waste shaft; a man-and-material and salt hoisting shaft; an up-cast ventilation shaft and mine exhaust filter station; mine-level support, service, and maintenance facilities as required; minimal surface-level salt loading facilities; a mine operations and administration building; and minimal surface-level support facilities. The tentative schedule includes a conceptual design study to be completed in March 1975, based on a site in southeastern New Mexico, and design and construction of the PPR to be completed during the early 1980s.

The development of a connector for use in remote handling of waste containers is under way. A prototype has been fabricated and successfully strength-tested. A conceptual study of waste package retrieval from both bare salt and sleeved holes has been completed. A desk study of candidate materials for use as sleeves in the PPR burial concept has been made; experimental testing of one or more of these materials is planned.

Pilot Plant Experimental Program

The pilot plant will be operated to achieve two goals: to demonstrate the ability to transport and handle high-level waste at a salt-mine repository without mishap, and to confirm various technical aspects bearing directly on the operational and long-term safety of the burial scheme.

Only enough waste need be buried to accomplish these goals; however, all of this waste must be readily retrievable.

We estimate that approximately 100 waste packages will be adequate to demonstrate the transportation and handling aspects, and that an additional 200 to 300 packages will be required for specific experiments. All but 10 to 20 of these packages will be doubly contained and placed in sleeved holes in the salt to facilitate rapid and positive retrieval. The remaining packages will be buried directly in the salt without the secondary container or the sleeve; and, in some cases, the primary container will be intentionally breached to allow early contact between the waste and the crushed salt backfill. A specially developed overcoring device will be available for retrieval of the waste packages buried directly in the salt.

The specific experimental programs, in addition to the transportation-handling phase, will cover the areas of heat removal, formation and release of explosive and noxious gases, radioactive nuclide transport, and rock mechanics. The duration of these experiments is expected to be in the range of 5 to 15 years.

1. INTRODUCTION

J. O. Blomeke

As a direct consequence of the favorable outcome of nearly 15 years of laboratory and field experiments performed by ORNL in the investigation of bedded salt formations as a repository for high-level wastes, the AEC announced in June 1970 the tentative selection of the Carey Salt Company mine at Lyons, Kansas, as the site for the first federal repository for solid radioactive wastes. The selection was "tentative" because it was contingent on the outcome of additional work, mostly of a geologic nature, that was required to confirm the suitability of that particular site.

The subsequent geologic investigations revealed two problem areas, both of which have bearing on the long-term geologic integrity of the proposed Lyons site and are related to man's recent activities in that area. These problem areas were concerned with (1) dissolution of the salt formation by ground water flowing down abandoned, improperly plugged oil and gas wells into permeable aquifers underlying the salt; and (2) the past, present, and future operations of the nearby American Salt Corporation, which include hydraulic as well as mechanical mining of the salt for commercial purposes. Although our ongoing investigations gave promise that these concerns could be successfully resolved from a technical point of view, a rather formidable array of public officials, including the Governor and many members of the Kansas congressional delegation and the State Assembly, took positions opposing the use of the Lyons site. The residents of Lyons, who had previous exposure to this program during the course of the field experiments carried out there by ORNL during the 1960s, staunchly supported us. Nevertheless, it became apparent that a search for alternative sites in salt both within and outside Kansas should be implemented. The AEC also asked us for a new assessment of possible repository sites in geologic structures other than salt.

In the meantime, the AEC announced a three-pronged approach to resolving the problem of high-level waste management. First, the Atlantic Richfield Hanford Company (ARHCO) has been asked to design surface storage

facilities for construction at a site yet to be selected. These facilities will be adequate to store the high-level wastes produced by industry until a completely acceptable method for their permanent storage or disposal can be fully demonstrated. Second, ORNL has been asked to continue the work on salt with the objective of obtaining all the supplementary information and experience that are needed to verify its suitability. Finally, the Pacific Northwest Laboratory (PNL) has been asked to reassess all current and near-future possibilities for the permanent storage or disposal of high-level wastes. Cooperative programs in investigative areas of mutual interest have been established with ARHCO and PNL.

We plan to have the necessary information available to make a firm recommendation to the AEC for acquisition of a specific site for a salt-mine repository, regardless of whether it is at Lyons or elsewhere, early in 1974. We also expect to have prepared, by June 1975, a conceptual design, an Environmental Impact Statement, and a safety analysis of a facility that will be constructed in the early 1980s and will be operated initially as a pilot plant. During the pilot plant operations, all radioactive wastes will be emplaced and maintained in a fully retrievable condition while confirmatory information bearing on both operational safety and long-term geologic containment is accrued. We envision that the results obtained from the pilot plant experience will permit this facility to be eventually converted into a fully operational, permanent repository.

The status of the aforementioned geological investigations of the Lyons site, including alternative sites in Kansas and other areas throughout the United States, is presented in Sect. 2 of this report. Measurements of physical and mineralogical properties of rocks from the Lyons site and descriptions of the calculational models that are being constructed to analyze the effects of stresses and temperatures in the overburden of a repository are also presented in Sect. 2.

In addition to the geological and rock mechanics investigations, a substantial effort is being made on a variety of other tasks concerned with the design and operational safety of the repository. Investigations of the tendency of radioisotopes in the wastes to move through crushed and

solid salt are described in Sect. 3.1. The results of investigations, both experimental and theoretical in nature, on the effects of radiation and elevated temperatures on the salt in the immediate vicinity of the buried wastes, as well as on stored energy within the wastes themselves under storage conditions, are presented in Sect. 3.2. The detailed calculations of the thermal conditions to be imposed on a repository and its immediate environs as a consequence of radioactive decay heat from the wastes are summarized in Sect. 3.3, and studies of possible ecological effects of repository operation are discussed in Sect. 3.4. Sections 4 and 5 are devoted to conceptual design studies of the pilot plant repository and to a description of the proposed pilot plant experimental program, respectively.

2. GEOLOGICAL INVESTIGATIONS

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At the beginning of the period covered by this progress report, the various geologic investigations in progress were directed toward two basic objectives: (1) confirming the suitability of the tentatively selected Lyons site, and (2) performing analyses and evaluations required to demonstrate the long-term integrity of the containment provided by the salt deposits in that area. Early in the period, the confirmation studies highlighted two aspects of the site which seemed to cast some doubt on its suitability: (1) the proximity of the American Salt Corporation's operations, especially their hydraulic mining activities, and (2) the number of oil-and-gas test wells drilled on and adjacent to the site. These problems and the various investigations associated with them are described in Sect. 2.1.

Because of these problems, the effort in the geologic investigations was largely reoriented toward the identification of suitable alternative sites. The examination of potentially suitable areas in Kansas, which was carried out with the assistance of the Kansas Geological Survey and private consultants, is discussed in Sect. 2.2. In addition, a broadly based investigation of geological alternatives to the Kansas salt deposits was completed. The U.S. Geological Survey and various consultants participated in this study, the results of which are summarized in Sect. 2.3.

During this report period, all of the Lyons site confirmation studies not directly related to the salient problems were suspended, as were those related to natural containment analyses and evaluations that were specific to the Lyons site. The remaining analyses were broadened and generalized to be applicable to any site. The progress on the latter studies is reported in Sect. 2.4.

2.1 Lyons Site Investigations

The initial objectives of the site investigations at Lyons were:
(1) to confirm the suitability of the tentatively selected site, and

(2) to evaluate the long-term integrity of the containment provided by the salt in the area. Two fundamental questions raised during these investigations were concerned with: (1) the influence of previous hydraulic mining activities in the area, and (2) the effect of boreholes and potential dissolution around them on the integrity of the salt. A more general question regarding long-term containment involves the potential effects of erosion and possible climatic variations in the future.

Rock salt deposits occur as discrete beds in sedimentary basins and are usually associated with other sedimentary rock types (e.g., shale, mudstone, carbonates, and coal). Generally the salt beds are underlain by thick accumulations of these other sedimentary rocks which possess varying potential for oil and gas development. Since the drilling of boreholes is essentially the only technique available for securing detailed information on the stratigraphy at any location, a given site considered for a radioactive waste repository may be expected to contain several penetrations. In an area of active petroleum exploration, the salt is frequently punctured by a large number of oil and gas test holes. Since these borings may serve to connect any or all of the rock formations penetrated in drilling and to provide a conduit for fluids contained in the strata, their nature and occurrence are of special concern in the establishment of a radioactive waste repository.

There is little doubt that oil and gas borings can provide the framework for creation of subsurface solution cavities and hence instabilities in salt deposits where unique conditions prevail. There are several documented cases of such solutioning accompanied by surface subsidence within the central Kansas portion of the Permian basin.

To assess the effects of penetrating boreholes on the integrity and stability of bedded salt deposits, investigations have been initiated to determine and define the natural (geologic and hydrologic) and imposed (boreholes) conditions fostering dissolution and to develop mathematical models for predicting the rates and nature of cavity formation over a range of expected field conditions. In addition, work has commenced on

the development of materials and procedures for permanently plugging any boreholes that, if neglected, might eventually promote dangerous instabilities in the salt. The results of this investigative program are expected to permit the establishment of optimum land and mineral control limits for the pilot plant repository and to provide reasonable assurance that containment of the wastes will not be jeopardized by dissolution of the salt around boreholes. Summaries of the progress made during the year on the principal work areas of this program are given in Sect. 2.1.1.

In order to prevent the dispersion and/or migration of radioactive waste after emplacement in salt, it is essential that the waste remain isolated from circulating ground water. All underground cavities excavated in rock salt formations can fill with ground water through improperly sealed shafts, boreholes, and other openings. Thus, as part of the safety evaluation program for the utilization of the proposed Lyons site, an assessment of the underground mining operations of the American Salt Corporation was made. The implications of these workings on the proposed repository are discussed in Sect. 2.1.2.

Since a portion of the radioactive wastes to be placed in the pilot plant repository must remain isolated from the biosphere for hundreds of thousands of years, estimates are needed of the erosion potential by stream action and glaciation and the effects of these processes on the stability of the underlying salt formation for long periods of geologic time. A study has been made of the probabilities of rates of erosion and loading by glacial ice in central Kansas; and, although the work has special significance for that area, the findings have general application throughout most of the stable mid-continent area of the United States. The results of a portion of this work are presented in Sect. 2.1.3.

2.1.1 Borehole Dissolution and Plugging

Dissolution of Salt and Land Subsidence Around Boreholes in Central Kansas (T. F. Lomenick). - To date, five instances of salt dissolution and subsequent surface subsidence around boreholes have been reported in the central Kansas portion of the Permian basin. The most extensively investigated one is located in Russell County, approximately 55 miles northwest of Lyons. This sink, which includes a portion of

U.S. Interstate Highway 70, was consequently investigated by the Kansas State Highway Department. According to their report, the land surface has subsided at the rate of about 0.7 ft./year and, since 1954 (when the depression originated), has developed into a cavity spreading over an area of some 700 to 800 ft in diameter with a maximum depth of about 20 ft.¹ Exploratory drill holes into the sinkhole have revealed that extensive dissolution has occurred in the upper part of the salt bed with subsequent collapse of the overlying Permian and Cretaceous age beds. Apparently, the sinkhole developed around a single oil well that was first completed in 1936 and later converted to a salt-water disposal well. Records of the hole indicate casing deterioration in the salt zone and dissolution before abandonment. The prolific water-bearing Cretaceous sandstone above the salt and the permeable production and/or disposal beds below the salt are the principal geohydrologic parameters governing dissolution at the well. In 1957 a second sinkhole developed, about 1/2 mile west of the aforementioned one. It, too, progressed from dissolution of the salt around an abandoned oil well, which was reported to have casing deterioration in the salt zone. As was the case for the nearby sink, a fresh-water aquifer exists above the salt and a disposal aquifer below the salt at the well site.

Sinkholes in Barton County and Rice County are associated with dissolution in the salt around oil wells that were later converted to brine disposal wells and then abandoned. As is the case for all of these features, the borings serve as a conduit for the overlying fresh waters to migrate downward where they contact the soluble rock salt; the resulting brine then migrates to a deeper permeable zone below the salt.

Mathematical Modeling and Laboratory Investigations of Dissolution of Rock Salt Around Boreholes (T. N. Dixon*). — An existing mathematical model, developed for use in solution mining research studies, has been modified for calculating the rates of salt removal and the shapes of the ensuing cavities around boreholes. Simulated injections of 5 to 500 gpm for salt bed thicknesses of 200 and 400 ft have been investigated using this model. In general, the results indicate that initially most of the salt removed will come from the uppermost beds of the salt formation and that, even at the low rates of influx of water, a "morning glory" effect

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will be developed. With a flow rate of 5 gpm, the cavity shape after about 1 year (or when the bulk fluid in the cavity becomes saturated) is calculated to be as follows:

<u>Distance from Top of Salt Formation (ft)</u>	<u>Diameter of Cavity (ft)</u>
1	86
3	35
5	24
10	13
20	7
40	4
80	2
120	1
160	1
200	1

Using a 500-gpm rate it was found that, after a period of 128 months, the cavity diameter at the top would be 2970 ft and the concentration of fluid in the cavity only 75 to 80% of saturation. Thus, with high rates of water inflow, extensive dissolution would be expected to occur laterally in the upper part of the salt formation. Further modifications in the model are being made to calculate cavity shape and sizes after near-saturation of the bulk liquid in the cavity occurs.

In the case of boreholes that penetrate underlying aquifers having potentiometric heads which rise into the salt beds, dissolution of the salt can occur without the inflow of waters from overlying aquifers. Experimental as well as mathematical simulation techniques have been employed to determine the mechanism of salt transport in such well bores. In laboratory tests, salt blocks and flasks of saturated salt water were connected to fresh-water reservoirs by small-diameter tubes. With tubing diameters of 10, 3 and 1 mm, it was found that the transfer of salt from the upper zones to the underlying fresh-water reservoir is largely through free convection. Further tests using smaller-capillary tubing are planned to determine the point at which free convection does not occur. In addition to the experimental work, a numerical model of the dissolution and transport process is being developed. The validity of this model will be determined by comparing the results obtained by using it with those obtained in actual experiments.

Plugging of Boreholes (F. M. Empson, T. Tamura). — To ensure protection of the salt from the action of water in aquifers above and below the salt bed, effective plugging of all penetrating boreholes is necessary. In the vicinity of Lyons, Kansas, this requires that fresh-water aquifers above and dilute brine aquifers below be prevented from coming in contact with the salt in any way. The plugging procedures used routinely for sealing exhausted or dry oil and gas wells are designed primarily to prevent (1) drainage of fresh-water aquifers down unplugged holes to lower aquifers, and (2) salt-water contamination of the fresh-water aquifers by brines from high-pressure aquifers moving upward. State regulatory bodies normally specify plugging procedures and must approve the actual placement of the plug.

Many types of hardware and techniques are available for placing cement and other materials in wells. They are used to seal off water-producing formations from oil and gas productions and to fix casing in place. However, the more sophisticated techniques are seldom used in making the required plug of dry or depleted wells. The normal practice is to place the minimum-cost plug that will be acceptable to the regulatory body. It is the opinion of most individuals knowledgeable in the field that such plugs are not very effective. If plugging operations are not properly carried out, the cement may fail to set completely and/or the plug may slip down the hole.

Discussions have been held with a number of individuals and organizations having experience in well plugging and cementing and/or in materials used in these operations, and a number of cements have been selected for laboratory testing. Two types of expanding cement were obtained from the Ideal Portland Cement Company; one of these was Type S expanding cement (Ada, Oklahoma), and the other was Type III Stress-Ex (Portland, Colorado). Standard portland cement (Type I) was obtained locally for comparison purposes.

The purpose of the first test series was to determine the water permeability of the selected cements when prepared according to the American Petroleum Institute Recommended Practice for Testing Oil-Well

Cements (API RP 10B, 12th Ed., 1963). A water-cement ratio of 0.46 was used in all preparations. The plugs were sealed in steel pipe, using epoxy, and the system was pressurized at 100 psi with nitrogen gas. Distilled water was used in these flow tests so that the eluate could be analyzed for calcium ion content, which serves as a measure of durability of the plug. The results obtained are given in Table 2.1. In two cases, the cement was substituted with 50% pozzolan (flyash from the Tennessee Valley Authority steam plant at Kingston, Tennessee) in order to observe the effect of this additive on permeability and durability.

The data show that both Type S and Type III cements are superior to standard Type I portland. The permeability after 5 or 7 days of curing is lower for the expanding cements. Type III Stress-Ex appears to be extremely impermeable; in three of four test runs, no water flowed through the plug after 24 hr at 100 psi. Data obtained from Core Laboratories, Incorporated (Dallas, Texas) on the permeability of several cores from Kansas show that the permeability of the formation is in the range of 0.3 to 0.1 millidarcy. Thus, plugs using expanding cements are less permeable than the formation.

The eluate was also analyzed for calcium ion concentration. When water continuously flows through set cement, it will gradually remove the lime and in time destroy the cement. Consequently, a low calcium dissolution rate is a desired characteristic. The calcium data in Table 2.1 further support the use of expanding cements for plugging. The pH of the eluate is lower for the expanding cement, which is additional confirmation that smaller quantities of calcium hydroxide are in solution.

Although the permeabilities of the cements are relatively low compared with the permeability of the formation, the formation-cement bond poses a problem in sealing open holes. It is common practice during drilling to use drilling muds to aid in the operation. These muds line the walls of the formation and will affect the bonding strength of the cement to the formation. The seriousness of the problem can be noted from the data in Table 2.2. All of the tests reported here, except No. 7, were conducted using Berea sandstone. The sandstone was used to reserve

Table 2.1. Permeability of Plugs, and Calcium Content and pH of Eluate,
from Various Cements After Curing in 20°C Water
for Indicated Time at Atmospheric Pressure
(Water-cement weight ratio = 0.46)

Cement	Curing Time (days)	Flow Rate (ml/min)	Permeability (millidarcy)	Calcium Content (meq/ml)	pH
Type I portland	5	0.256	0.85	0.0028	11.0
	7	0.035	0.11	0.006	11.4
	19	0.006	0.02	0.0079	12.2
Type I with 50% pozzolan	5	0.171	0.55	0.035	12.1
	7	0.47	1.54	0.003	11.2
	19	0.003	0.01	0.013	10.4
Type S expanding	5	0.032	0.10	0.0006	8.1
	7	0.027	0.08	0.0003	8.1
	19	<0.001	<0.003	0.0004	11.8
Type III	5	No flow for 24 hr			
Stress-Ex	7	0.01	0.02	0.0009	9.0
Type III with 50% pozzolan	5	No flow for 24 hr			
	7	No flow for 24 hr			

Table 2.2. Bonding Strengths of Type III Stress-Ex Cement Plugs to Formation
(Water-cement weight ratio = 0.46)

Test No.	Core	Core Condition	Pressure (lb/cm ² of surface)	Observation
1	Berea sandstone	Dry core	375	Formation broke before any extrusion.
3	Berea sandstone	Core prewetted	290	
4	Berea sandstone	Pretreated with native mud ^a	100	Formation broke, but plug partially extruded.
5A	Berea sandstone	Pretreated with chemical mud ^a	<10	Plug easily extruded.
5B	Berea sandstone	Chemical mud scraped off	290	Formation broke.
6A	Berea sandstone	Replicate of 5A	<10	Plug extruded.
6B	Berea sandstone	Replicate of 5B	345	Formation broke.
7A	Sandstone core from Kansas	Pretreated with chemical mud	<10	Extruded.
7B	Sandstone core from Kansas	Chemical mud scraped off	335	Formation broke.

^aNative mud is natural mud derived from the local formation and mixed with salt and water. Chemical mud consists of bentonite clay, starch, preservative, oil mixed with water, and salt.

the limited supply of cores from the Kansas site for testing after the technique had been perfected.

Cores of Berea sandstone were drilled to provide holes 3 cm in diameter. The cement plugs were made using Type III Stress-Ex cement at a water-cement weight ratio of 0.46. The water-cement slurries were poured into the holes and allowed to set for 24 hr in a 100% relative humidity chamber. Then the plugged core was placed in a Carver press equipped with a plunger, and pressure was applied. Plugs that were set in cores without any mud treatment bonded well to the surface. The bond strength is given in terms of pressure applied per square centimeter of plug-formation contact surface. About 300 lb/cm^2 was required to cause failure. In each case, the formation broke before the plug extruded when no mud was used.

When native mud (test 4) was used to coat the walls, the formation broke at 100 lb/cm^2 after about 20% of the plug had extruded. On the other hand, the plugs were easily extruded when chemical mud was used (tests 5A, 6A, 7A); the pressure required was less than 10 lb/cm^2 . The extruded plugs showed a layer of mud forming a skin around the plug. In each case, the mud remaining in the core was scraped with a wire brush; then the core was replugged. Subsequently, the plugs bonded strongly to the formation (tests 5B, 6B, 7B). The weak bonding between the plug and the formation coated with the muds suggests that, in field situations, pretreatment will be required to remove the mud prior to cementing. Techniques that have been mentioned for improving bonding include: (1) plugging under turbulent slurry flow conditions; (2) using a washing fluid or mud to displace troublesome mud prior to cementing; (3) adding mud-kill agents to the cement slurry; (4) using latex cements and non-portland cement, such as Dowell Dexet, which can tolerate muds; and (5) mechanical scratching. Applicability of one or several of these techniques will be explored since most holes are drilled with some addition of mud.

2.1.2 Implications of the American Salt Corporation's Underground Workings on the Proposed Federal Waste Repository at Lyons, Kansas (T. F. Lomenick)

The proposed site in Kansas for a federal waste repository is located northeast of Lyons, in Rice County. Figure 2.1 is a map of the area showing the location of the facility with respect to the City of Lyons and to the underground workings of the American Salt Corporation. In general, the initial plans for operation of the facility were to utilize a portion of the abandoned Carey mine for burial of the alpha-contaminated or low-level waste, while specially excavated space would be developed in the salt formation northeast of the existing mine for burial of high-level, beta-gamma waste. In Fig. 2.1 it is seen that the shaft to the American mechanical mine is about 2 miles south of the existing shaft to the Carey mine. During the 1930s and 1940s, an effort was made to connect the two mines by extending the Carey workings southward and the American mining northward; however, with the cessation of operations at the Carey mine in the late 1940s, the project was abandoned. At this time the two extensions were still approximately $1/4$ mile apart. The American Salt Corporation's hydraulic or solution mining operations are located to the south of the mining area, where a $1/2$ -mile-wide strip of undisturbed and unmined salt is preserved between them and American's mechanical workings (Fig. 2.1). The solution mining operations generally consist of pumping fresh water into wells that penetrate the salt formation and withdrawing the resulting brine. To increase the efficiency of these operations, hydraulic fracturing was used in 1965 in an attempt to establish circulation underground between two brine wells located about 600 ft apart. This single test, which proved to be unsuccessful, was conducted in the extreme southeastern part of the area about 3 miles south of the proposed location of the high-level part of the waste facility (Fig. 2.1).

Solution Mining. - According to Vincent,² the Lyons Salt Company was organized in 1911 and a salt plant was erected apparently near the present-day location of the American plant, approximately 1 mile south of Lyons. After a few years of operation, the ownership of the Lyons Salt Company was transferred to the American Salt and Coal Company, which had general offices in Kansas City, Missouri. The plant has continued to operate

Fig. 2.1. Map of a Proposed Waste Repository Area, Showing Its Location with Respect to the City of Lyons, the American Salt Corporation's Underground Workings, and Nearby Oil and Gas Fields.

under an abbreviated form of this company's name (i.e., the American Salt Corporation), even though that organization became a part of the Cudahy Company in 1928 and Cudahy later (1971) merged with the General Host Company.

Brine wells have been used for mining salt at the plant since the beginning of operation. A sketch (redrawn from an earlier one presented by the American Salt and Coal Company) depicting solution as well as mechanical mining is shown in Fig. 2.2. In solution or hydraulic mining, water is pumped down the wells through an inner casing that extends to near the bottom of the salt formation. The circulating water dissolves the salt, and the saturated brine is brought to the surface through the annulus between the inner casing and the outer one (which generally extends only to the top of the salt deposit). This method of mining at the American Salt Corporation has not changed appreciably from the early years of operation, although improvements have been made in such techniques as the drilling of the wells, pumping of fluids, and the emplacement of casing in the holes. Cement has been used to bond casing to the wall rock at the mine since the early 1940s.

Figure 2.3 is a map of the solution mining area showing the location of the brine wells. From the available data, it is not possible to estimate accurately the quantities of salt that have been removed from the areas surrounding each brine well, or even from the solution mining area as a whole. (Many wells were abandoned for indeterminate periods of time before being plugged, and some wells are known to be interconnected.) However, maximum or upper-level estimates of the quantities of salt removed from the area can be made indirectly by assuming that the plant operated at full capacity during its lifetime. This method of estimating indicates that only about 5 to 7% of the underlying salt has been removed from the area. The plant capacity was about 500 bbl/day (70 tons/day) for the period 1908-27.^{2,3} (Vincent² states that the plant was opened in 1911, while Otto Rueschhoff, current President of the American Salt Corporation, judges that the plant has operated since about 1908.³ In order to preclude underestimating the quantities of salt removed from the area, the earlier date for commencing operations was utilized.)

Fig. 2.2. Sketch Depicting Two Methods of Mining Salt at the American Salt Corporation, Lyons, Kansas. (Redrawn from an early photograph supplied by the American Salt and Coal Company in "Pit and Quarry," p. 32, July 29, 1931)

Fig. 2.3. Map of Solution Mining Area, American Salt Corporation, Lyons, Kansas. (Redrawn from map supplied to ORNL by the American Salt Corporation, December 1971)

Thus the area enclosing wells 1 through 5 (Fig. 2.3), which were drilled and operated during this 20-year period, could have produced as much as 5×10^5 tons of salt or a gross cavity space of $7 \times 10^6 \text{ ft}^3$. The thickness of the salt formation within the area averages about 275 ft, with salt comprising approximately 80% (or 220 ft) of the section and interbeds of shale and anhydrite the remaining 20% (or 55 ft). Therefore, the original quantity of salt in the 10.5-acre area surrounding wells 1 through 5 is estimated to be 7×10^6 tons, or $104 \times 10^6 \text{ ft}^3$. With the removal of $7 \times 10^6 \text{ ft}^3$ of the salt, the area now contains $97 \times 10^6 \text{ ft}^3$ of rock salt, or about 93% of the original mass.

In 1928, the installation of evaporator pans at the plant resulted in an increase in capacity to 250 tons/day.³ Subsequently, the plant capacity was increased to 450 tons/day in 1968, and is expected to be expanded to 1000 tons/day by 1973.³ The area enclosing wells 6 through 55 covers approximately 133 acres and originally contained about $1274 \times 10^6 \text{ ft}^3$ (or 86×10^6 tons) of salt. With a plant capacity of 250 tons/day for the period 1928-67 and 450 tons/day for the period 1968-71, as much as $59 \times 10^6 \text{ ft}^3$, or 4×10^6 tons (or ~5%) of the salt could have been removed from the area during that time.

For those areas in which the brine wells are still active, the quantities of salt removed from the formation can probably be estimated more accurately by assuming that production at the average rate of 18 gpm has continued uninterrupted since the wells were drilled. With this method of calculation, the amount of salt removed from the areas underlying the active wells totals about 3×10^6 tons ($44 \times 10^6 \text{ ft}^3$), or approximately 6% of the reserves of salt (50×10^6 tons or $741 \times 10^6 \text{ ft}^3$) within the same area. It is of interest that this extraction ratio is in the same range as the estimates, using the maximum plant capacity values.

The available data indicate that 5 to 7% of the salt underlying the solution mining area at the American Salt Corporation mine has been removed. The shape and extent of the cavity space developed by this method of mining cannot be established with the available data, especially in

the areas where the wells are interconnected; however, because of the single well injection and recovery system, it is concluded that most of the mined salt has been dissolved from the areas in and immediately surrounding the wells, leaving relatively undisturbed salt in the mid-regions between wells. The areas of undisturbed salt are undoubtedly greater between the more recent solutioning wells than between either the older ones or those where interconnecting passageways have developed.

The currently available data make it difficult to confidently predict the subsidence patterns that could develop within the solution mining area; however, since from 93 to 95% of the salt in the formation is still intact, extensive surface subsidence over large areas is not envisioned. Indeed, no detectable sinks, depressions, or visible land surface subsidence has occurred to date; likewise, none has been detected above the mechanical mine. Furthermore, with the relatively small radii of the dissolved cavities around the brine wells compared to the large quantities of undisturbed, surrounding salt, cavity closure would be expected to proceed through lateral flowage and at a slower rate than for the mechanically mined openings at the American Salt Corporation, where about 70 to 75% of the salt in a relatively thin and laterally extending bed is removed and cavity closure would develop largely through vertical flowage. In the case of either hydraulic or mechanical mining, the ensuing surface subsidence will most likely proceed at a very slow rate and will probably result in a general subsidence of a few feet over both areas without extensive fracturing and deformation of the overlying rocks. However, in the event that unexpected collapse features and extensive surface subsidence should develop within the solution mining area, the perturbations could be confined locally to the solution-developed cavities and to the rocks and land surface immediately overlying them by sealing and plugging the deep boreholes that penetrate underlying aquifers within the area (Fig. 2.1). Without passageways to deeper, permeable rocks, any ground water infiltrating into the cavities would quickly become salt-saturated and immobile (because of the higher density of the brine) and thereby preclude further cavity growth.

Finally, the 1/2-mile-wide barrier of undisturbed rock salt between the solution and mechanical workings of the American Salt Corporation, coupled with the 1/4-mile-wide barrier of undisturbed rock salt between the Carey mine and the American Salt Corporation's mechanical mine, would serve to protect the proposed repository from any foreseeable ground-water perturbations associated with solution mining.

Other important evidence for the expected stability of the solution cavities at Lyons includes the absence of extensive land subsidence above the many cavities that have been developed in the Hutchinson salt member throughout central Kansas in the past 80 years. In addition to the extensive solution mining activities at Hutchinson and at Lyons, which have been in progress since 1887 and 1908, respectively, salt has been extracted hydraulically from wells near the cities of Sterling, Ellsworth, Wellington, Kingman, and Anthony.² More recently, several hundred cavities have been developed in the salt for the storage of liquefied petroleum gases at Hutchinson, Rago, Conway, and Bushton.^{4,5} Thus, although many man-made solution cavities have been developed in the salt since its discovery, the cavities, as well as the rocks above them, have apparently remained remarkably stable. The only documented case of subsidence attributed to solution mining in Kansas known to the author is that reported to have occurred around a salt well in the city of Hutchinson in the mid-1920s.⁶ As recorded, the subsidence was centered around a brine well and was apparently confined to a roughly circular area having a diameter of about 600 ft. Also, it was observed that movements at the land surface continued for about 2 months and resulted in a maximum subsidence of about 1 ft.

In order to delineate more precisely the sizes and shapes of the existing cavities and thus provide the framework for confidently predicting subsidence within the area, it would be advisable to probe at least some of the active brine wells (and perhaps even a few abandoned and plugged holes if they are reenterable) with sonar and other wire-line devices. In addition, a series of holes could be drilled, logged, and probed in and around the solution mining area to determine the nature and extent of any cavity development in the areas between and adjacent to the brine wells.

Hydraulic Fracturing. - In the past two decades, hydraulic fracturing has been used extensively in some parts of the United States and Canada for cross-connecting wells for the purpose of solution extraction of salt.^{7,8} Fractures are generally initiated at the base of the salt by the application of hydraulic pressure through specially prepared perforations that extend through the casing and for short distances into the salt rock. Continuous pumping then extends the fractures until communication is obtained with the target wells. Eventually, low-pressure connections are made between connected wells and the system becomes fully operational. This solution extraction technique, commonly referred to as "fracing" in the salt industry, has generally been found to be superior to the single-well injection and withdrawal technique in that greater recoveries of salt are obtained, brine concentrations are higher, and lower development and operational costs are realized.

In April and May 1965, a single "fracing" test for the solution extraction of salt was made at the American mine. This abbreviated test is believed to be the only one ever conducted in Rice County, even though "fracing" is reported to be used in salt mining operations in Reno and Sedgwick Counties.⁹ The locations of the injection well (No. 47) and target wells (Nos. 45 and 46) for the tests are shown in Fig. 2.3. Figure 2.4 depicts the injection horizon, the locations of the well plugs, well casing particulars, and the stratigraphic sequences at the two connected wells. As seen in Fig. 2.4, the injection well was drilled to a depth of 955 ft, or to near the bottom of the salt formation. Casing was then set at a depth of 951 ft, and the annular space between the casing and the wall rock was filled with cement to the surface. For the primary target well (No. 46), which was formerly a dry oil and gas test hole drilled to a total depth of 3352 ft in 1949, casing was set and cemented at 689 ft. To isolate that portion of the hole which penetrates the salt from the rocks below it, a cement plug was emplaced from 976 ft to 1160 ft. The secondary target well (No. 45) was formerly an active brine well. About 1 year before the test, it was drilled to the bottom of the salt and casing was set and cemented to a depth of 685 ft. After the injection well had been plugged at 914 ft, the casing was perforated

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Fig. 2.4. Generalized Cross Sections of Injection and Target Wells for Hydraulic Fracturing Test Made at the American Salt Corporation Mine, Lyons, Kansas.

for fracing at 892 ft. Initially, a pressure of 1250 psig was established for "fracing;" however, since no fluids (saturated brine) were taken, the pressure was increased to 2000 psi. At this time, the salt formation began to accept fluids and apparently fracturing commenced. Immediately, the "fracing" pressures were lowered to 1250 psig and brine was pumped into the formation at a rate of approximately 200 gpm. Within 5-3/4 hr after pumping was initiated, a connection was made between the injection well and the primary target well. Fresh water was then pumped at the rate of 170 to 185 gpm, using an injection pressure of 645 psig, into the injection well, and brine was removed from the target well. To prevent precipitates from accumulating in and around the well casing of the brine return well, flows were periodically reversed in the injection and target wells, at least for the first few days of operation. Injection pressures continued to drop steadily from 645 psig to 465 psig during a period of approximately 13 days after the connection had been made. This is indicative of a gradually developing low-pressure cross connection. However, on the 14th, 15th, and 16th days of operation, the volumes of brine recovered were, respectively, 14,600, 25,600, and 187,000 gal less than the volumes of fresh water injected. This condition prompted a halt in injections until tests could be made in the injection well to determine the condition of the cement plug and to locate the fracture in the primary target well. The plug in well 47 was found to be in place and showed no evidence of leaking; nevertheless, it was not possible to locate the fracture in well 46 with logging tools since a mechanical obstruction was found in the hole at a depth of about 687.5 ft (at or near the bottom of the casing). After it had been determined that the fluids were not escaping into other nearby wells within the area, the project was abandoned.

With the available data concerning the fracing test, it is not possible to delineate precisely the nature and extent of the subsurface rock fracturing and thereby specify the exact disposition of all of the fluids. The nature and directions of fractures in rock formations initiated hydraulically through perforated boreholes are largely unpredictable unless some definable fracture behavioral patterns have been established for the formation through numerous previous tests. Some of the more

important factors that govern hydraulically induced fracture behavior in rocks include the nature of the initial perforations in the casing and rock, bonding of the casing to the host rock in the injection well, bedding characteristics of the rocks, and the in-situ state of stress of the rocks to be fractured. Even though few, if any, of the factors have been evaluated for the American Salt Corporation test, it is apparent that some fracturing did occur in a horizontal or near-horizontal direction because a cross connection was unmistakably made between two wells located approximately 600 ft apart.

In general, the pressure required to raise overburden will vary from 0.9 psi to 1.8 psi per foot of overburden.⁷ The depth of injection for the American Salt Corporation test was about 890 ft; thus, bottom hole pressures of from 800 to 1600 psi (ground-level pressures of 400 to 1200 psig) would be necessary to maintain an open fracture. After the fracture had been initiated, pumping pressures of 645 to 450 psig were measured. Thus, for the first 13 days of the test, essentially all of the injected fluids were probably channeled through fractures that existed between the two connected wells; however, possibly as the result of mechanical plugging of the passageway with reprecipitated salts and/or clay and other impurities after the 13th day of operation, the fluids then probably began to fill other parts of the initial fracture by raising the overburden and/or fracturing spread in other directions. (No records of pumping pressures at the time of fluid loss are available.) Once the pumping had been stopped and well pressures relieved (approximately 15,000 gal of fluid was bled from the injection well to relieve the pressure), no further expansion of the fracture system occurred and the existing fractures undoubtedly closed via settling of the overburden and plastic deformation. The injected fluids would have been expected to dissipate by solution and intrusion into rock pores, leaving perhaps some small and isolated bodies of brine trapped in the rock mass.

In the summer of 1965 (a few months after the "fracing" test) well 46 (the target well) was converted into a conventional solution mining well, according to Rueschhoff, by drilling out the obstruction at the top of the salt, which was apparently a 10- to 12-ft-thick layer of

shale.¹⁰ Pressure testing showed that the fractures that had developed around the well during the "fracing" tests had healed, and there was no indication of leakage of fluid from the single solution well system. Approximately 2 years after the fracing test was abandoned, the injection well was reopened and the wellhead pressure, which had remained constant at about 320 psig since closure of the well immediately after the test, was relieved. This maintenance of pressure clearly indicates that the fractures around this well have also healed.

Mechanical Mining. - Figure 2.1 shows the location and extent of the mechanical workings of the American Salt Corporation. The shaft for this mine was sunk in 1918, and mining has continued uninterrupted since that time. The workings now extend over an area of approximately 375 acres.³ The salt is mined by the room-and-pillar method; the latest and most persistent pattern is one of 50-ft-square pillars and 50-ft-wide surrounding rooms, which produces a salt extraction of about 75%. The mining level lies about 1000 ft below the surface and consists of a 9-ft-thick layer of salt containing a minimum of 95% sodium chloride. This bed is precisely the same one that was worked at the nearby Carey mine. In general, the rock section, including the salt, at the American mine is very similar to that at the Carey mine; however, since the American mine lies at the northern extremity (in Rice County) of the buried Arkansas River channel, a 50- to 75-ft-thick layer of water-bearing sediments covers a large part of the land surface above it. To ensure that these waters do not fill the mine when it is abandoned, the shaft should be plugged similarly to those at the proposed waste repository.

Long-term subsidence of the land surface over the American mine will undoubtedly be much the same as that at the Carey mine since the geologic framework is essentially the same at both mines and the mining methods and extraction ratios are comparable. With the relatively thick sections of salt (200 ft) and shale (500 ft) above the single mining level at the two mines, it is expected that cavity closure will occur largely through plastic deformation of the rocks and that land subsidence above the mines will proceed at a slow rate, leaving a structurally displaced but impermeable, protective rock cover above the salt.

As seen in Fig. 2.1, the American mechanical workings lie between the Lyons Gas Field on the east and the Shumway and Shumway West oil fields on the west. Essentially all of the oil and gas test holes and wells in this region penetrate the salt rocks as well as the overlying and underlying aquifers. Thus, to prevent mine flooding, rather extensive sections of unmined and undisturbed salt should surround these boreholes. In extending their workings westward and near to the Shumway oil field, the American Salt Corporation's mining plan was to leave at least a 200-ft-thick barrier of unmined salt around any salt penetrating boreholes within the area.³ However, on April 19, 1971, brine, drilling mud, and cement were struck while drilling a 7-ft shot hole horizontally into a working face near the westernmost extension of the mine.¹¹ Since the nearest known borehole (Holinger No. 1) was recorded to be about 300 ft to the south, the encounter was unexpected. Initially, fluid flowed from the hole at a rate of a few gallons per minute; however, the discharge apparently slowed rapidly to a "fast seep" and after a few months stopped completely.¹² In general, the fluid contained high concentrations of sodium, calcium, magnesium, chloride, and sulfate ions. The high concentrations of sodium and chloride may be the result of contact of the fluid with the salt rock, whereas the calcium, magnesium, and sulfate ions probably reflect the presence of cement and drilling mud. To delineate the intrusion, 1-1/2-in.-diam holes were drilled into the working face above and below the "discovery" hole. The intrusion was encountered after 12 ft of penetration in the top hole and 15 ft in the bottom one, while offset drilling established that it was about 18 in. in width.³ Undoubtedly, a cavity exists behind the working face of rock salt since water was circulated freely between the three boreholes.

Regardless of whether the encountered hole is actually the Holinger No. 1 well or some other (unidentified at this time) hole, the principal concern is that of present and/or future flooding of the mine with waters from overlying and/or underlying aquifers that have been penetrated in the drilling. At this time, it is certain that the borehole encountered in the mine is not open to fluids in the overlying and underlying aquifers. Apparently, the fluids that flowed from the hole for a short time after

it was intercepted with the shot hole consisted of displaced, residual, or trapped materials from drilling and plugging operations; however, in the event that the plug or seal now in place in the hole should be faulty, leaky, or otherwise unserviceable, the mine will surely flood unless the seal is repaired or the hole is replugged since the formation waters above or below the salt could fill the mine within a relatively short period of time.

Although flooding of the mine would undoubtedly represent a financial loss to the American Salt Corporation, it should not endanger the proposed waste repository since a 1/4-mile section of undisturbed salt separates the Carey workings from the American mine. Furthermore, this barrier would remain essentially intact because any incoming fluids would soon become saturated and stagnant. Brines are known to fill abandoned mines within 500 m of the Asse II salt mine repository for radioactive waste in West Germany.¹³ Saturated brine has a density of 1.2 and cannot be displaced by fresher solutions unless drainage pathways are provided to deeper depths. Perhaps the only conceivable passageway for the downward movement of fluid in the American mine would be through open or unplugged boreholes. Thus, by plugging all boreholes within the American Salt Corporation mine that penetrate the salt section and the permeable rocks below it, the proposed waste repository would not be affected by the presence of this mine, even if flooding occurred.

Summary and Conclusions. - The American Salt Corporation's underground workings adjacent to a proposed repository at Lyons include hydraulically mined cavities as well as mechanically developed excavations. Solution mining activities have been confined to an area of about 140 acres, and it is estimated that from 5 to 7% of the salt underlying this area has been removed. Although the exact sizes and shapes of the cavities existing around the brine wells are not known, it is assumed that salt removal has been greatest adjacent to the brine wells and that the ensuing cavities have been at least partially filled with slabs and particles of shale and anhydrite impurities. To date, no visible land subsidence has occurred within the area and, because of the relatively small fraction of salt removed, large-scale and spectacular deformations of the rocks above the

salt formation would not be expected. Furthermore, in the unlikely event that deep and extensive subsidence did develop within the area, its localization and confinement could be ensured by plugging the few deep boreholes that penetrate the aquifers underlying the salt within the area. These boreholes would provide the only means for movement and removal of the dense brine waters from the cavity area.

