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THE PERMEABILITY OF SALT-CRYSTAL INTERFACES TO BRINE

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ABSTRACT

To investigate the movement of brine along grain boundaries in polycrystalline salt, measurements have been made of the radial flow of brine through the interface between cylindrical salt crystals under axial stresses to 140 bar and temperatures to 80°C. For constant conditions, the total flow of brine showed a linear dependence on the logarithm of time, and the reciprocal permeability increased linearly with time. Loss of salt from the interface by pressure solution effects was more than enough to account for the decrease in the apparent thickness of the interface (i.e., that which may be estimated for an interface of the same permeability formed by plane parallel surfaces). This apparent thickness, initially as large as 10 μm , decreased to as little as 0.2 μm with exposure to stress and flowing brine. It decreased quickly with sudden increases in axial stress and usually increased, though not reversibly, with decreases in stress. The rate of increase in the reciprocal permeability with time was roughly proportional to the stress and to the square of the hydraulic pressure drop. Assuming similar apparent thicknesses for the grain boundaries in polycrystalline salt, permeabilities are predicted that are quite consistent with the low values reported for stressed core specimens.

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1. INTRODUCTION

In halite deposits, which are being considered as a medium for the storage of radioactive waste, a small amount of water is present in the form of brine inclusions or hydrated mineral impurities such as clay. During the operational period when a repository is being established, additional water can of course gain access; and after the repository is sealed, the halite could be exposed to aquifers as a result of some unlikely future event. The behavior of water in bedded halite and dome salt has therefore become a matter of interest. Of concern is the rate at which water can reach the waste canisters, the effect of the water on the mechanical properties of the salt, and the permeability of the bedded salt to the flow of brine under various conditions.

Jenks and Claiborne (1981) have reviewed the current state of knowledge of the migration of brine in salt. Most attention has been given to the behavior of the brine inclusions, which tend to migrate up the thermal gradient produced by the radioactive decay heat from the waste. Most of the experimental and theoretical effort has been devoted to the study of intracrystalline behavior of the inclusions. Relatively little attention has been devoted to the role of the grain boundaries in brine migration.

The permeability of undisturbed bedded halite to the flow of brine appears to be $<0.5 \text{ nm}^2$ ($<0.5 \text{ } \mu\text{darcy}$) at repository depths. Measurements on core specimens in the laboratory often give much higher values, presumably because of the formation of interconnecting microcracks in the specimen when the lithostatic loading is removed. Gloyna and Reynolds (1961) studied the effect of axial stress on core specimens and found permeabilities to be in the range 0 (presumably $<0.5 \text{ nm}^2$) to 10^5 nm^2 . Permeability decreased with increasing stress and was greater for dome salt (the purer form) than for bedded halite.

Previously we have reported a study of the consolidation of salt crystals in the presence of brine (Shor et al. 1981). The procedure consisted of forming a settled bed of salt crystals from a suspension in saturated brine and then measuring the rate of consolidation and the decreasing permeability when the bed was stressed by a perforated piston. Consolidation was followed almost to completion. The kinetics could be represented quite well by the expression

$$\phi(t) = \phi(0) - (A/B) \ln [1 + Bt/z(0)^3], \quad (1)$$

where ϕ is the void fraction, t is the time, A and B are rate constants, and $z(0)$ is the initial average particle size. The rate constant A and the initial void fraction, $\phi(0)$ appeared to vary linearly with the applied stress. The above expression was adopted from a model for sintering proposed by Coble (1961) which has been quite successful in representing the sintering behavior of metals and alloys. Its success in representing the consolidation behavior of salt suggests that sintering processes may be important here as well.

The permeability of the consolidating salt to the brine flow decreased rapidly as the void fraction decreased and was roughly proportional to the square of the particle size. But the measure-

ments were not accurate enough nor extensive enough to indicate the dependence on the applied stress. Nor did they suggest at what point in the consolidation process the compaction rate becomes limited by the permeability of the bed to the brine flow; i.e., limited by the rate at which the brine can escape rather than by the rate at which the crystals can be consolidated.

The present measurements were undertaken to investigate how the permeability of a well-defined interface between two salt crystals depends on the applied stress, the initial surface condition, the amount of brine passed, and the temperature. A knowledge of these dependencies might permit reliable predictions of how the permeability of disturbed halite (or the final consolidation and permeability of backfilled salt) would decrease with time under various specified repository conditions.

