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THERMAL RESPONSES IN UNDERGROUND EXPERIMENTS IN A DOME SALT FORMATION*

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ABSTRACT

Identification of suitable sites and construction of radioactive waste repositories is the goal of the National Waste Terminal Storage (NWTS) Program. To provide design information for a repository in dome salt, in-situ experiments with nonradioactive heat sources are planned.

Three such experiments using electrical heat sources are scheduled to be carried out in a salt dome. The purpose of these experiments is to acquire rock mechanics data to ascertain the structural deformation due to the thermal load imposed, to study brine migration and corrosion, and to provide thermal data. A data acquisition system is provided with these experiments to monitor temperatures, heat fluxes, stresses, and ground displacement.

A thermal analysis was made on models of each of these experiments. The objective of the analysis is to verify the capability of making accurate transient temperature predictions by the use of computer modeling techniques. Another purpose is to measure in-situ thermal conductivity and compare the results with measurements taken from core samples.

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The HEATING5 computer program was used to predict transient temperatures around the experiments for periods up to 2 years using two-dimensional and three-dimensional heat transfer models. The results of analysis are presented with the associated boundary conditions used in the individual models.

INTRODUCTION

The U.S. Department of Energy (formerly U.S. Energy Research and Development Administration) is considering alternatives for the permanent disposal of radioactive waste. It appears that permanent disposal can be most effectively accomplished by converting the waste to a highly concentrated form and burying it in geological formations. Heat generation in the high-level waste (HLW) and the resulting major thermal problems must be accommodated in the design of the waste repository. These considerations limit the amount of waste material that can be stored in a given repository area.

TEMPERATURE LIMITS IN REPOSITORY DESIGN

Many geological formations are under consideration by the National Terminal Waste Storage (NTWS) Program for the establishment of federal repositories. Dome salt, bedded salt, shale, and granite are presently being investigated. The Office of Waste Isolation (OWI) is currently in the process of formulating a conceptual design for a repository in salt formations. There are many factors that must be considered in establishing proper heat loads for such a repository: (1) structural integrity of the rooms and formation, (2) stability of the solidified waste, (3) brine migration, and (4) pertinent environmental considerations.

The design involves detailed heat transfer and rock mechanics studies. The thermal expansion of the salt induces strain and causes deformation that could ultimately result in collapse of the room if the temperature is not controlled. It is also necessary to control the temperature to limit upheaval and eventual subsidence on the surface that might in time lead to the formation of a lake or sever a protective sheath of shale beneath an aquifer. It may also be desirable to limit temperatures at specific depths due to environmental considerations.

IN-SITU EXPERIMENTS

In order to provide reliable design information, in-situ experiments have been made in Lyons, KS, which have been documented in Project Salt Vault[1] using both radioactive waste and electrical heaters for waste simulation. At present, experiments involving only simulated waste have been planned for installation in a domed salt formation by OWI to validate the previous work done in the salt vault experiments. The present experiments in the domed salt formation do not involve any radioactive material. It is these experiments which will be discussed.

The objectives of the thermal analysis involved in the experiments are: (1) ascertain strategic location for thermocouples and instrumentation in the salt bed, (2) exhibit the feasibility of using a computer program to accurately predict the transient temperature distribution anywhere in the experiment, (3) determine method of obtaining in-situ thermal conductivity as a function of temperature from regression analysis of the temperature data, and (4) compare the thermal conductivity obtained from the in-situ calculations with laboratory measurements made on the core samples.

CONFIGURATION OF DOMED SALT EXPERIMENTS

Three experiments have been designed for installation in an existing salt mine in a domed salt formation at Avery Island, LA, as shown in Fig. 1. These experiments will be used to compare the effect of sand and salt backfill on the pressure exerted on the protective sleeve in addition to the objectives previously mentioned. The experiments are strategically located between the salt pillars. Experiments A and B are monitored within a 50-ft radius, while experiment C is confined within a 40-ft radius. The experiments are separated by at least 110 ft, which in 2 years should cause no thermal interference with each other.