The single hydraulic fracturing test conducted within the solution mining area to connect brine wells was terminated after 16 days of operation when fluid input volumes were found to greatly exceed fluid recoveries. The unrecovered fluids were apparently dissipated by solution and intrusion into rock pores, and perhaps even some small isolated bodies of fluid were trapped in the formations when injections were halted and the raised overburden resettled and closed the fractures. It has been demonstrated that the fractures around both the injection and recovery wells have healed since the conclusion of the test. Thus, the fracturing test apparently did not create permanent and open fractures in the salt or change the impermeable nature of the salt within the area appreciably.

The mechanically mined workings of the American Salt Corporation, which extend over an area of about 375 acres, have been developed at the same stratigraphic level as the abandoned Carey mine, which is part of the proposed waste repository. In addition, the two mines have been developed using the room-and-pillar method of mining, with about 75% of the salt being removed at the mining level and the remaining 25% comprising the supporting pillars. Under these conditions it is expected that deformation within the mine will proceed at a slow rate and the overlying rocks will adjust without significant amounts of fracturing and faulting. It is conceivable that ground water could enter the American Salt Corporation's mine via leakage at the shaft or perhaps through various boreholes that penetrate the salt formation, such as the one encountered recently along a working face in the extreme western reaches of the mine. Effective sealing of the shaft and nearby boreholes would, of course, preclude the entry of water into the mine through these perturbations; however, even if the mine should fill with water, the water would not migrate into the repository due to a 1500-ft-wide barrier of undisturbed rock salt separating

the two existing mines. Furthermore, by plugging all boreholes within the mining area, which are the only pathways for the downward movement of brine, any waters in the mine would stagnate and cavity growth would be precluded.

Although the underground workings of the American Salt Corporation must be considered for any potential perturbation to a nearby repository, they must also be viewed as a distinct asset since the mechanically mined openings, as well as the hydraulically developed ones, could serve as disposal bins for the several million tons of impure salt that would be generated from mining activities associated with the repository. The filling of these unused workings would also promote further ground stability and minimize land subsidence within the potentially affected areas.

2.1.3 Potential Effects of Future Continental Glaciation on the Proposed Nuclear-Waste Repository at Lyons, Kansas (G. F. Stewart*)

A basic assumption in this research is that the glacial age is still in progress, and that presently an interglacial interval prevails. For the sake of discussion of the potential effects of glaciation on the repository, the probability of another episode of glaciation within the life-span of the repository is assumed to approach certainty.

Of the four glacial stages of the Pleistocene, only the Nebraskan and Kansan glaciers advanced as far southward as Kansas. These glaciers extended only into the northeasternmost part of Kansas (Figs. 2.5 and 2.6). Information contained in geological and geophysical literature and discussed below suggests that, if continental glaciation should occur during the lifetime of the proposed repository and if glaciers should extend at least as far southward as the Kansan glacier, then bedrock in proximity to the proposed repository might be affected to some extent. An estimate of this effect is discussed below. Potential changes caused by loading by glacial ice may include:

- (1) regional depression of the entire crust beneath the ice,
- (2) fracture of the crust near the margins of the glaciers,

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Fig. 2.5. Nebraskan, Kansan, Illinoian, and Wisconsinan Drift Borders in Central United States, Showing the Approximate Maximal Positions of Advancement of Pleistocene Continental Glaciers. (After R. F. Flint, Glacial and Pleistocene Geology, p. 338, Wiley, New York, 1957)

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Fig. 2.5. Location of Lyons, Rice County, Kansas, in Relation to Glaciated Area of Kansas. (According to D. E. Zeller, Kansas Geological Survey Bulletin 189, p. 61)

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Fig. 2.7. Internal Structure of the Earth, Shown Diagrammatically. (From ref. 14)

- (3) induced diapiric movement in the salt,
- (4) gentle flexure in the upper part of the basement and sedimentary bedrock, and
- (5) folding and faulting of shallow bedrock, as caused by ice-push.

The following discussion considers the maximal and minimal cases of deformation.

Depression of the Crust by Glacial Ice. - The crust of the earth encloses a dense mantle. The thickness of the crust ranges from about 30 to 70 km beneath the continents but is less than about 8 km at some places beneath the ocean basins.^{14,15} In this study the crust is considered to be a spherical shell that is uniformly thick, isotropic, and elastic (see Fig. 2.7). Under slow rates of loading, as in the cases of glaciation and sedimentation, the mantle should react as a highly viscous liquid.^{14,16}

Continental glaciers are assumed to persist for periods of time sufficient to allow the crust to be depressed, with an equilibrium state to be established by isostatic adjustment. This assumption implies a steady-state model, in which viscosity of the mantle is not a factor in calculations of amounts of crustal depression.

Extant continental glaciers, namely those in Greenland and Antarctica, are assumed to be similar to continental glaciers of the Pleistocene. Accordingly, the cross-sectional profile of these former continental glaciers should have been approximately parabolic.^{17,18} Maximal thickness of the ice in the central parts of the glaciers is assumed to have been as great as 3000 m.^{19,20} The location of the thickest part of the Wisconsinan continental glacier was in the Hudson Bay area, Canada.^{21,22} If a continental glacier comparable in size and extent to the glaciers of the Pleistocene were to develop within the forthcoming several thousand years, its central region presumably would also be near Hudson Bay.

Depression of the earth's crust by ice sheets and isostatic uplift in response to unloading has been recognized for more than a century.^{21,23} Deflection of the crust by ice sheets has been studied in Greenland and Antarctica, where the ice-bedrock contact is depressed below sea level

at some places.¹⁸ Much research has been done in North America on rebound from loading by ice.²⁴ Deflection of the crust by water in Pleistocene lakes and in modern reservoirs has also been described.²⁵⁻²⁷

Deformation of the crust as related to shape and thickness of ice sheets has been studied by several workers on the basis of models.^{14,22} Most models assume a continental glacier that would be circular in plan view. The models that are judged by us to be most realistic consider the cross-sectional form of the glacier to be parabolic, convex upward.

Loading by glacial ice or by large bodies of water induces regional differential pressure in the crust and in the upper part of the mantle. According to the generally accepted theory of isostasy, slow flowage in the mantle and downward flexure of the crust take place until equilibrium is established. The magnitude of crustal depression is related to the thickness of the ice or water load. Crustal deflection is generally about 25 to 30% of the total thickness of the load, inasmuch as the densities of ice and water are each about one-fourth the density of the mantle. (The relative density of the mantle is about 3.37,¹⁴ whereas the relative density of ice is 0.9.)

Potential deformations of the crust under axisymmetric loads of glacial ice with parabolic profiles, maximal and central thicknesses of 3000 m, and radii of 50 to 2500 km are shown in Fig. 2.8. The assumption is held that the central region of the Kansan continental glacier was in about the same location as the central region of the Wisconsinan glacier, a short distance west of Hudson Bay, Canada.^{21,22} Therefore, a radius of about 2300 km approximates the southernmost advancement in Kansas of the Kansan glacier. About 2500 km approximates the radius of a continental glacier of which the southern edge would extend to Rice County, Kansas.

On the basis of Fig. 2.9, a continental glacier of the future as extensive as the Kansan glacier may not depress the crust in Rice County but may cause an elevation in the crust of a few meters. A glacier that would extend into Rice County should depress the crust beneath Rice County almost 50 m (Fig. 2.8).

Fig. 2.8. Crustal Deflections Under Axisymmetric Loads with Parabolic Profiles, Such as Ice Sheets with Central Thicknesses of 3000 m and Variable Radii. (After figure given on p. 5244 of ref. 14)

Fig. 2.9. Crustal Deflection Beneath an Ice Sheet with a Central Thickness of 3000 m and a Radius of 2500 km. Vertical exaggeration, 1000X. (From data in Fig. 2.8)

Probable Stresses in the Crust from Ice Loading. - A continental glacier that is basically circular in plan and parabolic in cross section should produce essentially three kinds of stress in the crust:

- (1) Vertical and horizontal compression under the ice.
- (2) Horizontal tension near the margin of the ice sheet.
- (3) Shear stress near the margin of the ice sheet.

Table 2.3 shows predictions made by Brothie and Silvester for stresses and deflections that could be produced at the surface of the crust by the load of a continental glacier 3000 m thick in its central region and having a radius of about 1450 km. The values shown in this table for stresses near the glacier's perimeter are considered to be an approximation of stresses that might be present near the margin of a glacier that would reach into central Kansas. These values should be conservative approximations (i.e., slightly overestimated); a glacier with a radius of 1450 km would, of course, be a more concentrated load than a glacier with a radius of 2500 km, extending into Kansas.

As discussed above, the crust would deform under a load of ice 3000 m thick in the central part until the amount of displaced mantle equaled the weight of the ice. This deformation of the elastic crust would create compressive, tensional, and shearing stresses within the crust. Table 2.3 shows the magnitudes of the radial and tangential stresses, which would be orthogonal. Radial stresses would be directed outward from the center of the glacier. As shown in Fig. 2.10, the horizontal stresses would be compressive under the main body of ice and tensional in a "bulge" near the margin of the glacier that would extend from about 1200 km to about 1650 km from the center of the glacier. Shear stress would be near zero under the main body of ice but would be comparatively large near the margin of the ice sheet.

Application of Brothie and Silvester's information directly to the Lyons area should include consideration of the veneer of sedimentary rocks that overlie basement rocks. A conservative approximation of the upper limits of stress in the sedimentary strata in the region near the ice margin can be made if the stresses shown in Table 2.3 and Fig. 2.10 are

Table 2.3. Deflections and Stresses in the Crust Beneath an Ice Sheet of Parabolic Profile,
Central Depth 3000 m, and Radius 1450 km^a

Distance from center, km	0	290	580	870	1160	1450	1500	1600	1700	1800
Deflection, m	801.93	769.12	673.00	512.76	288.06	22.60	3.74	-3.86	-1.07	0.11
Radial stress, $N m^{-2} \times 10^{-3}$	-1627	-1479	-1503	-1483	-1928	10,300	7883	1231	-402	-180
Tangential stress, $N m^{-2} \times 10^{-3}$	-1627	-1495	1500	-1495	-1620	1486	1326	263	-59	-33
Shear stress, $N m^{-2} \times 10^{-3}$	0	16	9	8	-31	104	-684	-356	-14	26

^aData taken from J. F. Brotchie and R. Silvester, "On Crystal Flexure," J. Geophys. Res. 74(22), 5240-52 (1969).

Fig. 2.10. Magnitudes of Stresses Produced at the Surface of the Nonsedimentary Crustal Rocks by an Ice Sheet with Maximal Thickness of 3000 m, Parabolic Profile, and Radius of 1450 km. Maximal stresses should occur within a bulge near the margin of the glacier. Negative and positive stresses denote compression and tension, respectively. (From data in ref. 14 and Table 2.3)

scaled by the ratio $E_{(\text{sedimentary rocks})}/E_{(\text{basement rocks})}$, or 0.17. This results in maximal compressional, tensional, and shearing stresses of $0.34 \times 10^6 \text{ N/m}^2$ (~50 psi), $1.75 \times 10^6 \text{ N/m}^2$ (~255 psi), and $12 \times 10^4 \text{ N/m}^2$ (~17 psi).

Probable Effects of Stress on Rocks Above the Proposed Repository. - The lower limit of structural stability of bedrock above the repository site could be approximated on the basis of these premises:

- (1) If fracture of rocks at the repository should occur, it would probably be the result of tensional stress in rocks above the salt strata and within the marginal bulge. Tensional stresses are the largest of the computed stresses, and tensional fracture should occur at shallow depths where confining pressures are small.
- (2) Silty shale is the most abundant rock type in the stratigraphic column at Lyons, Kansas.
- (3) Shale should be the weakest rock in the stratigraphic column, and therefore should be the first to fracture, if fracturing were to occur as suggested under (1) above.
- (4) Strata above the salt-bearing strata are about 800 ft thick, and thus should be subject to confining pressures ranging from about 1 bar to about 55 bars.²⁸
- (5) Approximation of the strengths of Permian shale in the subsurface above the proposed repository can be made by reference to measurements of strengths of shale by triaxial testing, as described below.

Shale from the Green River formation (Eocene, Colorado) and from the "5900-Foot Sands Shale" (Pennsylvanian, northern Texas) deformed dry, at room temperatures, under triaxial compression, showed the following ranges of values of strengths (estimated from ref. 28):

	<u>Confining Pressure (bars)</u>	<u>Depth Approximating Confining Pressure (ft)</u>	<u>Ultimate Strength (approximate)</u>
Green River Shale	0	0	620 kg/cm ² (8800 psi)
Green River Shale	50	750	750 kg/cm ² (10.7 x 10 ³ psi)
"5900-Foot Sands Shale"	0	0	750 kg/cm ² (10.7 x 10 ³ psi)
"5900-Foot Sands Shale"	50	750	1000 kg/cm ² (14.2 x 10 ³ psi)

If shear strength is taken as one-half the differential stress that corresponds with ultimate strength,²⁸ then the minimal shear strengths of the Green River shale and the "5900-Foot Sands Shale" should be about 4000 psi and 5000 psi respectively. If tensile strength were to be estimated at about 4% of breaking strength (as suggested by Hills²⁹ and Billings³⁰), then tensile strengths of the Green River and "5900-Foot Sands Shale" should be about 350 and 400 psi, respectively, near the surface and about 400 and 550 psi at depths of about 750 ft.

The Green River shale is much younger than the "5900-Foot Sands Shale"; yet, the values of the strengths are not markedly different. Although it is recognized that the values shown above are by no means parametric in the statistical sense, the similarity of strengths of two shales greatly different in age suggests the premise that strengths of the "5900-Foot Sands Shale" could approximate strengths of Permian shale in the bedrock at the proposed repository. On the basis of this premise, predicted stresses in shallow bedrock due to glacial loading and approximate strengths of the bedrock compare as follows:

	<u>Vertical Compressional</u>	<u>Shear</u>	<u>Horizontal, Tensional, and Compressional</u>
Estimated stress (maximal), psi	50	17	255
Estimated strength (near-surface), psi	10,000	5000	400
Estimated strength (near 750 ft), psi	14,000	7000	550

On the basis of the data shown above, the conclusion can be derived that stresses which would be introduced into the veneer of sedimentary rocks by an ice sheet located near the repository do not seem to be large enough to cause fracturing, except perhaps in the instance of tensional stresses introduced near the surface.

Seemingly, the extreme circumstances would occur if the margin of a continental glacier were to advance to a position near Lyons, Kansas. The repository would then be located within the belt of maximal stresses where, according to the approximations above, fracturing due to horizontal stresses might be possible near the surface but probably not at depths of about 700 to 800 ft. However, two qualifications should be mentioned.

1. The estimates of the tensile strength and the performance of shale do not take into consideration the effect of a slow buildup of stress. Application of stress to shale over long intervals of time might lead to moderate adjustment of the near-surface bedrock without the creation of new fractures. Estimation of rates of loading that might be expected can be made by reference to Pleistocene glacial history.

The approximate durations of the four glaciaticns of the Pleistocene seem to have been as follows: Nebraskan, 250,000 years; Kansan, 500,000 years; Illinoian, 100,000 years; and Wisconsinan, 120,000 years.³¹ Assuming that the mean rate of advancement of the continental glaciers was about 100 m per year,³²⁻³⁵ that the Kansan and Illinoian glaciaticns approximate the maximal and minimal durations of any future glaciaticns, and that the mean rates of retreat of the continental glaciers were about equal to the mean rates of advancement, then a continental glacier could advance to Rice County, Kansas, within about 30,000 years after the onset of a glacial episode and could overlid the terrain for as short a time as 60,000 to 70,000 years or as long as 470,000 years. Assuming that the terrain of the proposed repository would begin to be affected when a glacier approached within about 400 km,* the time lapse from the inception of stress on bedrock at the repository to the advancement of the

* This assumption is based on data given in Table 2 of ref. 14 (p. 5244), which show that stresses introduced by an ice load affect the crust at distances as great as 350 km from the ice sheet's margin.

glacier's margin to a position above the repository should be about 4000 years.

2. Strengths discussed above were determined from rock-mechanics testing, wherein the assumption is held that rock is solid. Of course, the general truth is well known that bedrock near the surface of the earth is jointed. Since joints were observed in cores taken at the repository site,^{36,37} the inference can be drawn that small fractures may be abundant in the shallow bedrock. Therefore, the question exists as to how strictly the stress-strength relationships above should be interpreted. However, jointing in the shallow rocks should not be regarded as an altogether unfavorable aspect because shallow bedrock might accommodate slowly imposed stresses (discussed above) by numerous minor adjustments along extant fractures. Therefore, it is possible that major fracturing of the shallow bedrock would not occur.

The general hypothesis that stresses introduced into bedrock near the margins of continental glaciers might cause fracturing of shallow bedrock can be tested on the basis of field geological evidence.

If the Kansan glacier had conformed to the assumptions of shape and thickness stated above, if a marginal bulge in the crust had existed, and if the horizontal stresses within the bulge had been as great as those indicated by extrapolation of Brothie and Silvester's computations, then fracturing of the uppermost few hundred feet of bedrock might have occurred in northeastern Kansas. If faults of this origin exist, they should be present in bedrock at the surface. They might be expected to strike sub-parallel to the general boundary of the Kansan ice sheet, and to extend for several miles at the surface.

The areal geology of northeastern Kansas has been studied by a large number of geologists and is considered to be reasonably well known. Geologic maps of some parts of northeastern Kansas include areas across which the boundary of the Kansan ice sheet extended.³⁸⁻⁴¹ In this region, faults or folds attributed to glaciation are few; they extend only a few tens of feet into the bedrock and only a few hundreds of feet horizontally.⁴²

Considering the state of knowledge of the areal geology of north-eastern Kansas, it seems valid to infer that (1) faults caused by Kansan ice in the uppermost few hundred feet of bedrock do not exist, or (2) faults of this kind are minor and are so few and so local as to have gone unrecognized, or (3) major faults exist but have not been discovered by geologists who have studied the terrain. Of these hypotheses, the nonexistence of "deep" faults caused by the Kansan ice sheet is considered by us to be the most likely to be true; the existence of undiscovered major faults owing to glaciation is considered to be the least likely to be true.

Near the borders of the Illinoian ice sheet on Long Island, Cape Cod, Martha's Vineyard, and some other islands of southern New England, unconsolidated Cretaceous, Miocene, and Pleistocene deposits are extensively folded and faulted.⁴³⁻⁴⁵ The deformation is superficial since faulting probably extends to only about 50 ft below sea level.^{43,46} The ice at the glacier's margin was more than 400 ft thick.⁴³ However, within this region, folds that are overturned southward and northward-dipping thrust faults⁴³ indicate that faulting was caused primarily by ice-push and drag beneath the ice, rather than by fracture of the bedrock due to weight of the ice.

Terrain in southwestern Illinois mapped carefully by Rubey⁴² was partly overridden by the Illinoian ice sheet. Little direct evidence of erosion by ice was recorded.⁴⁷ Although the ice front has probably been stationary for at least 800 and possibly several thousand years, and the areal geology of the region is favorable for detection of recent structural movements, no evidence of a former marginal bulge of Pleistocene faulting or folding was observed.⁴⁷

A belt of postglacial faults in eastern New York and southeastern Quebec⁴⁸ is suggestive of the kind of faulting that might have developed in regions that bordered ice sheets. This is the only such example that we have discovered. The faults occur almost exclusively in shales and slates; they are closely spaced, and occur mostly in planes of cleavage.⁴⁸ Vertical displacement ranges from only 1/4 to 15 in. and is commonly 1 in. or less; however, the cumulative displacement across zones of these faults could be large.⁴⁸ Several hypotheses were advanced as explanations of

the faulting, including stresses caused directly by superincumbent ice. However, the authors favor hypotheses involving expansion of the bedrock and preferential faulting in the shale and slate.⁴⁸ Inasmuch as the authors did not comment on the extent of faulting into the subsurface, it seems reasonable to infer that the depth of faulting is not known.

Apparently, no definite evidence exists to show that glaciation causes extensive folding and "deep" vertical faulting of competent bedrock near the ice border. However, this presumed lack of evidence is regarded as being insufficient to deny the geophysical theory that ice sheets can cause large stresses in crustal rocks within a marginal bulge. However, the paucity of evidence of deformation suggests (1) that stresses near the ice front were commonly not large enough to cause more than superficial fracturing of the shallow bedrock or (2) that large stresses were imposed slowly and were accommodated by moderate deformation of bedrock without deep faulting.

Probable Effects of Ice-Push. - As discussed above, ice-push and ice-drag deformed a few hundred feet of Pleistocene, Cretaceous, and Miocene deposits on the islands of southern New England. It should be emphasized, however, that strata were unlithified when disturbed. In the Midcontinent, faulting and folding of competent Paleozoic rocks caused by ice-push is entirely superficial. Where ice-push deformation has been identified, only a few tens of feet of bedrock are disturbed.^{42,49}

Probable Effects of an Ice Sheet on Salt Strata in Central Kansas. - A diagrammatic profile of an ice sheet of radius 2500 km and theoretical maximal thickness of 3000 m is shown in Fig. 2.11. The profile is consistent with the basic form of the ice cap on Greenland, which is about 3000 m thick although much less extensive.⁵⁰ The profile also closely resembles a reconstructed cross section of the marginal Wisconsinan ice sheet in southern Indiana.⁵¹

Figure 2.11 is assumed to approximate the general cross-sectional form of any ice sheet that might extend into the Midcontinent. On the basis of this assumption, the inference can be drawn that, if an ice sheet were to advance 300 km into Kansas in a south-to-southwesterly

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Fig. 2.11. Approximate Profile of an Ice Sheet with Maximal Thickness of 3000 m and Radius of 2500 km, Extending from Its Center to Its Margin. Vertical exaggeration, 500X. (Constructed from data in refs. 19, 20, 50, and 51)

direction, a maximum of about 1000 m of ice should lie above the repository. This amount of ice would be approximately equivalent to a load of sedimentary rock about 300 m thick. (The relative density of ice is 0.9; the relative density of sedimentary rock is about 2.7.) Therefore, the ice should exert a vertical stress on the order of 1000 psi on the bedrock.

Gera⁵² suggested that the minimal thickness of salt necessary for the initiation of diapirism is 300 to 400 m; salt strata at the repository site are altogether only about 90 m thick. During the early part of the Tertiary Period, the Permian of central Kansas was overlain by more than 750 m of Cretaceous rocks.⁵³ The force of overburden of the complete Cretaceous section was approximately 2500 psi, a load equivalent to more than 2000 m of ice. Moreover, the Cretaceous rocks were being eroded sub-aerially and thus did not impose a uniformly distributed load on the Permian. However, no evidence of diapirism in the salt of central Kansas has been reported. Nor has evidence of diapirism been reported in the salt deposits of the upper mid-western states or of Alberta and Saskatchewan, Canada.⁵⁴⁻⁵⁷ In these regions, salt is thicker at many places than it is in Kansas; also, loading of bedrock by ice was greater than loading that could be expected in Kansas.

In general, minimal conditions necessary for the initiation of large-scale, short-term (geologically speaking) flow of salt seem to be an overburden pressure of about 12,000 psi and temperatures greater than 200°C.⁵³ Inasmuch as depth of burial of salt in central Kansas is about 800 to 1000 ft, overburden pressure due to bedrock alone should not exceed about 1000 psi and overburden pressure due to bedrock and glacial ice should not exceed about 2000 psi. These stresses are obviously much less than the stress presumed to be required for initiation of large-scale salt flow.

The ambient temperature of the rock salt at the repository site is about 21°C. The maximum temperature within the repository is predicted to be 200°C, and should occur about 50 years after emplacement of nuclear waste. Thereafter, it should decrease rapidly, presumably until it stabilizes near the present temperature.

The following points can be advanced as evidence to show that salt flow or diapirism resulting from loading by glacial ice should not occur at the repository.

- (1) The rock salt in central Kansas is thinner than the minimal amount presumed to be necessary for diapirism to occur.
- (2) Stress on the salt when loaded by glacial ice would be less than the amount judged to be required for diapiric flow.
- (3) The temperature of the salt may approach the threshold for diapiric flow; but, because of the small force of overburden, elevated temperatures should not lead to diapirism of the salt — even if loading by ice and highest temperatures of the repository were to occur simultaneously. (The probability of this has been shown to be effectively zero by a foregoing argument.)

Summary and Conclusions. — Three assumptions are held: the late Cenozoic glacial age is still in progress; the present is an interglacial interval; and the probability of another continental glaciation approaches certainty.

Continental ice sheets depress the crust of the earth by flexure and cause isostatic adjustment. An ice sheet that would enter central Kansas should flex the crustal rocks upward by a few meters as it approaches the terrain containing the repository; in the event that it should override the repository, it would depress the crust by about 50 m. Compressional, tensional, and shear stresses would be introduced into the sedimentary rocks. Comparison of stresses estimated to be caused in the bedrock above the repository with estimated strengths of the bedrock indicates that an ice sheet's approach to or overriding of the repository should not cause deep fracturing of the rocks.

Areal geologic evidence from Kansas, southern New England, and Illinois, all of which are regions that were entered by ice sheets of the Pleistocene, indicates that disruption of bedrock by the former ice sheets was only superficial. No faults owing to glaciation are known to extend as deep into the subsurface as the location of the proposed repository, even in southern New England, where the ice moved across unlithified

deposits. Effects of ice-push and ice-drag on bedrock in central Kansas should be negligible. Stresses introduced into the bedrock by glacial loading should cause no flow of salt within the repository.

2.2 Alternative Site Reconnaissance in Kansas

The search for alternative sites in the underground salt deposits of Kansas was performed in two stages. First, the available information on eight county-sized areas pertinent to waste disposal was compiled and the areas were assessed for their suitability. The results of this study are given in Sect. 2.2.1. Then, using the information collected in the first study, three specific potential sites were identified and further investigated. This work included field reconnaissance and the drilling and testing of one core hole at each potential site (Sect. 2.2.2).

2.2.1 Screening Survey

In December 1971, the State Geological Survey of Kansas prepared a report on eight county-sized areas that were considered potentially suitable for the storage of high-level radioactive wastes. These areas, shown in Fig. 2.12, were selected on the basis of the general knowledge of each area, the presence of at least 150 ft of salt at a depth of less than 2000 ft, and a minimum of oil and gas development. For each of these areas, the following types of data were compiled: (1) geology and hydrology; (2) population centers and densities, transportation facilities, and other cultural features; (3) locations and status of oil and gas wells, as well as an estimate of the potential for future petroleum exploration; and (4) the characteristics of the salt formation as inferred from electric logs. The information collected for the report was obtained only from readily available sources, both published and unpublished file data; no field work or other investigations to generate original information were undertaken. It was compiled in "Preliminary Geological Investigations of Supplemental Radioactive Waste Repository Areas in the State of Kansas," edited by E. E. Angino, C. K. Bayne, and J. C. Halepaska. An abridged version of this report was subsequently published as Kansas Geological Survey Special Distribution Publication No. 60 under the title "Supplemental Areas for Storage of Radioactive Wastes in Kansas," compiled by C. K. Bayne. The descriptions of the eight study areas in the following sections were taken from these reports.

Fig. 2.12. Map of Kansas, Showing the Eight Areas Involved in Site Screening Studies.

Area 1. - Area 1 (Fig. 2.12) includes parts of Ellsworth, Lincoln, Mitchell, Osborne, and Russell counties in central Kansas in an area drained by the Smoky Hill River and the Saline River. Structurally the area lies in the Salina basin, just east of the Central Kansas Uplift.

Geology and Hydrology. - About 500 ft of rock consisting principally of shale but also containing dolomite, anhydrite, and gypsum is present above the Hutchinson salt member of the Wellington formation and below the Stone Corral formation. The lower 250 ft, which belongs to the Wellington formation, is primarily gray and blue-gray shale but contains some red shale in the upper part. The upper 250 ft, which comprises the Ninnescah shale, is primarily red shale but contains some gray shale. Neither the Wellington nor the Ninnescah contains water in this area.

The Stone Corral formation overlies the Ninnescah shale and is comprised of about 20 to 25 ft of dolomite, anhydrite, and gypsum. Anhydrite and gypsum are the dominant components. Little, if any, water can be obtained from this unit.

The Harper sandstone overlies the Stone Corral formation in this area. The Harper, which consists principally of red, silty shale and contains little sandstone, will yield little or no water to wells. The upper surface of the Harper is an erosional surface and marks the boundary between Permian and Cretaceous rocks in the area.

The Cheyenne sandstone is the lowermost Cretaceous unit present in Kansas. In Area 1 the Cheyenne does not crop out and is present in the subsurface only in the westernmost part. In much of Area 1 the Cheyenne consists of a very fine, silty sand and is not an important aquifer; however, west of this area (and probably locally in Area 1), it contains large quantities of sand, and moderate quantities of highly mineralized water should be available.

The oldest rock unit that crops out in this area is the Kiowa formation. This unit conformably overlies the Cheyenne sandstone where the Cheyenne is present and unconformably overlies Permian rocks where it overlaps the Cheyenne. The Kiowa consists primarily of dark-gray and brownish shale but also contains thin to massive sandstone beds, thin shell beds, and

lignite. In the southern part of the area, a full section of the Kiowa, if present, is about 150 ft thick. The unit thins toward the north and may be less than 100 ft thick in Mitchell and Osborne counties. Sandstone beds in the Kiowa are more common in the southern part of the area. Here yields of water as large as 100 gpm may locally be available to wells. Toward the north and west, where the Kiowa thins and sandstone beds are less common or absent, little or no water is available.

The Dakota formation overlies the Kiowa formation. The Dakota is composed of clay, shale, sandstone, and (locally) some lignite. Light-gray, dark-gray, and red shale comprises about two-thirds of the total thickness of the unit, which is about 250 ft. Sandstone beds occur throughout the unit. The Dakota is the principal aquifer in this area. Yields of wells may locally be as much as 250 gpm but more commonly are less than 50 gpm. In Ellsworth County and southern Lincoln County, the water from the Dakota is of good quality; however, it may be too highly mineralized for use in Osborne, Mitchell, and Russell counties.

Cretaceous rocks that overlie the Dakota formation in Area 1 are, in ascending order, the Graneros shale, the Greenhorn limestone, and the Carlile shale. The Graneros is a dark-gray, clayey to platy shale which weathers to a brownish color. The thickness of the unit ranges from about 25 to 35 ft in Area 1. The Greenhorn limestone is composed of about 70 to 90 ft of thin, chalky limestone beds interbedded with thicker, chalky shale. These limestone beds range in thickness from a fraction of an inch to about 10 in. The thickest and most prominent bed is the "Fencepost limestone," which occurs at the top of the Greenhorn. The Carlile shale is composed primarily of chalky shale but contains thin beds of nodular, chalky limestone in the lower part. Thin beds or seams of bentonite occur throughout the Graneros, Greenhorn, and Carlile in this area. None of these units is a good aquifer. Only small quantities of water are available from the upper weathered parts of the units.

Alluvial deposits that occur in the valleys of the Smoky Hill River and the Saline River and in the abandoned Wilson Valley, which extends from the Saline River near northwest Ellsworth County southeastward to the Smoky Hill River (a few miles west of the city of Ellsworth), are arkosic-type materials indicating a western source. These deposits are

generally little more than 50 ft thick. Water yields are near 250 gpm at the maximum but are more commonly less than 100 gpm. The alluvial deposits in the abandoned Wilson Valley are somewhat thicker; however, these deposits occur in a channel cut in an upland area which has been beheaded at both ends by more recent erosion or downcutting of the streams. The channel is largely drained of water and yields only small quantities.

Population and Transportation. - Cities within Area 1 are mostly located in or near the valleys of the principal streams. Railroads built in the area were located in the valley areas to avoid steep grades, and cities grew along the railroads. The main line of the Union Pacific Railroad crosses Ellsworth and Russell counties in the southern part of the area, and a branch line of the Union Pacific Railroad serves the northern part of the area in the valleys of the Saline River and Wolf Creek. Interstate Highway 70 and State Highways 4 and 18 traverse the area from east to west. State Highways 14, 181, and 232 are north-south thoroughfares through the area.

Oil and Gas. - A few wells producing small amounts of oil and gas have been drilled in the southern part of Area 1. The most recent discovery is the Wilson gas field, which is located north of the city of Wilson in northwestern Ellsworth County. Several areas of township size in the northern part of the area contain no drilled holes. Much of Area 1 lies in the western part of the Salina Basin, an area not considered to be promising for future development of oil and gas.

Salt. - The Hutchinson salt occurs in Area 1 at depths ranging from about 600 ft in the southeast to about 1200 ft in the northwest. Nearly 300 ft of salt is present in the west-central portion of the area. The salt thins toward the east and north. Salt in about one-third of the total area is near or less than the minimum required thickness of approximately 150 ft.

Area 2. - Area 2 (Fig. 2.12) includes part of southeastern Trego County and eastern Ness County. The northern part of the area is drained by the Smoky Hill River; the southern part is drained by Walnut Creek. Structurally the area lies on the west flank of the Central Kansas Uplift.

Geology and Hydrology. -- The geological features of this area are similar to those in Area 1. The Hutchinson salt member is overlain by the Wellington and Ninnescah shale. The upper Wellington is composed of about 200 ft of gray and blue-gray shale. Some thin anhydrite and dolomite beds are also present. The Ninnescah shale is comprised of about 200 ft of predominantly red shale; however, some gray shale is present. The Wellington and Ninnescah include no permeable units and contain little, if any, water in this area.

The Stone Corral formation, which overlies the Ninnescah shale, is composed of about 25 ft of anhydrite and probably some gypsum. Permeability has not been developed in these rocks; and a negligible amount, if any, of water is present in the formation.

The Harper sandstone overlying the Stone Corral is composed principally of red siltstone and shale in this area. The unit is about 150 ft thick and contains little sandstone. It is not an important aquifer.

Lower Permian rocks between the Harper sandstone and the Blaine formation, consisting of the Salt Plain formation, the Cedar Hills sandstone, and the Flower-pot shale, have an aggregate thickness of about 500 ft in Area 2. Moderate to large quantities of highly mineralized water are available from these rocks.

The Blaine formation is present only in the southern part of Area 2, where it is about 15 to 20 ft thick.

Lower Permian rocks consisting of the Dog Creek formation and the Upper Permian Whitehorse formation are present in the southern part of the area but are absent in the northern part where they were probably removed by pre-Cretaceous erosion. Small to moderate quantities of water are probably available in local areas from sandstone in the Whitehorse.

Lower Cretaceous rocks consisting of the Cheyenne sandstone, Kiowa formation, and the Dakota formation are present in the area and unconformably overlie Permian rocks. They have an aggregate thickness of about 500 ft. The Kiowa is quite thin and contains little, if any, sandstone.

Moderate to large quantities of highly mineralized water are available from the Cheyenne, and yields of up to 300 gpm of good-quality water have been obtained from wells in the Dakota.

Upper Cretaceous rocks consisting of the Graneros shale, Greenhorn limestone, Carlile shale, and the Niobrara chalk, with an aggregate thickness of about 450 ft, crop out in Area 2. Little, if any, water is available from the Upper Cretaceous rocks in this area.

Thin deposits of silt, clay, sand, and gravel comprising part of the Ogallala formation of Pliocene age are present on the highest uplands in Area 2. Small quantities of water are locally available from these deposits.

Alluvial deposits of Pleistocene and Recent age are present in the valleys of the Smoky Hill River and Walnut Creek. Yields of wells in these deposits in the Smoky Hill Valley may be as much as 500 gpm in local areas. In the Walnut Creek Valley, yields of wells generally do not exceed 50 gpm; however, locally as much as 200 gpm may be obtained.

Population and Transportation. - Population centers in the southern part of Area 2 are located along a branch line of the Atchison, Topeka, and Santa Fe Railroad in the Walnut Creek Valley and in the northern part of Ness County along a branch line of the Missouri Pacific Railroad.

State Highways 4 and 96 cross the area in an east-west direction, and U.S. Highway 283 runs north-south along the west side of the area.

Oil and Gas. - There is a highly developed area of oil and gas production in the eastern part of Area 2. The western part of Area 2 has had less development, although scattered fields with one or two wells each are present. Area 2 is currently (1971) quite active and will probably continue to be so in the future. It is located on the western flank of the Central Kansas Uplift, and oil and gas are produced from small structural and stratigraphic traps on the truncated Mississippian surface.

Salt. - In area 2 the Hutchinson salt occurs at depths ranging from about 1800 ft in the southeast to about 2200 ft in the northeast. The depth to the top of the salt is greater than 2000 ft in about one-half of the area. The thickness of the salt ranges from about 150 ft in the

northeast to about 300 ft in the south. The thickness throughout essentially the entire area is greater than 150 ft. The quality of the salt is judged to be lower than that of the Lyons repository site or of Area 1.

Area 3. - Area 3 (Fig. 2.12) includes parts of Pawnee, Edwards, Hodgeman, and Ford counties. The northwestern part of the area is drained by tributaries of the Pawnee River; the remainder is drained by the Arkansas River. Structurally the area lies on the western flank of the Central Kansas Uplift.

Geology and Hydrology. - The upper part of the Wellington formation and the Minnescah shale are present between the Hutchinson salt and the Stone Corral formation. In the northern part of Area 3 the combined thickness of these rock units is about 400 ft; in the southern part it is about 500 ft.

The Stone Corral formation overlies the Minnescah shale. This unit, about 25 to 30 ft thick, is composed principally of anhydrite in Area 3.

The Harper sandstone, the Salt Plain formation, the Cedar Hills sandstone, and the Flower-pot shale, with an aggregate thickness of about 630 ft, are present between the Stone Corral and the Blaine formations. Moderate to large quantities of highly mineralized water are available from this section of rocks in Area 3.

The Blaine formation, composed principally of gypsum and about 20 ft thick, is overlain by about 250 ft of silty shale and dolomite. Little sandstone is present in these rocks in this area, and only small quantities of water are available.

About 400 to 450 ft of Lower Cretaceous rocks composed of the Cheyenne sandstone, Kiowa formation, and the Dakota formation unconformably overlies the Upper Permian rocks in Area 3. Much of the Cheyenne is comprised of sandstone, and moderate to large quantities of highly mineralized water are available from the unit in this area. The Kiowa formation is not an important aquifer. The Dakota formation, which crops out in a small area in the northwestern part of Area 3, is composed principally of clay, shale, and sandstone. A few miles west of the western border of Area 3, the

sandstone in the Dakota thickens and is very permeable. As much as 1000 gpm of good-quality water can be obtained from wells in this area. Eastward the sandstone thins and is less permeable, and yields of wells are considerably smaller; however, yields of 200 to 300 gpm can be obtained locally.

The Upper Cretaceous Graneros shale and Greenhorn limestone crop out in the northwestern part of Area 3. These units are composed of shale, chalky shale, and chalky limestone and yield little or no water to wells.

Thin deposits of sand, gravel, silt, and clay, which comprise a part of the Ogallala formation of Pliocene age, are present in the northern part of this area. These deposits yield small to moderate quantities of water to wells in local areas.

Pleistocene deposits underlie most of the land surface of Area 3. Older rocks occur at the surface only in the northern and northwestern parts of the area. In the uplands west of the Arkansas River Valley the surface is immediately underlain by loess. The loess overlies older Pleistocene silt, clay, and, locally, sand and gravel. Small to moderate quantities of water are available locally in this area. Alluvial deposits in the Arkansas River Valley commonly yield as much as 1000 gpm to wells.

Population and Transportation. - Population centers in this area are located along the railroads. Kinsley, the largest city, with a 1970 population of 2283, is located in the Arkansas River Valley at the junction of the mainline of the Atchison, Topeka, and Santa Fe Railroad and the Great Bend Branch of the Santa Fe.

U.S. Highway 50 crosses the southern part of the area from east to west; U.S. Highway 56 crosses the area from northeast to southwest; and U.S. Highway 183 crosses the area from north to south.

Oil and Gas. - Relatively small fields from which oil or gas has been produced are found in all parts of Area 3. At the present time there is little drilling activity; however, the area is located on the west flank of the Central Kansas Uplift, and the possibility of finding oil in stratigraphic or structural traps on the truncated Mississippian surface will probably generate more interest in the future.

Salt. — The Hutchinson salt occurs in Area 3 at depths of about 1650 ft in the northeast and about 1950 ft in the western part of the area. The salt ranges in thickness from about 350 to 400 ft. Its quality is comparable to that found in Area 2.

Area 4. — Area 4 (Fig. 2.12) includes all of Comanche County, which is adjacent to Oklahoma in south-central Kansas. The western part of the area is drained by the Cimarron River and its tributaries. The eastern part of the area is drained by Salt Fork Creek. Structurally the area lies on the northern flank of the Anadarko Basin in a part of the basin that has been called the Dodge City Embayment. The area is located west of the Pratt Anticline and southwest of the Central Kansas Uplift.

Geology and Hydrology. — In Area 4, the upper part of the Wellington formation and the Ninnescah shale between the Hutchinson salt and the Stone Corral formation have an aggregate thickness of about 800 ft. The section of rock between the top of the Ninnescah shale and the top of the Blaine formation, composed of the Stone Corral formation, Harper sandstone, the Salt Plain formation, Cedar Hills sandstone, Flower-pot shale, and the Blaine formation, is about 600 ft thick. The Stone Corral is composed principally of anhydrite in the area; the Blaine formation is predominantly gypsum. The other rock units in the area are chiefly silty shale or siltstone; however, in local areas much sandstone occurs in the Cedar Hills sandstone. Sandstone is less prominent in the Salt Plain formation. Moderate quantities of highly mineralized water are probably available from the sandstone beds.

The Flower-pot shale is the oldest rock unit that crops out in Area 4. The Flower-pot is overlain by the Blaine formation, which is, in turn, overlain by the Dog Creek formation of Lower Permian age and the Whitehorse formation of Upper Permian age. Salt which occurs just below the Blaine in counties north and west of Area 4 is not present in this area. The Whitehorse has the greatest areal distribution of the bedrock units in the area. Small exposures of the Big Basin formation occur in the southern part of the area.

The Lower Cretaceous Cheyenne sandstone and Kiowa formation unconformably overlie the Whitehorse formation in the northeastern and central parts of Area 4, and locally overlie the Big Basin formation in the southern part of the area. The Cretaceous rocks are overlain by sheetlike deposits of sand and gravel of probable early Pleistocene age. Only small quantities of water are available from the Cretaceous rocks near the outcrop.