The approach was to establish a planar, circular interface between two cylindrical salt crystals which could be stressed axially, and to introduce saturated brine at the center of the interface, permitting it to flow radially to the outer circumference under a known hydrostatic pressure drop. For the idealized case (in which the surfaces of the interface are perfectly smooth and parallel, the fluid is incompressible, the flow is laminar, and there are no end effects), the flow is given by the expression

$$dV/dt = \frac{4\pi h^3 \Delta P}{3\eta \ln(r_2/r_1)}, \quad (2)$$

(Bird et al. 1960, pp. 106, 114). Here V is the volume of fluid, h is half the distance of separation of the surfaces, r_1 and r_2 are the inner and outer radii of the annular interface, η is the viscosity of the fluid, and ΔP is the hydraulic pressure drop between the inner and outer circumference of the interface.

Equation 2 indicates that the flow through such an ideal circular interface should be proportional to the hydraulic pressure drop (ΔP) and to the cube of the half-thickness (h). We shall make use of this expression to calculate the apparent thickness of the interface between salt crystals as a function of the conditions of measurement, and to relate the flow in our experimental geometry to that which would be expected for a more conventional geometry. The conditions of measurement have included axial stresses in the range of 12 to 140 bar (1 bar = 0.1 MPa) and temperatures of 20, 50, and 80°C.

2. EXPERIMENTAL

Optical quality sodium chloride crystals were obtained from the Harshaw Chemical Company in the form of 10-cm-long cylindrical blanks ground to diameters of 1.14 and 1.27 cm. A piece of each size was cut to suitable length and a 0.159-cm axial hole was drilled in the one of smaller diameter. A Monel piston was fitted to this piece (Fig. 1) and cemented in place with a rapid-setting epoxy cement. Sealing occurred mostly at the wall of the small tube projecting into the central hole of the crystal. No leakage was detectable during tests.

The crystal surfaces to be placed in contact, which were normal to the cylindrical axis, were then prepared as reproducibly uniform as possible by grinding in a jig against a flat surface faced with 400 grit "wet-dry" carborundum paper. Random motion and very light pressure produced a matte or frosted-appearing surface not unlike that of ground glass. In the cell, one crystal axis of each piece was colinear with the cylindrical axis of the cell, but no effort was made to match the remaining orthogonal crystal axes of the two pieces.

Fig. 1. Cell for measurement of the permeability of an interface between salt crystals under axial stress.

In the cell (of Monel, 1.27-cm inside diameter) the upper (piston) crystal was stressed against the lower (anvil) crystal by means of a pneumatic ram pressing against the Monel piston. Lateral creep of the salt under prolonged stress was constrained by a Monel sleeve cemented to the upper crystal. This sleeve which fit loosely in the cell, also eliminated friction with the cell wall. The crystal projected 1 to 2 mm beyond the sleeve, and the perimeter of this unconfined part of the crystal defined the outer boundary of the working area for the measurements. The inner boundary was defined by the central hole.

The arrangement of the apparatus is shown in Fig. 2. All materials contacting brine at temperature were glass, Monel, or Teflon, except for some Altex fittings of nylon and a titanium delivery tube to the receiver. Brine saturated at room temperature was contained in a pressurized reservoir in which the air pressure source was isolated from the brine by a neoprene barrier. An alternate low-pressure brine supply was produced by gravity feed (up to 100 cm of head). Brine from the desired reservoir was fed through a presaturator to the 0.159-cm-diameter axial hole in the upper crystal, through the annular space between the contacting crystal surfaces, and out via a collecting annulus at the periphery. Force applied to the piston by the pneumatic ram produced axial stresses from 10 to 155 bar (1 to 15.5 MPa).

Temperature was controlled (usually to $\pm 0.02^\circ$ at 20 and 50°C , and to $\pm 0.1^\circ$ at 80°C) by submerging the entire cell, its stress-bearing frame, and the brine presaturator (with filter) in an ethylene glycol bath. Saturated brine at room temperature was fed to the cell at pressures always

Fig. 2. Arrangement for brine delivery to and collection from the crystal interface.

less than 10% of the axial stress and usually less than 2% in order to distort the net axial stress across the interface as little as possible. Brine flow was small and never more than a few milligrams per minute. The flow was continuously monitored for periods of a week or more, in most cases with a recording Mettler balance. To achieve a continuous delivery (rather than a succession of drops), the delivery tube was kept below the liquid surface in the receiver and the depth was adjusted periodically to keep buoyancy and surface tension effects suitably constant.