Experiment A is provided with a 5 kW continuously operating heater that is centrally located in the allocated area. Experiments B and C are similarly equipped with 4 kW heaters. All of the experiments contain stress meters, extensometers, and thermocouples. Experiment A is primarily concerned with temperature distribution, and is therefore more heavily instrumented with thermocouples, while experiment C contains more strain gages for determining pressures encountered on the protective sleeve due to the thermal expansion of the salt.

The purpose of these experiments is the acquisition of thermal, rock mechanics, brine migration, and corrosion data. These data will be used in the design of a federal repository similar to the one shown in the artist's conception (see Fig. 2).

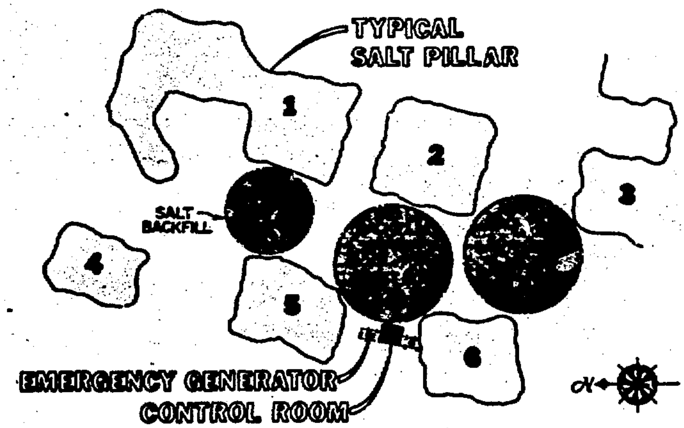

Fig. 1. Experiment Locations at a Depth of 550 Ft in a Domed Formation at Avery Island, LA.

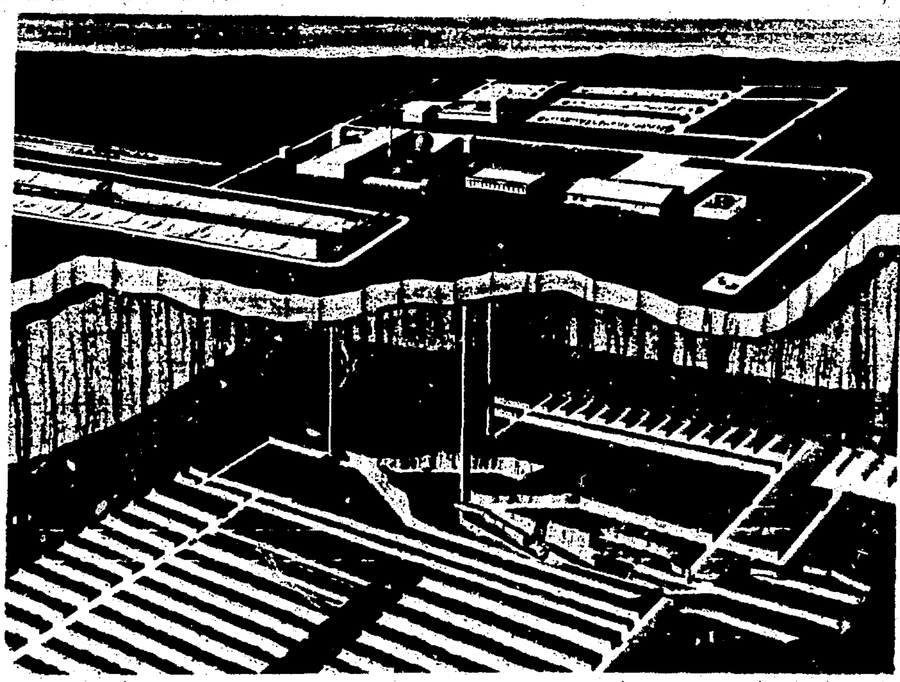

Fig. 2. Artist's Conception of a Waste Repository.

CALCULATIONS OF TEMPERATURE DISTRIBUTION

Analytical solutions have been developed[2] to obtain transient temperature distributions in salt similar to those derived by Carslaw and Jaeger[3] for point, finite line, and disk sources in an infinite media. The thermal conductivity of halite varies by a factor of 2.6 to 1 over the temperature range of 20°-250°C. For this reason, the solution will have to be obtained from a nonlinear analysis.