Alluvial deposits of Pleistocene age which occur in the western and southwestern parts of Area 4 are generally thin. The sheetlike deposits in the northern part of the area may be as much as 100 ft thick. Wells in this area may yield several hundred gallons of water per minute locally. Near the outcrop margins the deposits are largely drained and yield only small quantities of water.

Alluvial and low terrace deposits in and adjacent to the principal streams are generally thin and yield only small quantities of water to wells; however, locally, these deposits thicken and may yield several hundred gallons per minute.

Dune sands occurring adjacent to streams in the western part of the area and in an upland position in the central part of the area are thin and unimportant as a source of water.

Population and Transportation. - Population centers are located along the Englewood Branch of the Atchison, Topeka, and Santa Fe Railroad. Coldwater, with a 1970 population of 1206, is the largest city. U.S. Highway 160 crosses the area in an east-west direction; U.S. Highway 183, a north-south thoroughfare, serves the northern part of the area.

Oil and Gas. - Area 4 contains scattered oil and gas fields. Numerous dry holes have been drilled throughout the area; nevertheless, there are several areas in which little or no drilling has been done. Exploration has been quite active in Area 4. Production, which arises from the Pennsylvanian, Mississippian, and Ordovician rocks, is related to structural and stratigraphic traps.

Salt. - The Hutchinson salt occurs in Comanche County at a depth ranging from about 1650 to 1800 ft. The thickness of the Hutchinson salt in this area ranges from approximately 450 to 500 ft. The quality of the

Hutchinson salt in this area is judged to be poorer than that of the Lyons repository site or of Area 1. It is similar to that of Areas 2 and 3.

Area 4 is not far distant from areas where solution has occurred in the salt beds. Collapse features, which are believed to be associated with solution of salt along faults, occur in Meade County, to the west. In Clark County, the Big and Little basins are collapse features probably associated with salt dissolution in a local area. These solution features are likely associated with dissolution of the Blaine salt, which occurs about 600 ft above the Stone Corral. There is no known evidence of solution in the Hutchinson and Cimarron salts.

Area 5. - Area 5 includes all of Harper County, which borders Oklahoma in south-central Kansas. This area is drained in the west by Spring Creek and in the east by Bluff Creek and the Chikaskia River, all of which are tributaries of the Salt Fork River in Oklahoma. Structurally Area 5 lies within the Sedgwick Basin on the east flank of the Pratt Anticline.

Geology and Hydrology. - Although about 250 to 300 ft of the upper part of the Wellington formation is present between the Hutchinson salt and the base of the Ninnescah shale in this area, it contains little, if any, water. The Ninnescah shale is about 400 ft thick in the southern part of the area but thins toward the north. The upper part of the Ninnescah crops out in eastern Harper County but yields little or no water to wells in the area except from the upper weathered zone in the outcrop area, where small quantities of water are available locally.

The Harper sandstone and the Salt Plain formation overlie the Ninnescah in Area 5. The Stone Corral formation, which lies between the Ninnescah formation and the Harper sandstone in other areas of the state, is absent in Harper County. The Harper sandstone and the Salt Plain formation are composed principally of red, silty shale but locally contain thin beds of fine sandstone. Their combined thickness in this area is about 500 ft. Water is generally not available from the Harper sandstone or the Salt Plain formation in this area except for small supplies, locally, from the sandstone beds.

Deposits believed to be a part of the Ogallala formation of Pliocene age crop out in the southeastern part of Area 5 in a high upland position. These outcrops are thin and largely composed of sand and gravel derived from Cretaceous and Permian rocks. These deposits yield no water to wells in the area.

Pleistocene sand and gravel deposits of the Nebraskan and Kansan stages are present in the uplands in northern and northwestern Harper County. These deposits are as much as 100 ft thick and, locally, may yield as much as 300 gpm of water to wells.

Kansan age deposits occur in a high terrace position along Bluff Creek in the southern part of Area 5. In this area, much silt is present in the deposits and yields to wells are generally low.

Sand and gravel in channels beneath thick silt deposits occupying the slope between the upland Nebraskan and Kansan deposits and Sand Creek Valley in the area near and east of the city of Harper are probably Illinoian in age. These deposits may yield as much as 500 gpm of water locally.

Alluvium and low terrace deposits in and adjacent to the stream valleys yield only small quantities of water to wells.

Population and Transportation. — Population centers in Area 5 are located along railroads. The Kiowa Branch of the Atchison, Topeka, and Santa Fe Railroad and several other branch lines of the Santa Fe serve the area. A branch line of the Missouri Pacific Railroad serves the southern part of the area. U.S. Highway 160 crosses the area in an east-west direction; several state highways cross the area in both east-west and north-south directions, thereby connecting all of the cities to the highway system.

Oil and Gas. — A portion of the Spivey-Grabs-Basil oil and gas field, one of the larger fields in Kansas, covers much of the northwestern part of Area 5. Several smaller fields are located principally in the northern and eastern parts of the area. Many exploration holes have been drilled throughout Harper County. Most producing wells have not had large initial yields, but they have continued to produce for many years. The area is considered to have good potential for future exploration.

Salt. - In Area 5 the Hutchinson salt occurs at a depth of about 550 ft in the northeast and about 1000 ft in the northwest and southwest. The thickness of the salt ranges from about 200 ft in the east-central part of the area to about 400 ft in the west. The salt is about 350 ft thick in the area of least drilling activity. Although the quality of the salt in this area is the poorest of that in any of the eight areas studied, the absence of water above the salt beds makes Area 5 suitable for consideration.

Area 6. - Area 6 (Fig. 2.12) includes 12 townships in western Reno County, north of the North Fork Ninnescah River. The southern portion of the area is drained by the Ninnescah River; the northern portion is drained by the Arkansas River. Structurally the area lies in the northwestern part of the Sedgwich Basin and on the eastern flank of the Central Kansas Uplift.

Geology and Hydrology. - Lower Permian rocks consisting of part of the Wellington formation, the Ninnescah shale, and the Stone Corral formation occur above the Hutchinson salt but do not crop out in Area 6. The upper portion of the Wellington formation consists of about 200 ft of principally gray shale, although it contains some red shale near the top and a few thin beds of anhydrite and dolomite. The Ninnescah shale is composed of about 300 ft of red shale and minor amounts of siltstone. The Stone Corral formation is comprised of about 20 ft of anhydrite and dolomite. Little or no water is available from these rock units in this area.

The Harper sandstone, which overlies the Stone Corral formation, is the oldest rock unit that crops out in Area 6. This unit, composed of silty shale and siltstone, is about 150 ft thick and dominantly red in color. The Harper sandstone yields small quantities of water to a few wells from the upper weathered part of the formation.

Sand and gravel deposits that contain considerable quantities of silt and are believed to be part of the Ogallala formation of Pliocene age are present in an upland position in the southern part of Area 6. These deposits are red or dark reddish-brown and are composed of materials largely derived from Permian and Cretaceous rocks. They occur in relatively

thin, sheetlike deposits. Other sand and gravel deposits, similar in lithology and color, occur in channels in this same general area but at a somewhat lower elevation. These deposits may be earliest Pleistocene in age (Nebraskan) and derived from the older Ogallala deposits. Small to moderate quantities of water are available to wells from these deposits.

A deep channel cut into the Permian bedrock extends southeastward from the northwest corner of the area to a point about 7 miles south of the northeast corner of the area. This channel is filled with Pleistocene stream deposits. The lower part, locally as much as 100 ft thick, contains red and reddish-brown sand and gravel similar to the channel deposits in the southern part of the area. These deposits, which are thought to be Nebraskan in age, contain highly mineralized water. The Nebraskan deposits in the channel area are overlain by younger Pleistocene deposits of probable Kansas and Illinoian age. These younger sheetlike deposits underlie the surface and rest on Permian rocks throughout all of Area 6, except in and near the valley of the Minnescah River. The Pleistocene deposits may be as much as 100 ft thick and yield large quantities of water to wells in local areas.

Dune sand, principally of Wisconsinan age, overlies the earlier Pleistocene deposits in a significant portion of the area. The dunes are well stabilized in most of the area; however, some of the dunes in the northwest are active and drainage is poorly developed.

Thin loess deposits overlie the Kansas and Illinoian deposits in the southeastern part of Area 6.

Recent alluvium and low terrace deposits are present in the valleys of the Arkansas and Minnescah rivers. In the Minnescah Valley, these deposits are thin and only moderate quantities of water are available. Yields of wells in excess of 1000 gpm are obtained in the Arkansas River Valley.

Population and Transportation. — Population centers are located along the main lines of the Rock Island and Pacific Railroad in the southern part of Area 6, along the main line of the Atchison, Topeka, and Santa Fe Railroad in the central part, and along the Great Bend

Branch of the Santa Fe in the north. The largest city within the area is Arlington, which had a 1970 population of 503. Hutchinson, located about 12 miles east of the area, had a 1970 population of 36,885.

U.S. Highway 50 crosses the area in an east-west direction, and State Highway 14 crosses the eastern portion of the area in a north-south direction. State Highway 61 crosses the area in a northeast-southwest direction in the southern portion of the area.

Oil and Gas. - The Zenith-Peace Creek Field in northwestern Reno County dominates the oil and gas production in Area 6. Other smaller fields occur in the northern two-thirds of the area. Production is from rocks ranging in age from Ordovician to Permian. Large areas are present in the southern part of Area 6, where no production has been obtained although the area has been extensively drilled.

Area 6, located in the northwestern part of the Sedgwick Basin and on the eastern flank of the Central Kansas Uplift, has possibilities for additional production from stratigraphic traps.

Salt. - The Hutchinson salt occurs in Area 6 at depths of about 700 ft in the eastern section to about 1000 ft in the west, and ranges in thickness from 350 ft to about 435 ft. The thickest salt deposit occurs near the center of the area, where it overlies a structural high. The possibility that thickening of the salt was the result of mass flow was investigated in one phase of this study. It was found that the correlation between the thicker salt sections and the structural highs could be satisfactorily explained by facies changes, pinchout, overlap, and other original depositional features. The quality of the salt in Area 6 is intermediate between that of Lyons and that of Area 5, and somewhat better than that of the salt of Areas 2 and 3.

Area 7. - Area 7 (Fig. 2.12) includes all of Rice County, which is located near the center of the State. The area is drained on the south and west by the Arkansas River and on the east by the Little Arkansas River. A small area in the northeastern part of Rice County is drained by tributaries of the Smoky Hill River. The eastern part of the area lies within the Sedgwick and Salina basins. The western one-half of the county is located on the flank of the Central Kansas Uplift.

Geology and Hydrology. - The upper part of the Wellington formation between the top of the Hutchinson salt and the base of the Ninnescah shale ranges in thickness from about 250 to about 300 ft. The Wellington is composed principally of gray and blue-gray shale but contains thin beds of red shale and anhydrite. Little or no water is available from the unit in this area.

The upper part of the Ninnescah shale crops out in eastern Rice County. This unit, which is composed chiefly of red and reddish-brown shale, is about 300 ft thick in the area. Only about the upper 50 ft of the unit is exposed. The Ninnescah contains little or no water except in the upper weathered part, which yields small quantities of water to wells in the outcrop area.

The Stone Corral formation overlies the Ninnescah shale and crops out in eastern Rice County. On the outcrop, the Stone Corral is about 6 ft thick and is composed principally of dolomite. West of the outcrop, the Stone Corral is about 18 ft thick in the subsurface and is composed of anhydrite, dolomite, gypsum, and shale. The Stone Corral yields small quantities of water to wells in the area of outcrop and contains only small quantities of water near the center of the county. The Stone Corral contains little, if any, water in the northern and western parts of the county.

The Harper sandstone, overlying the Stone Corral, is the youngest Permian rock unit in Area 7. The Harper is about 150 ft thick in places where a full section is present. The unit is composed principally of red, silty shale and red siltstone and yields little or no water to wells in the area.

Lower Cretaceous rocks overlie the Harper sandstone in this area. The contact between these rocks and the Permian rocks marks a major unconformity in this area. The oldest Lower Cretaceous rock unit in Kansas is the Cheyenne sandstone, which overlies the Permian Harper sandstone in the western part of Area 7. The Cheyenne is composed of very fine, silty sandstone and siltstone and is not an important aquifer. The Cheyenne does not crop out in this area.

The Kiowa formation overlies the Cheyenne sandstone in the western part of Rice County. Eastward the Kiowa overlaps the Cheyenne and rests on the Harper sandstone. It is about 150 ft thick in places where a full section is present; however, it thins to zero thickness toward the south and east. The availability of water in the Kiowa is dependent on the presence of the sandstone beds as well as on their thickness (a few inches to several tens of feet). Yields of wells range from only a few gallons per hour to as much as 50 gpm.

The Dakota formation overlies the Kiowa formation in the northern part of Rice County, and may reach a thickness of 200 ft. The unit thins to zero thickness toward the south. It crops out principally in the headwater area of the Little Arkansas River. In the north-central and northwestern parts the Dakota is overlain by silts of Pleistocene age and crops out only in small isolated areas. This formation is principally composed of clay, shale, and sandstone but contains some lignite and beds of iron-cemented sandstone. Colors range from red, brown, and gray to white. Sandstone beds occur throughout and may comprise about one-third of the total thickness. The quantity of water that may be obtained by wells from the Dakota is dependent on the amount of sandstone present. Maximum yields are probably about 200 gpm; however, smaller yields are more commonly obtained.

The Ogallala formation of Pliocene age is represented in this area by a soil caliche formed during the long period of weathering that occurred prior to Pleistocene deposition in the area. The soil caliche is thin and not present everywhere.

Pleistocene rocks unconformably overlie the bedrock units in much of Area 7. Alluvial deposits are present in the valleys of the Arkansas River, Cow Creek, and the Little Arkansas River. Early Pleistocene channel deposits underlie alluvial deposits in the west-central part of the area roughly parallel to Cow Creek and in the south-central part of the area underlying the valleys of the Arkansas River and Cow Creek. Large quantities of water are available from these deposits.

Dune sand overlies the alluvial deposits in the valleys of the Arkansas River and Cow Creek. It overlies channel deposits or Cretaceous

rocks in west-central Rice County and Permian rocks in southeastern Rice County. The dune sand deposits are not important aquifers in Area 7.

Loess underlies the surface in much of the upland areas of the county. Very small quantities of water are available to wells locally from these deposits; however, most wells penetrate the deeper rocks to obtain more dependable supplies.

Population and Transportation. — Population centers in Rice County are located along railroads serving the area. Lyons, the largest city, is located near the center of the County and is served by branch lines of the Atchison, Topeka, and Santa Fe Railroad, the Missouri Pacific Railroad, and the St. Louis and San Francisco Railroad. The main line of the Missouri Pacific Railroad serves population centers in the extreme northern part of the county. The city of Sterling, in the southern part of the area, is served by the Great Bend Branch of the Santa Fe Railroad.

U.S. Highway 56 passes east-west through the center of the county. State Highway 4 passes east-west through the extreme northern part of the area, and State Highway 14 crosses north-south through the center of the area.

Oil and Gas. — Rice County is one of the most heavily drilled areas in Kansas. Oil and gas fields occur throughout Area 7, and many exploratory holes have been drilled outside the fields. Production has been obtained from rocks ranging in age from Precambrian to Permian. The western part of the area is located on the eastern flank of the Central Kansas Uplift; the eastern part lies in the westernmost sections of the Salina and Sedgwick basins. Although the area is already highly developed, exploration is expected to continue at a high level of intensity.

A natural gas storage area is located near Alden (in the southwestern part of Rice County).

Salt. — In Area 7 the Hutchinson salt occurs at depths ranging from about 450 ft in the east to about 1000 ft in the west. The thickness of the salt ranges from 230 to about 390 ft. The quality here is similar to that of Area 1 and somewhat better than that of Areas 5 and 6.

Area 8. - Area 8 consists of a large area of far-western Kansas, which is composed of Wallace, Logan, Greeley, and Wichita counties and a small part of western Scott County (Fig. 2.12). The northern half of the area is drained by the Smoky Hill River; the southern part is drained by White Woman Creek, which empties into the Scott-Finney depression and has no connection with major trunk streams. The area lies in the northern part of the Hugoton Embayment.

Geology and Hydrology. - Permian rocks between the Blaine formation (Lower Permian) and the Morrison formation of Jurassic age thin toward the north and east in this area. The Permian section of rocks is about 320 ft thick in Greeley County. It is about 280 ft thick in Wichita County, and about 170 and 150 ft, respectively, in Wallace and Logan counties. Thinning is probably due to post-Permian--pre-Jurassic erosion. Generally the rocks are composed principally of silty to sandy shale; however, the Whitehorse formation in Area 8 contains sandstone and should yield some highly mineralized water to wells.

The Morrison formation in this area is about 100 ft thick and is composed principally of shale and sandy shale but may contain thin beds of limestone locally.

The Lower Cretaceous Cheyenne sandstone, the Kiowa formation, and the Dakota formation have a nearly constant aggregate thickness of about 400 ft in Wichita, Greeley, Wallace, and Logan counties. Both the Cheyenne and the Dakota contain appreciable amounts of sandstone and should yield moderate to large quantities of water to wells. Water from the Dakota is locally of usable quality, but Cheyenne water is probably too highly mineralized for use.

Upper Cretaceous rocks between the top of the Dakota and the base of the Niobrara chalk are composed of shale, chalky shale, limestone, and chalk. These rocks comprise the Graneros shale, Greenhorn limestone, and Carlile shale and are about 400 ft thick. Little, if any, water is available from these rocks.

The oldest bedrock unit that crops out in this area is the Smoky Hill chalk member of the Niobrara chalk. Although this unit is extensively

exposed in the valley of the Smoky Hill River in Logan County, it crops out only in small exposures in the valley of Chalk Creek in Scott County. It is not exposed in Wichita County. In parts of Wallace and Logan counties the Niobrara chalk is about 650 ft thick where it has not been eroded. In northwestern Wichita County the Niobrara is about 500 ft thick but thins toward the south and east.

The Pierre shale overlies the Niobrara chalk in parts of Wallace and Logan counties. The Pierre may be as much as 600 ft thick locally in Wallace County but thins toward the east where it has been eroded. This unit may be present below the Ogallala formation in northern Greeley County, even though it is apparently absent in Wichita and Scott counties.

Earliest Ogallala deposition occurred in relatively shallow, broad channels cut in the eroded and beveled Cretaceous surface. Continued deposition of these clastic deposits soon filled the channels and, by middle Ogallala time, had topped the divide areas between the channels. At the end of Ogallala time, this area, most of western Kansas, and large areas in adjoining states formed a broad alluvial plain with a gentle eastward slope. Since the end of Ogallala deposition, several hundred feet of Ogallala and Upper Cretaceous rocks has been eroded in the valley of the Smoky Hill River. The thickest Ogallala deposits in Logan County are presently found in the northern part. These deposits thin to zero thickness toward the Smoky Hill River Valley. Thin deposits of Ogallala occur in the uplands in western and southwestern Logan County.

In Wallace County more than 300 ft of Ogallala is present in local areas; however, the normal thickness is considerably less. The Ogallala is quite thick in north-central and northeastern Greeley County, although somewhat thinner than in Wallace County. In western and southern Greeley County it ranges in thickness from 150 to about 200 ft. The formation thins to less than 50 ft in local areas in the southern part of Wichita and Greeley counties.

Moderate to large supplies of water are obtained from the Ogallala in northern Logan County. In Wallace County, where the thickest deposits occur, wells yielding as much as 1500 gpm are obtained; however, well

yields of about 1000 gpm are more common. In western and southern Greeley County, where the Ogallala is thin, much less water is available to wells. In northern Wichita and Scott counties, yields of wells are commonly about 1000 gpm. Yields of wells diminish southward in these counties, and only small quantities of water are available in the extreme southern part of the area.

During the Pleistocene several hundred feet of older deposits were eroded in Logan County and in the eastern part of Wallace County.

Pleistocene fluvial deposits occur as low terrace deposits or alluvium in the Smoky Hill Valley and in the valleys of the larger tributaries. Erosion during this period was much less severe in Greeley and Wichita counties and in the western part of Scott County. In eastern Wichita County, White Woman creek flows about 100 ft below the highest uplands on either side of the stream. The degree of erosion was probably controlled by the fact that White Woman Creek flows into a closed basin and does not have surface access to a through-flowing stream. Thin alluvial deposits of Pleistocene age occur in the valleys of White Woman and Ladder creeks in these counties. Larger water supplies are generally not available from Pleistocene deposits in the western part of Scott County or in Wallace, Logan, Greeley, and Wichita counties, except locally in the Smoky Hill River Valley.

Loess, principally of late Pleistocene age ranging up to 50 ft in thickness, overlies older deposits in much of Area 8. In the upland areas the loess overlies Ogallala deposits. In the valley of the Smoky Hill River, thin loess overlies Cretaceous rocks in local areas.

Faulting and Solution Features. - Numerous small faults can be observed in the Cretaceous rocks in Wallace and Logan counties. Generally, displacement along faults is small; however, a displacement of as much as 35 ft has been observed in Wallace County. From our present knowledge of the area, it is not known whether faulting affects deeply buried rocks in the area or is confined only to the Cretaceous rocks. Faulting is seen only in the Cretaceous rocks and does not appear to have affected the Ogallala or younger deposits. If the faulting is deep seated, it

no doubt extends beyond the area where it can be observed. On the other hand, if the faulting is related to adjustments that may have occurred due to unloading of the Cretaceous rocks when great quantities of overlying rocks were eroded, the faulting may be relatively shallow and confined to the valley area where erosion occurred.

Two instances of development of sinks or collapse of surface rocks have occurred in Wallace County since this area has been inhabited — one in 1900 and the other in 1926. The area affected by the latter measured about 350 by 250 ft and was reported to be 300 to 500 ft deep before being filled with water from the Smoky Hill River. Other areas of sinking in which Cretaceous rocks are affected have been observed in Wallace County. These may represent collapse features that occurred before the area was inhabited. The abnormal saturated thickness of the Ogallala in local areas in Wallace County may be an indication of old collapse features. No similar collapse features have been observed in Logan County.

The cause of the collapse of surface rocks may be attributed to the chalk or, if the faulting in the area is deep-seated and affects the deeply buried rocks, dissolution of salt may have occurred, thereby permitting the overlying beds to collapse. Chalk is soluble in water to some extent, especially if the water is slightly acidic. However, in Area 8, large quantities of water are not known to occur in the chalk; nor is the chalk cavernous on the outcrop.

Large quantities of water are available in the Lower Cretaceous rocks several hundred feet above the Blaine salt. Migration of this water downward through the salt via fractures or faults could have caused dissolution.

Population and Transportation. — Population centers in Wallace and Logan counties, with the exception of Russell Springs (Logan County), are located along the Union Pacific Railroad, which enters the area at the northeast corner of Logan County and enters Colorado near the center of the west line of Wallace County.

The only incorporated cities in Wichita and Greeley counties are located near the centers of the counties, along the Missouri Pacific Railroad.

Wallace and Logan counties are served by U.S. Highway 10, which passes east-west through the area. State Highway 25 crosses Logan and Wichita counties in a north-south direction. State Highway 27 crosses Wallace and Greeley counties from north to south. State Highway 96 is an east-west highway serving Wichita and Greeley counties.

Oil and Gas. - Only a limited amount of oil and gas drilling has been done in Wallace, Logan, Greeley, and Wichita counties and in the western part of Scott County. Production from a few wells has been small. This area is in the northern part of the Hugoton Embayment, north of the large Hugoton Gas area. At the present time the part of eastern Colorado that adjoins Area 8 is receiving considerable attention by oil operators. There is considerable potential for finding production from structural and stratigraphic traps in Wallace and Greeley counties. Few wells have been drilled in Wichita County, and only minor oil and gas production has been obtained in this area.

Salt. - Area 8 was included in this study when it was recognized that salt deposits just below gypsum beds of the Blaine formation met the assigned study parameters of thickness and depth. This salt deposit is referred to as the Blaine salt. In northwestern Wallace County the Blaine salt occurs at a depth of about 2800 ft and is only about 100 ft thick; in central Logan County it occurs at a depth of about 1750 ft and is nearly 300 ft thick but thins rapidly toward the north and east. The Blaine occurs at a depth of about 2000 ft and is about 300 ft thick in eastern Greeley County; however, the depth to salt increases and the thickness decreases toward the west. In northwestern Wichita County the salt occurs at a depth of about 2000 ft; in southeastern Wichita and western Scott counties it occurs at about 1450 ft. The thickness ranges from about 350 ft in the north to about 440 ft in the south. Results of a study of core description and radioactive logs indicate that the salt in this area is of better quality than that in any of the other areas examined.

Summary and Ranking. - Based on the information collected in this study, the Kansas Geological Survey ranked the eight areas according to their suitability as follows:

Area 1 appears to be the best prospect for future study. It is distant from regional oil and gas development and offers large areas from which sites having very few or no existing oil wells within the buffer zones could be selected. The character and quality of the salt deposit appear to be suitable.

The likelihood of unknown hydraulic connection between the salt and an aquifer above or below the salt in Area 1 caused by an old drill hole or fracture pattern is slight. The potential for oil and gas development is considerably less than in any of the other seven areas considered.

Area 8 (eastern part) contains a rather thick salt deposit of high quality about 1700 ft deep and consequently is rated above all other areas except Area 1. Furthermore, it lies in extreme western Kansas, far to the west of major regional oil and gas producing areas. The western part of the area is on the eastern fringe of an oil and gas development in eastern Colorado and, therefore, will probably undergo vigorous exploration even though it is largely undrilled at the present. Additional problems in this part of the area could be anticipated because of anomalous structural and hydrologic conditions.

Area 5 is ranked next because this area has considerably less ground water above the salt than any other area. Of course, this advantage must be balanced against a salt formation which appears to be of marginal thickness and poor quality. Although oil and gas exploration has been active, sparsely drilled areas do exist.

Area 6 lies to the south of the Lyons site on the southeast flank of the regional oil and gas development trend. The area has been, is being, and will continue to be actively explored. The salt deposit is somewhat thicker and shallower than at Lyons and should be of comparable quality. Problems involving water above and below the salt beds will be as great as in any area studied. Because of old oil and gas holes and copious quantities of ground water in the area, Area 6 ranks below Areas 1 and 5, but above Areas 2, 3, and 4.

Area 2 lies on the western side of an area of regional oil and gas development. It is now undergoing active exploration and, in addition,

has good potential for future oil and gas development. The area is marginal in terms of the properties of the salt deposit in that it is nearly 2000 ft deep. The potential for problems relative to water above and below the salt, in addition to old holes and depth to salt, makes this area a poor candidate for further study.

Area 3 can be categorized much the same as Area 2 and is a poor prospect for future study.

Area 4 lies to the west of regional oil and gas development and to the east of a large area that appears to have undergone some salt dissolution and faulting. The study area has been (and is still being) actively explored for oil and gas. This area, like Areas 2 and 3, is marginal in meeting the requirements of thickness, depth, and purity of the salt deposit. The salt is about 1700 ft deep. Problems concerning water above and below the salt, existence of old holes, depth to salt, and salt dissolution immediately to the west make Area 4 a poor prospect for future study.

Area 7 lies on the east flank of the regional oil and gas development. This area contains the largest number of producing wells, the greatest history of exploration, and the highest potential for future development of any area considered. The salt deposit is of good quality, ranges in depth from 450 to 1000 ft, and is 230 to 390 ft thick. (This area contains the Lyons site.) Medium to low quantities of ground water exist above the salt. Large number of old oil and gas holes, the presence of water above and below the salt, possible deep-seated structural problems, a high potential for development in the future, and an inadequate buffer zone make Area 7 the poorest candidate for future study.

2.2.2 Site Explorations

The second phase of the site reconnaissance work in Kansas involved the identification and more-detailed examination of three specific sites. This was accomplished by first identifying three areas of approximately 36 square miles each, based on the conclusions of the screening survey and on the information compiled in that survey. Two of these areas were located in Lincoln County (Study Area 1); the third was in Wichita County

(eastern part of Study Area 8). The best specific site, encompassing approximately 2 square miles, in each of these three areas was then selected. This selection was based on field reconnaissance of the areas, with particular attention being paid to topographic and cultural features. The three sites, identified as A and A₁ in Lincoln County and D₁ in Wichita County (see Fig. 2.12), as well as the area immediately surrounding them, were then further investigated. These investigations consisted of continued field surveys and the drilling and testing of a core hole through the salt formation at each of the three sites. The results of these investigations are discussed below.

Site A. - Site A is located in south-central Lincoln County, Kansas, and includes the SE 1/4 Sec. 21, S 1/2 Sec. 22, all of Sec. 27 and the E 1/2 Sec. 28, T. 13S., R. 8W.

Topographic, Surface Geologic, and Cultural Features. - Most of the area within a 5-mile radius of the site is drained by tributaries of the Saline River. A drainage divide is located about 5 miles south of the site. South of the divide, drainage is to the Smoky Hill River. Spring Creek, west of the site, and Elkhorn Creek, east of the site, generally maintain a small flow throughout the year but may cease to flow during prolonged drought periods.

The topography consists of relatively flat-topped hills with steep walls breaking downward to relatively narrow valleys. Maximum relief is about 250 ft. In the 1440-acre site area, the hill tops are underlain by thin deposits of Carlile shale. These deposits have a maximum thickness of about 20 ft in this area. The escarpment near the edge of the hill tops is held up by the Greenhorn limestone, which is about 65 ft thick in this area and extends well down the hill slopes. The Graneros shale underlies the Greenhorn and is about 30 ft thick. This unit generally occupies the lower part of the slope. The Dakota formation is locally present in the lowest part of the hill slopes and underlies thin colluvial or alluvial deposits in the valley bottoms.

High-pressure natural gas lines traverse this part of Lincoln County. Two parallel lines, which run in a north-south direction, are present adjacent to the east side and partially within the 1440-acre

site area. There are no service connections to these lines within a 5-mile radius of the site. The lines are owned by the Cities Service Company. Four high-pressure natural gas lines running in a northeast-southwest direction are present about 5-1/2 miles northwest of the site. These lines are owned by the Pipeline Company of America. No service connections are present within the area.

A buried communications cable trending north-south crosses the area about 1 mile east of the site. This cable connects with an east-west trending cable, which is about 1 mile south of the site at its nearest point. These cables are operated by the Bell system. Another buried cable, which is operated by the United States Air Force, runs in an east-west direction about 3-1/2 miles south of the site. Local service is furnished residents in the area by aboveground lines.

Electric power is supplied to the local residents by the Sunflower Electric Cooperative. Most of the power lines serving the area are single-phase, 7200-V lines. A three-phase 7200-V line runs west along the section line 3 miles south of the site. A main power transmission line crosses the general area in a northwest-southeast direction about 2 miles south of the site. This line, which is owned by the Central Kansas Power Company, is designed for 230,000 V but is presently energized at 115,000 V.

Hydrology. - The area surrounding Site A is generally well supplied with domestic and stock water supplies. Although the Dakota formation is the principal aquifer in the area, a few wells obtain water from alluvium or colluvium in the stream valleys. Although some wells are located on the tops of hills, most are located on the slopes or in the valleys. Depths of wells in the area are quite variable, ranging from about 30 ft in some valley areas to more than 300 ft in upland areas where Lower Cretaceous rocks are fully penetrated.

The potential yields of wells in this area are difficult to estimate. Generally, stock and domestic wells are not fully penetrating but are only deep enough to furnish the required quantity of water. Records were obtained for only three wells that produce appreciable quantities of water. A well located just south of Interstate Highway 70 near the

south border of Site A produced 195 gpm, and another well located adjacent to I-70 about 8 miles west of the site produced about 100 gpm. A third well located about 3 miles south of the city of Lincoln produces about 250 gpm. All of these wells obtain water from Lower Cretaceous rocks.

Core Drilling. - The test hole (AEC No. 3) was drilled at the northeast corner of the site at a ground elevation of 1620 ft. The formations penetrated and their depths and thicknesses are shown in Fig. 2.13. In general, the formation contacts were slightly lower than had been predicted, based on correlations of logs from nearby oil and gas test wells. As a consequence, the thickness of the Hutchinson salt (157 ft) was considerably thinner than the 240 ft expected. The sections of the hole which were cased and those which were cored are also shown in Fig. 2.13.

Hydrologic Testing. - The U.S. Geological Survey performed hydrologic tests in each of the three holes. In general, the objectives of these tests were: (1) to confirm the expected extremely low permeabilities immediately above and below the salt section, which is an indication that natural dissolution has not occurred, and (2) to determine the quantity of water available in aquifers above the salt as a part of the assessment of the potential for future dissolution. The results of these tests are summarized in Table 2.4.

For AEC Hole No. 3 at Site A, these results can be interpreted as follows: First, tests 1 and 2 indicate that the zone immediately below the salt (depth, 967-1100 ft) is very tight and has a very low permeability. The zone immediately above the salt (409-967 ft, by difference) is also tight and has a low permeability, although not quite as low as the zone below the salt. Test 3 was performed by pumping the well after having perforated the casing opposite the sandstones of the Lower Cretaceous (Dakota). Results of the test indicated that a properly constructed well at this location probably would produce at least 300 gpm of water, which is adequate for stock or domestic supplies and might be sufficient for some sprinkler irrigation. This yield was somewhat more than had been expected.

AEC HOLE NO. 3

Fig. 2.13. Simplified Geological Log of AEC Hole No. 3.

Table 2.4. Summary of Hydrologic Tests

Hole No.	Test No.	Interval Tested (ft below land surface)	Static Water Level (ft below land surface)	Specific Capacity (or Relative S.C.) (gpm per ft of drawdown)	Transmissivity (gpd/ft)	Type of Test Performed
3	1	967-1100	211.61 ^a	2.4×10^{-5}	3.9×10^{-3}	Slug (swabbing)
3	2	409-1100	211.61 ^a	6.5×10^{-4}	1.5×10^{-1}	Slug (swabbing)
3	3	226-380	186.19	7.26	16,400	Pumping (drawdown)
4	1	1186-1275	262.46	3.1×10^{-5}	5.3×10^{-3}	Slug (swabbing)
4	2	650-1275	262.46	5.8×10^{-4}	6.0×10^{-2}	Slug (swabbing)
4	3	408-573	201.44	2.71	8,670	Pumping (drawdown)
5	1	1950-2150	928.47 ^a	2.6×10^{-5}	8.6×10^{-4}	Slug (injection)
5	2	1214-2150	928.47 ^a	2.4×10^{-4}	2.6×10^{-1}	Slug (injection)
5	3	1259-1376		b	b	Slug (injection)
5	4	742-980	556.00	0.083 ^c	160 ^c	Pumping (drawdown)

^aIndicates an estimated value.^bSee text.^cValue based on slug withdrawal analysis.

Salt Core Examination. - Detailed examination of the core samples obtained from AEC Hole No. 3 (see Fig. 2.13) indicated that the salt is of the same general character as that encountered at the Lyons site. Correlation of the core with logs from this well and nearby wells was sufficiently good to suggest continuity of the major beds. The top and bottom contacts of the salt formation were recovered intact. At the top contact, there was a small zone of missing salt marked by an anhydrite-shale breccia zone, immediately above which the sequence was horizontal. This indicates that dissolution occurred before deposition of the overlying material and was not associated with recent ground-water activity, which confirms the results of hydrologic tests in the well.

Three zones of good-quality salt, each approximately 20 ft thick, were identified in the depth range of 876 to 942 ft. These zones would be of potential interest for waste disposal operations.

Site A₁. - Site A₁ is located in northwestern Lincoln County and includes all of sections 8 and 17, T. 11S., R. 10W.

Topographic, Surface Geologic, and Cultural Features. - The area surrounding this site is drained by tributaries to the Saline River. Although most of the streams within the 2-square-mile area are not perennial, Spillman Creek, which drains much of the northeast part of the area, flows most of the time except during prolonged drought periods. Wolf Creek, on the south, maintains some flow at all times.

Topographically, Site A₁ is a relatively high upland. The area, which is flat to rolling, is underlain by thin loess deposits overlying the Upper Cretaceous Carlile shale except in the southwest corner, where the upper part of the Greenhorn limestone crops out in the valley of a small stream. The Graneros shale and the Dakota formation, the oldest exposed rocks, crop out about 2 miles south of the southern part of the 2-square-mile area. About 30 ft of Carlile is present in this area. The Greenhorn is about 90 ft thick and is underlain by 40 to 50 ft of Graneros shale. The combined thickness of the Dakota and Kiowa formations is approximately 420 ft. Alluvial deposits occur in Spillman Creek Valley and in Wolf Creek Valley.

One 12-in. crude oil pipeline traverses in a west-northwesterly to east-southeasterly direction about 1.5 miles north of the 2-square-mile area. This line is owned by the Amoco Pipeline Company.

No buried communications cables, except service cables extending from the overhead lines to the service outlet, were observed within a 5-mile radius of this site.

Electric power in this area and to the south is furnished by single-phase, 7200-V lines owned by the Sunflower Electric Cooperative. North of this area, power is furnished by the Mankato-Jewell Electric Cooperative. The nearest three-phase service is at either Lucas or Sylvan Grove.

Hydrology. - This area is, in general, adequately supplied with water. The Dakota formation is the principal aquifer. Alluvium in the valleys of Wolf Creek and Spillman Creek yields moderate supplies of water to wells within a 5-mile radius of the 2-square-mile area. The quantity of water available from many of the wells in the alluvium is sufficient for stock or domestic supplies. One well in Spillman Creek Valley is reported to have an initial yield of about 300 gpm; however, the saturated thickness of the alluvial deposits at this site is thin, and this well would probably yield no more than 100 gpm if pumped continuously. Surface water in the principal streams generally has a high chloride concentration at low flow stages, and it is probable that the alluvial deposits also contain water with a high chloride content locally.

Water from the Dakota is locally of poor quality in Lincoln County. Within 5 miles of the site, much of the water has a high sodium bicarbonate content. The chloride and sulfate concentrations are generally low in the southern part of the area but increase toward the north. The water may be unusable in the north and west.

Core Drilling. - The test hole (AEC No. 4) was drilled at the center of the east side of the site at a ground elevation of 1630 ft. The formations penetrated and their depths and thicknesses, along with an identification of the zones cased and cored, are shown in Fig. 2.14. Again in this hole, the thickness of the Hutchinson salt was only 166 ft (much less than expected), and the overlying formations were penetrated at slightly greater depths than anticipated.

AEC HOLE NO. 4

Fig. 2.14. Simplified Geological Log of AEC Hole No. 4.

Hydrologic Testing. - The procedure of the hydrologic testing in AEC Hole No. 4 at Site A₁ was essentially identical to that at Site A. The results, which are shown in Table 2.4, indicate that both the zone below the salt (1186 to 1275 ft) and the zone immediately above the salt (650 to 1186 ft by difference) are very tight and have extremely low permeabilities. The pumping test results for the Lower Cretaceous rocks indicate that this well should yield about 250 gpm of water if pumped at its maximum capacity. This production is adequate only for stock or domestic use and is about the quantity expected in this area.

Salt Core Examination. - The salt in AEC Hole No. 4 (see Fig. 2.14) is also typical of the Hutchinson. Correlation of the core and log with logs from a single existing well in the area is good, and continuity of major salt and anhydrite units within the salt section is to be expected. Both upper and lower salt contacts were recovered intact and unbroken. The loss of salt at the top of the section is marked by an unconformity within the salt section itself and by minor solution breccia within the overlying anhydrite-shale sequence. Overlying beds are horizontal within 2 ft of the top of the salt section. There is no evidence of dissolution by recent ground-water activity.

Only two zones were identified as being of sufficient thickness and quality to be of potential interest for waste disposal operations - one at a depth of 1073 to 1093 ft and the other at 1096 to 1118 ft. Both of these zones include sections of poor-quality salt.

Site D₁. - Site D₁ is located in south-central Wichita County and includes the SE 1/4 Sec. 22, S. 1/2 Sec. 23, all of Sec. 26, and the E. 1/2 Sec. 27, T. 19S., R. 37W.

Topographic, Surface Geologic, and Cultural Features. - The area surrounding the site is drained by White Woman Creek and Sand Creek, which is a tributary of White Woman Creek. Neither of these streams flows except for short periods following very heavy precipitation. White Woman Creek flows into the Scott basin or the Scott-Finney depression and has no surface connection with trunk streams in this part of Kansas.

Topographically the area consists of relatively flat, high upland with a gentle eastward slope. The area also has a gentle slope toward the principal streams and may become gently rolling near the streams. The upland area is underlain by 20 to 30 ft of loess, which thins to zero near the valleys of White Woman and Sand creeks. The Ogallala formation, which crops out only in the valleys of these creeks, underlies the loess. The average thickness of the Ogallala within 5 miles of the site is about 80 ft. Only locally is the Ogallala more than 100 ft thick in this area; however, the formation thickens considerably toward the west and north, well beyond the site. In the valley areas it thins to less than 50 ft locally. The Ogallala overlies the Niobrara chalk of Upper Cretaceous age, which is about 210 ft thick. Several hundred feet of the Niobrara was eroded before deposition of the Ogallala. The rock units below the Niobrara and above the Morrison formation and their thicknesses are: Carlile shale, 240 ft; Greenhorn limestone, 110 ft; Graneros shale, 55 ft; and the Lower Cretaceous Dakota formation, Kiowa shale, and Cheyenne sandstone with a combined thickness of 360 ft.

A graveled road runs north-south through the site. No buildings, power lines, or communication lines are present on the site. A 10-in. high-pressure natural gas line, owned by the Kansas-Nebraska Natural Gas Company, runs in a northeast-southwest direction about 2 miles south of the site. A three-phase power line runs east-west 1/2 mile north of the site, and additional single-phase and three-phase lines serve other parts of the general area. Communication lines within the 5-mile radius are all of the overhead type.

Hydrology. — One of the principal criteria considered in choosing this area for study was the general lack of large supplies of ground water; however, this area is well supplied with water for stock and domestic purposes, and several small irrigation wells are operated within a radius of 5 miles. An irrigation well 0.5 mile north of the site boundary has a reported yield from the Ogallala formation of about 390 gpm. A well located 2 miles southeast of the site yields 90 gpm, and two wells located approximately 2 miles west of the site each yield about 160 gpm. No irrigation wells are in operation (except the one well mentioned above)

south and east of this site, although there are numerous wells, all of which obtain water from the Ogallala formation, toward the north and west. Yields range from about 100 to about 1000 gpm. Only the lower part of the Ogallala is saturated in this area, which accounts for the low yield of wells. At the well just north of the site, the depth to water before pumping commenced was about 94 ft. However, in early 1972, the water level was approximately 104 ft (below land surface). It is obvious that the level had decreased about 10 ft (or about 25% of the saturated thickness) after installation of the well. A corresponding decrease in yield from this well probably occurred during this period. There has been considerable lowering of the water level further to the north of the site, and yields are reported to have decreased.

