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March 24, 1981

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THERMAL PROPERTIES OF AVERY ISLAND SALT
TO 573 K AND 50-MPa CONFINING PRESSURE

ABSTRACT

Thermal conductivity, thermal diffusivity, and thermal linear expansion were measured on two samples of Avery Island rock salt up to simultaneous temperatures and pressures of 573 K and 50 MPa. Thermal conductivity at room temperature measured 6.3 ± 0.6 W/mK and decreased monotonically to 3.3 ± 0.4 W/mK at 573 K. Thermal diffusivity decreased from $3.0 \pm 0.8 \times 10^{-6}$ m²/s at room temperature to $1.4 \pm 0.5 \times 10^{-6}$ m²/s at 573 K. Thermal linear expansivity increased from $4.8 \pm 0.3 \times 10^{-5}$ K⁻¹ at room temperature to $5.6 \pm 0.3 \times 10^{-5}$ K⁻¹ at 573 K. The thermal properties showed no measurable ($\pm 5\%$) dependence on confining pressure from 0-50 MPa for any temperature tested. The thermal conductivity values were not distinguishable ($\pm 5\%$) from intrinsic (single crystal) values measured by others. Diffusivity fell about 20% below intrinsic values, and linear expansivity about 20% above intrinsic values. Thermal conductivity values for Avery Island salt measured recently by Morgan are as much as 50% lower than values measured here and were probably strongly affected by sample handling prior to measurement. The pressure independence of the thermal properties measured in our study suggests that thermally-induced microfracturing is nearly nonexistent. This lack of thermal cracking is consistent with the high (cubic) symmetry of halite.

INTRODUCTION

To determine the long-term thermomechanical behavior of an underground repository for radioactive wastes, we tested the thermal response of the rock to the physical and chemical conditions *in situ*. To accomplish this, we designed a laboratory experiment to measure the thermal properties of large-grained samples under pressure, temperature, and hydrologic conditions similar to those in a nuclear waste repository. We report here data taken from the first rock type tested, a coarse-grained domal salt from Avery Island, Louisiana.

The interest in isolating radioactive waste is obvious. Burying waste in the earth would be a straightforward means of isolation, were it not for the fact that most rocks, being brittle materials, tend to crack under an applied load. If rock around a waste repository is cracked, the isolation condition may be violated. The permeability of the rock could increase, allowing fluid movement and radioactive interchange with the biosphere. All rocks in the upper kilometers of the Earth's crust, in fact, contain some fractures. Furthermore, the heat load imposed by radioactive waste could be expected to cause further cracking, especially on the microscopic scale, owing to local mismatches in thermal expansivity.

Microcracking can also be induced (even in thermomechanically isotropic materials) by a sufficiently strong thermal gradient. Hydrostatic pressure normally suppresses fracturing and works to close existing fractures. Early studies of rock behavior showed that the effect on cracks tends to be more pronounced at low pressures (Brace, 1965). As more cracks close with increasing pressure, the effect becomes more subtle. Crack effects become unimportant above pressures of 50-300 MPa, depending on rock type (Brace, 1965).

Measurements of thermal properties at room pressure cannot reliably be applied to the repository situation. Microcracking, because of the open spaces (porosity) it creates, generally impedes thermal conductance. Both theoretical models and laboratory experiments have shown porosity has a substantial effect on thermal conductivity, with the magnitude of the effect dependent on the arrangement of the pore space (see Sweet [1979] for a review).

Walsh and Decker (1966) theoretically related thermal conductivity to crack porosity to construct a model of thermal conductivity vs pressure. Experimentation using uniaxial stress to approximate hydrostatic pressures supported the model well. Intrinsic and bulk thermal conductivity differed by as much as 15% in dry rock at zero pressure. The effect of pressure on conductivity parallels the pressure dependence of crack porosity. Therefore, the location of a waste repository, somewhere between the surface (lithostatic $P = 0$) and 1-2 km deep ($P = 25$ to 50 MPa), puts the repository rock where the pressure effect is expected to be strong.