HEATING5[4] and TRUMP[5] computer codes have been successfully employed at Oak Ridge National Laboratory (ORNL) for determining the temperature distribution in near- and far-field models in conjunction with the NTWS program. The HEATING5 program has been used for most of these analyses and offers the capability of implicit solution techniques which yields a high ratio of real time to computer time in a transient analysis. The models employed in these analyses contain from 500 to 2500 nodes and require from 12 to 90 minutes of CPU time on our IBM 370-195 computer.

A plan and section view of experiment A is shown in Fig. 3. A 12-in. diameter sleeve, 1/4-in. thick, protects the heater canister from the pressure of the salt. Sand is used as backfill material. Thermocouple probes extend down to 25 ft and provide up to seven thermocouples in the vertical location. The plan view indicates the layout of the in-situ instrumentation. Note that heat flux monitors have been installed at strategic locations to check the heat flow in both the axial and radial directions.

Experiments B and C contain 8 peripheral heaters on a 6-ft diameter circle around the central heater and have a power rate that is a function of time. These heaters are 14 ft long and extend from 7 ft to 21 ft below the floor of the room. The central heaters used in each of the experiments will be operated on a continuous basis at a power level of 4 kW. The heat zone, filled with cast aluminum, has a diameter of 8 in. with an active length of 8 ft that is heated with 1/2-in. tubular heaters.

Experiment A contains sand as a backfill. Experiment B contains no backfill between the undisturbed salt and the protective sleeve, whereas experiment C contains crushed salt. It is desired to determine the effect of the backfill material on the pressure exerted on the protective sleeves in experiments B and C. There are 239 thermocouples, 8 resistance thermometers and 84 thermisters, 5 heat flux meters, and 11 stress gages in these experiments.

A data acquisition system is used to log and store most of the experimental data. The data will be stored on magnetic tape during