Core Drilling. - The test hole (AEC No. 5) was drilled at the northwest corner of the site at a ground elevation of 3337 ft. The formations penetrated and their depths and thicknesses are shown in Fig. 2.15. The position of the Blaine salt in the Permian section relative to the Hutchinson salt can be seen by comparison with Fig. 2.14. In this case, the various formations were approximately at the depths expected, based on correlations with geophysical logs from oil wells thinly scattered throughout the area. The sections of this hole that were cased and those that were cored are also shown in Fig. 2.15.

All three of the holes (AEC No. 3, AEC No. 4, and AEC No. 5) drilled at the three potential sites were plugged as soon as testing was completed. The plugging procedure, which was the same in each case, was to set a Halliburton E-Z plug at the bottom of the 8-5/8-in. casing, fill the casing with 6% gel cement, and squeeze with a standing pressure of 400 psi.

Hydrologic Testing. - The results of the hydrologic testing program performed in AEC Hole No. 5 at Site D₁ are given in Table 2.4. The results of test 1 (depth, 1950 to 2150 ft) indicate that the zone immediately below the salt is tight and has a very low permeability. Test 2 (depth, 1214 to 1950 ft by difference) indicates that the formations immediately overlying the salt accepted injected water at a significant rate, that is, about 5.4 gph. Because two sandstone sections

AEC HOLE NO. 5

Fig. 2.15. Simplified Geological Log of AEC Hole No. 5.

(upper, 1332 to 1345 ft; lower, 1540 to 1570 ft) had been identified within the zone isolated for test 2, an effort was made to isolate and test one of them. This was accomplished in test 3, in which the upper sandstone was straddled with packers located at depths of 1259 and 1376 ft. This upper sandstone would not accept water during the short test; therefore, it is deduced that the transmissivity indicated in test 2 was mostly in the sandstone lying immediately above the Blaine anhydrite (see Fig. 2.15).

The pumping test of the Dakota formation in this well (test 4) was inconclusive since it was not possible to pump the well continuously (with the pump available) without excessive drawdown. It is possible that drilling fluids had damaged the formations, thereby precluding a valid test. The results given in Table 2.4 represent extrapolations of these "slug" pumping tests.

At this site, efforts were also made to test the Ogallala formation, which is the principal aquifer in the area. However, this test was also inconclusive, and no results can be given. It is believed that an inappropriate development technique led to a partial plugging of the screen. It should be noted that an irrigation well in this formation located only 1/2 mile distant has a reported yield of 390 gpm.

Salt Core Examination. - The Blaine salt sequence contrasts strongly with the Hutchinson salt both in character and quality. The formation is essentially massive throughout and (except for some thick shales) banding and "fine stratigraphy" such as exhibited by the Hutchinson are nonexistent. The overall clay content is estimated to be 20%, with many large beds exceeding this value. The clay is mostly bright red and, whereas some of it is intracrystalline, most of it forms a matrix around the well-developed salt crystals, which are often 1/2 in. in size. Because of this high overall clay content and the paucity of sections with low clay content, units of potential interest for waste disposal could not be identified.

The existence and characteristics of this salt formation were known only by inference from oil field geophysical logs prior to the drilling

of AEC Hole No. 5. Therefore, it is not surprising that the characteristics of the salt were considerably different from those expected. From a scientific viewpoint, this hole was, by far, the most interesting of the three. This is further illustrated by the recovery of cores of a red sandstone containing well-sorted quartz sand grains cemented solely by salt (halite). The cleavage planes of large salt crystals (2 in.) forming the matrix could be seen on fracture surfaces. Such rock, of course, could not exist at the surface since it completely disaggregates when the salt is dissolved. As far as can be determined, this type of rock is unnamed and has never been described in the literature.

Summary and Evaluation. - Based on the information collected in the investigations of these three sites, the following conclusions have been reached.

1. Site D₁ in Wichita County appears to be unsuitable for further consideration as a potential waste disposal site. The reasons for this conclusion are based primarily on examination of the core and can be summarized as follows:

- (1) Overall high clay content.
- (2) Paucity of sections with low clay content.
- (3) Suspected lack of lateral continuity of the units.
- (4) Possible hydrologic problems at the Blaine anhydrite contact and the important Ogallala aquifer.
- (5) The possibility of severe structural and support difficulties expected to be encountered as the result of the clay being deposited as a matrix around individual salt crystals. This problem would be further amplified as the depth increased.

The fifth reason is perhaps the most important one.

2. Both Site A and Site A₁ are suitable for further consideration in spite of the fact that the overall thickness of the salt formation is less than desired. This lack of desired thickness may necessitate a reduced thermal loading in order to restrict the thermal environment

imposed upon the overlying shales and would have to be examined closely in the analysis of the long-term integrity of containment of the wastes; however, it should not disqualify these sites at this time. The two sites are approximately equivalent in most respects, except that Site A appears to have a slightly more satisfactory high-quality salt zone for mining operations than does Site A₁. On the other hand, Site A appears to have slightly greater ground-water supplies than does Site A₁.

2.3 Geological Alternatives Study

In addition to the previously described explorations in Kansas, a fairly extensive and broadly based series of studies was undertaken to examine geological formations outside Kansas which appeared promising as alternatives for the location of a pilot-plant radioactive waste repository. These studies covered bedded salt deposits in other parts of the country and also included salt domes and anticlines, argillaceous formations, and some specific mines previously proposed as possible sites.

The preliminary survey of alternatives was not carried out in the detail of the Kansas investigations. All of the information collected was obtained from published or file sources and did not involve the generation of new data. However, the study was designed to uncover as many alternatives as possible and identify those which seemed most promising for further study within the confines of the present concept of the repository.

The overall objectives of this investigation were: (1) to provide a review of the potential geologic alternatives, including background information, as part of a comprehensive evaluation of alternative waste management strategies and for use in documents supporting a pilot plant repository, such as the Environmental Impact Statement, PSAR, etc.; (2) to identify promising specific locations where pilot plant facilities could be constructed in the near future; and (3) to confirm that the disposal formation ultimately selected is not only acceptable but also one of the best possible solutions.

The basic requirement of the disposal formation is that it must be capable of safely containing the radioactive materials until radioactive decay processes have reduced the activity to nonhazardous levels. The critical mechanism for the dispersal of activity into the environment is leaching and transport by ground water; therefore the disposal scheme must ensure complete isolation of the radioactive wastes from circulating ground water. Although many geologic environments are characterized by the absence of circulating ground water, it will be necessary to ensure that this condition will be preserved for geologically significant time periods. Consequently, the disposal formation must be not only impermeable

but also sufficiently plastic to close openings and heal any possible fractures.

Geologic evidence shows that all rock types can be deformed plastically under the appropriate conditions of temperature and confining pressures. However, only a limited number exhibit this characteristic to a sufficient degree under conditions likely to be encountered in practical waste disposal operations. Of the geologic materials meeting this requirement, rock salt is the most widely available. In view of this, the principal emphasis of the present study has been focused on certain of the salt deposits of the continental United States, specifically the salt formations of:

- (1) The portion of the Permian basin found in southeastern New Mexico.
- (2) The Salina basin of Michigan.
- (3) The Williston basin.
- (4) The Supai salt basin and Luke salt body in Arizona.
- (5) The Gulf Coast salt dome region.
- (6) The Paradox basin of Colorado and Utah.

It has also been suggested that, under certain favorable conditions, selected argillaceous sediments may behave plastically and display other suitable characteristics for waste disposal. Thus a nation-wide screening survey of shale formations as an alternative to salt deposits was included in the investigation.

In addition, three specific sites in calcareous formations were examined, in spite of the generally unfavorable properties of these geologic materials.

Finally, one special non-site-specific study is included here because of its direct relevance to the question of site suitability. This study concerns the natural dissolution and stability of salt in the Permian basin as a whole.

2.3.1 Salt Domes and Anticlines

Large masses of pure halite have been brought to shallow depth by plastic deformation in many existing salt structures. Several features related to the genesis of diapiric structures raise problems with regard

to demonstrating the suitability of a given structure as a site for a radioactive waste repository.

The principal considerations are:

1. Salt domes tend to be irregularly shaped. To ensure adequate separation of any excavation from the margin of the structure, the boundaries of the salt mass need to be delineated with great precision.
2. Salt domes and anticlines result from the upward migration of large volumes of salt from deeply buried source beds. This upward migration, or uplift, takes place at the rate of only a few millimeters per year, and some domes are probably still rising.⁵² In evaluating a specific dome or anticline, it would be necessary to demonstrate that the dome or anticline is not currently active, that rejuvenated movement is not foreseeable, and that residual stress concentrations from past movement (which would interfere with the excavation or the programmed closure of the mine) do not exist.
3. Because they intrude through overlying sediments, domes are not protected from dissolution by ground water circulating in overlying and adjacent sediments. For this reason, adequate investigations of the characteristics of ground-water flow and of possible dissolution rates would be required before a particular structure could be considered for disposal.
4. It would be necessary to demonstrate that the salt structure has the stability required to isolate the waste from the biosphere for hundreds of thousands of years, and that the reliability of containment would not be reduced by the temperature increase due to generation of decay heat.

Gulf Coast Region (R. E. Anderson,* D. E. Eargle*). — The Gulf Coast salt-dome province can be divided into five basins. Figure 2.16 shows the location of these basins and the associated domes (263 on shore only). In order to narrow the field to a small group with potential suitability, many domes can be eliminated on the basis of excessive depth and present usage. Table 2.5 shows the number of rejected domes, as well as the number of potential domes remaining for each basin.

* U.S. Geological Survey.

Fig. 2.16. Index Map of Gulf Coast Province, Showing Salt-dome Basins. A = northeast Texas basin; B = north Louisiana basin; C = Mississippi basin; D = south Texas basin; E = south Louisiana basin; 1 = Tatum dome; 2 = Vacherie dome; 3 = Palestine dome; 4 = Hockley dome. (After W. G. Pierce and E. I. Rich, U.S.G.S. Bulletin 1148, Plate 4, 1962)

Table 2.5. Number of Rejected and Potential Salt Domes in Various Basins of the Gulf Coast Province, and Basis for Rejection

Salt-dome Subprovince	Salt-dome Basin	Basis for Rejection					Total Rejected	Potential Domes
		Depth ^a	Multiple Usage	Petroleum Production	Gas Production	Salt Production		
Interior	Northeast Texas	6	0	3	3	1	13	7
	Northern Louisiana	6	0	1	4	0	11	8
	Mississippi	60	0	0	2	1	63	14
Coastal	Southern Texas	3	0	1	0	1	5	1
	Southern Louisiana	73	30	29	2	1	135	6
	Total	148	30	34	11	4	227	36

^aMany of the domes rejected on the basis of depth also have active oil and gas production.

Additional domes could probably be eliminated on the basis of such factors as size, potential flood hazard, ground-water problems, land use, etc. Available data were compiled on the 36 potentially suitable domes. It appears that information providing a basis for an adequately supported evaluation of the salt structures for siting a waste repository exists for only 4 of the 36 shallow unused domes: Tatum, in Mississippi; Vacherie, in northern Louisiana; Palestine, in northeastern Texas; and Hockley, about 30 miles northwest of Houston. Some facts pertaining to these four domes are tabulated in Table 2.6. Their locations are shown in Fig. 2.16.

One of the major information deficiencies relates to the inability to estimate size and shape of domes at particular depths. The upper surfaces of many well-known domes are irregular, which suggests that the same condition may be revealed for the unused potential domes, for which data are presently scarce, if more extensive investigations are undertaken. Because the tops of many of these domes are quite near 2000 ft of depth, the possibility of being forced to much greater depths by irregularities in the upper surface becomes critical.

Thus far, studies of the Gulf Coast Region indicate that the interior salt-dome province is more suitable than the coastal one, based on the following considerations.

1. Many interior salt domes have probably been structurally stable since late Tertiary, based on the undisturbed conditions of blanketing sediments, whereas coastal domes are probably younger and, even if they are not undergoing active diapirism, are certainly in a more structurally unstable environment.⁵⁸

2. In northern Louisiana and Mississippi, water in wells located down the hydrologic gradient from salt domes does not tend to be more saline than in other wells. Deformed strata above and around some domes are elevated to levels where increased recharge has produced flushing of some aquifers to deeper levels than in the surrounding undeformed areas. These relationships suggest either that dissolution of salt is not occurring or that, if it is, the rate is below the detection capabilities of the sampling system.

Table 2.6. Data Summary for Selected Salt Domes in the Gulf Coast Province

	Tatum	Vacherie	Palestine	Hockley
Depth to cap rock, ft	530-675	658	120	74
Depth to salt, ft	1460-1605	777	122	1010
Diameter at 500 ft, ft	0	0	~3000	0
Diameter at 2000 ft, ft	4000	4300	~7500	>13,000
Approximate depth to base of fresh water in surrounding aquifers, ft	1500	400-500	1400	1800-2000
Nearest population center	Purvis, Miss., 8 miles E	Gibbsland, 10 miles NE; Minden, 12 miles NW	Palestine, 4.7 miles NE	Hockley, 4 miles N; Central Houston, 31 miles SE
Distance to rail	Purvis, Miss., 8 miles E	3-1/2 miles W, 6 miles N	2-1/2 miles SE	4 miles N
Distance to highway	2 miles N and 2 miles W	6 miles E	2 miles SE	4 miles N
Nearest surface-water body	Pearl River, 13 miles W	L. Bistineau, 6 miles W; Bushaway Creek crosses structure	Small, shallow saline lake on dome; Trinity River, 10 miles SW	Brazos River, 10 miles W
Quality of surface drainage	Good	Fair to good	Good	Good
Topographic relief over structure, ft/mile	100	50	80	Almost level
Number of wells to salt	16 + salmon-shot ^a checks	6	16	Numerous
Number of other wells in 5-mile radius	>39	>18	12 + Long Lake Field (~50)	>20
Structure contour map available?	Yes	Yes	Yes	Yes?

^aNuclear device was exploded at a depth of 2600 ft.

3. The shallow domes in the coastal subprovince are more extensively used by the petroleum industry than those in the interior.

Paradox Basin, Utah and Colorado (R. J. Hite,^{*} S. W. Lohman^{*}). - The Paradox basin of southeast Utah and southwest Colorado contains a series of northwest-trending salt anticlines which reach within 500 to 3000 ft of the surface along the northeast edge of the basin. Figure 2.17, an index map of the Paradox basin, shows the location of various salt anticlines. The total area underlain by salt is approximately 12,000 square miles. The evaporite deposits of the basin occur in the Paradox member of the Hermosa formation of Middle Pennsylvanian age.⁵⁹

The salt anticlines are of two types: those in which the salt units are conformable with overlying rocks, and those in which they are unconformable or intrusive. The latter type is characterized by a complex salt core and the development of a cap rock. These capping units of gypsum, dolomite, and black shale were originally interbedded with halite, but ground-water leaching has removed the more soluble salt. Estimates of average leaching rates in post-Cretaceous time are on the order of 22.4 ft of salt over a period of one million years from the crest of a typical anticline.

The greatest original thickness of salt was deposited in a structural trough and was probably on the order of 5000 to 6000 ft; however, this thickness has been modified by subsequent flowage of the salt and is as great as 14,000 ft in one anticline. At their maximum development the salt deposits consist of 29 evaporite cycles, of which halite and potash minerals (if present) generally form 70%. The halite units range from a few feet to several hundred feet in thickness. The total water-insoluble content of the halite seldom exceeds 2 to 3% by weight. The relatively impermeable nonchloride units of the cycle are remarkably persistent markers throughout the basin and, where penetrated in drilling, commonly produce small flows of brine or oil and gas. Occasionally, hydrocarbon accumulations large enough for commercial production are encountered. Formation fluids are commonly under abnormally high pressure, requiring

^{*} U.S. Geological Survey.

Fig. 2.17. Index Map of Paradox Basin, Southeast Utah and Southwest Colorado. (From Robert J. Hite, Geological Society of America Special Paper 88, Fig. 1, p. 322, 1968)

the use of high-density mud in drilling. Underground mining operations in these deposits require the standard safety precautions for "gassy" mines.

The northern end of the basin is characterized by low population density and livestock grazing. Industrial development consists of uranium mines and mills, several oil and gas fields, and one potash mine. Much of the area is deeply dissected by canyons with relief of more than 8000 ft. Several paved highways and a railroad traverse the area; nevertheless, much of the basin remains fairly inaccessible.

2.3.2 Bedded Salt Deposits

Large areas of the United States are underlain by bedded salt. The following discussion is limited to selected areas of the Permian basin, the Arizona salt deposits, the Salina basin, and the Williston basin. Particular emphasis is placed on the southeastern New Mexico portion of the Permian basin, where salt beds of appropriate thickness, purity, and depth exist over fairly large areas.

Stability of Bedded Salt in the Permian Basin (G. O. Bachman,* R. B. Johnson,* F. A. Swenson*). - The Permian basin in the western Interior of the United States is a series of sedimentary basins in which halite and associated salts accumulated during Permian time. The region includes the western part of Kansas, Oklahoma, and Texas and the eastern parts of Colorado and New Mexico.

Following a long period of relative stability in the early Paleozoic, the region underwent considerable tectonism during Late Pennsylvanian and Early Permian time. Such features as the Central Kansas Uplift and the central basin platform in western Texas and southeastern New Mexico were uplifted, while thick accumulations of sediments were deposited in the adjacent subsiding basins. As the region stabilized in Late Permian time, these basins were partially restricted, giving rise to salt deposition. These basins were not contemporaneous or continuous throughout the region; as a result, the salt units are numerous and discontinuous. In general, salt deposits began earlier in the northern part of the basin (Kansas and

* U.S. Geological Survey.

northern Oklahoma), with the salt becoming progressively younger toward the south.

The region has been relatively stable since the Permian, undergoing slight regional warping, one major incursion of the sea, and periods of erosion. Deep-seated faults or igneous intrusions are rare. On the other hand, subsidence and collapse of the land surface related to dissolution and other shallow processes have been commonplace in the Permian salt basin. Some dissolution and reorganization of salt deposits probably have been occurring since deposition of the salt more than 230 million years ago. However, the processes of preservation must have been dominant over processes of removal; otherwise, the highly soluble minerals could not have survived in bedded form throughout this great length of geologic time.

Local subsidence features that appear to be directly related to shallow dissolution of salt include Clayton basin, Nash draw, and San Simon sink in southeastern New Mexico. Additional features exist in southwestern and central Kansas, western Oklahoma, and the Texas panhandle.

Bedded salt in the subsurface is stable only if it is protected from a continuing supply of fresh ground water. Channels that provide movement for a continuing supply of ground water include: (1) solution channels opened from adjacent porous and permeable rocks, (2) fractures, and (3) drill holes.

The presence of karst topography is a major criterion for recognizing areas in which dissolution has been active in the past. Therefore, the dating of karst development can be a useful means for estimating the rate of dissolution. During the present work, the Pliocene Ogallala formation was taken as a point of reference for dating the development of recent topography. Deposition of this formation, which was widespread in the Permian basin, began about 12 million years ago and ceased approximately 5 to 7 million years thereafter. Most of the erosion and dissolution phenomena that are visible in the present landscape of the basin began during Ogallala time and have continued in the 5 to 7 million years that followed.

It is estimated that salt in the southeastern New Mexico area has been dissolved laterally at the average rate of 3.5 to 4.0 miles per million years. This conclusion is based on the following geologic assumptions:

- (1) The Ogallala formation formerly extended across the Pecos River Valley, at least as far as the front of the Guadalupe Mountains.
- (2) The Pecos River Valley in the vicinity of Carlsbad has been formed since Ogallala time.
- (3) The distance from the eastern front of the Guadalupe Mountains to the present western limit of major salt beds is about 18 to 20 miles.
- (4) The Ogallala formation has been eroded, and the Permian salt has been dissolved from this area during the past 5 million years.

It does not appear probable that salt extended much farther west than the front of the Guadalupe Mountains before Ogallala time; if the salt was less extensive before Ogallala time, the present estimate is conservative.

Climate is a major factor in the availability of ground water and the rate of dissolution. Climate has been varied and was subject to major fluctuations at various intervals since Ogallala time.⁶⁰ At least two major dune fields, one of which has been active within the past 6000 to 8000 years, have occurred in the basin since Ogallala time. Also, a forest covered the region about 10,000 years ago, prior to the most recent dunes. Estimates of future rates of salt dissolution include the assumption that climatic changes in the future will be of the same order as those of the past.

Large amounts of salt are carried by present-day rivers in the Permian basin. Some of this salt originates from the slow dissolution of the subsurface salt beds. The surface drainage of one western Texas basin carries about 670 tons of sodium chloride in solution per day. If spread equally over the area being drained, this amounts to only 0.5 ft of salt solution per thousand years. As mentioned previously, the availability and rate

of circulation of ground water are the controlling factors in dissolution. The movement of ground waters in the Permian basin is relatively slow, ranging from 0.015 ft/year in the San Andres limestone (a Permian formation) to 0.4 ft/year in the more-permeable Triassic rocks.

Southeastern New Mexico Area (A. L. Brokaw,^{*} C. L. Jones,^{*} M. E. Cooley,^{*} W. H. Hays^{*}). — The Permian basin in southeastern New Mexico contains extensive evaporite deposits in the appropriate thickness and depth ranges. Potash minerals have been extracted in the area for approximately 50 years. The potash area is located in eastern Eddy County and western Lea County, 15 to 30 miles east-southeast of Carlsbad. Figure 2.18 shows an index map of the area. The topography can be broken down into four major divisions: foothills of the Guadalupe Mountains, the high plains, isolated areas of low hills, and widespread pediments and alluvial planes. These topographic provinces are locally modified by collapse features. The general area is sparsely populated; except for widely scattered ranch and farm dwellings, the only population centers within 20 miles are Carlsbad, Loving, and four other small communities.

The area of the potash mines includes the northern end of the Delaware basin, a late Permian depositional trough whose edge is commonly defined as the front of the largely buried Capitan Reef. The entire sedimentary sequence includes strata from Ordovician through Quaternary age and has a total thickness in excess of 20,000 ft, with up to 13,000 ft of Permian strata. The oldest rocks exposed in the area are of Late Permian age, but abundant information on older rocks is available from drilling.

The strata in the vicinity of the potash mines have been tectonically stable since Tertiary time and are only slightly deformed. The principal structural units are large-scale features related to late Paleozoic sedimentation: the northern Delaware basin, the shelf north and west of the basin, and the central basin platform to the east. These structures were tilted slightly eastward during pre-Pliocene Tertiary time, resulting in a regional eastward dip of from 1 to 2°.

^{*} U.S. Geological Survey.

Fig. 2.18. Map of the Vicinity of the Potash Mines, Southeastern New Mexico. The northern boundary of the Delaware basin is defined by reef escarpment and the buried front of the Capitan reef. (After A. L. Brokaw et al., U.S.G.S. Open-File Report 4339-1, Fig. 1, 1972)

The salt deposits of the area are contained in the Late Permian Ochoan series, which is divisible into two parts: a thick lower section of salt-bearing evaporites including (in ascending order) the Castile, Salado, and Rustler formations and a thinner section above composed of the Dewey Lake redbeds.⁶¹

The Castile formation consists largely of interlaminated gray anhydrite and brownish-gray limestone, but it contains a large percentage of rock salt. It has a thickness of about 1500 to 1600 ft along the southern edge of the region, thins northward to about 1000 ft near the margin of the Delaware basin, and tongues out in the southernmost parts of the northwest shelf. All the salt is concentrated in a thick middle member which lies 200 to 300 ft above the base of the formation.

The Salado formation, the main salt-bearing unit of the area, ranges in thickness from about 1900 ft in the south to about 1000 ft at the northern edge. The formation is characterized by thick persistent units of rock salt alternating with thinner units of anhydrite and polyhalite. Thin seams of claystone underlie the anhydrite and polyhalite units, and a few beds of sandstone and siltstone are present at large intervals.

The Salado formation is divided into three informal units: a lower salt member, a middle potassium-bearing member known locally as the McNutt potash zone, and an upper salt member. The three members are similar in most respects, except for the occurrence of economically significant deposits of sylvite (KCl) and other potassium and magnesium evaporite minerals in the McNutt zone.⁶¹

The Rustler formation, which is the uppermost salt-bearing unit in the Ochoan series, is 300 to 400 ft thick in the southern part of the area and thins to about 200 to 250 ft in the north. It is mostly anhydrite and rock salt. Some dolomite is present in the upper and lower parts of the formation, and thin to thick units of sandstone and shale are interbedded at long to short intervals.

The Dewey Lake redbeds at the top of the Ochoan series consist of reddish-brown siltstone and fine-grained sandstone. The formation is 250 to 550 ft thick in the area.

Ground-water Hydrology. — Three main hydrologic units control the ground-water hydrology of the southeastern New Mexico area. These are: (1) the Pecos River, which receives the ground-water outflow from the potash mining area; (2) the water-bearing strata overlying the Salado formation; and (3) the Capitan limestone and other water-bearing strata underlying the Salado formation. The distribution and development of large solution features, particularly in the Nash draw and Clayton basin areas, exert a major effect on the occurrence and movement of ground water.

The Pecos River receives nearly all the natural discharge of ground water that moves through the rocks of the potash mining area. The principal places of natural ground-water inflow are at Carlsbad, where water derived from the Capitan limestone discharges to the river or to the alluvium bordering the river, and near Malaga bend, where highly mineralized water is discharged from the Rustler formation to the river. Most of the ground-water discharge from the mining area occurs in the reach of the river near Malaga bend.

The main aquifers or water-yielding units overlying the Salado formation are the Culebra dolomite member and basal solution breccia zone of the Rustler formation, the Santa Rosa sandstone, and the alluvium. The Culebra dolomite member, which occurs throughout much of the area, is the main source of water tapped by stock wells. The basal solution breccia zone of the Rustler formation, often referred to as the "brine aquifer," is the unit that is most significant in relation to the dissolution of halite in the upper part of the Salado formation. The approximate eastern edge of evaporite dissolution and removal by ground water in eastern Eddy County is indicated in Fig. 2.18.

The formations above the Salado seem to be connected hydrologically and can be treated as a single multiple aquifer system. The degree of development of the aquifer system is not known and cannot be determined from the existing hydrologic information, although the levels of water standing in wells are sufficiently uniform that potentiometric and water table contours can be constructed throughout the area. Dissolution

activity and associated collapse, subsidence, and fracturing have increased the overall permeability of the rocks and have enhanced the interformational movement of water in the aquifer system. In the mining area, the aquifer system seems to be best developed between the water-yielding units of the Rustler and between the Rustler and Gatuna formations.

Ground water in the formations above the Salado moves generally southward and southwestward across the potash mining area toward the Pecos River. Although the total amount of ground water discharging to the Pecos River is not known with any degree of confidence, it has been estimated that 200 gpm enter the river from the basal solution breccia zone near Malaga bend.⁶²

The potentiometric and water table contours outline a series of ground-water ridges and troughs, which are imposed on the regional southward-to-southwestward pattern of ground-water movement. A large southwestward plunging, ground-water trough extends from Malaga bend northeastward, roughly through Nash draw to beyond the mining area. Another much smaller trough is located east and southeast of the Project Gnome site.

The intergranular porosity and permeability of the Salado formation range from low to virtually nil. Locally, fractures and solution openings impart a spotty formational permeability. In the potash mining area, the Salado formation is dry except for small pockets of brine or brine and gas that have been encountered occasionally during mining and test drilling, and for water present in the leached zone developed at the top of the formation.

The Paleozoic sedimentary rocks underlying the Salado formation contain highly saline water and are under artesian pressure. These rocks are not exposed in the potash mining area but lie deeply buried in the subsurface throughout much of southeastern New Mexico and western Texas. In the potash mining area, the elevation of the potentiometric surfaces of different zones of these rocks ranges from a few feet to a hundred feet above or below the land surface.

Arizona Salt Deposits (J. W. Mytton^{*}). - In Arizona, salt is found in two completely different physiographic provinces: the Colorado Plateau and the Basin and Range Province.

Supai Salt Basin, Arizona. - The Supai salt basin embraces an area of approximately 2300 square miles on the Colorado Plateau in east-central Arizona. Paleozoic strata exposed along the Mogollon rim, a prominent escarpment marking the southern margin of the plateau proper, dip to the north and northeast at low angles to form a near dip slope that is commonly called the Mogollon slope. This topographic feature adjoins the Black Mesa basin north of Winslow and Holbrook and the Defiance uplift to the northeast. In the intervening lower land occupied by the Mogollon slope, the Little Colorado River flows northwesterly between St. Johns and Holbrook. The average annual runoff in the area ranges from less than 0.1 in. to more than 5 in.; the significant tributary runoff comes mainly from the Mogollon rim and mountains to the southeast. Figure 2.19 is an index map of the area.

Most of the area is underlain by thick, generally impermeable, shaly rocks of the Chinle and Moenkopi formations of Triassic age. The Kaibab limestone and Coconino sandstone of Permian age crop out only in the southwestern part of Navajo County. The Coconino is present in the subsurface throughout the area and is the most important aquifer in the region. It is recharged primarily in the area near the Mogollon rim and discharges principally in the Holbrook-Winslow and St. Johns areas.

Solution-collapse phenomena are present in the area of the Holbrook anticline, the largest of several predominantly northwest-trending folds of early Tertiary age within the area of the Mogollon slope. Sinks and related features are the results of dissolution of Permian evaporites. The Coconino sandstone directly overlies the evaporite section and accounts for the solution-collapse features.

The Supai formation, which contains the basal Permian beds, occurs only in the subsurface and consists of interbedded sandstone, siltstone,

* U.S. Geological Survey.

Fig. 2.19. Index Map of Supai Basin, Arizona.

and mudstone, and evaporite beds of anhydrite, gypsum, and halite.⁶³ It is about 1600 ft thick near the Arizona-New Mexico state line and thickens to more than 2600 ft southwest of Holbrook. The principal halite deposits, associated with anhydrite, dolomite, and clastic redbeds, occur as discontinuous units within an evaporite-bearing stratigraphic interval, 450 to 1300 ft thick, between the Fort Apache limestone member of the Supai formation below and the overlying Coconino sandstone. Depths to the top of the evaporite interval, which is marked by an anhydrite-gypsum zone, range from 600 to 2500 ft; the deepest parts are in the northeastern section of the Supai basin.

Indications are that the principal concentration of halite occurs in a zone 400 ft thick within the upper half of the evaporite interval along a 55-mile northeast-trending belt between Snowflake in Navajo County and Pinta dome in Apache County. Aggregate thicknesses of as much as 500 ft of salt have been reported, but individual beds in the basin do not exceed 160 to 200 ft. In general, salt comprises from 5 to 15% of the Supai formation.

A northeast-trending potash zone under an area of about 300 square miles has been delineated by exploration holes in the northern part of the Supai basin. The potash zone is within 150 ft of the top of the evaporite section, which is marked by an anhydrite bed in most places. Depths to the potash range between 700 and 2000 ft below the surface, the shallower depths being to the southwest and the deeper depths to the northeast. Most of the exploratory drilling for petroleum and natural gas has been done in the vicinity of the Holbrook anticline, where drilling objectives have been the Fort Apache limestone and rocks of Pennsylvanian age and older, and northeast of Holbrook, where high concentrations of helium have been found in natural gas in the Coconino sandstone and in rocks of Triassic age. The largest producing field is the Pinta dome field, about 35 miles northeast of Holbrook.

The Supai basin is bordered on the north and south by Indian reservations and contains a national park within its limits. The proximity of the Supai salt basin to the Santa Fe railroad and U.S. Highway 66, both

major transcontinental routes, makes the area easily accessible. In addition, the sparse population and limited agricultural development in the general area, as well as the tectonic stability, can be considered favorable characteristics.

Luke Salt Body, Arizona. - The Luke salt body is located in the Basin and Range Province in the vicinity of the Luke Air Force Base, 17 miles west-northwest of Phoenix.⁶⁴ According to published data, halite has been penetrated in five wells, and a sizable salt mass (at least 15 cubic miles, and possibly as much as 30 cubic miles) has been inferred from a large negative gravity anomaly. Interpretation of the gravity data indicates that the salt mass is prismatic, extending approximately 6 miles in a northeast-southwest direction and 10 miles in a north-south line with its base at a depth of at least 6500 ft. Its configuration suggests either the core of a salt structure or an undeformed sedimentary accumulation in which only the uppermost part has flowed plastically. The salt is apparently of late Cenozoic age. Low hills in the area probably result either from plastic flowage or differential compaction between the salt and surrounding sediments.

Based on gamma ray--neutron logs, the generalized lithology of the salt mass between 800 and 4500 ft is primarily very pure halite with shale interbeds underlying a 60-ft anhydrite caprock. Geohydrologic data indicate that the upper part of the salt mass affects the salinity of ground water contained in alluvial fill. The surrounding area is one of limited agricultural use, and most of the wells are relatively shallow and used for irrigation.

Figure 2.20 shows the location of the Luke salt body and other salt deposits in the Basin and Range Province.

Salina Basin: New York, Pennsylvania, West Virginia, Ohio, and Michigan. - Bedded salt deposits of Late Silurian age occur in the Salina formation, which underlies portions of New York, Pennsylvania, West Virginia, Ohio, Michigan, and southwestern Ontario.⁶⁵ Figure 2.21 is an index map of the area, showing the approximate extent of the Salina formation and the regional structural features associated with the salt units. The

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Fig. 2.20. Map of Arizona, Showing Structural Provinces and Location of Salt Deposits of the Basin and Range Province. (After E. A. Koester, Arizona Oil and Gas Conservation Commission Geology Report No. 1, Fig. 1, p. 2, 1971)

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Fig. 2.21. Index Map, Showing the Approximate Extent of the Salina Formation and Regional Structural Features Associated with the Salt. (After W. G. Pierce and E. I. Rich, U.S.G.S. Bulletin 1148, Fig. 3, p. 13, 1962)

total area underlain by salt is approximately 100,000 square miles, and the average thickness of the salt beds is on the order of 150 ft.

The Salina formation ranges in thickness from 0 to nearly 1000 ft and consists of shale, dolomite, limestone, salt, anhydrite, and gypsum. The areas of greatest salt accumulation are in southern New York in the Appalachian basin and in the Michigan basin. The greatest aggregate thickness of salt occurs in the Michigan basin, where it ranges from 500 ft at the margins to 1800 ft in the center. The depth of the salt in the Michigan basin is from 500 ft near the margin to 6000 ft in the center. In New York, the maximum combined thickness of salt is about 900 ft southwest of Syracuse, with as many as six beds present in places. Here the salt is overlain by a shale formation 40 to 600 ft thick. In Ohio, salt beds in the Salina are most numerous in the northeastern part of the state, where as many as eight have been recorded in wells. The aggregate thickness of the beds is from 0 to 300 ft; the thickest individual bed is about 50 ft. The greatest salt accumulations in Pennsylvania occur in the north-central part of the state, where there are eight beds with an aggregate thickness of about 650 ft. Individual beds range from less than 5 ft to about 200 ft in thickness, the thickest occurring near the top of the sequence. For the areas mentioned in New York, Pennsylvania, and Ohio, the top of the salt is about 1000 ft below the surface. The Salina in West Virginia lies at depths greater than 5000 ft.

In addition to the Salina salt of Silurian age, there is a Devonian salt in the Lucas formation. It is present only in the northern part of the southern peninsula of Michigan, and the areas of maximum aggregate thickness lie toward the deeper part of the Michigan basin at considerable depths. The Lucas consists of a series of salt units with anhydrite and shale interbeds; however, individual salt beds are measurable in tens of feet only.

Michigan Basin Hydrology (A. M. Piper^{*}). — The occurrence of water both in surficial glacial deposits and the underlying bedrock units deserves consideration.⁶⁶ The glacial drift over most of the Michigan basin is several hundred feet thick and is predominantly sandy. It has a high rate

^{*}Consultant, Carmel, California.

of recharge and stores water in relatively large volumes. In the most productive zones, buried sand and gravel outwash deposits, well yields range from several hundred to greater than 1000 gpm. Water from the upper drift contains about 200 to 500 ppm of total dissolved solids and is moderately hard (175 to 350 ppm as CaCO_3). The chemical character changes with depth with increasing total dissolved solids (up to 1500 ppm) and hardness (up to 1000 ppm).

Although the glacial drift is separated from the underlying bedrock by a stratigraphic hiatus, the water contained in strata above and below react as a single hydrostratigraphic unit. These waters are referred to as transition-zone waters due to the gradual change from fresh waters in the glacial drift above to brines in the bedrock beneath. The mixing is a product of three processes: (1) downward percolation of fresh meteoric water, (2) upward movement of nearly saturated deep brines due to natural migration from higher to lower pressure head and artificial drive induced by withdrawals from above, and (3) local dissolution of aquifer materials. Transitional waters are most abundant in areas where the drift is thin and nonwater bearing, with numerous wells penetrating the upper bedrock.

Strata close below the Devonian salt and both above and below the Silurian salt are known or presumed to be water bearing. Highly concentrated natural brines have been found at depth in all strata that are highly permeable over extensive areas. The Salina formation itself contains very pure brines of natural origin in addition to the bedded salts.

In the Michigan area, the 800-ft-thick Lower Mississippian Coldwater shale is potentially the major regional hydraulic barrier above the salt horizon. However, it contains potentially permeable beds of sandstone and limestone. The second most likely barrier, the Antrim shale of Upper Devonian age, contains "calcite balls" and appears to have developed some permeability by dissolution. On lithologic grounds, the two potential hydraulic barriers above the salt may be questionable.

Drilling operations have produced some artificial vertical transmissibility that affects the integrity of the salt. Extraction of salt as

artificial brine has accounted for a large fraction of the total production in Michigan and New York and nearly all the production in Ohio.

Specific Localities (K. K. Landes^{*}). - Four geologic areas within the boundaries of the Salina formation warrant further study, based on the presence of relatively thick salt beds at accessible depths. These are northeastern Ohio, western New York, and the southeast and northern portions of the southern peninsula of Michigan.

The Salina formation in Michigan is divisible into seven members, designated A (oldest) through G. Three of the members are predominantly shale (C, E, and G); three are predominantly salt (B, D, and F); and one is salt in the basin center but dolomite at the margins (A). The B salt is absent at the outer margin of the basin but has a relatively uniform thickness of 240 to 275 ft over most of the basin. The D salt is the most persistent of the salts, also nearly pure, but the thinnest (25 to 65 ft thick). The F unit ranges from 0 to 1200 ft, thin or absent at basin margins and thickest in the center; the percentage of salt in the unit increases outward and is highest near the north edge of the basin. This F salt has had the most mining activity. Both the F and B salts have been solution mined.

The Salina formation in southeastern Michigan underlies the densely populated Detroit metropolitan area. Suitable salt units from the B and A members of the Salina formation occur at depths ranging from 1120 to 2340 ft below the surface. The thickness of individual salt sections range from 30 to 200 ft. At least one mechanical mine is operating in the area at present, removing salt from 1140 ft below the surface. The southeastern Michigan region as a whole has excellent transportation possibilities, including major Interstate highways and railroads.

Much of the region has been drilled for oil and gas exploration and production. In addition, considerable solution mining of the salt, originally for production but more recently for storage of LPG, has taken place.

* Consultant, Ann Arbor, Michigan.

The most desirable Salina salt units in the northeastern portion of the southern peninsula lie along the Lake Huron shore in Alpena and Presque Isle counties. Several limestone units, the Traverse Group, and the Rogers City and Dundee limestones, all of Middle Devonian age, have been quarried extensively in the area. This activity has prompted the development of port facilities and rail connections. Drilling in the area has been minimal, but salt beds approximately 100 ft thick are known to occur between 1600 and 2100 ft. Shallower salt beds probably exist in many areas, but they are thinner.

In the Appalachian basin, the Silurian salts are generally deeper and have undergone greater deformation than those in the Michigan basin.⁶⁷ However, two areas, northern Ohio and central New York, contain relatively undisturbed salt at appropriate depths. The Ohio salt is in the vicinity of Cleveland and dips southeastward at approximately 30 ft/mile. It has been mined by solution methods, generally at depths greater than 2000 ft, and by dry methods, at depths from 1700 to 2000 ft. In the existing dry-mines, faulting in the salt is evident and noticeable problems associated with instability of the salt, such as floor heaving, roof spalling, and pillar deterioration, have been experienced. The maximum aggregate thickness logged in the area is about 300 ft; however, individual beds are measurable only in tens of feet, rather than hundreds. In addition, the area has been quite heavily drilled for oil and gas production and exploration.

The most likely area for further study in New York is in the center of the western part of the state immediately west of the Finger Lakes in Livingston County and eastern Canandaigua Lake County. West of this area the salt thins and is penetrated by numerous brine and gas wells. The salt is more unstable in the east due to past deformation. North of this area, the salt thins to extinction along a solution boundary; to the south, the salt is at considerable depth. In Livingston and Canandaigua Lake counties the salt occurs at depths of 1000 to 2000 ft and has a southerly dip of about 60 ft/mile. This county is the major salt producer in New York; and an existing mine, the Retsof, is the largest mine in the United States. The aggregate thickness of salt in this area may be suitable, but individual units are only tens of feet thick.

Williston Basin: Montana, North Dakota, and South Dakota. - The Williston basin is a sedimentary and structural basin covering an area of 150,000 square miles in the north-central United States and adjacent portions of Saskatchewan and Manitoba. The basin contains 15,000 ft of sediments, Cambrian through Tertiary in age, including at least 11 salt units. The oldest of these units is Devonian; the youngest is Jurassic.⁶⁸

A very general look at the stratigraphy in the center of the basin shows the top 7000 ft from the surface to Lower Jurassic to be mostly shales and sands. The next 2000 ft, from Lower Jurassic to Lower Mississippian, consists of carbonates, evaporites, and clastics. From 9000 to 15,000 ft (Lower Mississippian to basement), the rocks are basically carbonates and a few significant evaporites. The majority of the salt in the United States portion of the basin occurs at depths ranging from 6000 to 9000 ft below the surface. Figure 2.22 is an index map of the Williston basin.

The Devonian salt, Prairie formation, occurs at depths from 6000 to 12,000 ft and varies from 0 to 500 ft in thickness. There are six distinct Mississippian salts, primarily in the Charles formation; however, only one, the highest, is more than 100 ft thick. One fairly extensive Permian salt bed in the Opeche formation attains a thickness of 180 ft and occurs at depths ranging from 5800 to 7500 ft. The highest salt units, the Pine and Dunham salts, occur in Permian and Jurassic strata respectively. The Pine has greater areal distribution than most of the other salts and reaches a maximum thickness of 300 ft; the Dunham is more restricted and thinner than the Pine.

