Results of the Operation of Project Salt Vault: A Demonstration of Disposal of High Level Radioactive Solids in Salt†

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ABSTRACT

Disposal of high-level solid radioactive wastes from the processing of spent reactor fuels is of considerable interest in the development of a nuclear power industry. A demonstration of the disposal of high-level radioactive solids has been successfully completed in salt of the Hutchinson Member of the Wellington Formation at the inactive mine of The Carey Salt Company near Lyons, Kansas. Approximately 4,000,000 curies of radioactive material (as encapsulated Engineering Test Reactor fuel assemblies) was shipped from the National Reactor Testing Station near Idaho Falls about 1100 miles to the Lyons mine, transferred to mine level (1000 ft below the surface), and placed in experimental disposal holes. At the end of the testing period, the canisters were removed from the mine and returned to Idaho. Operations at Lyons were carried out without the use of hot cells. Maximum radiation exposure for any personnel was 200 mrem per quarter, principally to the hands.

Average radiation dose to the salt over the length of the holes was about 8×10^8 rads, and the peak dose was about 10^9 rads. The peak temperatures reached 200°C adjacent to the holes. The structural properties of salt did not appear to be altered by the high doses and dose rates. The extensive heating of the salt around the test holes did produce effects not completely anticipated. These results included: (1) the migration of small intercrystalline brine inclusions along thermal gradients and (2) the transfer of thermal stresses over seemingly extraordinary distances.

INTRODUCTION

Project Salt Vault was a demonstration of disposal of high-level radioactive waste solids from power reactors, with irradiated Engineering Test Reactor (ETR) fuel assemblies in lieu of actual solidified wastes. Design of and preparation for the demonstration was described in detail in a paper presented at the Second Symposium on Salt in May, 1965. The site of the demonstration was the inactive Lyons, Kansas, mine of The Carey Salt Company. The salt mined at Lyons was in the Hutchinson Member of the Wellington Formation. Preparations for the demonstration began in 1963, and the first radioactive material was placed in the mine in November 1965. Radioactive operations were terminated in June 1967, and the Lyons Mine was placed on standby February 1, 1968. This paper describes certain phases of the operation and summarizes important results.

The objectives of Project Salt Vault were: (1) to demonstrate the feasibility and safety of disposal of high-level radioactive solids in salt, (2) to design and demonstrate the equipment and techniques required to handle packages of high-level radioactive solids from the point of production to the disposal location, (3) to determine the stability of salt under the influence of heat and radiation, and (4) to secure rock mechanics and thermal data

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which are needed for the design of an actual disposal facility.

DESIGN AND OPERATION OF THE DEMONSTRATION

Project Salt Vault's design was described in detail in the Second Symposium of Salt (Empson, *et al.*, 1966). A brief description of the installation is given here. The reader is referred to the Proceedings of the Second Symposium and other references for more detail on equipment and mining.

The layout of the demonstration, consisting of four rooms off a 30-ft-wide entry, is shown in Figure 1. The array rooms at either end are 30 ft by 60 ft. The two rooms at the center are 40 ft by 60 ft. The fifth room located off the Experimental Entry provides access to the bottom of the Waste Charging Shaft from the surface. The arrays of seven holes on triangular spacing, 5 ft apart, are located in rooms 1 and 4. The 14 ETR fuel elements, packaged in seven canisters, were placed in the holes in Room 1, the fuel assembly array. The nonradioactive array was an electrically heated control. A second radioactive array located in the floor of the original mine level is not shown.

Design of the demonstration provided for use of four sets of fuel elements to be changed at 6-month intervals. Elements were selected from an ETR cycle discharged from the reactor at a time to allow packaging and shipment to Lyons approximately 90 days before the desired change-out time. They were chosen so that each of seven pairs would be approximately equal in radioactivity and heat generation.