For measurements at 50 and 60°C, a phase separation reservoir of 43-ml capacity was introduced into the brine exit line within the thermostat. Brine entering at the bottom of the reservoir displaced lighter dodecane which was cooled, collected, and weighed in place of the brine. This avoided the problems associated with precipitation of NaCl upon cooling of saturated brine. Because of the increased volume of liquid in the system, however, temperature control limited the accuracy with which low flow rates could be measured.

Data on effluent weight, time, and temperature were usually recorded by a data logger coupled with an HP 9835A computer. The time intervals between measurements varied from 1 to 120 min, increasing as the run progressed. Usually a run was started with a freshly prepared surface, freshly loaded brine, and a recharged saturator. After temperature equilibration and a flush with brine to remove air from the apparatus, the axial stress was applied and then the brine flow, the clock, and the weighings were started simultaneously. The axial loadings and the hydraulic head could be changed without otherwise disturbing the system once a run had started.

3. RESULTS AND DISCUSSION

3.1 Permeability

Early in this study, tests were conducted demonstrating that the radial flow of brine through the circular crystal interface used (Fig. 1) was indeed proportional to the hydrostatic pressure drop across the cell, as expected from Eq. (2). Since the inner and outer diameters of the interface were fixed throughout the measurements, it is convenient to define a permeability Pm as follows:

$$Pm = \frac{dG/dt}{\Delta P} \quad (\text{g min}^{-1} \text{ bar}^{-1}), \quad (3)$$

where the brine mass (G) was measured in grams, the time (t) in minutes, and the hydraulic pressure drop (ΔP) in bar.

In each portion of a run during which the applied uniaxial stress remained constant, the total weight of effluent brine (G) was found to increase in accordance with the expression

$$G(t) = G(0) + (\Delta P/b) \ln [1 + (b/a)t], \quad (4)$$

where $G(0)$ is the weight of effluent brine at time 0, and a and b are adjustable parameters. This expression, which bears a striking resemblance to Eq. (1) for the consolidation of salt in brine, was used to fit all the data by means of a least-squares computer program. The results are summarized in Table I and some of the runs are shown in Fig. 3, including curves obtained by fitting Eq. (4) to the data. As will be discussed, the highly variable parameters a and b depend on the initial condition of the surfaces, the uniaxial stress, perhaps the hydraulic pressure drop, and the temperature.

Differentiation of Eq. (4) shows that for constant conditions of temperature and uniaxial stress, the permeability of the interface as defined in Eq. (3) should decrease with time as follows:

$$Pm = 1/(a + bt). \quad (5)$$

3.2 Apparent Half-Thickness of the Interface

Combination of Eqs. (2) and (3)—with the brine density (ρ) in g cm^{-3} , h in cm, and viscosity (η) in Poise—gives

$$Pm = 6 \times 10^7 \times \frac{4\pi\rho h^3}{3\eta \ln(r_2/r_1)} \quad (\text{g min}^{-1} \text{ bar}^{-1}). \quad (6)$$

In this equation, h may be viewed as the apparent half-thickness of the interface (i.e., half the distance between perfectly flat and parallel surfaces that would produce this permeability).