A large portion of the available water supply in the Williston basin region is saline. Paleozoic strata underlying the salt units in the deeper portion of the basin contain highly saline brines. The only significant Mesozoic aquifers are Cretaceous, the principal one being the Dakota sandstone. This unit yields moderate to large supplies (150 to >350 gpm) of highly mineralized water, with localized artesian conditions.

The Dakota aquifer is approximately 1300 ft above the highest salt unit and separated from it by thick shales. The primary source of fresh

Fig. 2.22. Index Map of the Williston Basin. (After H. F. Reed, "Salt Deposits of the Williston Basin--United States Portion," Symposium on Salt, Northern Ohio Geological Society, Fig. 2, p. 150, 1961)

ground water is the limited shallow aquifers associated with river channels, either of existing streams or of former glacial outwash channels.

The salt units of the basin have been subject to dissolution since Devonian time. Early cases from Paleozoic and Mesozoic time are thought to be local features, 1 or 2 miles in extent. Larger-scale dissolution, resulting in the removal of large portions of the Devonian salt by subsurface waters, are known to be occurring at present in Saskatchewan and are inferred but not documented in the United States portion of the basin.

2.3.3 Argillaceous Formations (E. A. Merewether,* J. A. Sharps,* J. R. Gill*)

Argillaceous formations, more specifically claystones, mudstones, and shales, have been proposed as a promising alternative to salt deposits for disposal of radioactive waste. Argillaceous sediments are usually characterized by extremely low permeability and high ion exchange capacity; and, in many cases, they are sufficiently plastic to prevent fracturing and the generation of secondary permeability. Plasticity generally decreases with compaction (and hence depth of burial); however, several factors contribute to the physical properties of shale (e.g. mineralogical composition, stratigraphic relationships, and geologic history of the sediment), which makes it difficult to generalize regarding suitable environments in shales.⁶⁹

In general, shales of Paleozoic age are well compacted and competent. In regions that have undergone tectonic deformation such shales tend to be crisscrossed by fractures. Mineralogically, Paleozoic shales are dominated by minerals of the illite and chlorite types with little or no montmorillonite present. Younger argillaceous sediments are more likely to have preserved some of their original plasticity and usually contain significant amounts of montmorillonite.

In review, the desirability of argillaceous formations as possible disposal sites can be evaluated, based on the following factors:

* U.S. Geological Survey.

- (1) Formation dimensions (lateral distribution, thickness, depth).
- (2) Mechanical properties (plasticity).
- (3) Hydrologic properties (porosity, primary and secondary permeability, presence of water-bearing strata).
- (4) Geologic stability (faulting, seismicity).
- (5) Mineralogic properties (composition, ion exchange capacity).

A review of the United States by physiographic regions has pinpointed several argillaceous formations which appear, on first appraisal, to meet many of the desirable qualities. In Michigan, the Devonian-Mississippian Ellsworth shale is most suitable at shallow depths on the north and northwest sides of the Michigan basin, where it directly underlies glacial deposits. In the southeastern Michigan basin, the Mississippian Coldwater shale may be suitable. In central and northern Ohio the Devonian Ohio shale, Chargin formation, and Cleveland shale, and the Mississippian Bedford shale comprise a thick sequence which has many of the necessary characteristics. The Devonian rocks in northwestern Pennsylvania, which include the Hamilton Group, Tully limestone, and Genesee, Sonyea, and West Falls Groups, have some potential for further exploration. In southeastern New York and northwestern New Jersey, outcropping shales of the Ordovician Trenton Group may qualify. The Cretaceous Pierre shale and its lateral equivalents underlie much of the Rocky Mountains and Interior Plains regions. These shales range from 500 to 5000 ft in thickness and usually have very high contents of montmorillonite and mixed-layer illite-montmorillonite clay minerals.

2.3.4 Specific Sites (D. W. Byerly^{*})

The three mines briefly described in this section were considered as possible locations for a radioactive waste repository in spite of the fact that the lithologies of the formations in which they are developed are considered to be unfavorable.

Gager Mine, Sherwood, Tennessee. — The Gager Mine is located on the Cumberland Plateau in central Tennessee. It is developed in the Mississippian Monteagle limestone, which is 180 ft thick and quite variable in

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lithology. The mine extends horizontally about 1400 ft from the access on the flank of a nearly fiat, sandstone-capped ridge.

The Gager Mine was developed in three levels. The upper two are generally drier than the lowest; however, cave-filling, dripstone formations, and solution channels observed in various parts of the mine attest to the fact that it is affected by percolating ground water.

Barberton Mine, Barberton, Ohio. - The Barberton Mine is located 40 miles south of Cleveland in the western Appalachian basin. The mine is developed in the Columbus limestone of Devonian age. The limestone is overlain by 1600 ft of Devonian shales, with sandy shale (400 ft), sandstone (65 ft), and glacial drift (20 ft) completing the section. When the shafts were sunk, water was encountered only in the upper 300 ft of drilling. The mine is dry with no evidence of percolating water. This can undoubtedly be attributed to the thick, impermeable shale above. The mine is located at a depth of approximately 2300 ft; the mined volume is about 325×10^6 ft³.

Demopolis Cavern, Marengo County, Alabama. - The Demopolis Cavern, located in southwestern Alabama, is actually two LPG storage caverns which have been excavated in the Mooreville chalk. The Mooreville is a part of the Selma Group, Upper Cretaceous, which is essentially chalk containing some marl. The unit in which the storage caverns were developed has a total thickness of 300 ft and is a fairly uniform chalky marl overlain by a hard medium-bedded chalk. Of the Selma Group, the Mooreville is noted for its particularly low permeability. In places where it is exposed in a quarry face, a few solution channels are visible near the surface.

The storage caverns are located at a depth of approximately 300 ft and have a combined storage capacity of 15 million gallons.

2.3.5 Conclusions

Although the amount and detail of the information available for the several study areas assembled in this preliminary report were extremely variable, it is nevertheless possible to draw several tentative conclusions

concerning the potential of the areas studied for siting a pilot plant waste repository.

The chief conclusions are that the southeastern New Mexico area of the Permian basin appears to be the most promising of the areas studied and that additional, more detailed, investigations of this part of the basin are warranted. The principal factors leading to this conclusion are the large amount of geological data available because of the potash mining industry in the region; the presence of extensive and thick beds of high-quality salt located at appropriate depths; the possibility of disposing of excess salt in the existing potash mine excavations; the ideal surface conditions of low rainfall and low population density; and the fact that most of the area is currently in federal ownership. The major disadvantages appear to be related to an appreciable potential for future petroleum exploration and to certain hydrologic conditions.

Most of these hydrological problems involve local permeability of the formation overlying the salt unit and the resulting dissolution presently occurring at low rates in parts of the area. Although these problems must be investigated in detail, preliminary information suggests that they can be avoided by careful site selection.

All of the other areas studied seem to fall into two general categories: (1) those which appear to be promising for the future but which would require either further extensive investigation or the satisfactory resolution of the problems associated with some potentially disqualifying characteristics, and (2) those which appear to be unsuitable for further consideration at the present time.

The areas included in the first category are as follows: (1) structures of the Paradox basin, (2) the Supai basin, (3) portions of the Salina basin, and (4) certain selected Gulf Coast domes.

In the Paradox basin, the land surface characteristics such as population density, use, and ownership, etc., are again quite desirable and in many respects similar to those of the New Mexico area. Several salt structures in the form of large anticlines approach the surface to appropriate depths, and salt beds of suitable thickness and purity exist.

However, due to the folding of the area and the thickening and plastic deformation which the salt in the structures has experienced, the strata and the salt beds are no longer flat and horizontal. This means that some difficulties in the underground mining operations may be experienced and that it may be impossible to avoid the shales and the other nonchloride units interbedded in the salt. Occasionally, the nonchloride units contain oil, gas, and brine. This may mean, as confirmed by the experience of the single potash mine which has operated in the area, that the repository would be required to operate under the rules and procedures for coal and other "gassy" mines. Although the implications of such a requirement have not been analyzed in detail, satisfactory and practical operation of a waste repository would probably become exceedingly difficult.

The Supai basin in Arizona is also characterized by similarly desirable surface conditions of low population density and minimal utilization. Salt beds of appropriate depth, thickness, and purity appear to be present. The limited amount of detailed data available seems to suggest that the thickness of the salt beds is quite variable and that a sandstone aquifer at the top of the salt sequence may be responsible for some salt dissolution. These factors, taken together, imply that very extensive investigations would be required to confirm the suitability of any site in the Supai basin.

The most promising area of the Salina basin appears to lie in the northern part of the southern peninsula of Michigan. The salt beds in this area are isolated from circulating ground water by thick units of shale and anhydrite. However, in the areas where the depth to the salt is not excessive, the thickness of the suitable beds may not be adequate. Again, this implies that careful and extensive site selection and confirmation work would be required. The southeastern portion of Michigan is underlain by salt deposits having approximately the same geological characteristics as deposits in the northern part of the peninsula. However, these are considered much less desirable because of the extremely high population density around metropolitan Detroit. It is also possible that satisfactory sites could be found in other portions of the Salina basin, such as western New York State and northern Ohio.

Several salt domes that have been identified in the Gulf Coast region can be considered potentially suitable on the basis of present information. In these domes, the salt is located at appropriate depths and has not been developed for any other purpose. The purity of the salt in Gulf Coast diapiric structures is usually excellent, and the thickness of the salt in a vertical direction varies from 10,000 to 15,000 ft in the interior basins to greater than 30,000 ft in the coastal basins. Potential problems with Gulf Coast domes include questions about tectonic stability and rates of dissolution — both of which would require extensive investigation in order to confirm the suitability of any particular dome. In addition, the limited horizontal extent of domes, in relation to the requirement for a buffer zone surrounding the repository area, presents certain problems that might best be resolved by either a modification of the current waste disposal concept or the development of a new and different concept which would take better advantage of the shape of the salt mass.

The final grouping of areas includes: (1) the Williston basin, (2) the Luke salt body, (3) argillaceous formations in general, and (4) the three specific sites in calcareous rocks which were examined. For the reasons summarized below, it is felt that these areas offer limited potential and do not merit additional consideration at this time.

All of the salt deposits of the Williston basin are located at depths exceeding 4000 ft and, therefore, are too deep to be practical, at least with the present waste emplacement concepts.

The Luke salt body offers salt of high purity and satisfactory thickness in the appropriate depth range. However, the limited extension of the deposit and its proximity to the Luke Air Force Base and to the Phoenix metropolitan area are serious drawbacks.

The cursory review of argillaceous formations has not indicated any particularly promising environment or specific area. However, it should be emphasized that, with the scale of the present study, potential promising areas might have been overlooked. It should also be emphasized that a repository in these materials would probably require the

development of modified burial concepts and would certainly call for extensive investigation of the physical properties of these rock types at elevated temperatures.

Of the three specific sites in calcareous formations, the two shallow ones can be immediately rejected on the basis of insufficient isolation. The remaining one, the Barberton Mine in Ohio, is located in a dry limestone formation underlying 1600 ft of impermeable shale. Extensive studies would be necessary to evaluate the reliability of the shale as a barrier to ensure long-term containment of the wastes. However, at the present time, it is felt that the plasticity of the shale formation might not be adequate to maintain the integrity of the shale in case of tectonic movements.

2.4 Natural Containment Studies

The physical and mechanical properties of the geological formations of a disposal site influence the ability of the formations to adequately isolate the wastes. The thermal conductivities of the various formations involved become critical when thermal gradients develop as the result of heat transfer from the waste packages to the surrounding geologic medium. The development and operation of heat flow equipment for the measurement of thermal properties are discussed in Sect. 2.4.1.

Shale rocks are nearly always associated with bedded salt deposits. When these shales are subjected to the expected elevated temperatures, there is a possibility that certain clay minerals will experience partial dehydration, which, in turn, could lead to abnormally high pore pressures. Investigations of the potential for this process are described in Sect. 2.4.2.

The rock mechanics analysis discussed in Sect. 2.4.3 are directed toward evaluation of the mechanical effects that the operations of the repository will have on the surrounding rock strata and their potential for leading to conditions in which the geologic containment of the wastes could be breached.

2.4.1 Thermal Conductivity of Rocks (T. G. Godfrey, D. L. McElroy, S. H. Jury*)

The natural structural materials of a salt mine area vary from stone or shale-like substances to ordinary salt deposits. If such an area is to be used as a repository for nuclear waste, the thermal properties of these substances must be known. Thus we have developed and operated heat flow equipment for measuring thermal properties. This work yielded a new measurement technique, termed the "transient plane probe," plus other developments, all of which are described in Sect. 3.2.3.

Introductory Description of the Transient-State Plane Probe Heat Flow Equipment. - A survey of methods and apparatus for measuring the thermal conductivities and the thermal diffusivities of core samples was

*Consultant from the University of Tennessee, Knoxville.

required prior to making actual measurements of samples from a repository area. The following factors indicated the need for an apparatus with broad applicability: (1) the nature and number of core samples involved, (2) their anisotropic characteristics, (3) a minimum amount of machining of test specimens, (4) a precision of 1% consistent with relatively rapid measurement, (5) thermal properties ranging from inorganic powders to poorly conducting metals, and (6) use of specimens down to 3 in. in size.

The results of this survey showed that the plane probe, illustrated in Fig. 2.23, was best suited to the purpose. Its transient-state mathematical analysis and application to experimental results are relatively straightforward, making it more attractive than some others which use an approximate analysis.

The probe material is divided into two parts, with a thermocouple sandwiched in between. The thermal diffusivity, α_2 , and the thermal conductivity, λ_2 , of the probe material are known. The plane probe heater is etched spirally in the copper lamination of a printed circuit board of Fortin Micro-Clad Kapton.* The copper cladding can be obtained in thicknesses from 350 to 2800 μ in. (0.35 to 2.8 mils) on Kapton plastic in thicknesses from 0.5 to 3 mils. One face of the test specimen is ground flat, and a hole is drilled for inserting a thermocouple at a depth x_1 , as shown in Fig. 2.23.

The general principle of operation involves clamping the sandwich together and letting its temperature stabilize at a selected value. The PDP-8 computer is programmed to turn on the power supply and then measure the two thermocouple emfs and heater power at 15-sec intervals over a period of 130 to 150 sec. The computer processes these data and yields values of α_1 and λ_1 for the sample. By repeating the test at other temperatures, α_1 and λ_1 can be determined as functions of temperature.

Mathematical Analysis of the Plane Probe. - The plane probe mathematical representation for the transient data analysis is described below. The Kapton and copper cladding can be chosen so thin that one can assume

* Kapton is a trademark of the duPont de Nemours and Company, Wilmington, Del., for a polyimide film. Micro-Clad is a trademark of the Fortin Laminating Corporation, San Fernando, Calif.

Fig. 2.23. General Description of the Transient-State Plane Probe. The probe and heater are permanently bonded together and are pressed against the test specimen.

the heater is a plane which stores little or no heat. The 3-in. diameter is large enough, in comparison with the thickness of the sandwich shown in Fig. 2.23, that radial effects in the governing partial differential equation can be neglected, thus,

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2},$$

where $T = \tau - \tau_0$; τ_0 = starting reference temperature. At the heater,

$$F_0 = F_1 + F_2,$$

where

F_0 = total flux developed at the heater, Btu/hr·ft² of the plane probe,

$$F_1 = \lambda_1 \left. \frac{\partial \tau_1}{\partial x} \right|_{x=0},$$

$$F_2 = \lambda_2 \left. \frac{\partial \tau_2}{\partial x} \right|_{x=0}.$$

The solutions to the test specimen and probe parts are:

$$\tau_1 - \tau_0 = \frac{2F_0\sqrt{t}}{\frac{\lambda_1}{\sqrt{\alpha_1}} + \frac{\lambda_2}{\sqrt{\alpha_2}}} \operatorname{ierfc} \frac{x_1}{2\sqrt{\alpha_1 t}}$$

$$\tau_2 - \tau_0 = \frac{2F_0\sqrt{t}}{\frac{\lambda_1}{\sqrt{\alpha_1}} + \frac{\lambda_2}{\sqrt{\alpha_2}}} \operatorname{ierfc} \frac{|x_2|}{2\sqrt{\alpha_2 t}}$$

where

$$\operatorname{ierfc} x = \frac{e^{-x^2}}{\sqrt{\pi}} - x [1 - \operatorname{erf} x]$$

τ_1, τ_2 = temperatures read at respective thermocouples.

The ratio of the two solutions shows that, at any instant,

$$\left(\frac{\tau_1 - \tau_0}{\tau_2 - \tau_0} \right) \operatorname{ierfc} \frac{|x_2|}{2\sqrt{\alpha_2 t}} = \operatorname{ierfc} \frac{x_1}{2\sqrt{\alpha_1 t}}.$$

We can calculate a quantity Y , defined as:

$$Y = \frac{x_1}{2\sqrt{\alpha_1 t}}.$$

A plot of Y vs $1/\sqrt{t}$ has a slope $x_1/2\sqrt{\alpha_1}$, from which we can calculate α_1 . From the original solution for τ_1 , we can plot $\tau_1 - \tau_0$ vs $\sqrt{t}$ ierfc $\frac{x_1}{2\sqrt{\alpha_1 t}}$, and the slope is:

$$\frac{2 F_0}{\frac{\lambda_1}{\sqrt{\alpha_1}} + \frac{\lambda_2}{\sqrt{\alpha_2}}},$$

from which we can calculate λ_1 .

Currently the various parts of the probe are being fabricated and the computer program for the PDP-8 is being written. Other mathematical investigations of the probe have been made in order to better understand edge effects.

2.4.2 Mineralogical Studies

Water is undoubtedly the critical potential dispersing medium of radioactive nuclides introduced at depth in the earth's crust. Essential requirements of the disposal formation are the absence of circulating ground water and extremely low formation permeabilities. However, some water is always present in geologic materials; even rock salt, which is one of the driest geologic environments, has a brine content ranging from less than 1% to a few percent. In addition to free water contained in pores and fractures, water can exist in geologic materials in the form of adsorbed water and as water of crystallization.

Adsorbed water is abundant in clays, especially in the clay minerals of the smectite group.* Water of crystallization is present in several hydrous evaporite minerals (e.g., gypsum, polyhalite, and carnallite).

Because both adsorbed and crystallization water can be released upon heating, the mineralogical composition of the rocks in which the radioactive wastes might be placed is of interest. As a consequence of decay heat generated in the waste, geological materials overlying and underlying the disposal beds will be heated to relatively high temperatures to a distance of several hundred feet. Therefore, the mineralogy and possible

* Smectite is a group name for all clay minerals with an expanding lattice, except vermiculite; montmorillonite is the name of a specific mineral in the smectite group.

dewatering mechanisms must be investigated in all the zones that might be heated to significant temperatures. In addition, the possibility that dewatering might lead to the generation of abnormally high pore pressures, with the related potential instability, should be investigated.

These considerations led to three studies:

- (1) An examination of the mineralogy of shales overlying the Hutchinson salt.
- (2) A study of the mineralogy of the Hutchinson salt member.
- (3) Investigation of the occurrence and genesis of abnormal pore fluid pressures.

While the third study is general in nature and consists of a literature review aimed at an understanding of the problem, the first two studies are partially site specific. At the time these studies were initiated, the only available samples were those from the Lyons, Kansas, cores; thus it was decided to use them but to limit the number of analyses and concentrate on the development of techniques and equipment.

The results obtained to date in these studies are summarized below.

Mineralogy of Shales (Gale K. Billings*). — The tests performed on the shale samples include:

- (1) Determination of sodium by neutron activation analysis.
- (2) Determination of chloride for water-soluble salts.
- (3) Total carbonate for carbonate minerals.
- (4) Bulk sample x-ray diffraction.
- (5) Less than 2 μ (clay fraction) x-ray diffraction.
- (6) Less than 2 μ glycolated x-ray diffraction.
- (7) Less than 2 μ heated (625°C) x-ray diffraction.
- (8) Determination of unbound water.
- (9) Determination of structural water.

On the basis of these analyses, the quantitative chemical and qualitative mineralogical compositions of the rock samples have been defined. The

* New Mexico Institute of Mining and Technology.

results of the chemical analyses are shown in Table 2.7; the description and depth of the samples are given in Table 2.8.

The mineralogical analyses are qualitative in nature; however, they indicate the common presence of montmorillonite, mixed-layer clays, and chamosite. These minerals seem to be more abundant in the samples from the lower half of the core.

The data on quantitative mineralogical composition of the rock samples will be obtained by the use of an especially perfected computer technique. The method is based on two approaches: (1) assuming quasi-equilibrium, one can allocate the chemical elements in a rock sample to the minerals believed to be present on the basis of minimizing entropy of the system, using published thermodynamic data; (2) one can also approach mineralogical analysis by using the chemical data and a series of regression analyses to allocate the chemicals to theoretical, pure end-member mineralogy. Both a major element chemical analysis and a semiquantitative or qualitative mineralogical analysis are required.

In addition, an effort has been directed to the development of a water analysis technique capable of determining the amounts of interstitial, loosely bound, and structural water in clays.

Mineralogy of Evaporites (Otto C. Kopp^{*}). — An extensive search of the literature for articles related to evaporite mineralogy has served as background for this study and as the basis of a reasonably complete bibliography of the subject which is being generated.

The experimental work with samples involved (1) x-ray analyses for the determination of bulk mineral assemblages, (2) mineralogical determinations from petrographic thin sections, and (3) thermal analyses to define the dewatering of specific minerals and bulk rock samples. The samples studied were those from the core from AEC Hole No. 1 in Lyons, which had been judged to be rich in evaporite minerals, along with the samples obtained from the Carey mine in Lyons.

* University of Tennessee.

Table 2.7. Chemical Analyses (in wt %)

Sample No.	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃ ^a	K ₂ O	Na ₂ O	TiO ₂
1	43.35	18.45	3.35	5.19	12.25	7.47	1.49	0.59
2	6.81	3.60	21.70	8.57	0.72	1.04	0.30	0.00
3	48.89	16.42	13.18	4.63	12.12	5.82	1.71	0.81
4	41.80	17.85	1.55	3.62	14.23	7.11	1.46	0.64
5	46.65	20.40	1.44	3.23	14.76	7.88	1.37	0.69
6	51.75	16.60	2.45	4.99	10.13	5.48	1.72	0.80
7	54.90	15.65	0.95	6.55	8.65	4.99	1.47	0.69
8	54.72	15.47	1.69	4.35	9.10	4.79	1.81	0.79
9	47.01	17.13	2.11	7.63	11.33	5.96	1.83	0.72
10	57.50	15.52	1.83	5.24	8.07	4.99	2.26	0.68
11	45.56	16.84	2.51	6.66	13.18	6.71	1.68	0.60
12	47.37	17.32	3.38	5.39	12.94	6.75	1.68	0.67
13	49.34	17.13	1.44	5.22	18.54	7.18	1.72	0.75
14	52.97	13.87	4.02	6.95	5.54	4.69	1.74	0.67
15	38.51	11.31	8.06	9.47	7.70	5.54	1.64	0.45
16	20.06	3.72	16.19	13.06	5.75	4.00	1.45	0.15
17	47.76	15.83	1.06	4.44	9.97	5.66	2.66	0.77
19	49.73	12.74	1.36	6.62	11.69	4.35	2.55	0.80
20	37.66	11.21	7.71	10.00	8.26	5.10	1.77	0.41
21	29.99	7.00	4.59	14.62	9.08	4.27	2.17	0.42
23	46.39	13.58	0.99	7.36	12.37	4.68	8.16	0.58
24	41.20	12.87	2.07	4.80	9.95	4.64	8.35	0.46
25	38.03	12.96	3.90	8.34	8.78	5.12	2.28	0.53
26	37.18	14.30	1.43	7.17	10.80	5.08	4.38	0.58
27	35.93	12.26	5.35	8.36	7.91	4.98	2.73	0.47
28	45.93	11.73	1.01	6.74	12.71	4.04	3.00	0.74
30	42.14	10.90	9.67	7.51	6.59	5.45	1.61	0.39

^aTotal Fe as Fe₂O₃.

Table 2.8. Description and Depth of Analyzed Samples from
Corehole AEC No. 1, Lyons, Kansas

Sample No.	Depth (ft)	Description
1	324.9	5 in. intercolated red and green clays with very minor silt; sample from red horizon ^a
2	309.5	2 in. gypsum; 1 in. finely laminated white-gray clay shale; 1/2 in. above shale with stringers of gypsum; 3 in. white to gray clay shale (nonfissile); ^a 3/8 in. interbedded gypsum and shale
3	352.7	3-1/2 in. red siltstone massive; ^a 1-1/2 in. laminated siltstone
4	382	5 in. fine red claystone (minor silt) intercolated with minor blue-gray clay
5	393.5	3 in. red clay with minor silt
6	415	14 in. gypsum; 3 in. intercolated clay and gypsum; 5 in. red clay (minor silt); 2 in. intercolated gypsum and clay
7	435	1 in. red siltstone with secondary gypsum in fractures and bedding planes (~5%); 1-1/2 in. blue-green clay; minor gypsum ^a
8	456	3-1/2 in. red fine-grained siltstone; minor sprinkling of crystals (gypsum?) throughout sample
9	475	3 in. red and blue-gray siltstones with a few small pods of gypsum along bedding planes
10	495	3 in. reddish clay-shale; fractures filled with gypsum; also zones that appear to be secondary replacement (pods)
11	520	2-1/2 in. variegated red and green clay-shale
12	540	2 in. red clay; ^a 1 in. bluish clay and red clay more than 50% replaced by evaporite minerals
13	556	4 in. variegated shale—deep red to gray-white minor silt; deep red is much finer; ^a may be evaporites in whitish stringers.
14	575.5	3-1/2 in. gray shale with minor evaporite mineral crystals; darkest portion ^a
15	597.0	1/2 in. gray shale and evaporites; 1 in. gray shale; ^a 2 in. fracture filling - gypsum; 1 in. shale and gypsum

Table 2.8 (contd)

Sample No.	Depth (ft)	Description
16	522	1/4 in. evaporites; 3 in. gray-black shale, very hard (organic matter?); ^a 2/3 in. evaporites
17	634	1 in. black shale; 2-1/2 in. gypsum and shale in stringers; 3-3/4 in. gray-black shale; ^a 1 in. gypsum
18	655	3 in. massive gypsum stringers in green shale
19	674	4 in. red siltstone with minor pods and stringers of evaporites
20	726.6	4 in. variegated black-gray shale; black layers fissile and brittle
21	755.5	3 in. black shale with evaporite stringers; ^a 1 in. gypsum and black shale
22	767.5	3 in. gypsum (60%) and gray shale (40%); not sampled
23	805.5	Gray shale, shattered and containing 3 in. stringers of evaporites (<u>salt</u>)
24	870	2-3/4 in. red shale; gypsum filling fractures; minor blue-gray stringers
25	904	<u>Salt</u> encrusted on outside; 6 in. disturbed black mass (<u>soft</u>) some evaporite replacement; took horizontal split of darkest color section ^a
26	1061	3-1/2 in. gray-black shale with reddish <u>salt</u> fractures; minor gypsum
27	1094	5 in.; 70% shale; 30% evaporites
28	1118.4	4 in. reddish clay with evaporite stringers and secondary crystals; sampled middle section ^a
29	1181	4 in. evaporites with minor shale
30	1293	5 in. green clay

^aRefers to analyzed fraction when sample was not homogeneous.

Results of the x-ray analyses of samples from AEC Hole No. 1 indicate that gypsum disappears as a major phase at a depth somewhere between 600 and 800 ft. During the course of the x-ray analyses it was ascertained that determination of the amounts of gypsum and anhydrite present in the sample is possible at the 2 wt % level (and below). The procedure involves preparation of standard mixtures from halite, gypsum, anhydrite, shale, and quartz. The resulting powders are pressed in aluminum caps for 5 min at 4000 psi, resulting in disks for which the random effects of hand packing in ordinary holders are minimized. The data are defined by least-squares analyses to determine the best straight-line fits, and plots prepared in which the intensities of the diffracted x-rays are related to the percentage of gypsum and anhydrite in the mixture.

Static heating tests of gypsum and whole rock samples have been conducted for weight loss determinations. Tests were run on six size fractions of gypsum at $102 \pm 3^\circ\text{C}$, $75 \pm 3^\circ\text{C}$, and $60 \pm 3^\circ\text{C}$. No weight losses were detected in the samples after a period of 2 weeks at $60 \pm 3^\circ\text{C}$. Figures 2.24 and 2.25 show the dehydration curves for gypsum at $102 \pm 3^\circ\text{C}$ and $75 \pm 3^\circ\text{C}$ respectively. Dehydration proceeds at a much higher rate at $102 \pm 3^\circ\text{C}$, as was expected. The rate of dehydration is inversely proportional to the particle size, with the exception of the 50- to 100-mesh fraction. No explanation of the anomalous behavior of this fraction can be offered at this time; however, it seems probable that it is related to the experimental procedure. The weight losses observed at $75 \pm 3^\circ\text{C}$ correspond to the development of the hemihydrate phase ($\text{CaSO}_4 \cdot 1/2 \text{H}_2\text{O}$), although this has not yet been confirmed by x-ray analysis.

Thus far, the primary emphasis in the static heating tests has been on gypsum, but the more critical question to be addressed is the total amount of water that could be released from a whole rock sample upon heating. The weight losses of rock samples from AEC Hole No. 1 have been studied. Some of the results (i.e., results from the first group of six samples) are as follows:

Fig. 2.24. Dehydration of Gypsum as a Function of Time. Test made at $102 \pm 3^\circ\text{C}$ and 1-atm pressure.

Fig. 2.25. Dehydration of Gypsum as a Function of Time. Test made at $75 \pm 3^\circ\text{C}$ and 1-atm pressure.

<u>Depth (ft)</u>	<u>Weight Loss (%)</u>
305.7	15.5
426.5	19.0
542.8	14.5
674.5	8.0
1084.4	1.1
1228.0	2.8

To limit the probability of errors, it is necessary to use representative sample splits taken from cores which do not appear to have been affected by the drilling fluids or reactions that might have taken place during storage. Naturally, these weight loss determinations will not, by themselves, indicate the precise sources of the water (e.g., gypsum, clays, other hydrated minerals, fluid inclusions, intergranular films, etc.). Not enough data are available yet to draw firm conclusions. As anticipated, there is a decrease in the amount of dehydration water with increasing depth. The nearly 3% weight loss from the sample below a depth of 1200 ft could amount to about 2 liters of water per cubic foot of rock.

It must be emphasized that all these tests have been performed at atmospheric pressure, while the geologic materials in situ will be heated under the confining pressures existing at their respective depths. The effect of confining pressure on the phase change of hydrous minerals and on the thermally induced dewatering of rocks is an important point deserving further consideration.

Fifty-five specimens were selected from the core from AEC Hole No. 1 and slabbed in preparation for the cutting of oversized thin sections. The slabs were sent out to a laboratory that specializes in the preparation of petrographic thin sections. These sections will be studied as soon as they are returned.

Abnormal Pore Fluid Pressures. — Under normal conditions, water contained in the pores or fractures of rocks is under a pressure equal to the weight of a column of water extending from the depth considered to the top of the saturation zone. Assuming the top of the saturation zone to be coincident with the surface (practically true in most cases), the normal or hydrostatic pressure ranges from 0.43 to about 0.47 psi

per foot of depth, depending on the salinity of ground water. Any water pressures different from the hydrostatic value are considered abnormal; abnormal pressures can be lower or higher than hydrostatic. Abnormally high pressures are more frequent and are the only kind that will be discussed below.

Abnormal pressures can exist only in formations that are effectively isolated from the zones of circulating ground water. The seal is usually formed by very impermeable argillaceous sediments or by beds of rock salt; occasionally the sealing formation is constituted by massive beds of anhydrite, limestone, or dolomite. Several possible causes of high formation pressures are cited in the literature:

- (1) Aquifer head.
- (2) Rate of sediment accumulation in excess of the rate of fluid escape from the compacting sediments.
- (3) Tectonic deformation.
- (4) "Fossil" pressures (corresponding to a previous greater depth of burial).
- (5) Infiltration of hydrocarbons or magmatic fluids.
- (6) Osmotic phenomena.
- (7) Phase changes, for example, transformation of gypsum to anhydrite plus water or transformation of hydrated clay minerals to dehydrated minerals plus water.
- (8) Chemical reactions.
- (9) Precipitation of minerals with an attendant change in pore volume.

Aquifer head is the common and well-understood cause of water pressure in artesian aquifers; only cases of abnormal pressures that cannot be explained by artesian conditions will be considered below.

In the United States, abnormal pressures have been observed in the Gulf Coast region (most frequently occurring at depths of 8000 to 12,000 ft), in the Cenozoic basins of California (at depths ranging from 2000

to 14,000 ft), in the Paradox basin of Utah and Colorado, and in various other areas.^{70,71}

Numerous occurrences have been reported outside of the United States, especially in thick clayey sequences of Cenozoic ages. Abnormal pressures have been observed at a depth of only 1000 ft in Pakistan.⁷²

The oil industry has accumulated considerable experience with the occurrence of abnormal fluid pressures. Usually, abnormal pressures are observed in clayey beds or in sand lenses totally enclosed in argillaceous formations, especially in sedimentary basins of Cenozoic age. A few cases of abnormal pressures in ancient rocks, Mesozoic and even Paleozoic, are known, but they are always associated with sealing formations of exceptionally low permeability. This indicates that abnormal pressures are geologically transient phenomena and, therefore, that they must be associated with hydrodynamic conditions; however, when the sealing formations are very impermeable, the abnormal pressures can be retained for periods as long as several hundred million years.

In the sedimentary sequences where abnormal pressures are observed, rates of sedimentation are high and permeability, especially across the bedding, is very low. Under these conditions, the rate of escape of connate fluids from compacting sediments is less than the rate of sediment accumulation; consequently, the trapped fluids prevent compaction and support part of the weight of the overburden.

In deposits characterized by normal fluid pressure, the bulk density of shales is inversely proportional to the porosity and increases directly with the depth of burial. Figure 2.26 shows some average relationships between shale density and depth in different areas.

If we assume that an ideal sealing formation with zero permeability is present in a sedimentary sequence, no fluids could escape from the underlying units and no compaction would occur; hence λ , the ratio between fluid pressure and overburden pressure, would be equal to 1. Figure 2.27 shows the relationships between depth and porosity for various values of λ in an average shale. Cases in which λ has a value very close to 1 have been reported in the literature. It seems reasonable that a value of 1

Fig. 2.26. Average Relationships Between Shale Density and Depth. Curve 1--determined by Athy for Paleozoic shales in Oklahoma; curve 2--determined by Hedberg for Paleozoic shales in Kansas; curve 3--determined by Dickinson for Cenozoic shales in the Gulf Coast Area.

Fig. 2.27. Mutual Relationships of Depth, Porosity, and Fluid Pressure--Overburden Ratio in an Average Shale or Mudstone. Athy's curve is assumed to represent the condition of "compaction equilibrium."

for λ represents a limit condition; if fluid pressures in excess of geostatic pressure were achieved because of tectonic compression, overburden removal, or other mechanisms, the fluids would either uplift the overburden, thereby decreasing the density of the overpressured formation, or fracture the sealing zone. It follows from the above discussion that overpressured shales are undercompacted in relation to their depth and, therefore, are characterized by high plasticity and low density. As a result, overpressured shales are a potential diapiric material; in fact, many masses of diapiric shales have been identified in the Gulf Coast region. In many instances, shale masses are intruded along with salt to form a single diapiric core; in other cases, salt or shales are the only intrusive material.⁷³

Many geologists maintain that, in addition to the rapid rate of sedimentation over a sequence of sediments of very low permeability, other mechanisms must be invoked to explain the genesis of abnormal pressures. Frequently proposed alternatives are osmotic phenomena and the transformation of smectite minerals to the interstratified layer arrangement of illite and smectite.

Shale beds are known to behave as semipermeable membranes and, in many cases, pore waters in shales and sands are characterized by variable salinity; thus osmotic processes must take place in most sedimentary basins where abnormal pressures are observed. However, osmotic phenomena must constitute a secondary factor since they cannot, usually, account entirely for the observed pressures.

The diagenesis of argillaceous sediments with transformation of smectite to illite and mixed-layer clay minerals is well known, and is documented by the abundance of montmorillonite in Cenozoic marine clays as well as by its progressive reduction with increasing age and depth of burial; however its relevance to the genesis of abnormal pressures is, at the least, controversial.

Recently reported experiments in which samples of natural and pure sprayed-dried sodium montmorillonite were saturated with distilled and simulated sea water and then tested with various chemical solutions before

being compressed at pressures from 1000 to 200,000 psig, under pH conditions from 0.5 to 13 and at temperatures up to 193°C, have failed to show any modification of the clay minerals structure.⁷⁴ The duration of these experiments ranged from 7 to 21 days; therefore, a large uncertainty is due to the time factor.

To date, very few mineralogical analyses of clays in the abnormal pressure zones and in the overlying transition and normal zones have been published. Some of these studies seem to indicate that changes in clay mineralogy often coincide with the top of the high-pressure zone. The significant change reported is a decrease in expandable clay minerals like montmorillonite, accompanied by a relative increase in nonexpandable clay minerals like illite and chlorite.⁷⁵

Experimental determinations of reaction rates for significant transformations in the diagenesis of expandable clay minerals have been recently reported in the literature.⁷⁶

The following two reactions are probably significant:

The reaction rates indicate that, at 70°C, reaction (1) would form an illite/smectite with 65% illite layers in about 25,000 years; at the same temperature, reaction (2) would achieve the same result in less than 10 years. If these reaction rates are indicative of actual rates during diagenesis of the argillaceous sediments, the composition of naturally occurring illite/smectite should always be in equilibrium with the diagenetic environment.

In conclusion, smectite minerals undergo transformation to mixed-layer illite/smectite and the rate of the reaction is directly proportional to the temperature. During the transformation, interlayer water is mobilized and released to the pores of the sediment. However, the relevance of the process to the genesis of abnormal pressures is unknown. There is ample evidence to indicate that the water held directly on the surfaces of the clay particles is in a physical state different from that of liquid water. The film of nonordinary water is best developed on the

basal plane surfaces of the expanding-lattice minerals of the smectite group. Consequently, in argillaceous sediments, water in pores would be liquid water, while adsorbed water would be in a nonliquid, probably quasi-crystalline state.⁷⁷

Transfer of water molecules from the organized arrangement of the interlayer water to the liquid water in the pores would result in an increase in pore pressure only if the density of adsorbed water were greater than 1. The problems relative to the density of adsorbed water are particularly significant; unfortunately, this is the subject of substantial controversy. Density values as low as 0.73 and as high as 1.7 have been reported in the literature. Results of some of the more reliable experiments seem to indicate a density for adsorbed water on smectite surfaces of the order of 0.97 to 0.98.⁷⁸ If this is the case, the diagenesis of smectite minerals would have no effect on formation pressures.

In conclusion, it is obvious that the genesis of abnormal pressures is a complex phenomenon; many factors, not reciprocally exclusive, may be responsible; however, the occurrence of an impermeable seal in a zone of progressive compaction is a necessary and, probably, sufficient condition.

2.4.3 Rock Mechanics Analysis

In any full-sized waste repository, the salt formation and the surrounding rocks, especially those overlying the disposal horizon, will be subjected to a sequence of transient and permanent displacements and strains. These deformations will result from the combined effects of: (1) the designed closure of the mine openings, during which the plastic creep deformation of the support pillars, accelerated by the elevated temperatures, will allow the room ceilings to rest on the backfill salt, eventually reconsolidating and recrystallizing it; and (2) the bulk thermal expansion and induced thermal stresses caused by the transient temperature increase in the rock mass. The objective of the rock mechanics analyses is to provide an estimate of the magnitude of these deformations and an evaluation of their influence on the natural long-term containment offered by the geologic structure.

The analysis is being carried out in two principal parts. The first part, called the semiempirical analysis, consists of a computer model simulating, in three dimensions, the mechanical behavior of a repository area as it is loaded with waste over a given time span. This model is called semiempirical because the in-situ mechanical and deformational property parameters of the model are determined by correlation with deformations actually measured during the Project Salt Vault experiment. Because of the large size of any actual repository and the nature of this model, it is not possible to utilize a detailed geologic column and properties for the various rock types involved. Furthermore, the calculated deformations cannot be rigorously interpreted; instead, this model yields only the general outlines and shapes of the total deformations and serves to identify those areas which experience the most severe conditions.

The objective of the second part of the analysis, the finite-element modeling, is to provide the details of the displacements and strains in the areas of interest. In these two-dimensional calculations, the details of the geologic section are modeled more realistically, taking into consideration physical properties of each rock type as determined by laboratory tests conducted on core specimens.

Semiempirical Model. - As a part of the analysis of the Project Salt Vault experimental results, a two-dimensional analysis of this type was carried out and is described in Sect. 13 of ORNL-4555.⁷⁹ As the first step in the current effort, this earlier analysis was enlarged to three dimensions and otherwise generalized and then recorrelated with the deformations measured during the experiment at Lyons, Kansas (Project Salt Vault). The correlation was performed by modeling the five-room experimental area in 5-ft-square elements and sequencing both the excavation of each of the rooms and the power history of individual heaters. The "seam closures" calculated at eight of the segments were then compared with the vertical mine convergence occurring at those locations, as measured during the experiment. Based on the comparison, a different set of physical property parameters was chosen and the process was repeated. Figures 2.28 and 2.29 show the comparison of the model and measured convergence for the run which was considered to be an adequate correlation. Figures of this type

Fig. 2.28. Comparison of Measured Convergence with Calculated Mine Closure.

Fig. 2.29. Comparison of Measured Convergence with Calculated Mine Closure.

are obtained for each of the eight points. The values of the physical property and model parameters used in this "correlated" run are given in Table 2.9. Both the 2-D model and the 3-D model are based on a creep deformation law obtained empirically by Lomenick,⁸⁰ who found that:

$$\epsilon = 1.3 \times 10^{-37} \sigma^{3.0} T^{9.5} t^{0.3} .$$

It is interesting to note that "correlation" creep parameters obtained for the 3-D model are closer to these values than were earlier obtained for the 2-D model.

This model is currently being used to develop data for comparison with the finite-element analysis and in a parametric analysis of the small area to be used as a pilot plant. Efforts are also currently in progress to drastically extrapolate this model, with respect to both space and time, so that the evaluation of actual repository operations can commence.