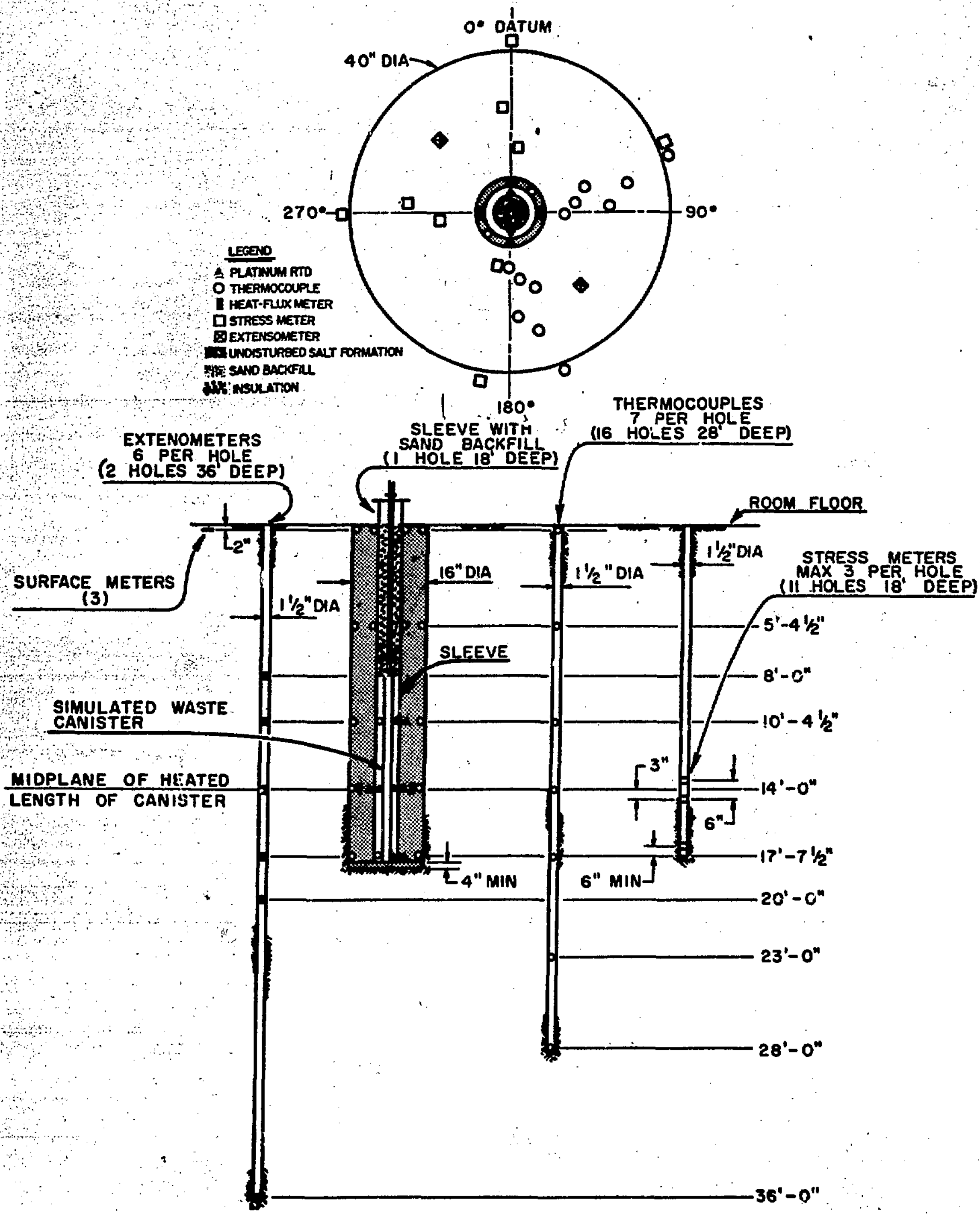

Fig. 3. Plan and Profile of Instrumentation Employed in Experiment C with a Sand Backfilled Hole.

the 1 1/2-year experiment. In addition, unmonitored extensometer data will be manually recorded to obtain deformation in the salt.

PHYSICAL PROPERTIES OF DOMED SALT

The halite formation is essentially pure sodium chloride containing less than 0.1% moisture and found to exhibit practically no anisotrophy in work performed by D. D. Smith[6] using a new laser technique. The thermal diffusivity and specific heat obtained from his analysis are shown in Fig. 4. A density of 2.16 gm/cc was used for the salt in these determinations. It is presently planned to take biaxial samples on the cores from the experimental holes and use DYNATECH analyzers for obtaining the measurements.

ERRORS DUE TO THERMOCOUPLE BACKFILL MATERIAL

Several problems were encountered in the emplacement of the thermocouples in 1 1/2-in. holes drilled in the floor of the room. The undisturbed salt has a thermal conductivity about 10 times that of crushed salt or sand which were prime candidates for backfill material. A two-dimensional nonlinear heat transfer model was used to compare the error by backfilling the thermocouple hole with a variety of materials. Errors as high as 8°F were found as shown in Fig. 5. By using compounds with a constant thermal conductivity of 2.0 Btu/hr·ft·°F, the maximum error could be reduced to about 1.5°F. It was finally decided to use crushed salt for the backfill material due to the fact that it will reconstitute itself into the solid form in the hotter regions and in the cooler regions it would be of less significance due to the higher conductivity.

HEAT TRANSFER MODEL FOR EXPERIMENT A

The predictions of the temperature in these experiments have been obtained from transient analysis using the HEATING5 program. A two-dimensional model of experiment A is shown in Fig. 6. The boundary conditions assume natural convection and radiation off of the floor to 70°F ambient air. The initial temperature was assumed to be 70°F throughout the models, although probably a gradient of about 1°F per 100 ft could exist in the actual situation. It should be pointed out at this point that thermal conductivity measurements within plus or minus 10% are deemed more than adequate for these studies.