Rock salt has been considered as a potential waste repository material for several reasons. A primary reason is its high thermal conductivity (as measured at ambient pressure). Another is its relatively low plastic flow strength and high ductility, which makes it less permeable to fluid flow under

loading conditions that would produce cracking in most other rocks. In addition, rock salt differs from most other rocks in extended geological formations in that it is composed of a single, thermomechanically cubic phase. Differential thermal expansion, hence microfracturing due to temperature change, would be expected to be minimal except in a strong thermal gradient. However, experimental confirmation is lacking.

SAMPLE MATERIAL

Two samples were cored from a single 400-mm-diameter core supplied by RE/SPEC, Inc., Rapid City, S. Dak. The 400-mm core, labeled C-11 by RE/SPEC, Inc., was taken from the Avery Island domal salt formation at the site of an *in situ* heater test in excavations at the 163-m level (Fig. 1). The

FIG. 1. Map of Avery Island salt mine at the site of the heater test. Samples for this study came from main heater hole at Site C. (Reprinted with permission of RE/SPEC Inc., Rapid City, S. Dak.)

specific location of Core C-11 was the bottom of the central heater hole at Site C (Fig. 1), 5.28-5.73 m below the floor level of the mine. Chemical analyses of samples from the Avery Island Mine show roughly 99.1% NaCl (by weight), 0.7% water insolubles, 0.2% CaSO_4 (anhydrite) and 0.02% water (Kaufmann, 1960). The rock salt has a porosity of approximately 1% and the grain size of the halite ranges from 2.5-15 mm with an average of 7.5 mm (Carter and Hansen, 1980). The density of the rock salt has not been measured, but, based on the above analysis, should be near 2.16 g/cm^3 , the density of pure NaCl at room temperature.

EXPERIMENTAL TECHNIQUE

We describe the measurement apparatus in Abey et al. (1981). The samples to be measured are thick-walled cylinders, 203 mm in length with inner and outer diameters of 19 and 127 mm, respectively. For ease of machining, each sample is made up of three equally sized cylinders of rock. The samples are jacketed in thin-walled copper to exclude the pressure medium (argon) from the rock. Eight thermocouples positioned at eight different radii measure temperature in the sample. The large sample size and thermocouple redundancy (only two are necessary for a measurement) increase measurement precision on large-grained (>5-mm) samples by minimizing the effects of local sample variation. The measurement takes place inside an externally heated pressure vessel.

A small heater, located along the axis of the sample, establishes heat flow in an approximately axisymmetric, radial pattern. Steady-state heat flow allows measurement of thermal conductivity. Transient heat flow, usually imposed by a 60- to 90-s pulse from the central heater, allows measurement of diffusivity. The equations used for data reduction are given in Abey et al. (1981).

RESULTS

We tested two samples of Avery Island rock salt. Figures 2-4 show the results for thermal conductivity, diffusivity, and linear expansion, respectively. Because the first sample jacket burst near 473 K and 50 MPa, the only data it produced at known effective pressure (defined as confining

FIG. 2. Thermal conductivity vs temperature and pressure as measured on two samples of Avery Island rock salt. Large squares around higher temperature points of Run 1 indicate that measurements were made following jacket failure (see text); error bar indicates typical range of random error (1 std dev); dashed curve is drawn freehand through data.