Finite-Element Analysis. - This portion of the analysis is divided into three parts: (1) laboratory determination of the rock property parameters required for input into the finite-element models, (2) thermal elastic-plastic finite-element modeling of the repository site rocks, including simulated excavation, heat sources, and backfill compaction, and (3) thermal viscoelastic finite-element modeling of the repository site.

Experimental Results. - Specimens prepared from the core obtained at the Lyons site were analyzed in these tests in order to provide realistic values of the physical property parameters used in the mathematical models and to confirm and refine the testing techniques and equipment. As soon as core material from the selected site becomes available, a more extensive series of laboratory tests will be conducted. Simple-compression and indirect-tension tests made at room temperature and atmospheric confining pressure have been completed for samples from five of the nine rock layers to a depth of 1290 ft. Creep experiments, in simple compression and at room temperature and atmospheric confining pressure, have been completed using samples of Minnescah shale and Hutchinson salt.

Table 2.9. Model Parameters

Definition of Parameters	Value in 2-D Correlation	Value in 3-D Correlation
Elastic modulus of roof and floor rock, psi	10^6	10^6
Poisson's Ratio of roof and floor	0.4	0.4
Initial ambient temperature at mining, °K	300	300
Mean thermal horizon diffusivity in vicinity of heat sources, ft ² /hr	0.1	0.1
Premining vertical stress, psi	1000	1000
Elastic modulus of pillar, psi	1.5×10^6	10^6
Coefficients in creep equation ($\epsilon = A\gamma^a T^b t^c$)		
A	0.65×10^{-36}	0.65×10^{-37}
a	3.0	3.0
b	9.5	9.5
c	0.37	0.25
Pillar height, ft	14.0	14.0
Half width of elements, ft	2.5	2.5
Length of time steps, hr	120	600

A compilation of the overall physical-property data obtained to date from the testing program is presented in Table 2.10. A note of caution is advised in evaluating these rock parameter values on an absolute basis since sufficient test results are not available at this time to assess the statistical scatter of the data and to establish confidence limits. The experimental results obtained thus far are only preliminary in nature and simply serve to provide guidelines for quantitative levels of parameter magnitude. It must also be noted that the core samples obtained for testing were subjected previously to several freeze-thaw cycles. The influence of freezing and thawing on the mechanical properties of rock is difficult to ascertain quantitatively; however, from a qualitative viewpoint, an overall loss of "competence" in the rock structure would be suspected, particularly for the more porous rock and for shales containing entrapped water and swelling minerals. Some of the shale samples obtained for testing exhibit swelling and are, in general, somewhat friable and fragile.

The procedure for preparing the test samples proved to be quite time-consuming. In general, 2-in.-diam samples were dry-cored normal to the bedding planes from split-segments of 6-in.-diam core. The compression samples were cored to a nominal length of 4.5 in.; the ends of the sample were initially trimmed with a diamond saw (under dry conditions), resulting in a nominal length of 4.2 in., and then dry ground in order to achieve parallel ends. During both the coring and grinding processes, core breakage along a bedding plane frequently occurred; the broken cores were either abandoned or salvaged for tensile specimens. A tensile specimen consists initially of a 2-in.-diam core, approximately 2.5 in. long. The ends are trimmed with a diamond saw (under dry conditions), resulting in a nominal length of 2 in., and then hand-lapped on a grinding wheel. Numerous core samples, with a diameter of 0.75 in., were cut parallel to the bedding for the future assessment of anisotropic rock parameters.

As mentioned previously, all tests were conducted under conditions of room temperature and atmospheric confining pressure. In the compression tests, both short-time and creep, the core samples were loaded uniaxially, perpendicular to the bedding planes. Axial strains during loading were monitored by two strain gages, positioned along the axis of the core and

Table 2.10. Physical-Property Data for Rock at Lyons Site

Depth (ft)	Rock Type	Static Elastic Properties		Static Strength (psi)		Steady-State Creep Parameter [in. in. ⁻¹ (psi-sec) ⁻¹]
		E(10 ⁶ psi)	Poisson's Ratio	Compression	Tension	
0-70	Clay (lean) ^a	0.25	0.3			
71-170	Kiowa formation (clay shale interbedded with sandstone)					
171-295	Harper sandstone (silt-stone)	0.5	0.2	2600	170	
296-315	Stone Corral (dolomite, anhydrite)	5.8	0.34	3500	180	
316-630	Minnescah shale	0.6	0.2	2100	290	2.85 x 10 ⁻¹²
631-815	Wellington shale					
816-1080	Hutchinson salt	0.4	0.4	2300	350	0.84 x 10 ⁻¹²
1081-1250	Wellington formation (anhydrite and shale)				770	
1251-1290	Noland formation - Harrington member (dolomite, limestone)	3.3	0.32	5000	700	

^aAverage values available in the literature.

diametrically opposite of each other (to average bending effects); in addition, during the creep tests, the axial displacement of each core sample was measured by means of a pair of DCDT transducers. In the compression tests, the circumferential or lateral strains of each sample during loading were measured by two strain gages, positioned on the circumference of the core diametrically opposite to each other. The tensile strength of a rock sample was obtained indirectly by means of the Brazilian test. Diametrically opposite line loads were applied on the circumference of a core, parallel to its axis, and the tensile strength was calculated from the load at failure and the sample dimensions.

In general, the compressive and tensile strengths of the various members were less than anticipated, particularly for the Stone Corral. From the viewpoint of quantitative guidelines, the compressive strengths of the Harper sandstone, Minnescah shale, and the Hutchinson salt are of the order of 2500 psi, with tensile strengths ranging from 200 to 400 psi. The compressive and tensile strengths of the Stone Corral appear to be of the order of 3500 psi and 500 psi respectively. The members below the Hutchinson salt exhibit compressive strengths of the order of 5000 to 6000 psi and tensile strengths ranging from 700 to 800 psi. It must be emphasized that these values are preliminary and subject to revision and statistical clarification, pending the results of additional tests. In each instance, the rock sample did not fail violently but, instead, developed localized cracking with subsequent crushing and compaction.

Thermal Elastic-Plastic Finite-Element Model. — A note of caution is advised with regard to the absolute interpretation of the numerical results presented in this and the next sections. Although the analyses are mathematically sound (being based on the fundamental axioms of mechanics), the computed results are only as good as the assumed stress-deformation laws and the physical-property data input. To date, the results obtained experimentally in the laboratory are only preliminary, thus serving merely as guidelines for the selection of appropriate constitutive relations and for quantitative estimates of the magnitudes of rock parameters. By the same token, the computer results must be

regarded from more of a qualitative than a quantitative viewpoint. The essential features of the mechanical behavior of the repository site can be distinguished, and perhaps bracketed, by calculations based on reasonable estimates of the extreme variations in the values of the rock parameters for relatively simple constitutive laws. The refinement required for improved quantitative judgments is directly related to the scope of the laboratory testing program.

The elastic-plastic analysis has been directed primarily toward an evaluation of variations in the values of the moduli of elasticity and the tensile and compressive strengths of the rock members, in conjunction with the number of rooms in a row on the mine level, as regards the stress behavior for short time periods. Two finite-element models have been employed for seven production runs for the purpose of assessing the effects of mesh size, number of rooms, and variation in material properties on the elastic-plastic states of stress and deformation in the repository site. The first is a relatively coarse mesh, containing 434 nodes and 807 elements, of which 391 elements are in the Hutchinson salt formation. The second contains 875 nodes and 1683 elements, of which 1201 elements are in the salt layer. The first two computer runs on each of these models were made for the purpose of assessing the effect of the finite-element mesh size on the computations. The second model contains twice as many elements as the first but, more importantly, has approximately three times the number of elements in the salt layer in which the room is situated. Each model contained a single room. The maximum surface subsidence predicted by both models is the same (0.001 in.), and the maximum closure predictions for the room are within reasonable agreement (0.073 and 0.089 in. respectively). The latter difference is probably caused by numerical aspects of the computations. However, the smaller elements in the vicinity of the opening in the second model reveal several elements in tension, whereas the larger elements of the first model obscure the stress gradient near the roof of the room as evidenced by the lack of tension. A slight tension should, in fact, be present. Thus, a coarse mesh appears satisfactory for displacement calculations, but a refined mesh will be required for stress analyses.

The influence of the number of rooms on stress and deformation fields was examined on the basis of three production runs with the second, small-element model involving one, three, and five rooms. As the number of rooms increases from one to five to nine, the relatively high stress concentration in the solid salt on the outboard side of the end room moves beyond the influence range of the rooms near the center of the model. From a practical viewpoint, nine rooms probably represents an infinite row of rooms; hence, the column of rock strata containing any one of the central rooms may be selected for detailed analysis. However, there does appear to be a trend toward a slight expansion of the zone of roof tension as the number of rooms in a row increases. The salt around the rooms does not yield plastically for either five or nine rooms in a row. The maximum surface subsidence is less than 0.002 in. for an array of five rooms and less than 0.004 in. for an array of nine rooms; the corresponding maximum room closures are 0.110 in. and 0.112 in. respectively.

Results of the computer runs completed thus far support the general notion that the preliminary elastic-plastic analysis and associated methods of evaluation are appropriate to the evaluation of the rock mechanics aspects of a waste repository.

Thermal Viscoelastic Finite-Element Model. - The viscoelastic analysis has been directed toward an evaluation of variations in values of the creep parameter for the rock members, in conjunction with an infinite row of equally spaced rooms on the mine level, as regards the deformational behavior over long time periods. Again in this analysis, two models were employed for the purpose of assessing the effects of mesh size and variations in the steady-state creep rates of the rock members on viscoelastic states of stress and deformation in the repository site. The first is a relatively coarse mesh, containing 72 nodes and 100 elements, of which 33 elements are in the Hutchinson salt formation. The second contains 180 nodes and 298 elements, of which 222 elements are in the salt layer. Each model represents a cross section of the site, with a depth of 1300 ft and a width of 18 ft, containing one-half of a pillar and one-half of a room; in essence, the model represents a column of rock strata containing

a central room in an infinite row of rooms. The stratigraphic sequence of rock layers and corresponding rock parameter values are given in Table 2.10; whenever possible, the values of the rock parameters were taken from those obtained in the laboratory on core from the Lyons site.

The viscoelastic computer code is programmed to compute both transient and steady-state creep deformations according to the linear Burger rheological model, which is, in essence, a Voigt model and a Maxwell model coupled in series. However, the results obtained thus far pertain only to steady-state creep, as the parameters for the Voigt portion of the Burger model were unavailable. The computational process is exceedingly tedious and time-consuming, owing to the judicious process required for determining the proper time increment necessary for convergence of the calculations. Several development runs were required for establishing bounds on the time increment in relation to the magnitude for the steady-state creep parameter, as well as for establishing guidelines for updating the time increment during the computational process. Commonly, a time increment of 0.001 year for five to ten cycles is required to initiate the computations. The choice of the initial time increment is quite important; too small an increment will give rise to computational inaccuracies due to roundoff and truncation errors, while too large an increment will cause the computations to diverge. The time increment is generally updated by a factor of 2 or 5 after every five to ten cycles.

The first runs with each of the two models were made for the purpose of assessing the effect of the finite-element mesh size on the computations. The second model contains approximately three times as many elements as the first. The computed displacements differ by no more than 10% for small time intervals, say less than 1 year; however, for large time intervals the difference becomes progressively greater. The inaccuracies over long time spans occur as a result of the stress calculations, which may be exceedingly coarse for a relatively coarse mesh. The viscoelastic deformations are directly related to the deviatoric stresses, and the error due to a coarse calculation of the latter propagates in an accumulated fashion over a long time interval.

The effect of a variation in the magnitude of the steady-state creep parameter on the displacement field in the repository was examined on the basis of two production runs with the fine-mesh model. In the first run, the value of the creep parameter for the Hutchinson salt was taken as that given in Table 2.10, and the values of the creep parameters for the other seven rock members were assumed to be those given for the Ninescah shale. During the second run, all values of the creep parameter were reduced by two orders of magnitude. The sensitivity of the viscoelastic displacements to a variation in this parameter was quite apparent. For a value of the creep parameter of 0.345×10^{-12} in. in.⁻¹ (psi-sec)⁻¹ for the Hutchinson salt, the displacements of the roof and floor of the room are quite rapid and large, giving rise to complete closure of the room after three years. Conversely, a value of 0.845×10^{-14} in. in.⁻¹ (psi-sec)⁻¹ yields room displacements over a period of 25 years which appear physically reasonable (i.e., ~5 in. of floor heave and 4 in. of roof sag at the center line of the room). These computations suggest that complete closure of the room would result after 450 years. Of greater importance, however, is the fact that an accurate account of the creep deformation throughout all three stages of creep (transient, steady state, and tertiary), as obtained from laboratory experimentation, is a necessity due to the sensitivity of the computer code calculations to the creep-parameter values.

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3. OPERATIONAL SAFETY

3.1 Isotope Migration

A. P. Malinauskas

The significance of isotope migration must be considered with reference to two different time scales. Over the short term, the primary concern is one of safety to personnel while the waste repository is operational; consequently, we have investigated the possibility that rapid transport mechanisms, including hydrogen explosions, could endanger these individuals. In contrast, very slow transport processes, while unimportant over time intervals comparable to the repository operational period, can, in principle, compromise the concept of the salt impenetrability when viewed in terms of the period during which the waste material must be isolated from the biological environment. Furthermore, these slower mechanisms will probably determine the extent of overcoring required in the event that retrieval of the radioactive waste becomes necessary. Therefore, studies of the slower migration mechanisms have also been continued.

During this report period, the investigations regarding effects which are important over the briefer time span were, in effect, confined almost strictly to considerations of the likelihood of hydrogen concentrating in burial holes or rooms in sufficient quantities that explosions become a possibility; the particular studies made were concerned with the behavior of crushed salt columns in the presence of water vapor and, more directly, with hydrogen flammability in crushed salt.

The isotope migration mechanisms of potential significance, when viewed over the longer time spans which have been studied, have involved only surface diffusion. In addition, however, the experimental search for possible synergistic effects, as well as attempts to estimate the importance of aerosol transport, have been continued; these studies consist of "integrated" experiments, in which the transport of tagged species (in simulated waste) through crushed salt columns is being investigated.

3.1.1 Transport of Water Vapor Through Crushed Salt Beds Under Nonisothermal Conditions (R. B. Evans III, J. L. Rutherford)

Considerable attention has been given to measurements of the rates of migration of gases through crushed salt since this material will serve as backfill in salt-mine repositories.¹ Interest in water vapor transport, in particular, is generated as the result of several effects which are initiated when heat-generating waste containers are buried in bedded salt and then backfilled. The bedded salt contains brine-filled cavities. When the temperatures of the region surrounding the buried containers rise, thermal decrepitation and fracturing of the salt occur, and the brine-filled cavities migrate up the thermal gradients to the hot surfaces about the waste containers. As a result, brine is released near the containers.

Water vapor from the released brine, if not decomposed by the waste container, will then move upward in the crushed salt backfill toward low-temperature zones, where condensation can once again occur. As time progresses, the thermal gradient will extend to all points in the backfill, so that the condensation point can possibly move upward in the backfill until the process is terminated as a result of salt reconsolidation.

Moreover, the plausibility of the occurrence of these events has already been established. Decrepitation fractures were described by Bradshaw, Empson, and Boegly;² indications of free brine near buried heaters were reported by Kegley and Empson;³ measurements of water vapor production in burial holes were reported by Bradshaw and McClain;⁴ and observations of considerable reconsolidation of backfill adjacent to simulated waste containers were likewise noted.⁵ Hence the objective of the present investigation was to study the effects of water vapor transport through crushed salt beds under nonisothermal conditions, with particular attention being given to moisture-induced salt reconsolidation. Furthermore, for reasons of expedience, the studies were conducted in the absence of compaction effects (hole closure) resulting from plastic flow of the salt in the formation.

The first two experiments were performed with time-constant temperature profiles maintained along the lengths of the crushed salt columns; these experiments were undertaken to test the experimental approach as well as to observe consolidation effects under restricted conditions. Some of the data obtained have already been reported.⁶ In this section, we have summarized the results of these two experiments and then described another, dynamic experiment in which the crushed salt column temperatures were systematically varied, both with respect to position and time. Figure 3.1 is a schematic drawing of the apparatus with which all of the experiments were performed.

All of the beds were prepared by packing fine-grade salt (average grain diameter, ~ 0.8 mm) in 1-in.-ID Pyrex pipes. However, before the salt was packed, a 5-in.-OD Pyrex thermocouple well (item A in Fig. 3.1) was inserted and anchored in a permeable salt core (B), which had been secured in the pipe. This core also served to support the crushed salt bed (C).

A high-temperature zone was maintained about the core-bed interface by a heater (D), and satisfactory temperature profiles were developed and maintained by insulating the bed with a suitable material (E). Periodic observations of the bed were made through windows in the insulation; these windows were covered when not in use.

The water level in the heated beaker (see Fig. 3.1) was controlled by the position of the tube (F'), which led from the reservoir (F). Gas flow through the bed originated from the gas line (GG') and exited through an effluent line contained within the rubber stopper (H). The degree of water-level depression within the pipe containing the salt bed yielded pressure-drop values for flow determinations, whereas the temperature profile data were obtained from thermocouple surveys that were made along the length of the thermocouple well.

Because the Pyrex pipe was not insulated above the water level in the beaker, a condensate ring was observed inside the tube about 1 cm above the water level. The temperature at the location of the ring was determined to be only 5°C less than that of the water in the beaker. Since the temperature increased above the ring (i.e., in the direction of the insulated area), no further condensation was noted; hence the maximum water vapor

Fig. 3.1. Schematic Diagram of the Apparatus Used to Investigate Water Vapor Transport Through Crushed Salt Columns Under Nonisothermal Conditions. The components are identified and described in the text.

mole fraction with respect to the bed regions is given by the ratio of the water vapor pressure at the condensate ring temperature to the total atmospheric (i.e., barometric) pressure.

A dry-wet interface within the crushed salt bed will occur at that point at which the temperature corresponds to the dew point (DP). This temperature will always be greater than the source temperature because of the vapor pressure depression due to salt that is dissolved in the liquid. Specifically, over the temperature range of interest, the dissolved salt in brine on grain surfaces depresses the water vapor pressure by about 25%; thus, if near-equilibrium conditions prevail, the vapor pressure of water at the dew point will be about four-thirds that of the source vapor pressure. Therefore, the position at which condensation occurs within the salt bed can be determined from the temperature profile of the bed, the source temperature, and the temperature-pressure relationship for steam.

The initial experiment was conducted by delivering the water vapor to the crushed salt bed by means of a continuous flow of air through the bed. The water vapor, which had a pressure corresponding to that at the 69°C condensate ring, passed through the hot zone (T_{max} about 270°C) and then condensed at positions within the bed at temperatures equal to or less than 76°C. The experiment was terminated when the overall bed permeability decreased to near zero. The reason for the decrease was the formation of a consolidated bridge in the salt, whose midpoint corresponded to the 76°C dew point.

Formation of the bridge required only 3.6 days; moreover, the relationship between source temperature and dew point was verified. This agreement was due, in part, to the circumstances surrounding the experiment; for example, gradients in steam concentration were eliminated as a result of the continuous flow of air through the bed. Furthermore, this simplification permitted us to estimate water vapor transport through the bed and water retention in the bed. These computations suggested a small loss of effluent, with retention of 4.0 g of water; the amount actually retained was found to be 4.2 g.

In contrast, the second experiment was conducted at constant pressure with no air sweep through the bed except when occasional measurements of the permeability of the bed were being made. This experiment was terminated, again due to bridge formation, after 14.4 days of operation. As before, the water retained by the bed amounted to about 4 g. Calculations which were made on the basis that concentration diffusion was the water vapor transport mechanism indicated agreement with observations regarding the dry portion of the bed, and suggested that thermal diffusion effects could be neglected. Furthermore, the controlling mechanisms were found to depend on water vapor and brine effects above the dew point at the dry-wet interface in a manner too complex to be treated mathematically.

The calculated temperature profiles corresponding to various periods of time were then used to prepare, in stepwise fashion, a family of fixed profiles. Half of these profiles are graphically presented as solid lines in Fig. 3.2; the actual values obtained are shown as data points.

For this experiment, the length of the bed was increased from 12 in. to 26 in., auxiliary wrap-on heaters were employed, and a time-to-termination period of 28 days was arbitrarily adopted.

The same sequence of events recorded for the two previous experiments was observed to occur at least three times in this experiment. All of the moisture-related phenomena described earlier were again noted, along with additional features resulting from the time variation of the temperature profile. For example, the water initially tended to set up consolidation patterns, as had been observed in the previous experiments, but the continued increases in temperature forced the water further up the column before a bridge could be formed. As the wet region passed up the column, however, zones of varying degree of consolidation remained.

Each of the three experiments vividly demonstrated that the movement of small amounts of water, in the form of vapor or brine, could produce striking changes in the physical and gas transport properties of crushed salt beds under nonisothermal conditions. Such changes occur in moist regions as the result of consolidation and the attendant formation of condensation-evaporation cycles. These reflux cycles effectively move

Fig. 3.2. Comparison of Calculated Temperature Profiles Simulating Mine Conditions and Average Temperatures Which Were Maintained in the Crushed Salt Bed. Four time intervals are presented. Deployment of the heaters with respect to column locations is indicated.

the salt from cool to hot zones and, in the process, create voids and regions of high density. Even in moist regions, where refluxing is not extensive, some consolidation occurs.

With the exception of the mode of water injection, the conditions and configurations of the first two experiments were similar. As a consequence, several observations were common to both. Indications of condensation appeared at early stages in each experiment, and this condensation was followed by a continued accumulation of brine until a bridge formed. Also, in each case, reflux zones were established above the bridges. These zones exhibited severe erosion, since the refluxing brine moved salt into the bridge area. Actual grain movement was restricted because of caking; thus the erosion voids were stable and the bed height remained constant. The integrity of the bridge, once formed, depended upon water content as shown by results of postoperational flow tests.

Examination of the crushed salt beds after removal from the Pyrex pipes confirmed the in-place observations. Various degrees of consolidation were noted in the bed. Furthermore, gas flow tests which were made on sections of the consolidated cores indicated the region of lowest permeability to be that about the dry-wet interface, and appreciable permeability reduction was experienced above the erosion zones.

The last experiment in this series was most realistic with regard to simulation of mine conditions in that the temperature profile of the crushed salt bed was adjusted with time. Although the effects of factors which control the temperature gradients are open to question, a set of time-temperature data* was prepared for our use in thermal analyses. These data were applicable in an approximate manner to a single 5-kW waste container (6 in. OD x 10 ft) buried in a 10-in.-ID by 18-ft-deep hole. At time zero, adjacent containers (15 ft away) and backfill were assumed to be present. A complete description of the model employed in the calculations is given elsewhere.^{7,8}

* Data were obtained by W. G. Turner and R. D. Cheverton.

Salt in the high-temperature regions (at temperatures of about 400°C), which simulated the top of the waste container, was not altered appreciably; it either remained dry or was moist only for a brief period of time. Metal components in this region indicated no corrosion effects; thus it is clear that high-power-density containers have some merit because brine cannot exist in these regions at atmospheric pressure, and the absence of brine mitigates metal corrosion.

It is not clear whether moisture-induced consolidation in the crushed salt backfill will produce a plug which will sustain high gas pressures. Our results suggest that the formation of a plug cannot occur during early time spans. However, effects of hole closure due to plastic flow of the bedded salt have not been considered; in addition, our water vapor source concentrations may not be realistic. The need for additional, full-scale, in-situ tests is, therefore, indicated. Further, since plug formation remains as a likely long-term possibility, some gas permeability studies of bedded salt per se have been initiated.

3.1.2 Hydrogen Flammability Studies (R. A. Lorenz)

Corrosion of a 5-kW radioactive waste container would result in the release of about 400 moles of hydrogen per year if all of the water associated with brine inflow were converted by a corrosion mechanism into hydrogen and oxidized metal.⁹ On this basis, it is apparently possible to attain hydrogen concentrations in air in excess of 4 vol %, the explosive limit normally quoted. Consequently, we have undertaken a search of the literature to determine the extent to which the small pore size and the large surface area of crushed salt backfill will affect the ignition and flame propagation characteristics of hydrogen-air mixtures.

Virtually no information concerning flame propagation in unconsolidated porous media exists. The most detailed work of relevance is that of Holm,¹⁰ who determined the flame propagation (and hence ignition) limits of hydrogen-air mixtures in smooth copper tubes and in glass tubes at atmospheric pressure. Holm observed that tubes smaller than 0.09 cm in diameter would prevent propagation in hydrogen-air mixtures, although the propagation in mixtures containing 33 vol % of hydrogen were the most difficult to prevent. Tubing about 0.15 cm in diameter stopped flames

with a H_2 content less than 20% or greater than 50%, whereas tubing approximately 0.30 cm in diameter stopped flames with a H_2 content less than 10% or greater than 59%. Furthermore, for hydrogen concentrations up to 25%, similar results were obtained using holes in copper foil and mica plates; these observations indicate little sensitivity of material or hole length on the flame propagation characteristics.

Many studies have been made of quenching diameter, or quenching distance (i.e., the diameter of a tube, or the distance between parallel plates, below which it is not possible to ignite a given explosive mixture). These distances can be correlated with the properties of the gas mixtures about equally well using either molecular diffusion or thermal conductivity models. Beriad and Potter¹¹ employed this type of approach to develop relationships between the quenching distance and various geometrical parameters, and performed experiments with propane-air mixtures to test the relationships as they apply to rectangular channels, cylindrical annuli, and tubes. However, their correlations cannot be applied directly to unconsolidated porous media, even though an estimate can be made if equivalent geometrical parameters are employed.

The permeabilities of several grades of crushed salt to helium have been reported,¹² and calculations of the mean pore diameter, $\langle d_c \rangle$, have been obtained through the use of the capillary model relationship

$$\langle d_c \rangle = [32B_0/(\epsilon'/q)]^{1/2},$$

where B_0 is the viscous flow coefficient and ϵ'/q is the porosity-tortuosity factor for gas transport. A summary of these values and the characteristics of the crushed salt employed in constructing the beds is presented in Table 3.1.

Another method for obtaining a characteristic geometrical parameter evolves from a definition of the hydraulic radius. In terms of this definition, an equivalent diameter, d_e , is obtained via the relationship¹³

$$d_e = 4m = 4\epsilon_t/S_p,$$

Table 3.1. Comparison of Properties of Crushed Salt Beds

Grade of Salt	Size Range, Max./Min. (cm)	Viscous Flow Coefficient, B_p (10^{-9} cm)	Porosity- Tortuosity Ratio, ϵ'/η	Total Porosity, ϵ_t	Surface Area per Unit Bed Volume, S_B (cm^2/cm^3)	Mean Pore Diam., $\langle d_c \rangle$ (cm)	Equivalent Pore Diam., d_e (cm)	Estimated Flammability Limit (vol % H_2)
Medium	0.95/0.0044	244	0.237	0.375	15.7	0.057	0.096	>25, <40
50-50 wt % Med.-Fine Mixture	0.95/0.0044	3.28	0.125	0.268	64.8	0.0092	0.017	No ignition
Fine	0.34/0.0044	4.36	0.212	0.377	94.6	0.0081	0.016	No ignition
Truncated Run-of-Mill	0.80/0.007	1.97	0.157	0.344	131.	0.0063	0.010	No ignition

where m represents the hydraulic pore radius, ϵ_t is the total porosity of the septum, and S_p denotes the particle surface area per unit bed volume. Values of d_e for each of the four beds of crushed salt are also given in Table 3.1, and it is obvious that this parameter is consistently larger than the mean pore diameter, $\langle d_c \rangle$, calculated from the gas transport experiments. We, therefore, employed the equivalent diameters, d_e , and the data obtained by Holms using smooth tubes to estimate flammability limits for the various crushed salt beds (see Table 3.1). Since no tests of our method have been made, experimental verification of these results would be required if it became necessary to establish the flammability limits more precisely. In addition, with some grades of crushed salt, the fines would have to be excluded from the surface area calculation because of their tendency to segregate. The effects of water vapor and total pressure on the flammability limits have been investigated;¹⁴ over the range studied, the effects are small and may be neglected.

The quenching effects considered thus far involve distances between surfaces. However, an additional flame-quenching mechanism appears to be associated with the exposed surface area. For example, Dolan and Dempster¹⁵ studied the quenching effect of fine suspended powders of various materials on methane-air flames. They observed that, with NaCl particles 4.3 to 12.0 μ in diameter, quenching was achieved with a surface area of only 0.57 cm² of salt surface per cubic centimeter of air. This is, of course, considerably less than the range of 16 to 131 cm²/cm³, which is tabulated for the crushed salt beds. Thus, although we cannot provide a direct comparison between the quenching of methane-air flames and that of hydrogen-air flames, the large surface-area-to-gas-volume ratio that is characteristic of crushed salt beds will probably tend to enhance the flame-quenching ability of the beds.

It is not yet possible to estimate the characteristics of beds containing very coarse, as-excavated salt, whose use as backfill is desirable for reasons of practicality and economy. In beds of as-excavated salt, however, convection currents due to temperature and gas density gradients may assist in diluting the hydrogen to an extent which is sufficient to exclude the possibility of hydrogen explosions in partially ventilated burial rooms.

3.1.3 Surface Diffusion (B. K. Annis)

Until recently, our effort to estimate the significance of surface diffusion (and, by extension, of grain-boundary diffusion) as a mode of isotope migration has been centered on the use of La_2O_3 as an appropriate substitute for plutonium. Our results indicate that, unless more stringent requirements are adopted, surface diffusion is unlikely to be a source of safety hazards. As a further precaution, however, the experimental work has recently been extended to include an investigation of the behavior of SrO , which will provide a measure of the rate of transport of smaller molecules and, in addition, is of intrinsic interest.

The samples employed in the La_2O_3 surface diffusion experiments consisted of highly polished NaCl coupons (originally intended for use as windows in infrared spectrometers) with the approximate dimensions $17 \times 8 \times 2$ mm. A portion of each coupon was covered with a La_2O_3 film, as indicated in Fig. 3.3. Although reference is made in this figure to a La_2O_3 coating thickness of $633 \text{ \AA}$, which was employed in the final set of experiments (and from which most of the conclusions have been drawn), films of about $150 \text{ \AA}$ and $3000 \text{ \AA}$ were also examined in the course of the studies.

Some preliminary results, in which the concentration profile in the direction of the arrow in Fig. 3.3 were determined using an electron microprobe, were reported previously¹ for a sample that had been diffusion-annealed (for a few days) at 200°C . An unexpectedly moderate change observed in La_2O_3 surface concentration with distance from the assumed edge of the initial deposit was believed to be an artifact of the technique employed to mask the NaCl during deposition of the La_2O_3 film. Subsequent work supported this hypothesis. After the situation had been corrected, the microprobe data indicated that, if surface diffusion were occurring at a sensible rate, it must be proceeding at a level involving less than a monolayer of molecules.

Since concentrations of this magnitude are just at the limits of detectability of electron microprobes, other methods for determining the concentration profiles were explored. One of these involved bombardment of the surface with high-energy oxygen ions and observation of the induced

Fig. 3.3. Schematic Representation of the NaCl Coupons Used in the Surface Diffusion Studies. The arrow indicates the direction of the surface diffusion.

X-ray fluorescence of the lanthanum. The results indicated a somewhat higher sensitivity for this method than for the microprobe, but with a loss in spatial resolution. A second alternative, which utilized a spark-source mass spectrometric technique, was observed to provide a higher sensitivity with respect to a determination of lanthanum concentration than the two preceding methods; however, the practical difficulties inherent in obtaining slices of the samples corresponding to incremental distances of 0.5 to 1.0 μ m resulted in poor spatial resolution.

In an attempt to obtain a concentration profile of practicably measurable extent, La_2O_3 -NaCl diffusion couple samples were annealed at 420°C for periods of 14-2/3 and 36-2/3 days. Concentration analyses were then performed using all three techniques investigated previously. However, the performance of the electron microprobe had improved sufficiently in the interim that the data were better, in a statistical sense, than data obtained by the ion-induced fluorescence technique. For this reason, only representative microprobe and mass-spectrometric results are presented in Fig. 3.4. These results were obtained for a sample that had been annealed for 14-2/3 days. In order to present the data in the manner shown in the figure, in which transport is assumed to occur only at sub-monolayer coverage, it was necessary to derive a value for C_0 , the effective initial surface concentration. This value was obtained by estimating the number of molecules that would correspond to monolayer coverage. When the mass-spectrometric data, which are designated by the horizontal bars in the figure, were considered independently, it was possible to estimate both the diffusion coefficient, D , and C_0 . The latter result was in reasonable accord with the estimated value.

The upper curve in the figure corresponds to a hypothetical concentration profile which would result from a surface diffusion process whose characteristic surface diffusion coefficient is 10^{-8} cm^2/sec ; the lower curve is representative of 10^{-10} cm^2/sec . The mass-spectrometric data, which actually yield only an upper limit of the magnitude of the diffusion process, appear to correspond with the upper curve, whereas the electron microprobe data seem to favor the lower curve. Similar results were obtained for samples that had been annealed for 36-2/3 days.

Fig. 3.4. Relative Surface Concentration Profile of La_2O_3 on NaCl After a 14-2/3-Day Anneal at 420°C . The data points and associated vertical error bars correspond to electron microprobe measurements, whereas the horizontal error bars denote the results of spark-source mass spectrometric determinations. The two solid curves are theoretical profiles corresponding to the diffusion coefficient values indicated.

At this time an ion probe became available, and its potential was investigated. In this device, material is sputtered off the surface by a beam of variable size and then analyzed by a mass spectrometer. The beam can be scanned over the surface in much the same manner as is done with the electron microprobe.

Data were taken with one of the samples that had been annealed for 36-2/3 days; these data are displayed graphically in Fig. 3.5. The results were obtained by scanning the beam over patches approximately 70 μ long (in the direction of the edge of the original La_2O_3 deposit) and about 50 μ wide. Figure 3.5 is actually a superposition of two plots, one of which shows the logarithm of the theoretical concentration as a function of distance and the other shows the logarithm of the experimentally determined concentrations as a function of distance. Translation along the vertical axis indicates that the data are well-fitted by a diffusion coefficient value of $3 \times 10^{-10} \text{ cm}^2/\text{sec}$ with an estimated precision of 30 to 50%. A few data points, corresponding to distances closer than 250 μ , were purposely omitted because these points seemed to lie on a theoretical curve characteristic of a diffusion coefficient value of about $10^{-11} \text{ cm}^2/\text{sec}$. While this initial behavior may be an artifact of the deposition technique, it is interesting to note that a similar behavior had been observed in studies of the surface diffusion of sodium in mica.¹⁶

3.1.4 Isotope Migration Through Crushed Salt (H. W. Godbee)

A knowledge of the extent to which crushed salt backfill retards the transport of radioactivity is needed in order to evaluate the usefulness of salt as a barrier to the dispersal of radioactivity in a salt-mine repository. Therefore, a series of experiments designed to represent the situation in which high-level waste solids are exposed to crushed salt backfill is in progress. Simulated waste solids tagged with appropriate radioactive tracers, fission products and actinides, are used in these experiments.

Fission Product Migration in Crushed Salt. - In the studies of wastes containing fission products, two 4-in.-ID by 40-in.-high Inconel columns, each positioned within a furnace (Fig. 3.6) are used to hold the crushed

Fig. 3.5. Surface Concentration of La_2O_3 on NaCl After a 36-2/3-Day Anneal at 420°C . The data points represent results obtained utilizing an ion probe technique, whereas the solid lines are theoretical results corresponding to the surface diffusion coefficients indicated.

PHOTO 0453-72 A

Fig. 3.6. Photograph of Apparatus for Studying Movement of Fission Products in Salt.

X

salt and simulated waste tagged with appropriate radioactive tracers. A schematic diagram of this apparatus was presented previously.¹⁷ In the initial experiments, calcined waste containing ^{137}Cs in one setup and ^{106}Ru in the other was placed at about the midplane of a column of crushed salt, and the column was then positioned within its furnace. Each column contains 12 kg of crushed salt and 68 g of calcined waste tagged with 1 mCi of ^{137}Cs or 0.4 mCi of ^{106}Ru tracer. About 40 ml of air per minute is passed through the columns, which are held at 340°C . The transport of waste products up or down the column is monitored by gamma scanning the column for cesium and ruthenium with a detector crystal encased in a lead collimator and shield (Fig. 3.6).

Typical gamma scans along the columns containing ^{137}Cs and ^{106}Ru at 25°C and at 340°C are shown in Fig. 3.7. The shift in the peak of these curves as the result of the increase in temperature from 25 to 340°C was about 0.2 in. This movement corresponds closely to that expected (the columns are unrestrained in their upward movement) from the thermal expansion of the salt below the radioactive source if the coefficient of linear expansion of salt is about 4×10^{-5} in. in.⁻¹ $^\circ\text{C}^{-1}$. The count rate as a function of distance along each salt column has been fitted to an equation of the form:

$$C = C_m \exp\left\{-\frac{1}{2}\left[(X - X_m)/\sigma\right]^2\right\},$$

where:

C = counts per minute on the gamma scintillation counter,

C_m = maximum counts per minute,

X = distance along the salt column,

X_m = position of maximum counts per minute, and

σ = standard deviation.

Tables 3.2 and 3.3 show some of the results obtained for the salt column containing ^{137}Cs and ^{106}Ru , respectively, using this fit. Among the conclusions that may be drawn from the results shown in these tables are: (1) the material balance for cesium and ruthenium, as represented by the area under the profile, is closed on each successive scan; and

Fig. 3.7. Comparison of Counts per Minute vs Distances for Columns of Crushed Salt Containing Calcined Waste with ^{137}Cs and ^{106}Ru Tracers at 25°C and 340°C . Distances are measured downward from the top of the furnace.

Table 3.2. Results of the Fit to a Gaussian Curve of the Data Obtained by Gamma Scanning of a Salt Column^a Containing Solid Waste with ¹³⁷Cs Tracer

(1)	(2)	(3)	(4)	(5)	(6)
Profile No. ^b	Elapsed Time (days)	C _m , ^c Peak Height (counts/min) × 10 ⁻⁵	W, ^d Band Width at Half-Height (in.)	A, ^e Area Under Profile (counts min ⁻¹ in.) × 10 ⁻⁵	σ, Standard Deviation (in.)
1	0	1.7477	2.400	4.4466	1.019
2	4	1.7465	2.400	4.4433	1.019
3	29	1.7416	2.413	4.4545	1.025 ^f
4	36	1.7436	2.407	4.4494	1.022
5	57	1.7422	2.414	4.4583	1.025
6	78	1.7443	2.406	4.4481	1.022
7	101	1.7433	2.408	4.4509	1.023
8	134	1.7460	2.406	4.4527	1.022
9	141	1.7398	2.411	4.4466	1.024
10	169	1.7467	2.408	4.4592	1.023

^aColumn is 4 in. in diameter by 40 in. long and contains 12 kg of crushed salt and 68 g of calcined waste.

^bProfile 1 was obtained at 25°C with no air flow; profile 2 at 25°C with an air flow of 40 ml/min; profiles 3-10 at 340°C with an air flow of 40 ml/min.

^cObtained by fitting measured counts per minute, C, at various distances, X, along the salt column to an equation of the form $C = C_m \{ \exp - 1/2 [(X - X_m)/\sigma]^2 \}$, where X_m is the location of C_m.

^dW = 2.3548 σ.

^eA = 1.06 C_m W and represents the 1 mCi of ¹³⁷Cs originally placed in the waste.

^fThe increase in σ from that in profiles 1 and 2 at 25°C to that in profiles 3-10 at 340°C is undoubtedly caused by thermal expansion of the calcine and not by diffusion.

Table 3.3. Results of the Fit to a Gaussian Curve of the Data Obtained by Gamma Scanning of a Salt Column^a Containing Solid Waste with ¹⁰⁶Ru Tracer

(1)	(2)	(3)	(4)	(5)	(6)
Profile No. ^b	Elapsed Time (days)	C _m , ^c Peak Height (counts/min) x 10 ⁻⁴	W, ^d Band Width at Half-Height (in.)	A, ^e Area Under Profile (counts min ⁻¹ in.) x 10 ⁻⁴	σ, Standard Deviation (in.)
1	0	2.5696	2.253	6.1363	0.9567
2	7	2.5694	2.254	6.1378	0.9570
3	29	2.4948	2.294	6.0677	0.9744 ^f
4	36	2.4951	2.309	6.1080	0.9807
5	57	2.5081	2.321	6.1705	0.9856
6	65	2.5026	2.310	6.1290	0.9812
7	101	2.4981	2.308	6.1123	0.9802
8	112	2.4988	2.324	6.1553	0.9868
9	135	2.5022	2.327	6.1716	0.9881
10	167	2.5102	2.323	6.1806	0.9864

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^aColumn is 4 in. in diameter by 40 in. long and contains 12 kg of crushed salt and 68 g of calcined waste.

^bProfile 1 was obtained at 25°C with no air flow; profile 2 at 25°C with an air flow of 40 ml/min; profiles 3-10 at 340°C with an air flow of 40 ml/min.

^cObtained by fitting measured counts per minute, C, at various distances, X, along the salt column to an equation of the form $C = C_m \{ \exp - 1/2 [(X - X_m)/\sigma]^2 \}$, where X_m is the location of C_m. All counts were corrected to zero time, assuming the half-life of ¹⁰⁶Ru to be 368 days.

^dW = 2.3548 σ.

^eA = 1.06 C_mW and represents the 0.4 mCi of ¹⁰⁶Ru originally placed in the waste.

^fThe increase in σ from that in profiles 1 and 2 at 25°C to that in profiles 3-10 at 340°C is undoubtedly caused by thermal expansion of the calcine and not by diffusion.

(2) the diffusion coefficient for cesium and ruthenium under these conditions is zero, as indicated by the fact that the standard deviation of the counting profile for each isotope is not changing significantly with time. A completed material balance for each isotope on successive scans shows that no radial movement has occurred, since such movement would decrease the response of the detector and indicate that less cesium or ruthenium is present in the salt column. A completed material balance plus no change in standard deviation, or any other measure of band width, indicates that no longitudinal movement has taken place, since these two conditions can prevail only if the isotopes have retained their original place in the column. Application of Student's t-distribution to the eight standard deviations for cesium at 340°C (Table 3.2, column 6, profiles 3-10) shows that there is a 95% expectation that the true average standard deviation is between 1.022 in. and 1.024 in. Similar treatment of the eight standard deviations for ruthenium at 340°C (Table 3.3, column 6, profiles 3-10) shows there is a 95% expectation that the true average standard deviation is between 0.9791 in. and 0.9868 in.