Figure 2 shows the basic steps in the radioactive portion of Project Salt Vault. These are: (1) packaging, (2) shipment, (3) transfer into and out of the mine, and (4) temporary disposal in the

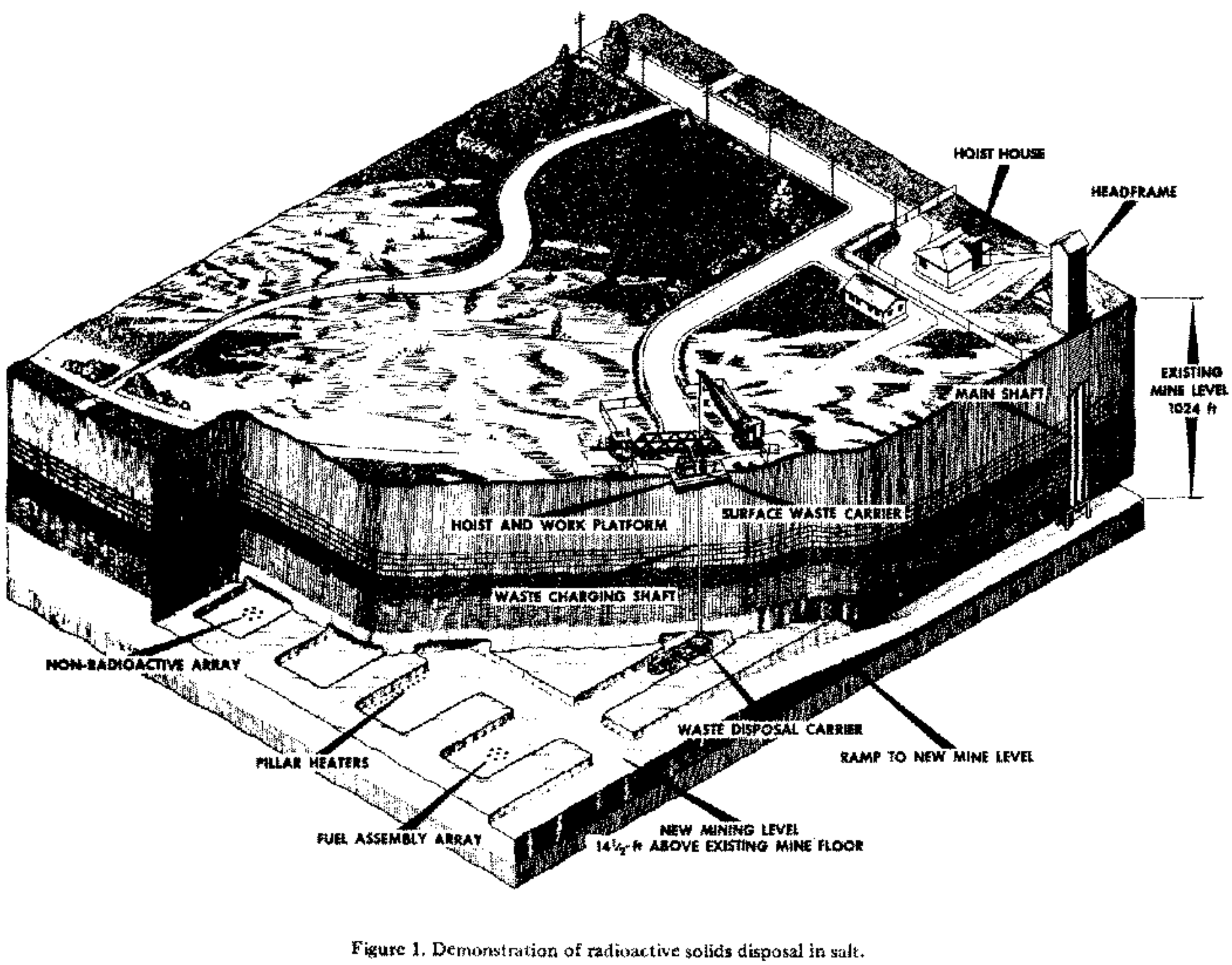

Figure 1. Demonstration of radioactive solids disposal in salt.

