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Thermal Properties of
Permian Basin Evaporites
to 493 K and 30 MPa Confining Pressure

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M. B. Durham, H. C. Heard, C. O. Boro,
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AUSPICES

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ABSTRACT

Laboratory measurements have been made of the thermal conductivity and diffusivity of four rock salts, two anhydrites, and two dolomites bordering the Cycle 4 and Cycle 5 bedded salt formations in the Permian Basin in Deaf Smith County, Texas. Measurement conditions ranged from 303 to 473 K in temperature, and 0.1 to 31.0 MPa in hydrostatic confining pressure. Within the $\pm 5\%$ measurement resolution neither conductivity nor diffusivity showed a dependence upon pressure in any of the rocks. Conductivity and diffusivity in all rocks had a negative temperature dependence. For the two Cycle 4 salt samples, conductivity over the temperature range explored fell from 5.5 to 3.75 W/m·K, and diffusivity fell from about 2.7 to 1.7×10^{-6} m²/s. One of the Cycle 5 salts was a single crystal which had anomalous results, but the other had a low conductivity, about 3.4 W/m·K, with very weak temperature dependence, and a high diffusivity, 3.8 to 2.5×10^{-6} m²/s over the temperature range.

In the nonsalts, conductivity and diffusivity decreased 10 to 20% over the temperature range explored, which was $308 < T < 373$ K. Typical values at 308 K for conductivity were 5.4 W/m·K for both anhydrites and 3.4 and 2.6 W/m·K for the two different dolomite samples. Approximate values at 308 K for diffusivity were 2.3×10^{-6} m²/s for the anhydrites and 1.4×10^{-6} m²/s for both the dolomites.

The coefficient of thermal linear expansion was measured for the Cycle 5 salt and nonsalts over $308 < T < 493$ and $0.1 < P < 30.0$ MPa. Typically, the coefficient varied from about 12×10^{-6} K⁻¹ at $P = 3.0$ MPa to 4×10^{-6} K⁻¹ at $P = 30$ MPa for both nonsalt rocks. In anhydrite, it decreased with increasing temperature at a rate of roughly 5×10^{-8} K⁻² at all pressures. In dolomite, the coefficient increased at roughly the same rate. Expansion of the salt ranged from 33 to 38×10^{-6} K⁻¹ and was independent of pressure and temperature.

FORWARD

The National Waste Terminal Storage Program was established in 1976 by the U.S. Department of Energy's predecessor, the Energy Research and Development Administration. In September 1983, this program became the Civilian Radioactive Waste Management (CRWM) Program. Its purpose is to develop technology and provide facilities for safe, environmentally acceptable, permanent disposal of high-level waste (HLW). HLW includes wastes from both commercial and defense sources, such as spent (used) fuel from nuclear power reactors, accumulations of wastes from production of nuclear weapons, and solidified wastes from fuel reprocessing.

The information in this report pertains to the _____ studies of the _____ Project of the Office of Geologic Repositories in the CRWM Program.

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LIST OF SYMBOLS

General.

P	hydrostatic confining pressure
T	temperature
C_p	heat capacity at constant P
ρ	density

Conductivity measurements.

λ	thermal conductivity
t	time
a	outer diameter of line probe
Q	power per unit length supplied by line probe
T_{probe}	temperature of the thermocouple within the line probe

Diffusivity measurement.

κ	thermal diffusivity
r	radial distance from the sample axis
b	radius of outer thermocouple

Expansivity measurement.

α	thermal linear expansivity
L_0	initial sample length
ΔL	final sample length minus L_0
ΔT	final temperature minus initial temperature

1.0 INTRODUCTION

There is an intensifying need for site-specific rock characterization for nuclear waste isolation. The Permian Basin bedded salt formations in the Texas panhandle are one of a handful of geologic locations in the United States under active consideration as sites for subsurface nuclear waste repositories. Long-term projections of the behavior of the rock formation that houses a repository are based on accurate knowledge of the physical and chemical properties of the host rock under in situ conditions. The present work is concerned with one such set of properties collectively called the thermal properties. They are the thermal conductivity, which characterizes the ability of a medium to transport heat under steady-state conditions; the thermal diffusivity, which characterizes the ability of a medium to propagate a heat wave (i.e., to transport heat in a transient situation); and thermal linear expansivity, the change in length caused by a change in temperature. The first two properties are often referred to as the thermal transport properties.