FIG. 3. Thermal diffusivity vs temperatures and pressure as measured on two samples of Avery Island rock salt. The same conventions apply as in Fig. 2.

pressure minus pore pressure) were at room temperature (10–50 MPa) and 373 K (50 MPa only). The jacket burst occurred because of the high thermal expansivity of the rock salt relative to the copper ($4.5 \times 10^{-5} \text{ K}^{-1}$ vs $1.0 \times 10^{-5} \text{ K}^{-1}$). Once jacket integrity was lost, the pressure medium was free to enter the pores and cracks of the sample, and effective pressure

FIG. 4. Thermal linear expansivity of two samples of Avery Island salt. Yang's curve (1981) is expansivity of single-crystal halite.

dropped below the confining pressure. The jacket leak was rather large and measurements continued for several days. We, therefore, assumed that effective pressure fell to near zero. We made no change in the jacket design for the second rock salt sample, so in anticipation of another jacket failure between 373 and 473 K, we decreased temperature increments and explored all pressures (in the order, 50, 30, 10 MPa) at each new temperature. The second sample jacket failed at 438 K and 10 MPa. We continued the first run to its intended limit of 573 K following jacket failure. The second run was terminated immediately following jacket failure.

Thermal conductivity (Fig. 2) and thermal diffusivity (Fig. 3) showed good agreement between runs. Both decreased with increasing temperature. Thermal conductivity showed no discernible pressure dependence where the jacket was intact, and showed no obvious discontinuity when the jacket lost its integrity.

Thermal diffusivity showed no dependence on pressure from 30–50 MPa, but increased by approximately 20% when pressure dropped to 10 MPa. This effect was observed in both runs and at all temperatures tested. Based on the direct relationship between conductivity and diffusivity, the same pressure effect (none) would be expected for each. Based on the microcrack model, either no pressure dependence (rock has no microcracks) or a decrease of diffusivity with decreasing pressure (rock has microcracks) would be anticipated. The rise of diffusivity with decreasing pressure was, therefore, considered anomalous and was tentatively explained away as a systematic error of unknown origin. The veracity of this explanation will be tested when a careful calibration of the apparatus is made.

The most extensive thermal expansion data (Fig. 4) came from the first run, where the temperature change was twice that of the second. The expansivity rose slightly with increasing temperature. The confining pressure for the first run was 50 MPa for all points. However, above 473 K, the pore pressure was also close to 50 MPa. Thus, the data indicate that expansivity does not depend on effective pressure between 300 and 573 K. The band of data from the second run (Fig. 4) represents repeated short excursions ($\Delta T = 40-80$ K) upwards and downwards in temperature at several confining pressures. We saw no dependence on confining pressure, nor on temperature, which was not surprising in light of the small temperature steps taken and the moderate temperature dependence detected in Run 1. The width of the band, compared to the height of the error bar for Run 1, indicates the reproducibility of the thermal expansion data.

DISCUSSION AND COMPARISON WITH OTHER DATA

Our measurements indicate that the thermal properties of rock salt (ignoring the anomalous behavior of diffusivity at 10 MPa) do not depend on confining pressure. In light of the suggested role of microcracks in rocks, such behavior might be expected only in a monomineralic rock (such as rock salt), whose single phase is isotropic. Halite has cubic symmetry and may be close enough to isotropic to prevent significant thermal cracking (in terms of heat storage and transport). The ductility and low flow strength of halite (Carter and Heard, 1970) may also help impede cracking. The data gathered here are self-consistent (again excepting diffusivity at 10 MPa), given the demonstrated relationship between microfracturing and enhanced thermal expansivity (Richter and Simmons, 1974; Cooper and Simmons, 1977; Bruner, 1979; Wong and Brace, 1979; Heard, 1980). The smoothly increasing coefficient of thermal linear expansion, uninterrupted by the jacket rupture and drop in effective pressure, indicates that uniform heating of rock salt generates very little open-crack porosity. Thermal conductivity in such a material could be expected to show no extrinsic pressure dependence.

