Most salt beds contain at least some water in the form of liquid inclusions within single salt crystals or in the larger intergranular cavities (i.e., pores). The storage of any heat-generating waste will establish thermal gradients in the salt. A liquid inclusion in a crystal of a soluble salt, when placed in a thermal gradient, will continuously dissolve on the hot side and crystallize on the cold side of the cavity, thus causing the cavity, with its included liquid, to move up the thermal gradient, toward the heat source. Inclusion movement is of consequence in the design of a waste repository as the included brines are probably more corrosive to possible canister materials than even a saturated NaCl solution.

Wilcox (1968) summarizes the extensive work (111 references) on the nature and rate of inclusion movement in various substances. Migration of inclusions is also a cause for degradation of laser crystals grown at high temperatures by the Czochralski technique (Hopkins et al., 1976). Most liquid inclusions move up the thermal gradient, but if the vapor bubble in the liquid is large relative to the liquid, and particularly if boiling occurs in the inclusion in the gradient, the movement may be in the reverse direction, down the thermal gradient (Wilcox, 1969; Anthony and Cline, 1972; Chen and Wilcox, 1972). The rate of movement is independent of inclusion size in many systems, but strongly (and directly) dependent on inclusion size in others (Wilcox, 1968); there may be a threshold size below which no movement occurs (~10 μm in KC1, Anthony and Cline, 1971). Large inclusions in several hosts break up during movement (Wilcox, 1968; Anthony and Cline, 1973). Many factors may affect the rate of migration, even in a given host: gravity, composition and surface tension of the liquid, inclusion size and shape, host crystal anisotropy, strain, and imperfections, external stress, volume percent of vapor bubble and presence of a foreign gas in it, etc. In salt, rate of movement in a given gradient can be expected to increase as ambient temperature increases, because the thermal coefficient of solubility, although small at room temperature, increases greatly as temperature increases. Higher ambient temperature also increases the rate by increasing the solubility, the diffusion coefficients, and the interface kinetics in any host; the increase in rate was found to be particularly striking in NaCl (Wilcox, 1968; p. 20). That the inclusions in the WIPP site salt have not moved measurably during geological time in the geothermal gradient (Roedder and Belkin, 1979) is perhaps an indication of an exceedingly slow rate under the natural gradient. It may also be a result of other weak factors, such as gravity, counteracting the thermal gradient effect.

The rates of migration of natural liquid-filled inclusions in salt from the ERDA no. 9 borehole at the WIPP site, Carlsbad, N. M., have been determined experimentally. The range of values of the two most important parameters investigated, ambient temperature and initial inclusion volume, are shown in the figure. Most runs were made at a gradient of 1.5°C·cm⁻¹, maintained perpendicular to (100), for 3-10 days. The runs were made at 1 atm pressure, with a heat-up rate at the start of the run of ≤30°C·hr⁻¹, so most of the inclusions studied have not decretipated, but have expanded beyond their original volume by deformation of the host salt. In each run, ~50 inclusions were selected, measured, and photographed against fiducial marks before and after the run. The points on the figure represent the intersections of a best-fit line through the results with the unit volumes indicated. At 160º ambient and a gradient of 1.5°C·cm⁻¹, 10⁹ μm³ inclusions (i.e., 1mm cubes) moved toward the heat source at a rate of 1.6 cm·yr⁻¹. Smaller inclusions moved more slowly, e.g., 10⁶ μm³ inclusions (i.e., 0.1 mm cubes) moved only 0.5 cm·yr⁻¹. The movement rates at 260°C for a given size are larger by a factor of ~3.2, but at 108ºC the rates are only ~10-20% lower than those at 160ºC. Higher gradients yielded higher rates, in approximately
direct proportion, but as a different sample was used for these runs, and samples from different WIIP strata have since been found to differ systematically in movement rate by factors of >3 (for reasons still unknown), exact comparisons are not possible. Such variation, but within a given sample, probably explains the anomalously low rates shown for the run at 201°C. Inclusions \(<10^5 \mu\text{m}^3\) maintain their original cubic shape during migration; larger inclusions change shape, tapering down in the forward direction and forming a peripheral fringe toward the rear. Inclusions forced to migrate perpendicular to (110) formed similar fringes, and moved at similar rates. In contrast, natural inclusions that have a large vapor/liquid ratio in these same samples (Roedder and Belkin, 1979) moved at \(\approx 1.5\) times these rates, but down the gradient, away from the heat source. Some observed phenomena remain unexplained.

In using rate data to calculate the amount of fluid that could be delivered to the canister area in an actual repository, it is important to remember that the great bulk of the liquid water in the WIIP salt is present in the form of a relatively small number of inclusions \(\geq 1\mu\text{m}^3\) size.

References