In an earlier paper we reported laboratory measurements of the thermal conductivity and diffusivity of rock salts from Cycles 4 and 5 of the Permian Basin (Durham et al., 1983). Here, we report further measurements on rock salt, anhydrites, and dolomites associated with the Cycles 4 and 5. Additionally we report thermal linear expansivity measurements on the same rock types. As before, the measurements are carried out at elevated temperatures and pressures in order to simulate in situ conditions.

2.0 SAMPLES AND STANDARD REFERENCE MATERIAL

All rock came from hole No. 1, J. Friemel, in Deaf Smith County, Texas. The samples were received in the form of core sections approximately 100 mm in diameter. Table 1 shows the core intervals involved and their relationship to the Cycle 4 and 5 Permian Basin bedded salt. For brevity we will refer to the evaporites studied as salt (i.e., the rock salt) and nonsalt (the dolomites and anhydrites). Salt samples were given the prefixes TP for combined conductivity and diffusivity and XP for expansivity. For the conductivity and diffusivity measurements on salt, four samples were prepared and were numbered TP12 to TP15. Conductivity and diffusivity were measured on the same samples. In addition, four salt samples were prepared from Cycle 5 for the expansivity measurements (XP5 to XP8). Two samples each of dolomite and anhydrite were prepared for each of the three thermal properties measurements, making a total of twelve nonsalt samples measured. Nonsalt samples were given the prefixes LP for the conductivity measurement, KP for diffusivity, and XP for expansivity and were numbered 1 to 4 in each group.

The standard reference material for the conductivity and diffusivity measurement was Pyroceram Code 9606 manufactured by Corning Glass Works (CGW), Corning, NY. Pertinent manufacturing details of the material are given by Flynn et al. (1964), and its thermal transport properties are shown in Figures 1 and 2. The Pyroceram used for the nonsalt conductivity experiment was slabbed at CGW in 1983. The Pyroceram used for the nonsalt diffusivity experiment was at least several years older and was the same standard used by Mirkovich et al. (1983). The Pyroceram for the salt experiment was slabbed at CGW in 1982. The standard we used here was the same standard used by Durham et al. (1983).

Two different reference standards were used for the expansivity α measurement, Carpenter 883 tool steel ($\alpha = 11.0 \times 10^{-6} \text{ K}^{-1}$, Carpenter, 1977) and fused silica ($\alpha = 0.54 \times 10^{-6} \text{ K}^{-1}$, Skinner, 1966).

Figure 1. Thermal diffusivity of Pyroceram Code 9606. The error bars encompass the scatter of the Mirkovich et al. (1983) data.

Figure 2. Thermal conductivity of Pyroceram Code 9606 (from Powell et al., 1966).

Table 1. Location of Sample Material in Hole No 1, J. Friemel,
Deaf Smith County, Texas.

<u>Samples</u>	<u>Rock Type</u>	<u>Core Intervals (depth in feet)</u>	<u>Location with Respect to Salt Cycles</u>
LP1, KP1, XP1	Anhydrite	2281.1 - 2281.9	after (above) Cycle 5
LP2, KP2, XP2	Dolomite	2499.0 - 2499.8	between Cycles 4 and 5
LP3, KP3, XP3	Anhydrite	2288.9 - 2289.8	after Cycle 5
LP4, KP4, XP4	Dolomite	2747.3 - 2748.1	before Cycle 4
TP12	Rock Salt	2658.6 - 2659.4	Cycle 4
TP13	Rock Salt	2371.4 - 2372.4	Cycle 5
TP14	Rock Salt	2716.4 - 2717.1	Cycle 4
TP15	Rock Salt	2408.8 - 2409.8	Cycle 5
XP5	Rock Salt	2472.6 - 2473.6	Cycle 5
XP6	Rock Salt	2472.6 - 2473.6	Cycle 5
XP7	Rock Salt	2472.6 - 2473.6	Cycle 5
XP8	Rock Salt	2472.6 - 2473.6	Cycle 5