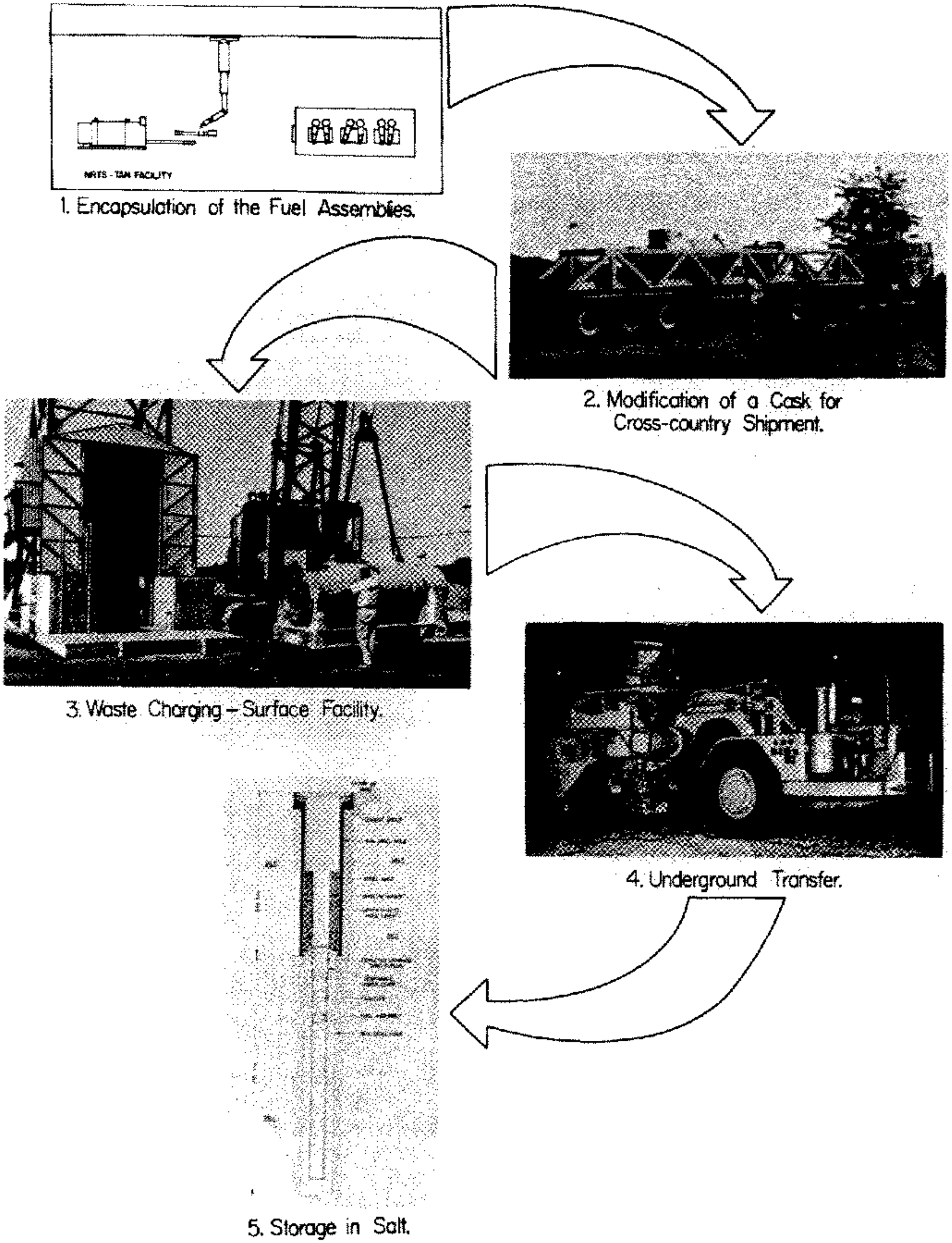

Figure 2. Project Salt Vault-major design phases.

mine. Packaging was carried out by the Idaho Nuclear Corporation in hot cell facilities at the National Reactor Testing Station.

The seven canisters were shipped in a 30-ton cask, equipped with forced circulation water cooling by means of a diesel engine equipped with an oversized radiator. The cask was shipped by truck using a special trailer assigned to the project and owned by the carrier. The cooling diesel was permanently installed on the trailer. Cask temperatures were monitored by the truck drivers while in transit to assure that the cooling system was functioning properly.

Following arrival in Lyons, the cask was erected over the waste shaft, a steel-cased, 19.1 in.-ID drilled and cased hole. The canisters were lowered one at a time into the underground transporter and, in the transporter, moved to the lined storage hole in the main array. At the end of 6 months, the canisters were moved from the Main Array to the Floor Array, and fresh canisters placed in the Main Array. At the end of a year the original canisters now in the old mine floor were returned to Idaho for reprocessing of the fuel elements.