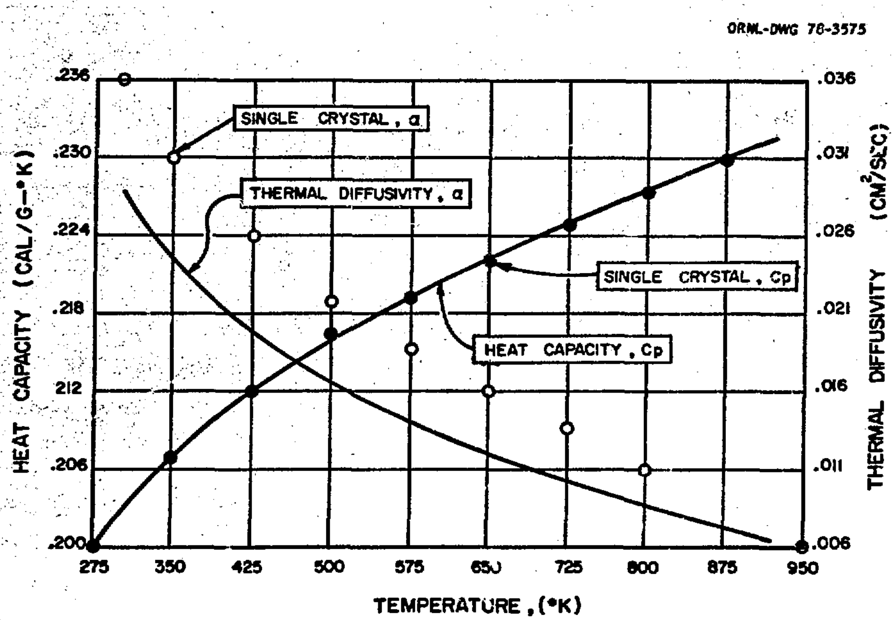

Fig. 4. Specific Heat and Thermal Diffusivity as Functions of Temperature Obtained from Domed Salt Samples Taken at Avery Island.

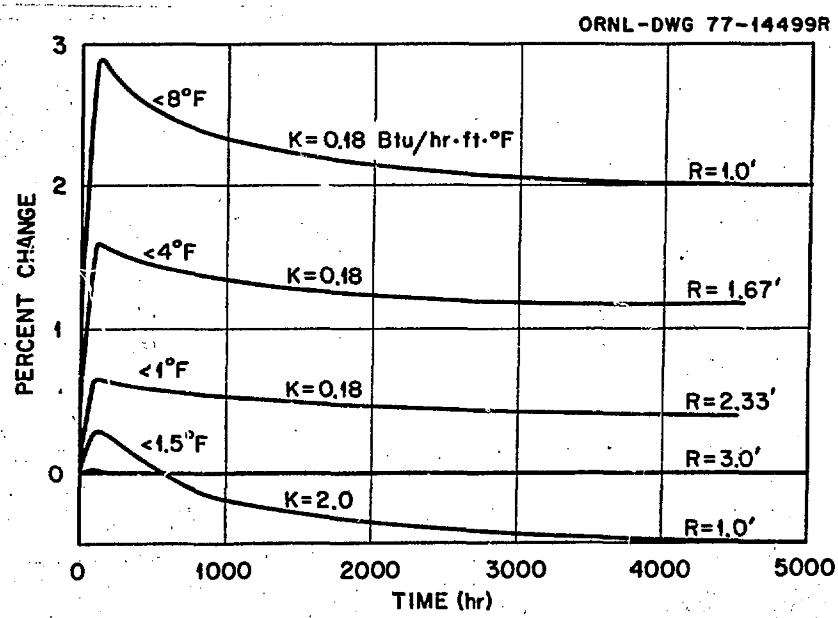

Fig. 5. Temperature Errors as Functions of Time for Backfill Material with Different Thermal Conductivities.