3.0 EXPERIMENTAL TECHNIQUES

3.1 General aspects. Four separate experiments were performed: the combined conductivity and diffusivity measurements on salt (TP), and individual experiments to measure the three thermal properties of the nonsalt--conductivity, diffusivity, and linear expansivity. Each of the four experiments was carried out in a separate apparatus, but all four shared a general technique for establishing ambient (P,T) conditions and changing from one condition to the other. In each case, the jacketed and instrumented sample was placed in an externally heated pressure vessel, and in each case the path followed in (P,T) space had the same form (Figure 3). The initial measurement was made at the highest pressure (25 or 30 MPa) and room temperature. Subsequent measurements were made at room T and descending P. Heating to the next higher temperature was then done with vessel pressure at $P = 25$ or 30 MPa, and P was again lowered in steps at fixed T for each measurement. The final measurement was made at the highest T and lowest P. This (P,T) path is commonly followed in making physical properties of rocks in order to minimize the potential for damage to the rocks by thermally induced cracking.

Pressure and temperature control for the TP experiment are discussed in the following section. Pressures for the LP, KP, and XP experiments were read with a Heise bourdon tube gage and controlled manually within the ranges shown in the data tables below. Pressure accuracy for the measurement of conductivity and diffusivity was about ± 1 MPa at $P > 3$ MPa and ± 0.1 MPa at $P < 3$ MPa. Pressure accuracy for the measurement of expansivity was ± 0.08 MPa over the range tested. In the case of the conductivity apparatus, the pressure medium was silicone-based oil. For the diffusivity and expansivity measurements, the pressure medium was carbon dioxide. Test temperature was measured by a single thermocouple (for each apparatus) in contact with the steel of the pressure vessel, and temperature was controlled with a dedicated digital controller. Temperature accuracy was the ± 1 to 2 K thermocouple, as stated by the manufacturer.

In this study, we put very strong emphasis on the use of standard reference materials to check measurement accuracy. The reference materials were very carefully chosen to have no pressure effect and to have thermal property values very close to those of the unknowns (except for salt expansivity). In return for the effort expended in using the standards, we have deemphasized the systematic analysis of errors in our measurement system. For instance, in the following LP experiment, we have a poor understanding of the characteristics of the probe-rock interface, but we have every reason to believe that the pertinent aspects of the interface (in particular, its constancy with time during a test) were faithfully reproduced by the unknowns and the standard. As a second example, the single temperature reading was sufficient in the XP experiment because the standards, by the use of careful calibrations, were effectively temperature probes themselves. In fact, they confirmed that the one thermocouple gave an accurate measure of sample temperature. The disadvantage of our somewhat "blind" reliance on reference standards is that the causes of spurious readings are sometimes

Figure 3. Schematic of the path followed in pressure-temperature space in all experiments.

impossible to trace. The advantage of the strategy, however, is that, to the extent the standards are chosen and used properly, the data on the unknowns are unquestionably accurate.

3.2 Conductivity and diffusivity, salt (TP experiment). Because of the large grain size of the rock salt compared to that of the anhydrites and dolomites, we used the apparatus described by Durham et al. (1983), which has the ability to measure thermal conductivity and diffusivity on the same sample. The geometry of the experiment is simple: It attempts to simulate the conditions of an infinite line heat source in an infinite medium. The execution, however, is complex and is explained in detail in Durham et al. (1983).