Table 1. Permeability of the interface between stressed salt crystals

$$Pm = (a + bt)^{-1} \quad (\text{g min}^{-1} \text{ bar}^{-1})$$

Run No. ^a	Stress (bar)	Hydraulic pressure (bar)	Brine flow (g)	Time (min)	$a(\pm)^b$ (bar min g ⁻¹)	$b(\pm)^b$ (bar g ⁻¹)	Standard deviation ^c (g)
(20°C)							
20ab	23.4	0.138	455.3	5810	1.4298(53)	9.92(25)E-5	0.94
20c	46.9	0.134	19.9	2808	11.80(77)	7.07(70)E-3	0.21
20d	34.4	0.134	31.9	7140	27.42(16)	1.013(56)E-3	0.059
20e	25.0	0.141	12.0	2570	30.37(21)	4.1(2.1)E-4	0.033
20f	46.9	0.138	20.2	10420	59.59(53)	2.96(15)E-3	0.090
20g	15.6	0.069	5.65	1830	34.7(2.8)	-9.4(3.0)E-3	0.15
30a	93.8	0.86-2.0	0.594	1697	303 (4)	9.88(35)	0.011
35a	91.6	4.1	13.93	3970	643 (30)	0.332(27)	0.17
40a	31.3	3.52	1.66	48	48.2(2.6)	2.91(18)	0.018
40b	23.4	2.59	1.42	109	164.9(3.4)	0.693(79)	0.0079
40c	11.72	1.08-1.28	6.07	1225	152.0(1.4)	0.1207(33)	0.0056
40d	30.6	3.12	8.80	2909	470 (13)	0.527(20)	0.063
40e	46.1	4.1	7.86	25730	2122 (21)	1.558(9)	0.026
40f	62.5	5.2	6.97	118726	1.153(49)E+5	-0.38(9)	0.28
60a	26.6	0.8/-1.39	47.2	5411	91.28(1.3)	0.0101(8)	0.40
60b	38.1	2.1	19.9	8364	873 (12)	0.0100(36)	0.13
70a	63	1.4	6.09	11210	810 (47)	0.453(26)	0.12
70b	92.9	2.06	4.11	11570	3058 (68) ^b	0.629(21)	0.048
70c	119.5	3.45	2.71	21107	11485 (78) ^b	1.938(19)	0.014
70d	142	5.17	0.673	16440	7.444(74)E+4	7.80(17)	0.0040
(50°C)							
100a	36	0.67	25.5	2120	35.61(36)	0.01890(47)	0.13 ^c
100b	65.7	0.67	3.0	1800	288.7(1.2)	0.1550(16)	0.044 ^b
100c	45.3	0.77	3.9	3949	603.9(9)	0.0758(7)	0.005
100d	75.0	0.77	2.18	3000	963.4(3.4)	0.0712(22)	0.0025 ^b
100e	95.4	0.8-1.6	4.1	8450	1106 (34)	0.365(34)	0.026 ^b
110a	115.7	2.06	1.30	3868	2546 (73)	2.60(8)	0.008 ^b
110b	95.4	2.07	0.381	3210	9389 (62)	6.15(7)	0.0007
(75°C)							
130a	65.6	0.096	2.33	2599	58.4(3.7)	0.0483(46)	0.065
130b	25.0	0.092	0.656	360	2.76(46)	0.509(44)	0.042
140b	62.8	0.095	2.33	1740	53.5(1.7)	0.0204(23)	0.028
140c	75.0	0.096	0.233	756	154 (13)	0.517(75)	0.007
150c	115.1	3.45	0.95	3650	389 ^a (740)	10.0(8)	0.032
150d	126.9	4.1	0.362	8560	1.07(36)E+4	26.3(2.7)	0.023

^aA new number was assigned when the crystal surfaces were renewed or reoriented.

^bFigures in parentheses indicate uncertainty in last digits.

^cDeviation of calculation from observed values of brine flow.

Fig. 3. Plots of weight of brine collected vs time; (a) Run 40e; $\sigma = 46.1$ bar, $\Delta P = 4.1$ bar, 20°C ; (b) Run 70c; $\sigma = 119.5$ bar, $\Delta P = 3.45$ bar, 20°C ; (c) Run 100b; $\sigma = 65.7$ bar, $\Delta P = 0.57$ bar, 50°C ; (d) Run 140c; $\sigma = 75$ bar, $\Delta P = 0.096$, 80°C . The curves were calculated using Eq. (4) with the parameters shown in Table 1.

From Eq. (5) this half-thickness is given in terms of the parameters a and b :

$$h = 0.001585 \left(\frac{\eta \ln(r_2/r_1)}{\rho(a + bt)} \right)^{1/3} \quad (\text{cm}). \quad (7)$$

The resulting values of h are plotted for a number of runs in Fig. 4. The values of h should be viewed only as a rough average for the separation distance between crystal surfaces. The actual surfaces, of course, contain irregularities which separate them and define the flow channels. These irregularities change with time, applied stress, and brine flow.

The apparent half-thickness was found to be in the range of 5 to 0.1 μm . Its change with time and applied stress shown in Fig. 4 illustrates a number of interesting effects: the rate of decrease of h with time is more rapid for higher applied stresses and temperatures. An increase in applied stress produces a sudden decrease in h , and a decrease in stress causes h to increase, though usually by a lesser amount than expected. Hysteresis is also suggested by the observation that h decreases less rapidly than expected, or even increases with time after a relaxation of the stress.

3.3 Pressure Solution Effects

Microscopic examination of the freshly prepared crystal surfaces at low magnification showed a uniform matte surface with sharp edges at the inner and outer circular boundaries. After completion of a run, the surfaces were usually found to be smooth except for occasional projections and depressions. The projecting features were mated to corresponding depressions on the opposite surface. Most frequently, these projections appeared to be portions of octahedra oriented to form square pyramids up to 100 μm on a side.