The salt data are compared in Figs. 4 and 5 to an extensive compilation by Yang (1981) of single-crystal NaCl data. The most serious disagreement is the diffusivity, which falls about 20% below Yang's values at any given temperature. The apparent disagreement in thermal expansivity (Fig. 4) may be

FIG. 5. Thermal conductivity and diffusivity of Avery Island rock salt compared to single-crystal data compiled by Yang (1981).

due to poor system calibration. Additional thermal conductivity measurements on rock salt for waste repository site-specific studies are reported by Morgan (1979) for two salts including Avery Island, by Acton (1978) and by Sweet and McCreight (1979) for the Southeastern New Mexico rock salt. These data are compared in Table 1. Only in the present study was true hydrostatic pressure

TABLE 1. Laboratory-measured thermal conductivities (in W/mK) for two rock salts as a function of temperature.

	300 K	373 K	473 K	573 K
This study (Avery Island)	6.3	5.3	4.0	3.3
Morgan (AI)	4.0	3.2	2.6	2.2
Acton (S.E. New Mexico)	8.5	6.3	--	--
	3-8 ^a			
Sweet and McCreight (SENM)	6.0	4.7	3.6	2.9

^aFor halite/anhydrite-mixed rock with > 50% halite (conductivity increases with increasing purity of rock salt).

applied to the test specimens. The data of Sweet and McCreight (1979) agree well with our data, Acton's (1978), and Morgan's Avery Island data (1979) are scattered, but consistently much lower than our own.

Although Morgan's samples were taken from a point in the mine horizontally separated from the source of our own by less than 50 m, he reports that the samples were weak and friable--in contrast to our own. A possible explanation for the difference in Morgan's samples is that they came from a 50-mm-diameter core, while ours came from a 400-mm core. His samples were, therefore, more prone to damage during coring. It is plausible that the lower conductivities reported by Morgan resulted from excessive fractures and microfractures within his samples, which were incurred during core drilling.

It should be pointed out that extensive mechanical testing (Wawersik and Hannum, 1980) and gas permeability measurements (Sutherland and Cave, 1979, 1980) of similar rock salt (Southeastern New Mexico bedded salt) have demonstrated that crack porosity in starting material is nonzero when in the laboratory. In both sets of experiments, those authors conclude that the source of crack porosity is sample handling (coring, transport, experimental preparation) because the manifestations of crack porosity (nonlinear pressure-volume relationship and high permeability at low pressure) can be permanently eliminated by applying pressures in the 10-30 MPa range. Salt is known to deform plastically with relative ease at differential stresses of the same order (see, for example, Carter and Heard, 1970), making permanent crack closure under low pressures plausible. In the present work, no measurements were made at zero effective pressure without our first having subjected the

sample to effective pressures of 10 MPa or more. It is possible therefore that any initial cracks that might have impeded heat transport in our samples were squeezed out of existence by the time the first measurements were made. The behavior of Southeastern New Mexico rock salt and that of Avery Island appear to be consistent.

SUMMARY AND CONCLUSIONS

Measurements of the thermal properties of Avery Island rock salt were carried out at elevated effective confining pressure and elevated temperature as part of this country's nuclear waste isolation effort. We conclude from the study that:

1. For $0 \leq P \leq 50$ MPa and $300 \leq T \leq 573$ K, the thermal conductivity, diffusivity, and linear expansion show no dependence ($\pm 5\%$) on confining pressure. Thermal conductivity at room temperature measures 6.3 ± 0.6 W/mK and decreases monotonically to 3.3 ± 0.4 W/mK at 573 K. Thermal diffusivity decreases from $3.0 \pm 0.8 \times 10^{-6}$ m²/s at room temperature to $1.4 \pm 0.5 \times 10^{-6}$ m²/s at 573 K. Thermal linear expansivity increases from $4.8 \pm 0.3 \times 10^{-5}$ K⁻¹ at room temperature to $5.6 \pm 0.3 \times 10^{-5}$ K⁻¹ at 573 K.

These are approximately the intrinsic values for single-crystal halite.

2. Handling salt samples between the field and laboratory may damage the material sufficiently that zero-pressure thermal conductivity of the bulk may be lowered by as much as 50%. The effect on conductivity can be permanently reversed by subjecting the rock to pressures of 10 MPa or more.

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