The sample is a thick-walled cylinder with inner and outer diameters of 21 mm and 102 mm and a length of 254 mm. It is dry-machined in a manner identical to that for the Permian Basin salt samples described by Durham et al. (1983). The sample is instrumented with six thermocouples in its interior that serve to measure the temperature gradient in the sample. The axial hole holds a low power heater that provides the temperature perturbation of the sample. To measure conductivity, this internal heater runs at a constant level. Knowledge of heater power and the temperature gradient in the sample is sufficient to determine conductivity. To determine diffusivity, the heater is pulsed, and the data needed are simply the temperatures in the sample as a function of radius and time.

The measurement and data reduction procedure for the conductivity measurement were exactly as described by Durham et al. (1983), with two exceptions: (1) One-third of the measurements, those at a "power ratio" (defined in Durham et al., 1983) of 1.4, were not performed, in the interests of saving time; and (2) a new set of "correction factors" (Appendix A, Table A1, Durham et al., 1983), were used based on new Pyroceram results. These are discussed further in Chapter 4, Results.

We did change the procedure for gathering diffusivity data. By the old method we imposed a poorly reproducible ($\pm 10\%$) step increase in voltage to the inner heaters and gathered temperature vs time and radius data at the rate of one full thermocouple set (six thermocouples) every six records. We improved both these aspects of the measurement. First, we imposed a step increase in current to the heaters and controlled the current in a feedback loop. The platinum resistance winding becomes more resistive with increasing temperature, so by the old method power to the windings tended to decrease steadily during the test; by holding the current constant, the power now tends to increase steadily during the test, providing a stronger signal to the thermocouples. Second, we removed some unnecessary software delays and made thermocouple readings on three-second cycles. Thus, the nature of the change in technique was to improve resolution by running the heaters more reproducibly, by increasing the strength of the temperature signal, and by doubling the number of data. Once the test was completed, the data of temperatures, times, and radii were reduced by the same computer program used by Durham et al. (1983).

3.3 Conductivity, nonsalt (LP experiment). The method used to measure conductivity of the nonsalt samples was the transient line-source technique. Touloukian and Ho (1981) give a brief description of the method and its applications. The sample is usually a cylinder with a small-diameter hole drilled the length of its axis. Into the axial hole is inserted a tightly fitting probe, which is a resistance winding plus one thermocouple (at the midpoint of the winding) encased in a metallic sheath.

A detailed derivation of the relationship between the temperature of the probe, the material parameters of the probe-rock system, and the power supplied to the probe can be found in Blackwell (1954) and Carslaw and Jaeger (1959). For large values of $\kappa t/a^2$ (symbols are defined in the List of Symbols), the relationship has the form

$$T_{\text{probe}}(t) = A \cdot \ln(t) + B + \frac{1}{t} \{C \cdot \ln(t) + D\} \quad (1)$$

The term A has the value $Q/4\pi\lambda$, so that given an infinitely wide medium and constant values for Q and conductivity, a plot of T vs $\ln(t)$ will asymptotically approach a straight line of slope $Q/4\pi\lambda$. Terms B, C, and D contain several important system parameters including the rock conductivity and diffusivity, the thermal capacity of the probe, and the contact resistance of the probe-rock interface. Although practical methods have been worked out to measure probe thermal capacity and interfacial resistance for situations where B, C, D = 0 in Equation (1) (Koski and McVey, 1983), the simplicity of the straight-line approximation

$$T_{\text{probe}} \approx \frac{Q}{4\pi\lambda} \ln(t) \quad (2)$$

remains very attractive. In our design, we have endeavored to use a sufficiently small probe-to-sample diameter ratio that the approximation is valid (i.e., the straight line is achieved) before the heat pulse senses the outer surface of the rock. The length-to-diameter ratio of the probe, 48, is well above the minimum of 30 prescribed by Blackwell (1956). Rather than prove the method by determining probe thermal capacity and interfacial conductance, we chose to demonstrate its validity (and calibrate our apparatus) by making measurements on a standard reference material with conductivity very near that of the unknowns.