The edges of the upper (piston) crystal showed rounding and loss of material, and there was a reduction in overall length. The lower crystal, which was of larger diameter, exhibited a raised rim where its outer surface had been unopposed (Fig. 1), and also a central raised portion opposite the hole through which the brine was delivered. The upper crystal had penetrated the lower one to a small depth and roughly equal amounts of salt had been lost from each, presumably because of the increase in salt solubility caused by the pressure. The two crystals showed no tendency to adhere to one another, however.

It is of interest to compare the loss of permeability of the crystal interfaces with the amount of salt that could have been removed because of the pressure solution effect. The magnitude of this effect has been calculated for NaCl by Jen's (1979) for various temperatures. His results were used to estimate the amount of salt removed by brine flow in each portion of a run. Since the stress exerted at points of contact will be higher than the applied stress because only a fraction of the area is in contact, the local increase in solubility should be greater than that calculated from the applied stress. On the other hand, even at the low brine flows used, the residence times were quite short (the values of h give times of the order of a second to a minute) and saturation may well not have been reached. Hence, the amount of salt dissolved from the crystals by pressure solution can be estimated only roughly.

From the applied stress, the flow of brine, and the coefficients of the pressure effect given by Jenks, the volume of salt dissolved was calculated to be much greater than (typically 100 times) the volume decrease represented by the change in the distance $2h$ between two perfectly smooth surfaces. From these calculations and the appearance of the crystals after the run, the loss of material

FIG. 4. Apparent thickness of crystal interface vs. time, from Eq. (7); (a) Runs 20 and 40 at 20°C; (b) Runs 60 and 70 at 20°C; (c) Runs 100 and 110 at 50°C; (d) Runs 130 and 140 at 80°C. The applied stresses are indicated for each sequence of measurement. Other conditions are given in Table I.

by dissolution was many times the amount of salt removal required to produce a smooth surface. Hence, we must conclude that pressure solution was a significant process in the loss of permeability of these salt-crystal interfaces.

3.4 Effect of Stress and Flow Rate

The values of the coefficients a and b in Table 1 are seen to vary over many orders of magnitude. It is evident from the changes of h with applied stress and time that h , and therefore a and b , are probably dependent on the applied stress. There is also a suggestion in the results that b depends in some way on the hydraulic pressure drop (i.e., on the flow rate of brine). This could be a reflection of the effect of pressure solution, since the amount of salt dissolved depends on the flow of brine as well as on the applied stress. While there was insufficient reproducibility in the measurements to separate the various dependencies of a and b on conditions, the following expressions predict the values of b derived from the measurements to within about one order of magnitude:

$$b \sim 0.002\sigma \Delta P^2 \quad (20^\circ\text{C}),$$

$$b \sim 0.01\sigma \Delta P^2 \quad (50, 80^\circ\text{C}). \quad (8)$$

Here σ is the applied axial stress (bar).

The parameter b determines the rate at which the permeability of the crystal interface decreases with time [Eq. (5)]. If b is indeed proportional to ΔP^2 and remains so as ΔP decreases, then the permeability should not change with time when there is no flow through the interface ($\Delta P = 0$), no matter what the stress. Since this seems unlikely, Eq. (8) should not be applied beyond the present range of measurement.

The parameter a , which is the reciprocal permeability at the beginning of a series of measurements, obviously depends on such factors as the initial condition of the surface and the sets of σ , ΔP , and t values to which the interface was previously exposed. From the instantaneous variation of h with increases in stress displayed in Fig. 4, it appears that a changes in the same direction as the applied stress, though there are insufficient data to identify the form of the dependence with any certainty.

3.5 The Permeability of Polycrystalline Salt

The present results can be extended to polycrystalline salt by using the apparent half-thickness (h) of a crystal interface. As Fig. 4 indicates, this thickness can be as great as $5 \mu\text{m}$ for freshly contacted surfaces and can become as small as $0.1 \mu\text{m}$ after sufficient exposure to flowing brine at stresses up to 140 bar. The permeability of polycrystalline salt can be roughly estimated from the values of h as follows: for an interface between two plane, parallel surfaces, the laminar flow of a noncompressible fluid is given by the expression

$$dV/dt = \frac{2h^3w}{3\eta} \left(\frac{\Delta P}{\Delta l} \right), \quad (9)$$

(Bird et al., 1960, p. 62) where again h is the half-thickness, w is the width of the interface measured normal to the direction of flow, and Δl is the length in the direction of flow over which the hydrostatic pressure drop is ΔP .