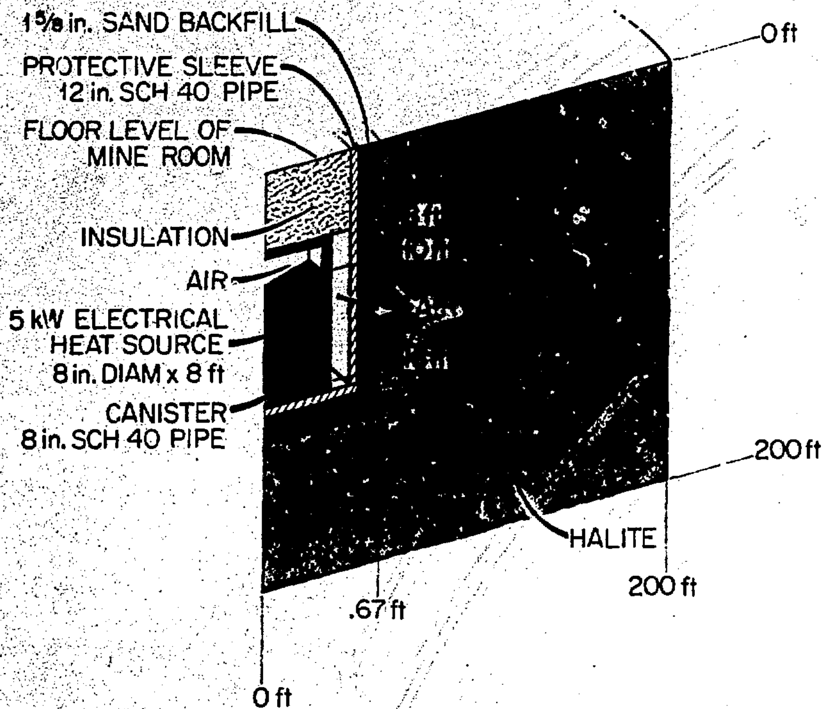

Fig. 6. Two-Dimensional Heat Transfer Model for Experiment A.

SIMULATION OF AN ARRAY OF CANISTERS FOR EXPERIMENT C

A special two-dimensional nonlinear computer code was developed to determine the power transient in the peripheral heaters to produce a maximum temperature of 400°F in the salt in 1 year with the central heater at a constant power level of 4 kW throughout the transient. This program utilizes the principle of superposition to simulate the effect of heat flow from a matrix of canisters of high-level waste.

The temperature distributions obtained from these calculations are accurate only within the radius of the peripheral heater. To verify these results, a three-dimensional model using cylindrical coordinates was formulated as shown in Fig. 7. The results of the three-dimensional computer analysis produced an identical temperature distribution within the radius of the peripheral heaters and confirmed the reliability of the special two-dimensional computer code. The three-dimensional analysis gives accurate temperatures throughout the model.

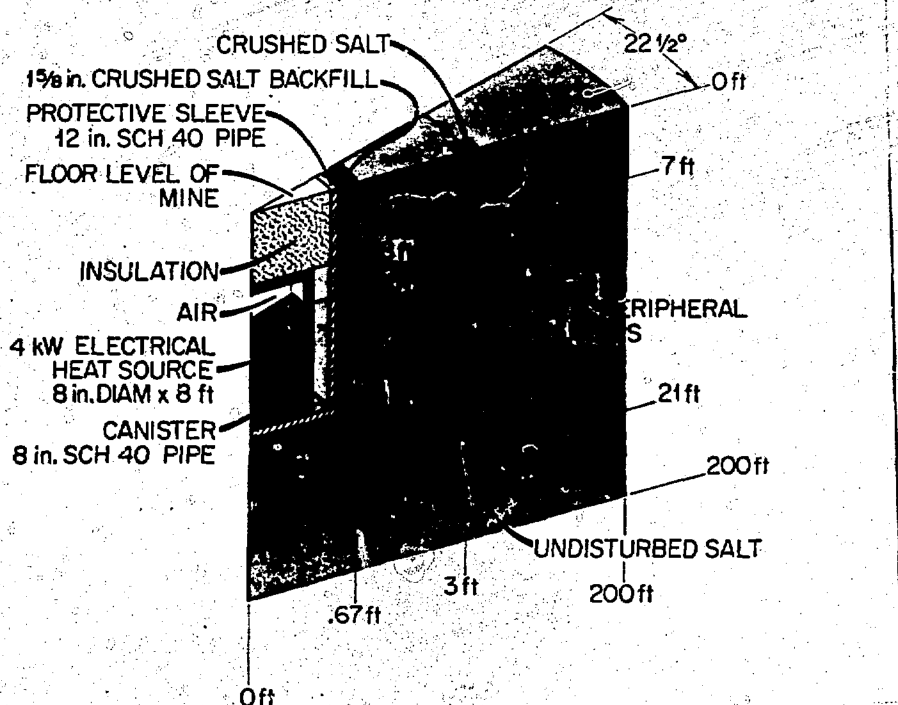

Fig. 7. Three-Dimensional Heat Transfer Model for Experiment C.