For the conductivity measurements, the sample (Figure 4) is a thick-walled cylinder with outer and inner diameters of 82.5 mm and 3.2 mm and a length of 152 mm. The machining steps on the rock itself, the drilling of the probe hole, facing of the ends, and turning of the outer diameter, are performed without water or other lubricants. The sample is encapsulated in a tube of lead 3 mm thick, which is brazed to stainless steel end caps that are 19 mm thick. The Pyroceram reference standard was prepared in the same manner as the rocks but was also instrumented with a thermocouple positioned at a radius of 19 mm (Figure 4). Input signals (probe voltage, probe current, probe thermocouple) are measured and stored by a minicomputer. The computer also controls the direct current (dc) power supply to the probe such that the input power stays constant. The resistance heater in the probe has a slightly temperature-dependent resistivity. The computer controls probe power to about

Figure 4. Cross section of sample assembly for thermal conductivity measurement by the transient line-source technique. The thermocouple hole at radius 19 mm was present only in the Pyroceram 9606 reference standard. Exact dimensions are given in text.

$\pm 0.1\%$ of a fixed level. Conductivity is calculated from a least-squares fit to the linear portion of the T vs $\ln t$ data. The limits of the linear portion are determined by the operator from a visual examination of the output graphed as T vs $\ln t$. The consequences of this visual technique are discussed in Chapter 5, Calibration and Measurement Error.

Figure 5 gives an example of such a T vs $\ln t$ run record. The initial rate of temperature change in the example is high, mainly because of the insulating nature of the probe-rock interface. The value of $dT/d(\ln t)$ then falls to a constant level, which is either the fortuitous action of two competing processes or is the achievement of the straight-line approximation, Equation (2). Finally, as the heat pulse reaches the outer rock surface, $dT/d(\ln t)$ deflects from the constant value. This deflection is usually upwards in our measurements, but it can also be downwards. Contributing factors are the conductivity of the medium beyond the outer rock surface (e.g., a higher conductivity medium would deflect $dT/d(\ln t)$ downwards) and short-circuiting of heat flow from the probe through the metallic parts of the sample assembly. The latter probably was a factor in our tests because the surrounding media (lead and oil) is more conducting than rock.

Because of the transient nature of the test, the rock becomes warmer during the course of the measurement. If conductivity is a function of temperature, error in the measurement can result. We performed measurements at two power levels: 5 and 10 W. As measured by the thermocouple in the Pyroceram standard, at 5 W the rock at 20-mm radius heats about 6 K in the course of measurement; at 10 W it heats 10 to 14 K. On the other hand, the temperature rise of the probe at 5 W (Figure 5) is so low that noise in the thermocouple measurement begins to be noticeable in conductivity (discussed more fully in Chapter 5, Calibration and Measurement Error). We allowed sufficient time between measurements, 45 to 90 min depending on conductivity, for temperatures to return to the same starting point.

3.4 Diffusivity, nonsalt (KP experiment). We measured diffusivity using a version of the Angstrom phase-shift technique adapted to a cylindrical geometry (Mirkovich, 1977) and further adapted for use under fluid confining pressure (Mirkovich et al., 1983). The sample assembly is a stack of three cylindrical sections of rock 25.4 mm in diameter totaling 63.5 mm in length (Figure 6). Two holes for 0.5-mm-diameter thermocouples are cored through to the circular midplane of the assembly. One hole is positioned at the axis of the sample, ± 0.05 mm, and the other at a radius of 11.20 ± 0.05 mm. The reason for making the sample assembly a stack of short pieces rather than a single 63.5-mm-long piece is that the position of the thermocouple holes has to be known to a fraction of a millimeter, and coring a perfectly straight hole 32 mm long was not within our technology. Once the sample is jacketed for use under pressure, a resistance wire is wound tightly around the entire length of the jacket surrounding the rock. A varying voltage applied to the resistance winding will cause a temperature wave to pass through the rock; its progress, which is a function of the thermal diffusivity of the rock, can be monitored with two thermocouples bottomed in the thermocouple holes. For our tests we applied to the winding a long-period (approximately 50 s), sinusoidally varying voltage between approximately 25 V and 1 V dc. This resulted in a temperature variation of ± 1 to 2° at the sample's outer

Figure 5. An example of a run record for the conductivity measurement. This sample is the Pyroceram standard at $P = 3.0$ MPa, (starting) $T = 299$ K, and 5-W power level. The linear portion of the curve is taken as the portion between 75 and 300 s and yields a value of conductivity = 3.82 W/m $\cdot$ K.