Plans are to continue these studies with ^{137}Cs and ^{106}Ru and to extend them to salt columns containing waste tagged with ^{85}Sr and ^{144}Ce .

Actinide Migration in Crushed Salt. — In the studies of wastes containing actinide elements, the experimental apparatus is identical in concept with that for the fission products but consists of four 2-in.-ID by 11-in.-high plastic columns in a glove box. The columns were made by stacking plates for purposes of later sectioning the column, at 1/2-in. intervals, for analysis of actinides. A photograph of the assembled columns in the glove box was shown previously.¹⁸ Each of the four columns was loaded with about 700 g of crushed salt and 6 g of plutonium (88.87% ^{239}Pu , 9.73% ^{240}Pu , 1.252% ^{241}Pu , and 0.140% ^{242}Pu). The plutonium, as the nitrate, was loaded into the midsection of each column. Air was passed upward through the four columns at rates of 0, 10, 20, and 40 ml/min, respectively. The initial tests with these plastic columns were carried out at ambient temperatures. The movement of plutonium was monitored, at approximately 1-month intervals, by scanning each column above and below the plutonium-bearing section with a Geiger-Müller (G-M) survey meter.

No movement of plutonium was detected after 6 months as determined by scans of the columns with the G-M meter. The columns are now being dismantled, and twenty 32-g samples of salt from each of them will be analyzed for plutonium to provide an independent check on the results obtained in the rough survey.

Metal columns are being fabricated so that the experiments can be continued at about 300°C, using calcined plutonium dioxide to simulate high-level waste exposed to crushed salt. Our plans include the use of a more accurate monitoring technique such as that employed in the fission product movement studies.

3.2 Radiation Effects

3.2.1 Energy Storage in Solidified Wastes (G. H. Jenks, C. D. Bopp)

The high-level solidified wastes in a repository will be exposed to a variety of nuclear radiations, including those produced by the alpha disintegration of transuranic elements. It is possible that some of the radiation energy will be stored in the waste solids as lattice damage; hence knowledge of the amounts and of the thermal annealing behavior is desired primarily for use in evaluation of hazards.

We analyzed¹⁹ experimental and theoretical data on radiation damage and energy storage in oxides and silicates and concluded that any energy storage in typical calcined waste oxides and glassy solids will result predominantly from displacements or "spikes" caused by elastic collisions of the heavy recoiling nuclei which are formed in the alpha disintegration of the transuranic elements within the wastes. Alpha radiation and, to a lesser extent, beta radiation will also cause some damage via elastic collisions. Energy storage in the radioactive wastes will probably be less than 200 cal/g;* however, we cannot exclude the possibility that it will be higher in some systems. Temperatures greater than 1000°C may be needed to effect the release of all stored energy with some wastes. The release will not be spontaneous unless there is a stepwise increase in temperature to a high level at which rapid release is initiated. After the wastes have been buried in a salt mine, stepwise increases in temperature are unlikely and, in turn, a spontaneous release of stored energy is improbable. Such increases in temperature, on the other hand, could occur under certain conditions during handling of a waste package prior to burial or in the course of a possible retrieval operation.

We also concluded that the radiation damage in radioactive wastes can be simulated in synthetic wastes, using fast-neutron or accelerator ion irradiations (alpha particles or protons). However, use of the latter

* Blomeke and co-workers²⁰ at ORNL have previously analyzed the effects on a salt repository of instantaneous release of 200 cal/g of stored energy within a waste can after burial. They concluded that a release of this magnitude would be tolerable.

type of irradiation is unattractive for one or more of the following reasons, depending on experiment design: (1) radiation damage effects in the necessarily small experimental samples may not be representative of those in bulk wastes; (2) high temperature gradients within a sample during irradiation may affect energy storage; (3) accumulation of projectile-ions (He^{2+} or H^+) within a sample may affect energy storage; (4) the very high dose rates achieved during irradiation with accelerators may affect energy storage differently from the lower dose rates in the actual wastes; and (5) the amounts of stored energy in the small samples may be difficult to measure. Fast-neutron irradiation is preferred in the study of energy storage in synthetic wastes. We recommend the Oak Ridge Reactor (ORR) for this purpose. Irradiations in the ORR for periods up to about 1 month would provide adequate tests of stored energy in simulated radioactive wastes.

We designed and constructed a Roux-type drop (to high temperature) calorimeter for use in our planned experimental work with synthetic wastes and with rock salt. The accuracy and the sample size requirements of our calorimeter at the high temperatures ($\sim 1000^\circ\text{C}$) that may be required for the waste samples are currently being investigated in calibration runs. Results to date indicate that this calorimeter will be satisfactory for measurements at 1000 to 1200°C with waste samples weighing about 100 mg. It should be possible to determine the stored energy with an accuracy greater than ± 1 cal/g, which will be adequate for our needs. The calorimeter is described below; the results of some preliminary measurements with irradiated halite and synthetic NaCl crystals are also presented.

Roux²¹ measured stored energy in irradiated oxides at 1200°C using a calorimeter similar to the heat-flow (quasi-isothermal) microcalorimeters employed in catalytic studies.²² The samples were dropped into the calorimeter, which was maintained at a temperature above the point at which the stored energy was released. Generally, both the pre-drop and the calorimeter temperatures were accurately measured; the transient cooling effect of the inner part of the calorimeter was determined by means of a thermopile and recorded.

Our instrument (Fig. 3.8) differs from that used by Roux in two ways, which result in a decreased construction cost and a reduction in the size of sample required. First, we omitted the reference cell, which is commonly used in heat-flow calorimetry to reduce effects from furnace temperature fluctuations. Instead, the constancy of the furnace temperature was maintained by direct means. The power for the furnace was provided by a dc supply which maintained a constant voltage within about 0.2%. The temperature regulator was eliminated in order to prevent the temperature fluctuation inherent in its operation; for this reason, an equilibrium period of a few days was required for the temperature to reach a constant level after an appreciable adjustment of the furnace voltage. The justification for omission of the reference cell in high-temperature work is that differences in the radiative heat leaks between the reference and measuring cells (produced by thermal gradients in the furnace) make matching of the thermal characteristics of these cells very difficult. The poor heat conductivity of the ceramic insulation of the thermopile enhances the importance of radiative heat transfer. Additionally, the space occupied by a reference cell would require a larger, more complex furnace in order to maintain the required low thermal gradients. Furthermore, the stringency of a constant base line for our work, in which measurements were completed within 5 min, was much less than in applications of heat-flow calorimetry where measurements extend over longer periods.

The second simplification of our apparatus as compared with Roux's instrument was the omission of the suspension system by which the sample container was lowered into the calorimeter. In place of this, we fabricated a sample container of sufficient design and strength to survive the impact received by directly dropping into the furnace.

The sample container was constructed by bending 5-mil platinum foil to form two hollow cylinders, both of which were closed at one end. The top cylinder fit tightly inside the bottom cylinder and extended almost the full length of the bottom cylinder (Fig. 3.8). The seams of the bottom cylinder were welded to increase the resistance of the cylinder to impact. The seams of the top cylinder were not welded in order that its dimensions could be adjusted to make a tight fit with the bottom cylinder. This design

Fig. 3.8. Roux-type Drop Calorimeter.

gave low thermal resistance between the top and bottom parts, which is particularly important for reproducibility between measurements in which the sample holder is disassembled to change samples. Sample containers of two sizes were used. The larger one, $3/16$ in. OD x 1 in. long, had a capacity of about 0.5 g of NaCl. Its dimensions were altered after several drops, after which it was rebuilt. The smaller one, $3/32$ in. OD x $1/2$ in. long, was suitable for very small samples of sodium chloride (less than about 30 mg). It was quite resistant to the impact sustained on dropping. The withdrawal procedure consisted in engaging a hook at the end of a 3-ft.-long wire with a small wire loop attached to the sample container. The hook was lowered until it reached the top of the sample container, and was rotated to engage the loop. Usually, retrieval was accomplished within a few trials; however, from the necessity of working "blind," success was not always achieved on the first attempt.

Generally, the reproducibility of calibration (as described below) is dependent on the method by which the sample container is positioned in the instrument. Early in this work it was found that sample containers to which spacers were attached had poor impact resistance. For this reason, positioning was accomplished by using a drop tube having a diameter only slightly larger than that of the sample container. A different tube was used for each sample container size. The $1/8$ -in.-ID alumina tube used with the smaller container was placed inside a mullite tube, which fit within the $3/8$ -in.-ID alumina tube. Thus, the smaller-diameter drop tube had more thermal shielding. In spite of this, however, the time-temperature curves for the thermopile signal did not differ greatly between the two sizes of drop tube.

In accordance with Roux's technique, about 90% of the thermopile signal was "bucked" out by a "tapered-transmission-line," electrical-analog simulator, in order to reduce the accuracy required for the recording. Such a procedure is practical since the variation in signal between different samples is generally less than 10%. The peak signal produced by the simulator was about 30 mV for the larger sample container. This signal was reduced to the required "bucking" strength (about 300 μ V) by a voltage divider, which was thermally insulated in order to avoid

interference from thermal emfs. The difference in the simulator and thermopile outputs was amplified by a Leeds and Northrup 9829 linear amplifier, using the 30- and 100- μ V ranges for the small and large sample containers, respectively.

Most of our work has been concerned with dropping sample containers into a calorimeter maintained at 500°C (in connection with measurement of stored energy in irradiated sodium chloride, although early work indicated a similar sensitivity at 1000°C). The signal (the difference in emf between the thermopile and the simulator) is recorded for a few minutes in order to obtain the base line immediately prior to, and for about 5 min after, dropping the sample container. About 75 to 95% of the area under the plot of signal minus base line vs time is produced in the initial 5 min. The remainder is calculated by extrapolation of the exponential function determined by the data in the interval from 3 to 5 min. This method avoids effects from the drift of the base line at longer time spans, and was found to give good reproducibility. A waiting period of about 60 min is required for return of a constant base line on the conclusion of an experiment. The calibration parameter, C ($\text{cal min}^{-1} \mu\text{V}^{-1}$), is calculated from:

$$C = \Delta H(W_2 - W_1) / \int_0^\infty (S_2 - S_1) dt, \quad (1)$$

where ΔH is the change in heat content, in calories per gram, of a standard material (in this case, NaCl was used) on increase of its initial temperature to the calorimeter temperature; W_1 and W_2 are different weights of the standard used in experiments 1 and 2, respectively; and S_1 and S_2 are the signal-vs-time functions determined in the two experiments.

The calibration parameter was found to be independent of sample weight, as shown in Table 3.4. This is in agreement with the results obtained by Roux. The values of C for the larger and smaller sample containers were 0.044 and 0.070 ($\text{cal min}^{-1} \mu\text{V}^{-1}$), respectively. The difference between these two values probably reflects the greater thermal shielding for the smaller sample-container - drop-tube combination, as was mentioned previously. In most experiments, the accuracy of calibration was limited to about 5% by either the accuracy to which the initial temperature of the

sample container was measured or the accuracy of weighing the samples. This could be improved (in work which justified the extra time involved) by more accurate weighings and temperature measurements.

Table 3.4. Calibration Constant of Larger Sample Container

Date	Sample Weight (g)		C
	Larger	Smaller	
6-24-72	0.242	0.192	0.043
7-24-72	0.139	0.113	0.044

The energy stored in several irradiated NaCl samples was determined by dropping the sample container twice into the furnace maintained at about 500°C in each case. (The stored energy was released rapidly in the first drop.) The stored energy, E (in calories per gram), was calculated from:

$$E = (C/W) \left(\int_0^{\infty} S_2 - S_1 \right) dt, \quad (2)$$

where W is the sample weight (in grams), S_1 and S_2 are the signal-vs-time functions determined in the first and second drops, respectively, and C is the parameter determined by Eq. (1).

Best results were obtained by dropping sample containers having a temperature greater than about 95°C since there was generally interference from adsorbed moisture at lower temperatures. In work at lower temperatures, it appeared that more moisture was adsorbed by irradiated samples prior to the first drop than after the radiation defects had been annealed. A good test for the absence of moisture effects was to conduct different experiments in which the area/volume ratio was changed by decreasing the particle size, but in which the other conditions were similar. If the results were nearly independent of particle size, reliance could be placed on those obtained with the large particle size. Best results have been obtained with artificial NaCl crystals that were crystallized from a melt and that, therefore, did not contain inclusions of liquid.

To date, insufficient work has been done to determine the full extent of interference from inclusions of brine in natural halite; however, since the small samples which have been used remained intact after being dropped into the calorimeter, any release of brine is probably confined to near-surface inclusions. It is thought likely that the release of brine may occur only in infrequent experiments such that statistical rejection of such experiments is practical.

3.2.2 Energy Storage in Rock Salt (G. H. Jenks, C. D. Bopp)

The rock salt that surrounds a can of high-level radioactive waste in a salt repository will be exposed to high gamma-ray doses and intensities (maxima of $\sim 2 \times 10^{11}$ rads and $\sim 5 \times 10^5$ rads/hr) and to elevated temperatures ranging up to about 330°C . Some of the absorbed gamma-ray energy will be stored as lattice disorder within the salt crystals under some or all of the exposure conditions. Knowledge of the amounts that will be stored is needed for evaluations of the hazards which would be associated with rapid release of the stored energy by thermal annealing.

Available experimental and theoretical information indicated that the amount of stored energy will depend on dose rate, dose, and temperature, but this information was too meager to permit extrapolation to repository conditions.²² We initiated an experimental investigation aimed at providing data that will permit extrapolation to repository conditions, and we designed and are constructing equipment for making experimental gamma irradiations of salt within the target region of spent HFIR fuel elements (dose rates up to 10^8 rads/hr, doses to $> 2 \times 10^{10}$ rads, and temperatures to about 330°C). We also studied the energy stored in samples of synthetic crystals of NaCl, supplied to us by E. Sonder of the Solid State Division, after gamma irradiation at 10^7 rads/hr. This work is summarized below.

Description and Status of Gamma Irradiation Facility. - Our HFIR gamma irradiation facility consists, basically, of a 3-in. NPS sched 10S stainless steel pipe extending from the space above the top of the HFIR pool into the target region of a spent HFIR fuel element on the bottom of the pool. The pipe provides a conduit through which the specimen holder, specimens, and associated equipment are inserted into and withdrawn from the gamma field of the fuel element. The top of the access

pipe is equipped with a flanged closure, which includes leads for passages of electrical and gas conductors. The specimen holder is 2 in. in outside diameter and 12 in. long. It will accommodate a variety of specimens simultaneously, including those with dimensions $1/2 \times 1/2 \times 3$ in., which may be needed in the study of thermal conductivity of irradiated salt.

Since the access pipe is immersed in water, it is necessary to consider the possibility that water will enter the pipe in some manner and that radiolysis of this water will produce explosive gas mixtures. To eliminate the possibility that an explosive gas mixture will be formed, helium gas is passed over the capsule and through the access pipe at a rate in excess of that required to dilute any radiolytic gas to a concentration below the explosive limit. The initial system with one purge line is presently being modified to provide for dual, redundant purge lines. We believe that this system, with associated flow detectors and alarms, will provide adequate assurance that no accumulation of explosive gas mixtures will take place.

Stored Energy in Gamma-Irradiated NaCl. - E. Sonder of the Solid State Division has supplied us with samples of Harshaw synthetic crystals of NaCl that were irradiated in a 10^7 -rad/hr cobalt source. We analyzed these samples for stored energy using the drop calorimeter at 500°C . The results of these measurements, together with results of heat-of-solution measurements which have been reported by others, are listed in Table 3.5. Descriptive information on the samples and on the drop calorimeter measurements is also included in the table.

As stated in the footnotes of Table 3.5, the stored energy in sample 2 apparently decreased during preheating at 113°C . Thermal annealing at 15°C above the temperature of irradiation was unexpected, and it did not occur with sample 1 (which had received the higher dose). The values for sample 2 (see Table 3.5) are for those for which no annealing was apparent.

Thermal analyses of sample 1 with the drop calorimeter (Table 3.5) gave stored-energy values that exceeded by factors of 1.7 to 2 those reported by others who used heat-of-solution calorimeters. At least part of the difference between the results of the two calorimetric methods

Table 3.5. Results of Stored-Energy Measurements on Synthetic NaCl Crystals
Gamma-Irradiated at 10^7 Rads/hr and $95 \pm 5^\circ\text{C}^a$

Sample No.	Dose (rads)	Experimenter	Method	Results
1	1.5×10^{10}	G. E. Eoyd and M. J. Mastroianni ^b	Heat of Solution	7.8 and 8.6
		S. Lindenbaum ^b (Univ. of Kansas)	Heat of solution	7.1 and 7.3
		C. D. Bopp	Thermal analysis with drop calorimeter	14.3 ^c 14.7 ^d 14.8 ^e
2	4.3×10^9	C. D. Bopp	Thermal analysis with drop calorimeter ^h	8.5 ^f 9.0 ^g

^aSamples of Harshaw synthetic crystals irradiated and supplied by E. Sonder of the Solid State Division; private communication from E. Sonder, August 1972. These samples were black, indicating the presence of colloidal sodium.

^bMeasurements quoted by E. Sonder, private communication, August 1972.

^cHeated at 105°C for 1 hr, then dropped from room temperature.

^dHeated at 111°C for 35 min and dropped directly from that temperature.

^eHeated at 95°C for 30 min and dropped directly from that temperature.

^fHeated at 92°C for 28 min and dropped directly from that temperature.

^gHeated at 95°C for 33 min and dropped directly from that temperature.

^hInitial thermal analyses of two samples of this material were made after heating the samples at 113°C for 40 and 60 min, respectively, and then dropping them directly into the furnace from that temperature. The respective stored-energy values were 5 and 4 cal/g. Some thermal annealing apparently occurred during this preheating.

can be reasonably explained by assuming that aqueous dissolution of trapped electrons and holes results in the formation of certain other species in addition to Na^+ and Cl^- (Sect. 3.2.3). A maximum difference factor in the range 1.5 to 1.8 has been estimated due to this effect. Experimental errors may also account for some of the difference.

The stored-energy values in Table 3.5 are much higher than the values (approximately 1 cal/g) previously reported by Sonder and Lindenbaum^{20,23} for synthetic NaCl crystals that had been irradiated by van de Graaff electrons at higher dose rates ($>10^9$ rads/hr) and at temperatures $\leq 80^\circ\text{C}$. The reason for this difference remains to be established. However, a conceivable explanation is that a dose-rate effect exists in which migration and clustering of defects into relatively stable aggregates (colloids)²⁴⁻²⁷ become important at the long exposure times prevailing at the lower dose rates.

The stored-energy values that were obtained for samples 1 and 2 with the drop calorimeter show an approximate square-root dependence on dose.

3.2.3 Radiation and Thermal Chemistry (G. H. Jenks)

Solutes Formed upon Dissolution of Trapped Electrons and Holes in Irradiated NaCl, and Their Effects upon Heat of Solution. - Damage produced in NaCl by the ionizing action of nuclear radiation is comprised of displaced atoms and of trapped electrons and holes. Chemically, the trapped electrons and holes are reducing and oxidizing agents, respectively; and dissolution of radiation-damaged NaCl results in the injection of oxidizing and reducing agents into the aqueous solution.^{21,22} The oxidizing agent entering solution corresponds to Cl^0 , and possibly Cl_2 , while the reducing agent can be treated as a hydrated electron, e_{aq}^- , or as Na^0 . The products formed by aqueous dissolution of these species may differ from those formed by dissolution of unirradiated salt (Na^+ and Cl^- only). Information on the identities and amounts of the products is of interest in connection with evaluations of reported results of measurements of heats of solution of irradiated NaCl. Such information is also of interest in our overall effort to establish the radiation and thermal characteristics of the brine inclusions.

We consulted our previous review²⁸ of available information on radiation and thermal chemistries of salt mine brines to select likely reactions of the trapped electrons and holes upon aqueous dissolution, and for these we calculated the difference between the heat of reaction and the heat of the reference reaction in which only Na^+ and Cl^- are formed from the defects. We also studied the pH of solutions of irradiated salt in order to help pinpoint the reactions of the defects.

Some possible dissolution reactions of trapped electrons and holes are represented by those listed in Table 3.6. The footnotes show the partial reactions²⁸ and also elaborate on the meanings and the significance of the listed values. The derivation of the reaction given in footnote i is described in Table 3.7. In addition, we note that an increase in pH is expected for some of these overall reactions, while no change in pH is expected with others. Reactions other than those given in Table 3.6 are conceivable but less probable. Those we have examined have values of $|\Delta H - \Delta H_{\text{ref}}|$ less than 1.7 eV.

The results of our pH measurements and some analyses of the pH data are listed in Table 3.8. These results show that the concentration of H^+ formed upon dissolution of irradiated salt is much less than that expected if trapped electrons and holes react to form Na^+ plus H_2 plus OH^- , and Cl^- plus H^+ plus HOCl and OCl^- , respectively (see Case 1, Table 3.6). Reactions and/or conditions which are consistent with these results are listed below. Other evidence supporting or discounting the given reactions is as follows:

- (1) Reaction of 98.5% of the defects according to Case 2, 4, or 5 (Table 3.6) would result in the small pH changes that were observed. To tentatively distinguish between these, we note that evolution of gas is observed when irradiated salt is dissolved in water. We note that other workers³⁰ have reported that the evolved gas is composed of 95 to 99% H_2 ; Case 4 reactions are thus supported by this evidence.
- (2) Reaction of 98.5% of the defects to form only Na^+ and Cl^- upon dissolution would result in the small pH changes that were observed. However, this possibility is discounted by the gas-evolution evidence.

Table 3.6. Possible Aqueous Dissolution Reactions of Radiation Defects in NaCl, and Comparisons Between Heats of Dissolution and the Stored Energy within the Crystal

Case No.	Partial Reactions	Overall Reactions ^a	$\Delta H - \Delta H_{\text{ref}}^b$ (eV per trapped electron or hole)	$\frac{\Delta H - \Delta H_{\text{ref}}}{\Delta H_{\text{ref}}} = F^c$
1	d,e	$\text{Na}^0 + \frac{\text{Cl}_2}{2} + \text{H}_2\text{O} \rightarrow \frac{\text{H}_2}{2} + \frac{\text{Cl}^-}{2} + \frac{\text{OH}^-}{2} + \frac{\text{HOCl}}{2} + \text{Na}^+$	-2.0	0.46
1	d,f	$\text{Na}^0 + \frac{\text{Cl}_2}{2} + \frac{\text{H}_2\text{O}}{2} \rightarrow \frac{\text{H}_2}{2} + \frac{\text{Cl}^-}{2} + \frac{\text{OCl}^-}{2} + \text{Na}^+$	-1.75	0.41
2	d,g	$\text{Na}^0 + \frac{\text{Cl}_2}{2} + \frac{\text{H}_2\text{O}}{2} \rightarrow \frac{\text{H}_2}{2} + \text{Na}^+ + \text{Cl}^- + \frac{\text{O}_2}{4}$	-1.4	0.32
3	h,e	$\text{Na}^0 + \frac{\text{Cl}_2}{2} + \frac{\text{O}_2}{2} + \frac{\text{H}_2\text{O}}{2} + \frac{\text{H}^+}{2} \rightarrow \text{Na}^+ + \frac{\text{H}_2\text{O}_2}{2} + \frac{\text{Cl}^-}{2} + \frac{\text{HOCl}}{2}$	-0.8	0.18
4	d,i	$\text{Na}^0 + \frac{\text{Cl}_2}{2} + \frac{\text{H}_2\text{O}}{2} \rightarrow \text{Na}^+ + \frac{\text{H}_2}{2} + \frac{5}{6} \text{Cl}^- + \frac{\text{ClO}_2^-}{6}$	-1.6	0.37
5	h,g	$\text{Na}^0 + \frac{\text{Cl}_2}{2} + \frac{\text{H}_2\text{O}}{2} + \frac{\text{O}_2}{4} \rightarrow \text{Na}^+ + \text{Cl}^- + \frac{\text{H}_2\text{O}_2}{2}$	-0.5	0.12
Reference reaction		$\text{Na}^0 + \frac{\text{Cl}_2}{2} \rightarrow \text{Na}^+ + \text{Cl}^-$		

^aThe specific chemical and physical forms of the trapped electrons and holes are not specified in these reactions. Na^0 and $\frac{\text{Cl}_2}{2}$ are merely illustrative of conceivable forms.

^bCalculated using heat-of-formation values from International Critical Tables, Vol. 5, p. 176 ff. The negative signs for values of $\Delta H - \Delta H_{\text{ref}}$ signify that the heats evolved in these reactions are less than those which would have been evolved if only Na^+ and Cl^- had been formed from the defects.

^cThis ratio expresses the fractional amount of stored energy associated with radiation defects in NaCl which would be missed in a solution calorimeter measurement. The actual value of ΔH_{ref} is uncertain. The listed values of F were obtained by assuming that the defects are present as elemental sodium and chlorine so that ΔH_{ref} equals the heat of formation of crystalline NaCl, 4.3 eV per $\text{Na}^+ \text{Cl}^-$.

Table 3.7. Derivation of Equation in Footnote i, Table 3.6

Combine Reactions (1) and (2):

Rewrite Reaction (3):

Neglect the explicit distinction between Cl^0 and Cl_2 . Then, Reaction (4) can be rewritten as Reaction (5):

which is identical with the reaction given in footnote i, Table 3.6.

Table 3.8. Results of pH Measurements on Solutions of Irradiated Salt and Analyses of pH Data

Description	Sample No.			
	1	2	3	4
	Harshaw salt sample 2, Table 3.5	Same as sample 1 annealed at 500°C in drop calorimeter	PSV ^a	PSV ^a
Stored energy, cal/g	8.8		~2 ^b	~2 ^b
Concentration of trapped electron-hole pairs in salt, ^c mole/mole	5.1 x 10 ⁻³		~1.2 x 10 ⁻³	~1.2 x 10 ⁻³
Concentration of NaCl in solution of sample, moles/liter	0.145	0.345	1.03	1.03
Number of defect pairs introduced into unit volume of solution, moles/liter	7.4 x 10 ⁻⁴		~1.2 x 10 ⁻³	~1.2 x 10 ⁻³
pH of solution of dissolved sample	8.03 ^d	5.9 ^d	7.8 ^e	7.5 ^f
pH of unirradiated salt solution	6.3 ^d	6.3 ^d	5.8 ^e	5.0 ^f
pH expected if all defects dissolve per Case 1 or 3 (Table 3.6)	9.03		9.15	9.15
pH expected if 98.5% of the defects dissolve per Case 2, 4, or 5 (Table 3.6)	8.0		7.8	7.5
pH expected with 10% excess trapped holes in sample ^g	~8		~8	~8
Fraction of defects dissolving per Case 1 or 3 if sample has no excess of trapped holes	0.015		0.015	0.015

^aSamples from Project Salt Vault, Hole 6.

^bValues determined with drop calorimeter.

^cCalculated assuming 4.3 eV per trapped electron-hole pair. The heat of formation of crystalline NaCl is 4.3 eV per Na⁺ Cl⁻ molecule.

^dSolvent was boiled and cooled, deionized water. Solutions 0.01 to 1.0 M in unirradiated Lyons salt had a pH of 6.3.

^eUnboiled, deionized water. Solutions 0.005 to 1.0 M in unirradiated Lyons salt showed a pH of 5.8. This low pH was probably due to CO₂.

^fTriply distilled water. Solutions 0.01 to 1 M in unirradiated Lyons salt showed a pH of 5.0. This low pH was probably due to HCl contaminant in the still.

^gAn excess of trapped holes could account for a reduction in pH below expected values. No excess of Na⁰ is consistent with the pH data.

- (3) All or most of the defects react according to Case 1, but the trapped holes are in 10% excess. Loss of Na^0 from the crystal would be necessary to produce the excess holes, and this seems unlikely.*

For cases 1 through 5, calculated values for the quantities $\Delta H - \Delta H_{\text{ref}}$ and F are presented in Table 3.6. F represents the fractional amount of stored energy which is omitted in a heat-of-solution measurement. The value for this quantity depends on the energy associated with the defects within the crystal. The lowest value for this latter quantity is probably the value for which the defects occur as clusters of elemental sodium and chlorine (i.e., 4.3 eV per defect pair). Higher energies may be associated with F-centers; 4.6 eV and 5.6 eV per F-center^{31,32} are recently reported values. We used the value of 4.3 eV to calculate the values of F in Table 3.6.

For Item (3) above, assuming that the defects occur as elemental sodium and chlorine, the heat of dissolution per Na^0 is 1.8 eV less than the heat of formation of $\text{Na}^+ \text{Cl}^-$ and the value of F is 0.41 (if no stored energy is associated with excess chlorine).

Composition of Encapsulated Brine in Lyons Salt. - Two different samples** of brine from the Lyons salt were analyzed† for Na, Mg, and Ca by emission spectroscopy. The results were in agreement within the precision of the analytical method, $\pm 5\%$ (Table 3.9). Also, these results were consistent with information obtained on the solubility of NaCl in solutions of MgCl_2 , and with previous information on the composition of brine inclusions in salt from a mine at Hutchinson, Kansas.²⁸

The present samples were obtained, in each case, by cleaving a NaCl crystal to expose a brine inclusion, immediately collecting the brine in

*The pH results show that there is no excess of Na^0 in the salt (i.e., no loss of chlorine occurred).

**Brine samples were collected by A. L. Sutton of the Reactor Chemistry Division.

†Chemical analysis was made by the ORNL Analytical Division.

a capillary via capillary action, and then immediately transferring the sample into an HCl solution in a small flask. Previous samples that had been allowed to stand within the capillaries for long periods (~1 day) gave nonreproducible and inconsistent results.

Table. 3.9. Results of Analyses of Encapsulated Brine from Lyons Salt

Element	Amount in Sample						Hutchinson ^d
	μg			M			
	No. 1 ^a	No. 2 ^b	No. 3 ^c	No. 1	No. 2	No. 3	
Na	44	19	-	1.89	1.92	-	2-1
Mg	50	23	31	2.03	2.21	1.6	2.3-3
Ca	1.3	0.7	-	0.03	0.03	-	Negligible
Br	-	-	1.7	-	-	0.03 (0.04) ^e	0.05

^aSample volume = 0.00101 cm³.

^bSample volume = 0.000428 cm³.

^cSample volume = 0.000774 cm³.

^dPreviously estimated from Holser's data for brine from Hutchinson salt.²⁸

^eAfter adjustment for possible loss of sample, as indicated by results for magnesium.

A spark-source mass spectrometer analysis for bromine was made on one of the previous samples, using ⁸¹Br as an internal standard. The concentration of magnesium in this sample, as determined by emission spectroscopy, was 1.6 *M*. The unadjusted value for bromine was 0.03 *M*. After adjustment for possible loss of sample as judged from the magnesium result, the bromine value was 0.04 *M*. Both values are in reasonable agreement with those previously estimated from Holser's data for Hutchinson salt.²⁸ However, it is notable that the magnesium concentration [Mg] is 2.1 *M* rather than the maximum of 3 *M* which we previously estimated. Accordingly, the maximum rate of formation of HCl from the hydrolysis of MgCl₂ is about two-thirds of the value previously used.

Most of the brine inclusions in the Lyons salt which we have examined are not completely filled with liquid; that is, each generally contains a small gas-phase bubble. Presumably these bubbles contain air which was

dissolved in the brines when the salt crystals were formed. We were interested in the amounts of air present in such bubbles from the standpoint of designing brine-radiolysis experiments that will simulate exposure conditions within a salt repository.

The results of the following simple tests on three different brine inclusions led us to conclude that the gas pressure within a cavity is 1 atm or less. In each of two such inclusions, a 20-mil hole was drilled through the crystal so that the drilled hole tapped the inclusions on a side near the bottom (a low-power microscope was used). No expansion of the bubble took place when the cavity was breached. However, air bubbles did enter the cavity, pass up through the liquid, and then join the original bubble. The third cavity was tapped (with a 20-mil drill) near the top; in this case, the bubble collapsed (possibly due to pressure from the drill) before air entered the cavity.

The relative volumes of gas and liquid within cavities can be inferred from the reported results of previous workers with salt taken from the 900-ft level of the American Salt Corporation mine at Lyons.³³ These investigators reported values for relative volumes of gas and liquid ranging from 0 to 0.04. They also reported that the bubbles disappear at temperatures from 70 to 100°C.

We concluded that the maximum concentration of air within the brine will be about 0.002 *M* and, accordingly, that the effects of this air on radiolysis will be negligible relative to the concentrations of radiolytic products (>0.01 *M* at the least) with which we are likely to be concerned.

3.2.4 Effects on Physical Properties (T. G. Godfrey, D. L. McElroy, S. H. Jury*)

The thermal and nuclear environment of the materials surrounding the waste containers, after their emplacement in the salt mine, will be quite different from that which these materials normally experience. Accordingly, it is necessary to establish the effects of this environment, singly and in combination, on the more important physical properties of the salt and its associated impurities. Our experimental program consists of thermal

*Consultant from the University of Tennessee, Knoxville.

conductivity measurements on both unirradiated and irradiated solid salt, on crushed salt backfill, and on crushed salt as it experiences reconsolidation due to compressive stress and temperature. An automatic constant-temperature ice bath was developed for use with these measurements. An experiment that simulated short-time conditions experienced by a waste container in an unlined hole was also performed.

Thermal Conductivity of Unirradiated and Irradiated Solid Salt. -

Our experimental program for measuring the thermal conductivity of solid salt is in the formative stage. We intend to use both pure NaCl and natural rock salt for our measurements, covering the temperature range 80 to 900°K. Samples in the form of 1/2 x 1/2 x 3 in. bars will be measured in a low-temperature longitudinal device³⁴ over the range 80 to 400°K; for the range 300 to 900°K, we will use 3-in.-diam disks in a radial heat flow apparatus.³⁵ These experiments will provide base-line data for subsequent measurements on salt bars and small disks irradiated at two different temperatures, two dose rates, and two total doses. The irradiated salt bars will be measured in the longitudinal device from 80 to 400°K, and the small (1/2 x 1/2 in.) disks will be measured in a comparative device³⁶ at 300°K.

Thermal Conductivity of Salt Powder. - We measured the thermal conductivity of two samples of crushed natural salt in air and in argon as a function of temperature over the range 300 to 850°K in a radial heat flow apparatus.³⁷ The Hutchinson salt samples, supplied by H. W. Godbee of the Chemical Technology Division, were identified as "fine" and "medium," and had the particle size distributions shown in Fig. 3.9. We determined that the "medium" sample would not uniformly pack in the apparatus; therefore, we adjusted the size distribution by screening and blending to approximate the distribution range of the "fine" (but coarser by a factor of ~5), as shown by the dashed line in Fig. 3.9. This blended "medium" sample would uniformly pack to the 60% bed density chosen for both powder experiments.

The results obtained for the "fine" salt samples are shown in Fig. 3.10. The chronology is indicated since powder samples often show an irreversible behavior due to thermal expansion effects, particle

Fig. 3.9. Particle Size Distributions of "Fine" and "Medium" Hutchinson Salt Powder and of the "Blended Medium" Sample Used for Thermal Conductivity Measurements.

Fig. 3.10. Thermal Conductivity of "Fine" Salt Powder in Air and in Argon as a Function of Temperature.

rearrangements, etc. The lower temperature measurements were made in an air atmosphere, while argon was used at temperatures above 380°K. Multiple sets of data were usually taken at each temperature in order to study and check the operation of the apparatus, and the land at each data temperature contains the indicated number of individual data points.

The thermal conductivity of the "fine" salt powder increased regularly with temperature since the temperature coefficient is largely determined by the gas phase. The dominance of the gas phase is further illustrated by the 25% decrease in conductivity when argon is substituted for air. Up to 620°K, the results showed no hysteresis; however, irreversible behavior was observed at higher temperatures. After exposure at the highest temperature, the subsequent result at 570°K was slightly lower than the value obtained earlier, whereas the final value obtained at 373°K was significantly higher than the first.

The apparatus was disassembled to the extent that the steel powder container could be gently tapped in an attempt to redistribute the powder within the container. Subsequent measurements at 373°K in air and in argon were considerably higher than all earlier ones. On complete disassembly of the apparatus, we found that the salt powder had more or less agglomerated and hence would not pour out. The lumps were very friable and easily broke to give the original particles. We believe that the explanation for the measured differences in the value of λ is the differences in thermal expansion for the steel can and the salt powder. On cooling from the highest temperature where the salt was plastic and free of strain, a gap was created at the outer radius of the salt annulus. (A steel core heater is located at the center of the salt). However, because of the partial sticking and clumping of the salt powder, its λ had increased sufficiently to overcome the added thermal resistance at the gap and thus resulted in the observation of a net increase in λ . The light tapping on the can apparently served only to filter some fine particles down into the outer gap, which reduced the gap resistance. No effect on the lumps of powder was noted.

The powder apparatus was modified several times during the measurements on the fine salt. Following these measurements, the performance and characteristics of the powder radial heat flow apparatus were studied by using a well-characterized MgO powder supplied by Godbee.³⁸ Godbee and Moore³⁹ has previously measured the λ of this powder. Two basically different assemblies of the apparatus were made with the MgO powder. The first one duplicated the system in which the reported fine salt values were obtained. The second was an improved version of the apparatus as suggested by earlier experiences. Comparison of the results for the two assemblies indicates that the first results for salt could have a temperature-dependent error, leading to a measured value about 9% too high at room temperature and decreasing to zero error at about 600°K. We feel that this is the maximum error that could be applied to the results for fine salt powder.

Figure 3.11 shows the results obtained in the improved apparatus on the "medium" salt, together with a curve showing the "fine" salt results from Fig. 3.10 adjusted for the 9% error cited above. The thermal conductivity of the "medium" salt approximates that of the "fine," but is slightly lower at low temperatures and significantly higher at high temperatures. There are two plausible explanations for this behavior. First of all, we have ignored the fact that the "medium" powder is much too large for the dimensions of the apparatus since one of the objectives of this experiment was to determine if decrepitation of the salt by the included brine would significantly decrease the thermal conductivity. Theoretically, the "fine" and "medium" powders should have essentially the same λ , even though they differ by a factor of about 5 in particle size. With respect to λ considerations, powders are not "fine" until their dimensions approach the gas mean free path. Therefore, we think that the low λ at 300°K is an effect due to the apparatus, and that the true value would be the same as for the "fine" salt.

The greater temperature coefficient of λ that leads to higher λ values for the "medium" salt is likely the result of radiative heat transfer. Radiative transfer would not be expected in the "fine" sample because of the much greater number of scattering boundaries. However, as few as four grains may span the annulus in the "medium" sample; therefore, the sample is semitransparent.

Fig. 3.11. Thermal Conductivity of "Medium" Salt Powder in Air and in Argon as a Function of Temperature. The results for "fine" salt are those from Fig. 3.10, adjusted for the error discussed in the text.

In general, the results for the "medium" salt follow the pattern of the "fine" salt; that is, up to 600°K, there is no obvious hysteresis or any apparent change because of decrepitation (if decrepitation has occurred). Under the very slow heating conditions of the radial apparatus and the temperature gradients, it is possible that the brine inclusions could diffuse harmlessly to boundaries rather than explode the grain. Post-experimental examination of the salt particles and a screen analysis should provide such information about the brine.

The three data points at 550°K in Fig. 3.11 show an interesting effect that is attributable to the discrepancy in thermal expansion cited earlier. The data marked "low" was obtained with a 2.5°C radial temperature drop across the salt, while the "high" had a 16.3°C drop. (The salt annulus is 2.2 cm thick). The increase in λ for the "high" was caused by the increased mechanical pressure from sample expansion. The marked drop in the "low after high" shows that the behavior of the powder is irreversible, probably because of plastic deformation.

An extension of this powder experiment is the application of the finite-difference heat conduction program HEATING3⁴⁰ to our particular geometries. This computer program is being used extensively for the thermal analysis task as reported in Sect. 3.3 of this report. We have used HEATING3 to thoroughly analyze the several powder radial devices employed in our laboratory, particularly that of Moore³⁹ and the ones developed subsequently. The program has verified our concerns about these devices and has pointed out some serious extraneous heat flows in the earlier powder radial apparatus. Of equal importance is the observation that HEATING3 calculations are substantiated by our laboratory measurements.

Effects of Consolidation on Thermal Conductivity of Salt Backfill. -

The powder surrounding a can containing nuclear waste will be subjected to both elevated temperature and compressive stress, and may ultimately be restructured. There is a factor of 10 or more change in thermal conductivity from the powder state to the restructured state, and this will cause a significant change in the temperature of the waste and its surroundings. Our results for salt powder in the previous section have shown

that measurable changes are observed even for very low stress levels. We are designing an experiment to measure directly the thermal conductivity of salt powder, as a function of time, temperature, and compressive stress, to the point that the sample is restructured to solid salt above 90% of theoretical density.

Waste-Hole-Backfill Simulation. - An instrumented probe made of 1/2-in.-OD by 4-in.-long 304 stainless steel tube with an internal heater and thermocouple and an outer welded-on thermocouple was used to simulate a waste container in an experiment designed to assess the early transient state of waste burial. A large block of solid salt with a 1-in.-diam, 6-in.-deep hole, and two thermocouple holes with radii of 11/16 in. and 1-5/8 in., respectively, was used to represent the mine floor.

The probe was suspended directly over the block and was heated at constant power in still air to a surface temperature of about 500°C. When equilibrium was obtained, the powered probe was dropped into the hole and a computer-operated data acquisition system⁴¹ monitored the response of the four thermocouples with time. Four different experiments were conducted with the probe. In the first experiment, the annulus between the probe and the salt was left empty. In the second, fine salt powder was poured into the hole 20 min after the probe was inserted. In the third, fine salt powder was poured in immediately.

The fourth experiment involved a different concept of backfilling that requires explanation. We can envision several potential problems in the use of salt powder as backfill. First, there is the matter of the very low thermal conductivity of salt powder. Also, the presence of powder might make retrieval by overcoring more difficult since a large core would have to be taken to ensure a solid salt outer surface. In addition, the salt powder would offer no resistance to the incoming brine. In light of this, we considered that some type of solid backfill might be desirable. A cement-type would not be feasible since the temperatures are excessive for a water-base cement. A likely candidate, ~60 wt % CaCl_2 -40 wt % NaCl , was discovered in the NaCl - CaCl_2 binary system. The melt, which has a eutectic at 500°C, is very fluid, is easy to prepare from cheap and available materials (especially the NaCl), should have a high thermal conductivity, would be free

of brine, and would rigidly encase the waste cylinder. Accordingly, for the fourth experiment, we prepared a crucible of melt of this composition at just over 500°C and poured it into the annulus immediately after the probe was inserted.