Radiation exposures to personnel were possible at only two steps in the operation at Lyons. The first was at the top of the shipping cask during the operation of coupling the hoisting cable to the canister. The second operation was at the array after placing the canister in the hole where it was necessary to disconnect the grapple and to retrieve thermocouple leads from the canister. In removing the canister, the reverse of these operations was necessary.

RESULTS

A total of about 4 million curies of fission product activity in 21 containers, each having an average of about 200,000 curies, was transferred to the disposal facility in the mine and back to the NRTS at the end of the test. No hot cells were used at the mine; and, even under these conditions, the maximum personnel exposure was about 200 mrem to the hands and head of a worker. In an actual disposal facility, hot cells *would* be required since the waste containers will offer only single containment. (The fuel cladding plus the sealed conister was considered double containment.)

All equipment performed as designed, with difficulty occurring only once during a transfer. This occurred during the second transfer into the mine when fragments of rubber from the inner surface of hydraulic hoses caused some malfunction of the door on the underground transporter. Therefore it is felt that the first two objectives of the demonstration—the demonstration of the feasibility and safety and the demonstration of handling equipment—were achieved successfully.

Radiation dose to salt.

The radiation dose accumulated in the salt at various points is shown in Figure 3. The curve determined by dots shows the originally calculated theoretical 2-year dose based on the nominal ETR fuel. The theoretical calculations had indicated that the peak dose to the salt would be about 7 or 8×10^8 rads, occurring at a depth of 2 1/2 cm into the salt due to the buildup factor. The actual measurements indicated a peak dose in the mine after about 19 months of operation of about 5 $1/2 \times 10^8$ rads, occurring at the wall of the hole as shown by the curve determined by triangles. The estimated *actual* average dose to the salt over the length of the hole is shown by the dashed curve

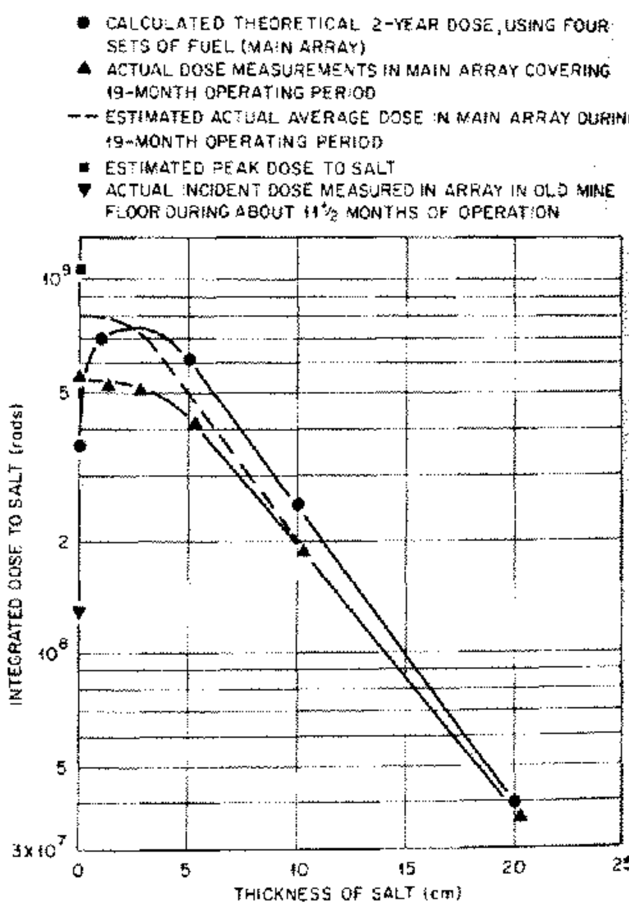

Figure 3. Comparison of measured and calculated dose to salt.

and is about 8×10^8 rads. The explanation of why this is higher than the measured values will be explained presently. The peak salt dose is estimated as about 10^9 rads. Dose dropped off very rapidly with distance out into the salt, with doses at 6 in. into the salt being only about 10^8 rads. Therefore, in each of the seven main array holes, a volume of about 14 ft^3 of salt was exposed to doses ranging from 10^8 to 10^9 rads. As anticipated from the laboratory studies, no significant effects due to the radiation were detected.

In the array in the old mine floor area which received the ETR fuel after it had remained about 6 months in the main array in the experimental area, the measured dose at the wall of the hole was a little over 10^8 rads. Again, the average dose over the length of the hole would be expected to be higher.