Figure 6. Schematic drawing of the sample assembly for the small sample diffusivity measurement (KP experiment).

thermocouple, depending on pressure and diffusivity. For the inner thermocouple located at a radius $r = 0$, the thermal diffusivity is a function of the cycle, the thermocouple spacing (called "b"), and the phase lag of the temperature wave between the outer and inner thermocouples (Mirkovich, 1977).

Signals for data processing consisted of those from the two sample thermocouples (Type K) and the sinusoidal output from the function generator driving the power supply to the sample coil. These signals were fed to an Analogic Corp. Data 6000 digital oscilloscope that gathered signals for five successive cycles and then processed the signals to determine period and phase lag. The raw data and processed information were then passed to a master computer that stored the raw data and calculated diffusivity values. Sample temperature was defined as the average temperature of the outer sample thermocouple during a five-cycle reading.

Samples were cored parallel to the axis of the original core. Water was used to lubricate the core barrel and the outer diameter was left as cored. Ends of the individual pieces were ground flat to a few micrometers using a surface grinder, again using water as a lubricant. The thermocouple holes were drilled without lubricant. All samples were left to dry in laboratory air for at least several days prior to jacketing and measurement.

3.5 Expansivity, Cycle 5 salt and nonsalts (XP experiment). Linear expansivity was measured by the technique described by Page and Heard (1981). Samples were solid cylinders 25.4 mm in diameter and 52.0 mm long. They were prepared simultaneously with the samples for the KP experiment using the same wet coring and surface grinding techniques. They were similarly dried in laboratory air. After preparation each test sample was jacketed in 0.3-mm-wall-thickness annealed aluminum tubing (Type 1100F) and mechanically sealed to loading pistons. A hole through one piston was vented to the atmosphere, thus ensuring that the pore pressure remained near 0.1 MPa at all (P,T) conditions during testing. The pressure vessel was fitted with an internal force gage for axial stress determination. Axial displacements of the test sample (ΔL) which resulted from changes in pressure, temperature, or axial loading were measured externally using a displacement transducer. Accuracies in axial load and ΔL were about 0.1 to 0.2 MPa and 8×10^{-4} mm, respectively. Because there was no internal heat source in the vessel (as there were in the case of the conductivity and diffusivity measurements), the vessel control temperature was the sample temperature.

Three displacement measurements were made on all test samples at each set of (P,T) conditions. Each sample was first pressurized to 25 or 30 MPa at 292 K in order to seat the piston-jacket-sample assembly. Using the piston drive, the assembly was then moved downward in the vessel to contact the force gage in order to determine the "touch point." The piston drive was then reversed and the process repeated two more times. The three determinations of touch point at the force gage at any pressure and temperature yielded an average reference length of the test sample at those conditions. New touch points determined at other pressure and temperature conditions yielded a ΔL resulting from the ΔP or ΔT . Linear expansion at any pressure was calculated from the averaged difference in sample length point between adjacent temperatures as

$$\alpha = \frac{\Delta L}{L_0 \Delta T}$$

4.0 RESULTS

The results for the conductivity, diffusivity, and linear expansivity of the rock salt, dolomite, anhydrite, and reference standard (where applicable) are plotted in Figures 7 to 12 and tabulated in Tables 2 to 7.