If we represent a polycrystalline aggregate as a continuum of salt penetrated by a grid of planar grain boundaries running in the direction of flow and spaced by a distance equal to the size of the crystals (z), then there will be $2/z$ grain boundaries of unit width per unit area normal to flow. The permeability of such a geometry (i.e., the flow rate per unit hydrostatic pressure gradient and per unit cross-sectional area), would then be given by

$$\frac{dV/dt}{(\Delta P/\Delta l)} = \frac{4h^3}{3\eta z}, \quad (10)$$

where $2/z$ has been substituted for w . Expressed as permeability in darcy units (i.e., flow in cm^3/sec of a liquid with viscosity of 1 cp through a cross-sectional area of 1 cm^2 and under a pressure gradient of 1 atm/cm), the result would be

$$Pm (\text{darcys}) = 1.351 \times 10^6 h^3/z, \quad (11)$$

with the half-thickness h and the crystal size z both expressed in centimeters. For h values in the range suggested by the present measurements, we thus may estimate the following darcy permeabilities for compacted salt:

Grain boundary thickness ($2h$, μm)	Permeability (μdarcy)		
	Crystal size, z (cm)		
	0.01	0.1	1
10	1,700,000	170,000	17,000
1	1,700	170	17
0.2	14	1.4	0.14

Gloyne and Reynolds (1961) reported permeabilities for halite specimens which were in the range of <0.5 to $10^5 \mu\text{darcy}$. Such a range is consistent with the presently observed range of h values if the crystal size is taken to be of the order of 1 cm.

Introducing the expression giving h in terms of the parameters a and b [Eq. (7)] into Eq. (11) gives

$$Pm (\text{darcys}) = 0.0211/z(a + bt), \quad (12)$$

where z is in centimeters and a , b and t are in the units shown in Table 1. For sufficiently large values of time, this may be simplified to $Pm = 0.02/bt$ darcys. It is tempting to suggest that b may be estimated from the correlation given by Eq. (8). While b may be expected to increase with the applied stress and (because of the pressure solution effect) with the hydraulic pressure gradient, there are as yet insufficient data to be certain that b is proportional to the square of the latter.

Even if true for the present measurements, this may be an artifact of the radial flow geometry employed.

It seems less likely that the time dependence of the permeability represented by Eq. (5) is an artifact of the flow geometry since the observed dependence of the total flow on time [Eq. (4)] is of the same form as that [Eq. (1)] for the rate of consolidation of polycrystalline salt in brine. Such a similarity is consistent with the fact that the linear decrease of the void fraction with the logarithm of time persists to very low void fractions (Shor et al. 1981), presumably to the point where the consolidation rate is determined by the decreasing permeability of the grain boundaries along which the brine must escape in order for consolidation to proceed. The rate at which brine is excluded from stressed specimens of halite that are almost fully consolidated is presently being investigated. The data obtained will perhaps give enough additional information to judge the overall rate at which the permeability decreases with time in stressed polycrystalline salt.

4. SUMMARY

In order to investigate the movement of brine along grain boundaries in polycrystalline salt, measurements have been made of the radial flow of brine through the interface formed between two cylindrical salt crystals under axial stress. For constant stresses in the range of 12 to 140 bar and at temperatures of 20, 50, and 80°C, the reciprocal permeability increased linearly with time [Eq. (5), Table 1] and the total brine flow exhibited a dependence on the logarithm time [Eq. (4)] of the same form as that observed previously for the decreasing void fraction of consolidating salt [Eq. (1)]. The calculations and the appearance of the crystal surfaces themselves both indicate that far more salt was removed from the contacting surfaces by the pressure solution effect than was needed to account for the decrease in the apparent interfacial thickness. This thickness—estimated from the formula for radial flow in a circular interface [Eq. (2)] between plane, parallel surfaces—was found to vary from 10 μm for freshly contacted crystals to as low as 0.2 μm after exposure to stress and flowing brine (Fig. 4). The apparent thickness decreased quickly with increases in stress and increased, though not reversibly, when stress was reduced. The parameter (b) reflecting the rate of change of the permeability with time, while widely variable, was approximately proportional to the product of the applied stress and the square of the hydraulic pressure drop across the interface [Eqs. (8)]. If the present values of the apparent interfacial thickness are assumed for grain boundaries in polycrystalline salt, permeabilities may be estimated that are consistent with the low values reported for stressed core specimens. Studies of the exclusion of brine flow from such specimens are needed to verify the dependence of the permeability of grain boundaries on the stress and the brine flow.

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