The results in Fig. 3.12 indicate that the can and the surrounding salt block experience very different temperature conditions before quasi-steady state is reached. It is obvious that the powder must be poured in very quickly in order to minimize the temperature rise of the waste container. However, the results for the molten eutectic experiment are of the greatest interest. The surface temperature of the can increased momentarily by about 70°C while the melt was freezing. Once frozen, the eutectic displayed its high conductivity in reducing the temperature of the can approximately 60 to 70°C below that achieved with the powder, a significant drop with respect to corrosion rates and other effects.

Development of an Automatic, Constant-Temperature Ice Bath. - There are numerous applications in the laboratory where constant-temperature ice baths are used. One of these, called the "longitudinal heat flow apparatus," utilizes a ice bath requiring constant replenishment of the ice. Over weekends, control is lost and considerable time is needed to reestablish steady state. The transient plane probe is also a device requiring a stable reference temperature. A completely automatic bath, such as that reported in the literature,⁴² is highly desirable.

During the past year a quarter-ton-capacity automatic ice bath was designed according to the literature, but with some modifications. Basically the unit consists of a 3/8-in.-OD copper refrigeration coil immersed in a stirred water bath. A constant-pressure expansion valve admits R-12 refrigerant from a mechanical refrigeration unit so that the coil is maintained at about 30°F . At this temperature, an ice deposit about 1 in. in diameter will be maintained on the coil.

Excess refrigerant overflows into a secondary evaporator, consisting of a SCR-controlled 1200-W heater clamped to a 10-3/4-in.-diam copper disk that is equipped with a spiral groove and cover to guide the R-12 as it is transformed from liquid to vapor. The original design reported

Fig. 3.12. Temperature Response with Time of the Probe Surface and the Solid Salt for Four Experiments Simulating a Waste Can in a Hole in Solid State. The probe center line temperature (not shown) was about 50°C higher than the surface temperature, and its response lagged slightly in time.

in the literature works well but involves a coil immersed in a stirred tank of heated antifreeze; such a design is slightly less convenient for a compact, portable unit.

3.3 Thermal Analyses

R. D. Cheverton

W. D. Turner

The high-level waste repository thermal analysis discussed in the previous annual report⁴³ was, to a large extent, limited to establishing calculational methods and technical feasibility. Since that time, parametric studies have been conducted with room and pillar width, waste container array and spacing, waste age and composition, and stratigraphic detail as variables. Preceding this effort, thermal conductivity temperature dependence was included in the three-dimensional heat-conduction code, and criteria associated with limiting temperatures were modified to achieve greater consistency. A topical report that discusses most of this work in detail⁸ has been written. The changes in the criteria and results from a few preliminary calculations were included in the previous annual report.⁴³

Verification of the accuracy of the mathematical techniques and models used in this work is under way, both at the University of Kansas and at ORNL.

3.3.1 Thermal Conductivity Temperature Dependence

The ORNL ADI (alternating direction implicit) code was modified to include the temperature dependence of thermal conductivity. It is now possible to recalculate the conductivity at each node for specified time intervals that consist of one or more time steps. The conductivity used for the time interval, $t_{m+1} - t_m$, is evaluated at the temperature,

$$T_n + \left(\frac{T_n - T_{n-1}}{t_n - t_{n-1}} \right) \left(\frac{t_{m+1} - t_m}{2} \right),$$

where

T_n is the last calculated temperature,

$T_n - T_{n-1}$ is the temperature change during the last time step,

$t_n - t_{n-1}$ is the last time step,

$t_{m+1} - t_m$ is the next time interval, which can consist of one or more time steps, and

$t_m = t_n$.

Sufficient accuracy has been achieved in the calculations by considering only the effect of temperature on the thermal conductivity of salt, and by reevaluating the conductivity for time intervals consisting of ten time steps.

3.3.2 Parametric Analysis for 1000-ft Depth

Models. — A typical 3-D(XYZ) model describing the general burial scheme and the stratigraphy at the Lyons site is shown in Fig. 3.13. Room, pillar, and container array combinations considered in most of the parametric studies are as follows:

- (1) 15-ft room; 25-ft pillar; single row of containers
- (2) 18-ft room; 30-ft pillar; single row of containers
- (3) 30-ft room; 30-ft pillar; double row of containers
- (4) 50-ft room; 50-ft pillar; double row of containers

Calculations were also made with multiple rows of containers in the 15-ft room and with more than two rows in the 30- and 50-ft rooms. In each case, the container was 6 in. in diameter and 10 ft long.

The pillar widths given above are tentatively considered to be minimum permissible values for a mine depth of 1000 ft. The minimum permissible room width is now assumed to be 18 ft (15 ft previously), and the maximum is assumed to be 50 ft.

Variables. — Variables considered in the parametric analysis were room--pillar width combinations, distance between containers measured along the length of the room (pitch), container arrays, and waste age. Waste ages of 1, 4, 10, and 20 years, and pitches of from effectively 0 to 50 ft, were included.

Waste Characteristics. — The high-level waste considered in the parametric studies was the typical LWR waste described previously.⁴³ Variations in the isotopic composition of the wastes were made for some calculations by increasing the ratio of actinides to fission products. The "typical" ratio of actinide to fission-product power at 10 years after reprocessing was 0.064. Other ratios included in the studies were 2, 10, and ∞ times this value.

Fig. 3.13. Three-Dimensional Model of a Unit Cell of the High-Level Mine: 15-ft Room.

Cladding hulls considered in a few calculations were also typical for LWRs. The cladding material was Zircaloy, and the hulls were assumed to be contaminated with 0.1% of the high-level waste.

Results of Analysis. — Results from the parametric analysis are reported as the maximum permissible gross and net loading surface densities, loading per container, and power per container as a function of pitch, waste age, and room size. Net area refers to the burial room floor area, and gross area refers to this latter area plus the pillar cross-sectional area. Permissible values are consistent with limitations imposed by the salt and waste temperature criteria.

Figure 3.14 shows gross loading surface densities for 10-year-old waste, corresponding to the salt and waste criteria. These criteria stipulate that, in the 10-ft-thick horizontal layer of salt in which the waste cylinders are buried, no more than 1% of the salt will be allowed to have a temperature in excess of 250°C and no more than 25% of the salt will be allowed to have a temperature in excess of 200°C. The minimum envelope of these curves, the trends of which are typical for all waste ages considered, constitutes the maximum permissible surface density. The right-hand portion of this envelope can be changed significantly by assuming different waste properties. The waste considered in the calculations has a relatively low thermal conductivity and maximum permissible temperature ($k = 0.25$ Btu/hr·ft·°F; maximum temperature, 1100°F). Increasing either of these values moves the waste portion of the curve to the right.

Complete sets of curves for 1-, 4-, and 10-year-old wastes are presented in Figs. 3.15, 3.16, and 3.17, respectively. These results indicate that, for a particular waste age, the difference between maximum permissible gross surface densities for the three room sizes is small. However, there are significant differences between net surface densities. For instance, in the case of a 10-year-old waste, the maximum permissible net surface density for a 15-ft room is about 37% greater than that for the 30- and 50-ft rooms. This constitutes a substantial saving in mining and salt disposal costs for the 15-ft room.

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Fig. 3.14. Gross Loading Surface Density for 10-year-old Waste in a 15-ft Roca in the High-Level Repository.

Fig. 3.15. Comparison of High-Level Repository Loading Surface Densities and Loadings per Waste Package for 1-year-old Waste and 15-, 30, and 50-ft-wide Rooms.

Fig. 3.16. Comparison of High-Level Repository Loading Surface Densities and Loadings per Waste Package for 4-year-old Waste and 15-, 30-, and 50-ft-wide Rooms.

Fig. 3.17. Comparison of High-Level Repository Loading Surface Densities and Loadings per Waste Package for 10-year-old Waste and 15-, 30-, and 50-ft-wide Rooms.

It is also observed that the younger the waste, the smaller the pitch (and hence the loading per container) for which the 1% salt and the waste criteria become limiting. This tends to provide incentive for improving the thermal characteristics of the younger wastes. However, handling and transporting considerations may limit the power per container, irrespective of waste age, to about 5 kW. In this case the relatively poor thermal conductivity and low allowable waste temperature considered in the analysis do not impose a serious restriction. On the other hand, it might be desirable to improve on-site handling and transport capabilities, along with waste characteristics, to permit greater loadings per container.

Based on the parametric analysis and previous economic studies⁴⁴ of interim storage aboveground, solidification, and transportation, it was tentatively concluded that a waste age of 10 years and the 15-ft-room, 25-ft-pillar combination would be the most economical.

Since the minimum width for a room has been increased to 18 ft for ease of access, a few calculations were also made for an 18-ft-room, 30-ft-pillar combination with 10-year-old waste. The results indicate that the maximum permissible gross loading surface densities were the same as those for the 15-ft-room, 25-ft-pillar combination.

Temperature histories for several points of interest in the repository are shown in Fig. 3.18 for 10-year-old waste in a 15-ft-room containing a 25-ft pillar. The locations of the particular points are identified alphabetically in Fig. 3.19. It is observed that the center line of the waste (curve a) and the container surface temperature (curve b) peak in about 5 and 15 years at 900 and 550°F, respectively. Near the base of the pillar, the maximum temperature rise (curve d) is 300°F and the corresponding time is 50 years. The maximum temperature rise at the base of the protective shale layer (curve g) is 170°F (130 years); in a stagnant fresh-water aquifer at 300 ft below the surface (curve f), it is 37°F (500 years); and at the earth's surface (curve e), it is 0.26°F (500 years). It is also observed that a temperature rise of only 1°F in the geologic formations surrounding the repository occurs 2500 ft beyond the edge of the mined area (well within the AEC-controlled buffer zone) and about 2000 ft below the earth's surface. The corresponding time is 6000 years.

Fig. 3.18. Temperature Rise vs Time After Burial for 10-year-old LWR Calcined Waste, 15-ft Room, 25-ft Pillar, and Single Row of 6-in.-diam Containers on 30-ft Pitch, Each Containing 165 kg of Waste Nuclides. Curves are for points alphabetically identified in Fig. 3.19.

VERTICAL CROSS SECTION OF REPOSITORY

Fig. 3.19. Simplified Cross-Section Diagram of Waste Repository.

3.3.3 Other Considerations

Phasing. - A phasing effect in temperatures exists because temperatures at all points first increase and then decrease. Peak temperatures can be increased or decreased by changing the sequencing of burial for a given burial array. In the parametric analysis, it was assumed that all waste was buried simultaneously; in reality, however, it is buried continuously over a finite period of time. A 2-D(RZ), single-container, superposition model was used to investigate the magnitude of phasing relative to results obtained with the simultaneous-loading model. Under the "worst possible" conditions, the actual peak temperatures on the surface of a container could be greater by about 240°F. However, the increase was only 40°F for a less extreme loading sequence, and the difference is much less than this for typical sequences. Thus the simultaneous-loading model, which requires much less computer time, is quite satisfactory for most problems.

Container Diameter. - Most of the calculations have been made by considering a 6-in. diam container. Anticipated waste densities are such that diameters of 10 to 12 in. will be required for 5 kW of 10-year-old waste. For a given waste thermal power level, increasing the container diameter decreases the surface heat flux. It also decreases the temperature at the waste-salt interface and the waste temperatures somewhat, but has a negligible effect on the 1% and 25% salt criteria temperatures.

Fringe Area Temperatures. - Working areas adjacent to loaded portions of the mine must be maintained at sufficiently low temperatures to permit safe operation of the repository. These fringe areas include the corridors, shafts, and areas undergoing excavation and loading. Calculations indicate that provision for reasonable ventilation and modest distances between routine working areas and buried wastes will prevent excessive temperatures in those areas.

Room Ventilation. - Calculations indicate that the peak temperature rise in the floor of a room, which has had 10-year-old waste placed beneath it, will occur 5 years after burial and will be only 20°F if the ventilation air flow rate in the room is 20,000 cfm. Under these conditions

the peak heat removal rate by the air is 55 kW per ft of room length, which is about 40% of the heat generated. The corresponding temperature rise in the air is 5°F.

Salt Thickness. - The thickness of the salt bed at some of the alternative repository sites is significantly different from that at Lyons. The primary concern is over thinner beds that expose the overlying protective shale to higher temperatures. Calculations indicate that reducing the thickness of salt between the shale and waste from 250 ft to 150 ft increases the salt-shale interface temperature 30°F. Temperature changes at the waste horizon were negligible.

Actinide Concentration. - Ten years after reprocessing, the typical high-level waste considered in most of these studies would have an actinide-to-fission product power ratio of 0.064. For a few calculations, this ratio was increased to 0.128, 0.640, and ∞. Results indicate essentially no difference in peak temperatures at the waste horizon, assuming the same power surface density at the time of burial (10 years). However, in the aquifer at a depth of 300 ft, and at the edge of the 1-mile AEC buffer zone, the peak temperatures slightly exceeded specified maxima in the case of 100% actinides.

Cladding Hulls. - Calculations were made for Zircaloy cladding hulls that were buried 1 and 3 years after reprocessing. There is little change in the effective half-life over this period of time; thus the permissible power per waste package is essentially the same for the two ages and was calculated to be 359 kW/gross acre.

The expected power from 1-year-old cladding hulls is about 95 W/metric ton of fuel (U + Pu), and the compacted volume is 2.1 ft³/ton. It has been proposed that a cylindrical container 10 ft long by 9 in. in diameter be used to contain the hulls for burial. Thus the initial power per package for 1- and 3-year-old hulls is 200 and 147 W, respectively. For two rows of waste packages in a 15-ft room, the pitches corresponding to these powers and to the maximum permissible power surface density are 1.2 ft and 0.9 ft, respectively.

According to ref. 45, shielding during burial operations will require about 3 ft between holes in the floor for the 1-year-old hulls. Thus, burial in a 15-ft room will not be very efficient. The use of multiple rows in a larger room tends to rectify this situation. A 23-ft room with a 27-ft pillar, six rows of waste packages spaced 3 ft apart, and a pitch of 3 ft result in the limiting power surface density with 200 W per package.

3.3.4 Parametric Analysis for 2000-ft Depth

One of the sites being considered for a repository has attractive salt formations at a depth of about 2000 ft. As the depth increases, the pillar-width-to-room-width ratio must increase for proper support of the overlying strata. A parametric analysis has been initiated to obtain the appropriate thermal data. Calculations for 10-year-old waste in an 18-ft-room, 60-ft-pillar combination with the same general stratigraphy as before indicate permissible power surface densities of 145 kW/gross acre for a 10-ft pitch and 140 kW/gross acre for a 30-ft pitch. The corresponding net surface densities are 629 kW/acre and 607 kW/acre, respectively. The gross values are about 6 and 10% lower and the net values about 53 and 47% higher for 10- and 30-ft pitches, respectively, than corresponding values for the 18-ft room, 30-ft-pillar combination proposed for the 1000-ft depth.

3.3.5 Accuracy Checks

The accuracy of the thermal analysis mathematical techniques and models is being checked independently by G. P. Willhite at the University of Kansas and by continuing efforts at ORNL. Willhite is developing an iterative ADI thermal diffusion computer code, and ORNL is developing a strongly implicit procedure (SIP) code. The latter code has already been used to check some of the 3-D(XYZ) ADI results, and the agreement is very good. Furthermore, it appears that the SIP code eliminates some minor convergence problems experienced with ADI; in addition, it may be significantly faster than ADI.

3.4 Ecological Assessment

R. C. Dahlmar

One objective of ecological assessment is to compile information on pathways of radionuclide movement in ecosystems associated with a salt-mine waste repository. By necessity, the assessment is general in scope because no on-site investigative work has been done. Nevertheless, the dynamics of strontium-90 has been estimated for plant-soil-litter segments of a generalized grassland ecosystem based on literature sources of information.⁴⁶ During this report period, efforts on assessment of radionuclide dynamics in the grassland ecosystem were focused on radiocesium movement through vegetative and food chain pathways.

Data were examined on plant-soil-microorganism relationships because microbes characteristically immobilize, chelate, and circulate mineral elements. A generic model of ^{137}Cs dynamics was designed for these components of a grassland ecosystem. The conceptual design closely approximated the ^{90}Sr predictive model because both nuclides tend to follow similar cycling pathways in the grassland ecosystem. A simple four-compartment model (live vegetation, dead vegetation, roots, and soil) accounted for most ^{137}Cs cycling. Although microbes are important biological agents in the cycling of mineral elements, their inclusion in a generic sense did not improve the resolution of radiocesium flow in this assessment.

Thus far in ecological assessments, it has been assumed that the source of contamination is chronic radioactivity from routine releases of fission products. Assessment efforts are now being redirected to examine ecological consequences of contamination events from upper limit accidents as described by Nichols.⁴⁷ Generally, pathways and transfer parameters of existing models can be used to describe the disposition of radioactivity for the majority of accidental releases of fission products, providing adjustments are made for source-term strength.

Efforts have been initiated to gather information on surface features, soils, and plant-animal communities at alternative sites being considered in the repository program. Maps and brief ecological data have been assembled from literature sources. However, preliminary field surveys have been delayed, pending selection of an alternative site.

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4. CONCEPTUAL DESIGN STUDIES

Kaiser Engineers, Incorporated, was retained during the past year to continue architect-engineer (A-E) services on behalf of the conceptual design of the salt-mine repository. A Conceptual Design Report for the Federal Repository, Lyons, Kansas, was prepared and issued in draft form in January 1972. In February 1972, a decision was made to withhold selection of a specific site temporarily and to pursue the design and construction of a pilot plant repository (PPR) in the FY 1976-77 time frame. Preparation of a conceptual design and submittal of a construction data sheet were scheduled for completion by the end of FY 1975.

4.1 Pilot Plant Repository Concept

B. F. Bottenfield G. W. Banfro
Z. J. Frederick

4.1.1 Scope and Definition

The objective of the PPR is to provide the means for resolving the major concerns regarding the safety of long-term storage of wastes in geologic formations that can be addressed only through in-situ operations, and to develop information on design, operation, and economics which can be applied to a full-scale storage facility. The design of the PPR will be aimed at a minimum-cost facility within the following guidelines:

- (1) The surface facilities will be designed to receive shipments of commercial reprocessing waste on a schedule geared to current projected production rates for these wastes through the mid-1980s. The estimated total number of waste packages to be buried in the PPR is about 400. The massive, nonexpandable structures will be designed to accommodate full-scale operations based on the maximum projected rates of waste generation in the late 1990s.
- (2) "On-line" equipment and facilities can be considered to be available for recovery from unplanned events or for special operations involving limited numbers of experiments.

- (3) All waste packages will be essentially free of external contamination, and the waste will be in an approved form. The means for establishing this level of cleanliness should be provided either at the pilot facility or at the shipper's plant.
- (4) All waste packages emplaced in the formation will be monitored and maintained as required to prevent migration of the waste and to ensure rapid retrievability. This does not prohibit limited experimentation, at a later date, in which special provisions are provided beforehand to allow retrieval of even bare wastes.
- (5) Adequate instrumentation will be installed in the storage rooms and elsewhere to make all necessary measurements of temperature, radiation, gross physical changes, stresses and strains in geologic structures, vapor pressure, water flow and buildup, etc.
- (6) Site selection, site size, and design of the PPR should not preclude its conversion, at the conclusion of the pilot operation phase of the program, to an operational storage facility. The duration of the pilot operation phase is assumed to be 5 to 15 years.
- (7) The facility design will include an ecologically acceptable means for disposing of excess salt.
- (8) No provisions for alpha waste burial should be made in the pilot facility design.
- (9) The salt layer for waste disposal will be assumed to be situated 2000 ft below the surface.

4.1.2 Mine Development Plan and Underground Facilities

The mine development for the PPR will provide the necessary mine-level facilities for burying and retrieving waste packages within sleeves in the salt during the PPR operation. The layout of these facilities is shown in Fig. 4.1. The overall development plan (shown in Fig. 4.2) indicates the relationship of the PPR mine to a possible future full-scale repository located in the 2-square-mile salt layer.

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Fig. 4.1. Auxiliary Underground Installations.

Fig. 4.2. Mine Development Plan.

The salt excavation for the PPR is to be completed during the construction phase of the project and in the most economical way. No salt will be removed from the mine during PPR operation; excess salt resulting from drilling holes for the burial of waste packages will be retained in the mine. Four significant features of the underground facilities are described below.

High-Level Waste Shaft. - This shaft, which will measure 4 ft in inside diameter, will serve as the means for lowering all waste packages from the surface facilities to the mine, and for retrieving those packages from the PPR in the event that it becomes necessary to transfer them to another repository at the conclusion of the pilot plant operation.

Men-and-Materials and Salt Hoisting Shaft. - This multipurpose shaft will measure approximately 14 ft in inside diameter and will be partitioned to provide for the following equipment and functions:

- (1) A hoist and cage for transfer of men and materials from the surface to the mine.
- (2) Hoisting capability to remove excess salt from the mine.
- (3) Ventilation air supply to the mine.
- (4) Space for mine utility and service ducting.
- (5) Manway and ladder for emergency egress from the mine.

The shaft will be sized for the PPR only; additional capacity, if required for a future full-scale repository, will require a new shaft.

Upcast Ventilation Shaft. - This shaft will be sized for the ventilation capacity of the PPR mine and will be partitioned to include a second emergency exit from the mine.

Support and Service Facilities. - Facilities will be provided underground for servicing mining and waste handling equipment, oil and grease storage, underground electrical distribution, first aid, and an office for mine-level supervision.

4.1.3 Surface Facilities

The surface facilities, which are to be constructed in a manner that does not preclude expansion, will be sized to accommodate a waste package throughput equivalent to that projected for the PPR, and for the staff of

personnel required to process these packages. The massive concrete cell structures and basement structures, whose expansion to a future full-scale repository would be exceedingly difficult, will be sized for the full-scale repository capacity.

High-Level Waste Receiving Building. - The high-level waste receiving building will contain facilities for receiving rail cars or trucks carrying waste casks weighing up to 110 tons, unloading the casks from the rail cars, cooling the massive shielding of the casks, unloading the waste packages from the casks remotely within a shielded cell, and lowering the packages into the mine through the high-level waste shaft. The floor plans of the two floors of the building are shown schematically in Figs. 4.3 and 4.4.

Support Facilities. - (1) Salt Disposal. - Minimum facilities for loading the mined salt into rail cars or trucks for transport and disposal will be provided at the top of the salt hoisting shaft; this capacity will be sized for the PPR only.

(2) Central Filter Station. - The filter station provides for the safe cleanup of the mine ventilation exhaust air at the top of the upcast ventilation shaft. The station will be located below grade.

(3) Mine Operations and Administration Building. - This building will contain quarters for the administrative staff of the PPR as well as facilities for carrying out certain functions relating to personnel working underground, such as the changeroom and personnel monitoring station.

(4) Other surface support facilities include an explosives magazine, warehouse and material staging and receiving space, an electrical substation, and a water supply tank.

4.1.4 Ventilation and Confinement System

The confinement zones of the high-level waste receiving building will be designed and constructed so that waste handling operations can be shut down without endangering the public health and safety during or following an earthquake or a tornado. Confinement zones will be maintained at a negative static air pressure with respect to the outside atmosphere to

Fig. 4.3. Plan of the Ground Floor.

Fig. 4.4. Plan of the Basement Floor.

ensure against any outleakage of air (see Fig. 4.5). All exhaust air from confined areas of the building will be passed through fans and HEPA* filters, located in an exhaust fan-filter room, prior to discharge to the atmosphere through a stack. Access between confined and unconfined areas of the building will be gained through air locks.

Ventilation air will enter the mine through the air supply compartment of the men-and-materials and salt hoisting shaft. Within the mine, the flow of ventilation air will be directed toward the waste burial area via the main and panel entries. A separate tunnel system located above the main entries will serve to isolate the exhaust air streams from the working areas and convey them to the base of the upcast vent shaft.

4.1.5 High-Level Waste Handling System

Waste will be received in sealed cans up to 24 in. in diameter, up to 10 ft long, weighing up to 8000 lb, and generating 1 to 5 kW of waste heat. These cans will be shipped in casks weighing as much as 110 tons. The temperatures of the cans will be lowered by cooling the shielding casks; and the cans will be unloaded individually in shielded cell facilities, lowered to mine level through the waste shaft, and then transported and buried in the salt bed using a shielded transporter.

A section through the high-level building is shown in Fig. 4.6. The shipping cask will be lifted from the railcar and lowered through the hatch in the floor of the cask unloading area onto an air transfer pallet in the air lock. It will be moved laterally into the cask service area, where the massive shield will be cooled by circulating water through the neutron jacket or channels in the shield. Finally the cask will be moved to a location under the cask port in the shielded transfer cell, where the cask will be sealed to the bottom of the cell. The cask port cover and the shipping cask shield plug will subsequently be removed, exposing the waste packages and the cask interior to the cell. Then the waste packages will be lifted from the cask individually and lowered into the mine shaft cage, which is located below the transfer cell port. The mine shaft cage, containing the waste package, will then be lowered to mine level.

* HEPA = high-efficiency particulate air filters.

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Fig. 4.5. Schematic of the Ventilation System for the Waste Receiving Building.

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Fig. 4.6. Section Through Waste Receiving Building.

At mine level, the cage will be received in a shielded station (see Fig. 4.7). The cage will be moved laterally to a position under a port in the top of the station, through which the waste package will be hoisted into the waiting shielded transporter. The waste package will be transported within the shielded transporter to the waste burial area, where it will be deposited in a previously prepared hole having an inert liner.

4.1.6 Schedule

Our schedule is contingent upon a great many considerations, not the least of which are Congressional appropriations and legislation authorizing us to proceed in certain areas. Other important considerations are, of course, the results of current and proposed research and development activities, particularly geologic-hydrologic investigations and consideration of alternative sites.

Our tentative schedule includes completion of a conceptual design study and report, based on a site near Carlsbad, New Mexico, by March 1975, and preparation of a construction project data sheet by June 1975. The data sheet will propose funding of the pilot plant repository project, with completion of construction scheduled for the early 1980s.

4.2 Waste Package Connector

M. K. Preston

The design for a connector that can be used in the remote handling of high-level waste containers at spent-fuel reprocessing plants and a repository was completed. A prototype connector was fabricated and has been subjected to preliminary cyclic and strength tests. The results of these tests, which were conducted for 4000 cycles with no load and for approximately 16,000 cycles with load, indicate that the connector exceeds the basic safety and load criteria. Future testing of the connector is planned in order to further evaluate its remote operating capabilities, its underwater operation, and the effects of heat on its performance. The connector design and the testing program are described in a topical report.¹

4.3 Retrieval Concepts

B. F. Bottenfield G. W. Renfro

A conceptual study of waste package retrieval alternatives was conducted; and a preliminary report, "Conceptual Study for Retrieval of High-Level Waste Cans Buried in Salt," was prepared by Kaiser Engineers. The report included five drawings and described concepts for retrieval of waste packages from sleeved holes during the PPR operating period and from direct burial in salt for longer-range planning. The sleeved burial concept will not be developed any further at this time; this phase of retrieval design will be the responsibility of the PPR operating contractor and will be initiated after the PPR is in operation.

4.4 Liner Integrity Studies

R. E. Adams D. L. McElroy
T. G. Godfrey

During the operation of the pilot plant, it is considered necessary to employ a double containment system for the high-level waste packages to ensure operational safety, to allow certain experiments to be performed, and to provide a positive means of waste retrieval (in case removal becomes necessary or desirable). We have conducted a desk study of this lined-hole concept with the goal of suggesting one or more candidate materials for experimental verification.

Experience has shown that the stainless steels are the best of the common materials from the standpoint of general resistance to corrosion. However, it has been clearly demonstrated that stainless steels are subject to gross stress corrosion cracking in a salt-bearing environment. Common carbon steels, on the other hand, experience a more rapid, but uniform, corrosion rate. Several special alloys, such as Hastelloy C, have a high resistance to corrosion, but their unit costs would be 10 to 50 times greater than those of the more common materials.

Our study has indicated that a carbon steel--concrete composite might be the best candidate for further study. High-temperature cements with silica flour for aggregate have been developed for application in

the petroleum industry to seal oil well casings to the rock strata for steam injection to simulate oil flow. These cements, which withstand temperatures up to 700°F (371°C) and have strengths as high as 15,000 psi, have also been successfully used in salt formations.

This concept would employ a thin (~1/4-in.) steel closed-end tube as a permanent form in the oversized hole in the salt, with the special cement or concrete poured in place in the 1-1/2- to 2-in.-wide salt-steel annulus. The concrete is the principal strength member, while the steel liner serves as the form and prevents chips from clogging the cavity in the event the concrete spalls. In most cases, nylon or steel fibers have been used as reinforcement in these cements; conventional wire mesh or rods would seem applicable for our use if thermal and solidification expansion characteristics can be adjusted for this purpose.

Although satisfactory performance of these cements in salt at high temperatures has been demonstrated, an experimental program will be necessary to establish their suitability for long exposures to the thermal, mechanical, chemical, and nuclear environment of a salt-mine repository.

4.5 Repository--Fuel Reprocessor Interfaces

B. F. Bottenfield J. O. Blomeke
G. W. Renfro

Meetings were held during the past year with personnel from three of the potential fuel reprocessors who will supply high-level waste to the PFR and the engineered storage facility: Allied-Gulf Nuclear Services, General Electric Company, and Jersey Nuclear Company. A set of waste cask and package acceptance criteria was prepared by ORNL in advance to provide a focal point for the discussions. The meetings provided a free interchange of ideas on such subjects as the following:

(1) Shipping Casks

- a. Maximum diameter and length
- b. Maximum weight
- c. Internal void dimensions

- d. Sealing to repository transfer cell
- e. Internal cask atmosphere
- f. Fabrication tolerances
- g. Cask cooling
- h. Contamination tolerances
- i. Connections and appurtenances

(2) Waste Packages

- a. Maximum diameter and length
- b. Maximum weight
- c. Method of handling (connector)
- d. Maximum heat generation
- e. Maximum temperatures
- f. Fabrication tolerances
- g. Container integrity
- h. Contamination tolerances
- i. Waste properties

(3) Other

- a. Rail car limitations

Based on many of the comments received from the reprocessors, we have revised the interfacial criteria in a number of respects for consideration by the AEC and participating contractors.

4.6 Reference for Section 4

1. M. K. Preston, Development and Testing of a Connector for Remote Handling of High-Level Waste Containers, ORNL-TM-3934 (September 1972).

5

5. PILOT PLANT EXPERIMENTAL PROGRAM

R. D. Cheverton

The objectives of the pilot plant operational period are basically (1) to demonstrate the ability to transport and handle high-level waste without mishap, and (2) to confirm various technical aspects of the burial scheme. Only enough waste need be buried to accomplish these objectives; however, all of this waste must be readily retrievable. The duration of the pilot plant experiments is indefinite but is expected to range up to 15 years.

Details associated with the presently proposed experiments are discussed below.

5.1 Transportation and Handling

To adequately demonstrate safe transportation and handling capability, many waste packages will have to be shipped to and buried in the pilot plant. A reasonable number for this purpose appears to be about 100; however, since the actual number of packages buried will depend on requirements for other experiments, the total could range as high as 1000. At least some of the packages should have a power level as high as is expected in the near future on a routine basis; this might be as much as 5 kW. It is expected that, on receipt at the pilot plant, most of the packages will have power levels of 2 to 3 kW and that the age of the waste will be 10 years.

At the time that the waste is buried, some question regarding the integrity of the containers from the standpoint of both internal and external corrosion will probably still be unanswered. Because of this and a desire for positive and rapid retrieval capability, it is tentatively proposed that the waste packages be placed in a secondary container and that the burial hole in the salt be lined with a relatively permanent material such as a ceramic or a ceramic-lined metal sleeve. A backfill material or grout would be required between the sleeve and the salt, and this combination must be capable of withstanding the compressive forces to be imposed on them as a consequence of salt flowage.

The exact nature of the secondary containment vessel will depend on the type of experimental data that are to be extracted from the waste package. Figure 5.1 indicates one possible design concept in which the cavity between the primary and secondary containers is not necessarily sealed at the top. Leakage of volatile radioisotopes from the primary container would indicate a breach of that vessel which could be detected by purging the cavity between the primary and secondary containers and sampling the gas. A thermocouple well is included along the axis of the waste package through the coupling to allow periodic measurements of the waste temperature. A sheathed thermocouple extending through a small hole in the shielding plug into the thermocouple well in the waste package would be used to make these measurements. Thus, no instrument lines would have to be attached directly to the package to obtain temperature and leakage data.

Monitoring of the waste will be performed continuously on a representative number of the packages. Variables to be measured will include the center-line temperature of the waste, the surface temperature of the container, and the contents of the purge gas between the primary and secondary containers. In addition, waste packages and their secondary containers will be periodically withdrawn from the sleeved holes to allow wall thickness and out-of-roundness measurements of the sleeve and to demonstrate retrievability.

We do not anticipate that any of the rooms will be backfilled during pilot plant operation unless such an operation is required for acquisition of experimental data (which is not likely). This will facilitate retrieval efforts. Furthermore, sufficient ventilation capacity and flexibility will be provided to cool specific rooms that must be entered for monitoring or retrieval of the waste.

In the event that the primary container is breached during pilot plant operation, the defective waste package will be moved to the above-ground transfer cell and recanned.

All phases of handling, with the possible exception of recanning and retrieval, will be encountered during the transfer of the waste package from the railcar to the burial holes. Since the secondary container will be attached by the reprocessor, visual inspection of the outer surface of the

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Fig. 5.1. Schematic of Waste Package and Its Secondary Container in Sleeved Hole.

primary container on receipt will not be possible. The existence of a defective package can be ascertained, however, by sampling the primary coolant used in the shipping cask.

5.2 Experimental Program

The presently proposed experimental program covers the areas of heat removal, formation and release of explosive and noxious gases, fission product transport, and rock mechanics. Each of these is discussed separately in the subsections that follow.

5.2.1 Heat Removal

The proposed heat removal experiments are intended as a check on the accuracy of the calculations, and as a means of providing information on the rate at which the thermal conductivity of the crushed salt backfill changes. For the calculational-check experiments, it is desirable to have one isolated waste package plus a second package located in the middle of an "infinite" array of packages. At a depth of 2000 ft, an infinite array will require an area about 350 ft square. Since the rooms are to be 18 ft wide by 300 ft long, separated by 60-ft pillars, and placed on opposite sides of a corridor, it is proposed that ten rooms occupying a gross area about 600 x 400 ft be considered. The maximum permissible gross surface power density is expected to be about 140 kW/acre for 10-year-old waste. Thus, assuming that essentially all the waste is 10 years old and is packaged in containers evolving 2 kW of power, the required number of waste packages is about 400. These packages and the isolated package (which will be located at least 100 ft from the outermost package of the arrays) will be placed in sleeved holes, and the sleeves will be grouted in place with a material having thermal properties similar to those of solid salt.

The only instrumentation required for these experiments will be thermocouples. Some of the thermocouples will be placed on the inside surface of the sleeve and at several other radial positions farther out in the salt. All of these thermocouple junctions will be located at an elevation corresponding to the horizontal midplane of the waste package. The others will be placed on the floor and walls of the room and in the pillars.

The calculational-check experiments will primarily yield data that can be used in comparison with the thermal properties of the various surrounding formations since the stratigraphic detail will be well known and the mathematical model will have been evaluated previously. If the calculated results compare favorably with those obtained experimentally, extrapolations in time can be performed satisfactorily.

To check on the time-dependent thermal properties of the backfill, it will be necessary to have an annulus of crushed salt backfill surrounding the sleeve of the waste package in the midst of the infinite array, as well as the sleeve of the isolated package. Presumably, the latter arrangement will result in a slower rate of reconstitution of the crushed salt.

The experimental procedure will consist of comparing the surface temperatures of the waste containers buried with grout around the sleeves with the temperatures of those having crushed salt around the sleeves. It is expected that the packages with the crushed salt backfill will experience two peaks in their temperature-vs-time curves as opposed to a single peak achieved with a solid "backfill." The latter peak, which occurs in about 20 years, results from the combined effect of thermal capacity of the various formations and radioactive decay of the heat source. The earlier peak associated with the crushed salt backfill results from the combined effect of thermal capacity and increasing thermal conductivity of the backfill, and will occur in about two days. If this peak is smaller than the second one, and if the thermal conductivity of the transforming backfill closely approaches that of solid salt within a reasonable time, the backfill will not impose a thermal limitation. In the event that these conditions are not achieved, a more restrictive limitation on mine loading will result.

5.2.2 Formation and Release of Explosive and Noxious Gases

The proposed long-term waste burial scheme calls for emplacement of a waste package directly in the salt without secondary containment or a sleeve. In the absence of a "noncorroding" sleeve in the hole, hydrogen will be produced by reaction of the metallic container with the brine that migrates through the salt to the waste package. Hydrogen will also be produced in the vicinity of the waste package as a result of radiolytic decomposition of the water present in the brine. It is possible, although

very unlikely, that potentially explosive mixtures of air and H_2 will exist in unventilated backfilled rooms. If necessary, however, several design and/or operational changes could be implemented to alleviate this hazard. In either case, experimental data are required to resolve the questions since uncertainties in the calculations are considered to be excessive.

Two experiments are proposed, the necessity for one depending on the results from the other. In the first experiment, gases emanating from the top of a backfilled hole located within the infinite array would be collected. The particular package used in this experiment would be buried directly in the salt (with no hole liner or secondary container) and covered with fine, crushed salt backfill. If the H_2 production rate became sufficient to promote the formation of explosive mixtures in the backfilled rooms, then the second experiment should be considered. The second experiment would be conducted with a backfilled room containing several waste packages buried directly in the salt. Small-diameter gas sample tubes would extend from the entrance of the room to different locations along the length of the room. Gas samples would be taken periodically to determine the concentrations.

The two experiments will also be useful for determining concentrations of noxious gases such as HCl. Calculations indicate that the concentrations of these gases will be well below acceptable limits, but confirmation of this fact is needed.

As a part of these experiments, some indication of brine flow rate will be obtained by collecting moisture from the upper regions of the backfilled hole during the later stages of the experiment. The removal of moisture from the backfill would be accomplished with electric heaters. The data obtained will provide information required for an estimate of total brine inflow.

5.2.3 Fission Product Transport

Once the primary container of a buried bare waste package is breached, there is a remote possibility that radioisotopes will migrate through the backfill to working areas during repository operation, and an even more remote possibility that some will migrate beyond the original boundaries

long after closure of the repository. Laboratory experiments indicate that significant migration is highly improbable. However, it is of interest to confirm some aspects of the laboratory findings by conducting in-situ experiments. Three basic experiments of this nature are proposed in the pilot plant.

(1) Gas Transport Characteristics of the Bedded Salt. - Two experiments are proposed. Each requires the drilling of two holes, one into the floor of a room in the midst of the infinite array and one at a location isolated from the array. In the first experiment, both holes will be capped and the increase in radon concentration in the holes will be observed. In the second, gas pressure would be applied to the holes, the system would be isolated, and the pressure decay rate would be observed. Each experiment is designed to determine the permeability of the salt to gas.

(2) Gas Transport Characteristics of the Crushed Salt Backfill. - This experiment will involve the injection of small amounts of a radioactive gas or helium into a backfilled hole near the surface of a directly buried waste package. Monitors will be used to determine the rate at which these gases emanate from the top of the hole. This experiment will be conducted in two parts: (1) within the infinite array, and (2) in an isolated area.

(3) Transport of Radioactive Nuclides Following Breach of the Waste Container. - A waste package will be buried directly in the salt in an isolated area, and the hole will be backfilled with fine crushed salt. Either prior to or following placement in the hole, the container will be breached, allowing waste to come in direct contact with the crushed salt. The top of the hole will be monitored for radioactive effluents, and cores will eventually be taken from the solid salt adjacent to the waste package. If significant release occurs from the top of the hole, it may be desirable to backfill the room and determine the transport rate into the corridor. It is also possible that supplemental heat in the form of actual waste (in sleeved holes) or electric heaters will be desired to obtain the higher temperatures associated with an infinite array.

5.2.4 Rock Mechanics

The purpose of the overall rock mechanics analysis program is to predict, as a function of time, the deformations, stresses, and strains that will be imposed upon the various formations associated with an operational waste repository. This predictive capability will be obtained by extrapolation of a mathematical model which describes the rock behavior. Since such a model would be based upon the in-situ deformational properties of the salt at the disposal horizon and the surrounding rocks, it will be necessary to determine these properties - to calibrate the model - by comparison with the known deformations around some fairly large excavations in the same or very similar geologic situation as that planned for the repository. The underground pilot plant area provides an ideal opportunity for obtaining those known deformations. Naturally, the effectiveness of the "calibration" of the mathematical model and the reliability of the predictions obtained with it will be increased as the area used, the number of installed heat sources, and the period of observation are increased.

The objective of the rock mechanics instrumentation network throughout the pilot plant area is to provide the data for completely describing the deformations which occur. Therefore, the details of this network will be highly dependent on both the design of the mine and the arrangement of the heat sources. While these details will be determined after the experimental design is finalized, it is anticipated that the instrumentation will consist primarily of a fairly large number of vertical room closure (convergence) gages augmented by a few arrays of horizontal and vertical rock strain gages, rock stress-change meters, and other instruments placed at particularly interesting locations.

5.3 Retrieval of Directly Buried Waste

The retrieval of directly buried waste will require special equipment that is not currently available. Before any waste is buried directly in the salt (without the secondary container and sleeve), this equipment must be developed and demonstrated in the pilot plant using nonradioactive, simulated waste packages. The demonstration will be performed with the

simulated waste package and the surrounding salt at ambient temperatures and at elevated temperatures. Elevated temperatures will be achieved via electric heaters that will be disconnected prior to removal of the waste package.

The retrieval equipment is expected to consist of an overcoring device that will remove a core of solid salt containing the waste package. The only expected sensitivity to elevated temperature in this operation involves the cutting efficiency, and the closure of the freshly cut hole on the bit. If closure is significant, reamers on the side of the bit can be used to maintain adequate clearance. Thus, the only temperature that need be reproduced accurately is that at the radial location of the cutter. Under normal conditions, a period of several years is required for the temperature at this location to achieve its maximum value. However, since temperature distribution per se is not important, higher heat rates can be used to obtain the desired temperature in much shorter periods of time.