4.1 Conductivity, salt. Thermal conductivities for the four salt samples range from about 5.5 to 3 W/m·K. Conductivity decreases monotonically with increasing temperature over the range studied, but the temperature sensitivity varies from weak (TP13, TP15) to strong (TP12, TP14). There is no effect of pressure on thermal conductivity within our measurement sensitivity that is better than ± 0.10 W/m·K over the 30-MPa range covered here (Durham et al., 1983). Thus, in Table 2 we have combined the data for all pressures at fixed temperature into a single value plus standard deviation, which in turn allows us to combine the data for all four rock salts on a single two-dimensional plot (See Figure 13, with other summary figures in Chapter 4, on page 55.) TP12 and TP14, both from Cycle 4, have similar conductivities, although TP14 has a more irregular dependence on temperature. Below 350 K its temperature sensitivity is stronger than that of TP12 and above 350 K it is weaker. TP15 has the lowest conductivity of the salts. The effect of pressure-temperature cycling was checked by remeasuring TP15 at three of the six temperatures. A slightly augmented temperature effect was found (but still no pressure effect); it is arguable whether or not the difference in the two runs on TP15 is significant given the estimated measurement reproducibility of ± 0.25 W/m·K (Durham et al., 1983), but it is apparently better than estimated reproducibility in the Pyroceram results (see below).

The results for TP13 are unique, as is the sample itself: It is probably a single crystal. Petrographic analysis of our samples is being performed elsewhere and was not available at the time of this writing; hence, sample-to-sample comparisons are difficult to make. However, it was obvious to us from the clarity of the core section and from the strictly parallel cleavage fractures within that TP13 was a single crystal of NaCl. Unfortunately, TP13 was the only sample where experimental difficulty was encountered. The metallic jacket ruptured early in the run. The jacket leak was sufficiently large that only the lowest pressure could be tested. The fact that we can't reasonably test the reference standard under similar leaky conditions puts the results for TP13 at a lower significance than those for the other salts. Compared in Figure 13 to the other salts, TP13 has a comparable conductivity, but practically no temperature sensitivity.

The Pyroceram reference standard was the same one used by Durham et al. (1983). The only change made was that the six sample thermocouples, which must be destroyed during disassembly from the apparatus, were replaced. The agreement between this run and the one by Durham et al. (1983) is impressive and reassuring: Differences are usually well within our estimated reproducibility of ± 0.25 W/m·K. Exceptions in most instances appear related to anomalies in the Durham et al. (1983) run. In fact, the variation of apparent (i.e., as measured in the apparatus) conductivity in (P,T) space is sufficiently smooth that we can improve the procedure for the correction of systematic inaccuracies, which is detailed in Durham et al. (Appendix A,

Figure 7. Results for thermal conductivity vs temperature and pressure, salt.

Figure 7. (Continued)

Figure 8. Results for thermal diffusivity vs temperature and pressure, salt.

Figure 8. (Continued)

Figure 9. Results for thermal conductivity vs temperature and pressure, nonsalt. The curve in (e) is taken from Figure 2.

Figure 10. Results for thermal diffusivity vs temperature and pressure, nonsalt. The error bars in (a)-(d) depict the random point to point error of $\pm 5.6\%$ (Table 8). The error bar in (e) depicts the total random plus systematic uncertainty of $\pm 9.6\%$. The curve in (e) is taken from Figure 1.

Figure 11. Results for thermal linear expansivity vs temperature and pressure. The "x" in (b) refers to a measurement at 0.1 MPa from Cheng and Liaw (1967).

Figure 12. Average thermal linear expansivity vs temperature at 3, 10, and 25 MPa for four Cycle 5 salt samples. Bar indicates 1 STD. The dashed curve at top indicates expansivity of pure salt at 0.1 MPa (Skinner, 1966).

EXPLANATION OF TABLE 2.