RESULTS FROM THE ANALYSIS OF CASE A

The temperature distribution is shown in contours generated from the computer output after 6 months, 12 months, and 18 months in Fig. 8. The heat source in these transients is the central heater which is producing heat at a constant rate of 5 kW throughout the transient.

SUMMARY

In-situ experiments have been designed to obtain pertinent physical and mechanical properties in a domed salt formation to gather data that will be used in the design of a federal repository for the terminal storage of radioactive waste. In order to strategically locate the heat sources and thermocouples in these experiments, it was necessary to thermally model the experimental site. The results of these experiments will be used to evaluate the in-situ properties of the salt, establish brine migration rates, determine corrosive effects of the salt, and evaluate the short-term effects of heat on the adjacent salt. The comparison of

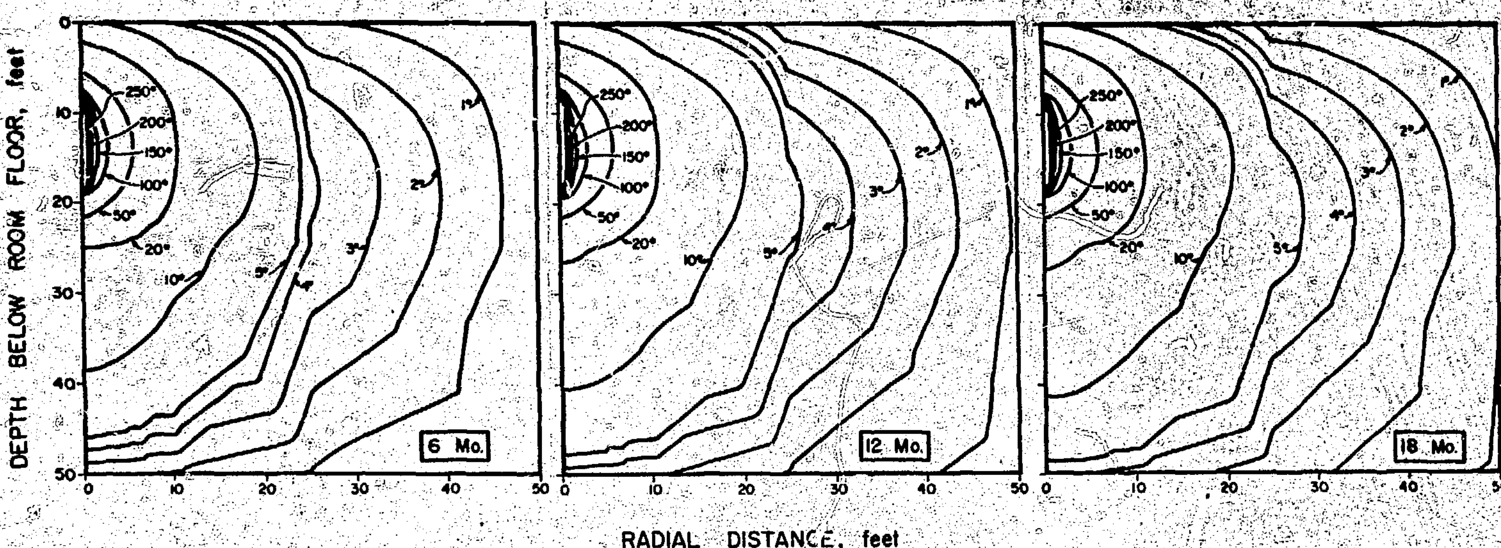

Fig. 8. Contours Showing Increase in Salt Temperature in Experiment A After 6 Months, 12 Months, and 18 Months.

results will be used to substantiate the use of the computer in predicting transient temperature distributions in a repository. These efforts have been originated and managed by the Office of Waste Isolation, UCC-ND, Oak Ridge, TN.

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