The reason that the measured values of the incident dose to the wall of the hole are too low is shown in Figure 4. Here the dose rate profile down the length of the can which contains two ETR fuel assemblies is plotted. The incident dose to the salt was measured at the junction between the two fuel assemblies. Due to nonuniform flux in the reactor, the average dose over the can length is about 1.4 times the dose measured at the junction and the peak dose is about 1.9 times the junction dose. This curve is typical for all cans.

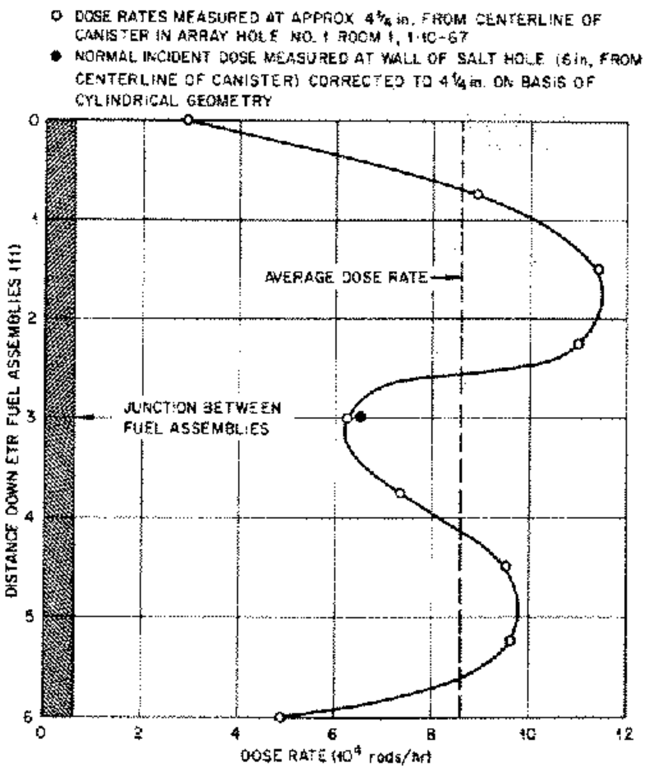

Figure 4. Dose rate distribution along ETR fuel assembly canister.

Effects of heat and radiation in array rooms.

Two distinguishable effects of radiation were observed. One was the intermittent production of extremely small quantities (less than 1 ppm in the off-gas) of an oxidizing gas. The generation of this gas appears to be a function of dose rate and dependent upon a threshold salt temperature of approximately 175°C. The reactivity and stability of this gas are such that no toxicity or chemical reactivity problems are expected. The other effect was the production of the blue colored salt previously observed in laboratory irradiations of salt. This color was annealed above temperatures of about 175°C.

The data shown on Figure 5 is typical of temperatures and of movement for both Room 1 and Room 4. Temperatures in each room were approximately the same and movement was the same. The salt temperature at 1 1/2 ft from the center hole of the array shows the effect of power interruptions during change-out periods and of the increase in power by 40% at 1240 standard days (from 1.5 kw per hole). The curves for roof sag, pillar convergence, and floor uplift show the beginning of heating, and the increase in power. In addition, the roof sag shows the lifting of the roof slab with installation of roof bolts (Bradshaw and McClain, 1970). These data are essentially the same for Rooms 1 and 4, indicating no effect of radiation. Peak temperatures reached with a power input of 1.5 kw were about 150°C in Rooms 1 and 4. After

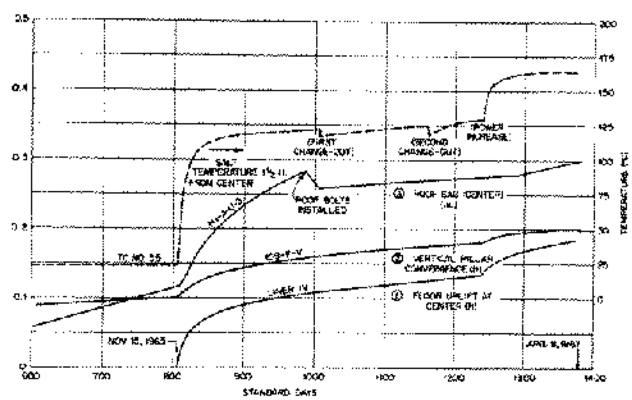

Figure 5. Variation of salt temperature and salt movement with time—Project Salt Vault.

the power input was increased on January 23, 1967, the peak temperatures increased to 200°C in Room 1, and 195°C in Room 4 at the beginning of June. A roughly circular ellipsoid of salt of about 12- X 15-ft diameter was raised to a temperature between 100° and 200°C.

The most significant finding in the field tests regarding the effects of heat on salt behavior was that the insertion of heat sources in the floor of a mine room produced a thermal stress whose effects are instantaneously transmitted around the opening (to the pillars and roof). The rapidity of this transfer is shown in Figure 6. These stresses produce increased plastic flow rates in the salt, and could possibly cause trouble if the roof of the room is too close to a shale layer (a plane of weakness). In the demonstration area such a shale layer existed, but it was found that conventional roof bolting techniques were adequate to handle the problem. In an actual disposal operation it is anticipated that rooms would be filled with waste, and then backfilled with crushed salt rapidly enough that roof bolts would probably not be required.

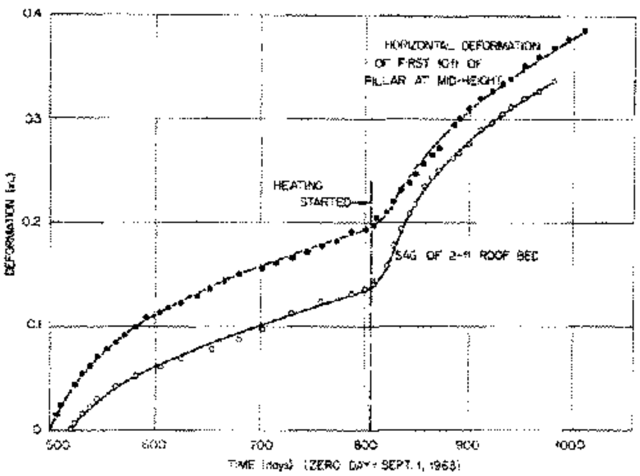

Figure 6. Transfer of thermal stress around a mined opening.

Results from the radioactive array in the original mine floor (Room 5) are quite similar to the results from the arrays in the Experimental Area. Differences are due to the large shale partings in the floor and to the absence of partings in the roof. Temperature rises and floor uplift in Room 5 are a few percent higher due to the poorer heat transfer properties caused by the presence of layers of shale and anhydrite in the floor.

Heated pillar.

Another phase of the Project Salt Vault experimental program was designed to obtain additional information on the thermomechanical properties of salt under transient temperature conditions. This was termed the heated pillar test and consisted of applying 33 kw of heat to a pillar 20 ft thick by 60 ft long. The heat was evenly distributed along each side through 22 heaters placed in the floor with the center of the 6-ft heated section at 9 ft below the floor. The movement of salt in the 20-ft-thick pillar and of the floor and roof of the two adjacent rooms is shown in Figure 7. The 33 kw heating rate divided equally along the two sides of the pillar represents approximately three times the heat flux into the pillar if the rooms were filled with anticipated actual solidified waste. The movement shown in the figure is therefore more rapid than would be expected to occur in an actual disposal operation.

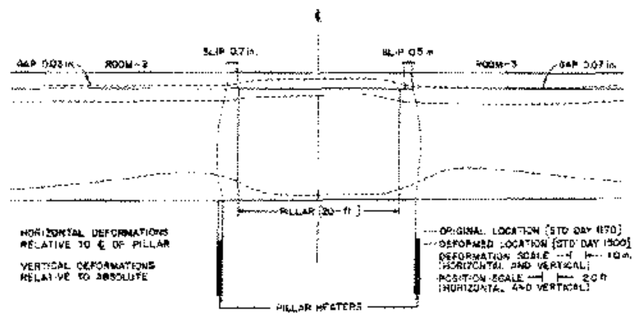

Figure 7. Movement of Salt Around the Heated Pillar.

Migration of brine inclusions.

It was found that small quantities of water, trapped in so-called "negative crystals" or brine-filled cavities, tend to migrate toward a heat source and into the disposal hole. Migration of brine-filled cavities occurs because of the slight increase in solubility of sodium chloride in water with increase in temperature. Salt dissolved on the warmer side of the cavity diffuses to the cooler side where it is redeposited. This phenomenon did not constitute a problem in the demonstration, since the water was removed by an off-gas system. Since the water inflow rate would be important in an actual disposal operation, a theoretical study of the migration mechanism was made, along with some experimental measurements. The theoretical relation of cavity migration rate as a function of temperature is expressed by this equation:

BRINE CAVITY MIGRATION RATE AS FUNCTION OF ABSOLUTE TEMPERATURE

$$v(T) = -\left(\frac{D(T)}{c(T)}\right)\left(\frac{dc}{dT}\right)\left(\frac{dT}{dx}\right)\left(\frac{3\,K_s}{2\,K_s + K_l}\right)\left(\frac{\rho_l}{\rho_s}\right)$$

$D(T)$ = Diffusion coefficient of NaCl in H_2O

$c(T)$ = NaCl concentration per unit volume of solution

$\frac{dc}{dT}$ = Rate of change of NaCl concentration as function of temperature

$\frac{dT}{dx}$ = Thermal gradient in salt

$\left(\frac{3\,K_s}{2\,K_s + K_l}\right)$ = Factor to correct thermal gradient in salt to gradient in solution

$\frac{\rho_l}{\rho_s}$ = Factor to correct solute (NaCl) diffusion rate to cavity migration rate

K_s = Thermal conductivity of solid NaCl

K_l = Thermal conductivity of saturated NaCl solution

ρ_l = Density of saturated NaCl solution

ρ_s = Density of solid NaCl

Figure 8 presents a comparison of the theoretical relationship of salt temperature and cavity migration rate with a number of experimental measurements of migration of cavities in transparent salt crystals from the Hutchinson, Kansas, mine. On the basis of the migration rates indicated by the theoretical curve, one would expect a total inflow per disposal hole of 2 to 10 litres, over a period of 20 to 30 years. Peak flow of 200 ml to 1 litre per year would be expected at about 1 year after burial. This release of water and resulting corrosion will not be a serious problem in actual disposal as facility design and operating procedure will prevent any release of activity to populated areas.

CONCLUSIONS

A demonstration of the disposal of high-level solidified radioactive wastes in a salt mine was successfully completed. Approximately 4,000,000 curies of radioactive material (as encapsulated Engineering Test Reactor fuel assemblies) was shipped from the National Reactor Testing Station near Idaho Falls, Idaho, to a salt mine at Lyons,

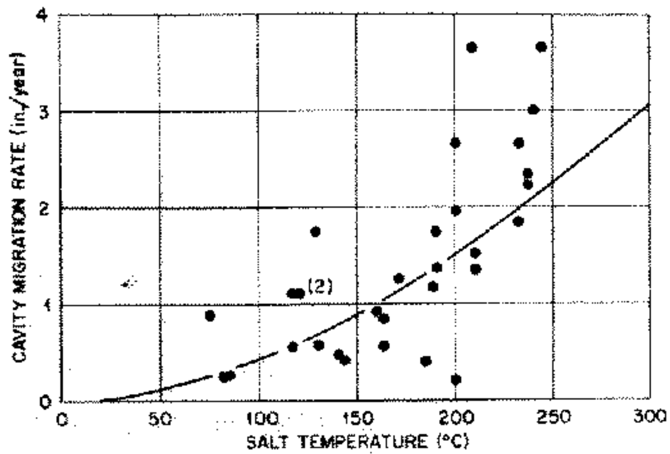

Figure 8. Comparison of theoretical and experimental migration rates of brine-filled cavities in rock salt.

Kansas, transferred to mine level (1000 ft below the surface), and placed in experimental disposal holes. After completion of the testing period, the canisters were removed from the mine and returned to the NRTS. Operations at Lyons, both at the surface and in the mine, were carried out without the use of hot cells. Maximum personnel exposure during any quarter was 200 mrem, principally to the hands of a worker.

The structural properties of salt were not significantly altered by the high doses and dose rates. The extensive heating of the salt around the arrays and the heated pillar did produce effects not completely anticipated. These effects included: (1) the migration of small intracrystalline brine inclusions along thermal gradients, (2) the transfer of thermal stresses very quickly over seemingly extraordinary distances, and (3) the influence exercised by shale partings in the bedded salt on the nature, direction, and amount of accelerated plastic deformation caused by the elevated temperature.

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