These following tables are a compilation of the raw data reduction, i.e., a compilation of the summary lines following calculations such as listed in Durham et al. (1983), Table B4, and include the application of the three-step recipe outlined in Appendix A of Durham et al. (1983). The columns signify the following:

FILE	Name of the raw data file, coded by pressure, temperature, and power ratio
START TIME	Hours:Minutes:Seconds
COND	Apparent conductivity from the experiment (W/m•K)
PWR	Average power output from central portion of inner heater (W)
P.R.	Power ratio
#PTS	Number of distinct conductivity measurements averaged to give COND
P	Confining pressure (psi, 145 psi = 1 MPa)
T	Temperature (°C) at the innermost sample thermocouple (R1) and at the fifth outward thermocouple (R5)
CORR COND	Actual conductivity (W/m•K), the result of applying the three-step recipe in Appendix A, Durham et al. (1983). These are the values plotted in Figure 7.
P.R. AVG	Average of the two values (at P.R. = 1.0 and 1.2) of CORR COND at a given P and T
P AVG	Average and one standard deviation of P.R. AVG over the (usually) five values at fixed T. These are the values used to plot the curves in Figure 13.

Note that the last three columns do not appear in the Pyroceram results (Tables 2f and 2g) because the results formed the basis for the calculation of CORR COND (see text for discussion).

Table 2a. TP12 Conductivity Results.

FILE	START TIME	COND	PWR	P.R.	OPTS	P	T(R1)	T(R5)	CORR COND	P.R. AUG	P AUG
TP0510	13:17:08	6.20	12.44	1.003	14	4512	32.0	29.8	5.64		
TP0512	13:18:35	5.57	10.68	1.204	9	4508	32.4	30.3	5.65	5.65	
TP0412	13:19:46	5.30	9.38	1.204	7	3360	32.2	30.4	5.47		
TP0410	13:20:36	6.02	10.39	1.002	9	3395	32.4	30.6	5.57	5.52	
TP0310	14:3:45	5.77	9.83	1.003	20	2256	31.1	29.5	5.57		
TP0312	14:5:45	5.12	8.50	1.203	9	2257	31.4	29.8	5.51	5.54	5.60 +/- 0.07
TP0212	14:6:35	5.23	7.33	1.204	11	1184	31.1	29.9	5.71		
TP0210	14:7:40	5.76	8.03	1.003	10	1154	31.4	30.2	5.64	5.67	
TP0110	14:15:3	5.55	7.54	1.003	18	549	31.1	30.0	5.59		
TP0112	14:16:38	5.00	6.60	1.204	9	543	31.2	30.2	5.62	5.61	
TP0520	14:23:20	5.21	11.48	1.003	12	4500	68.7	66.3	4.89		
TP0522	15:0:44	4.65	10.14	1.203	9	4485	68.8	66.4	4.87	4.88	
TP0422	15:1:39	4.75	9.26	1.203	10	3420	68.4	66.3	5.06		
TP0420	15:2:44	5.28	10.41	1.003	9	3422	68.5	66.4	5.04	5.05	
TP0320	15:9:59	5.14	9.37	1.003	19	2274	67.8	65.9	5.16		
TP0322	15:11:40	4.72	8.33	1.204	10	2316	67.9	66.1	5.30	5.23	5.02 +/- 0.13
TP0222	15:12:59	4.40	7.47	1.202	8	1210	67.5	65.9	5.00		
TP0220	15:13:52	4.92	8.40	1.004	9	1199	67.5	66.0	5.00	5.00	
TP0120	15:21:0	4.85	8.05	1.002	19	568	67.1	65.7	4.91		
TP0122	15:22:52	4.43	7.13	1.204	11	575	67.2	65.9	5.01	4.96	
TP0530	16:5:49	4.52	11.15	1.003	12	4526	104.9	102.2	4.49		
TP0532	16:7:17	4.01	9.88	1.204	7	4485	104.9	102.2	4.45	4.47	
TP0432	16:8:3	4.05	9.24	1.204	10	3404	104.5	102.1	4.39		
TP0430	16:8:58	4.45	10.35	1.005	11	3404	104.6	102.1	4.31	4.35	
TP0330	16:16:26	4.36	9.53	1.004	18	2242	104.1	101.7	4.40		
TP0332	16:18:6	3.92	8.44	1.204	11	2270	104.1	101.7	4.42	4.41	4.46 +/- 0.10
TP0232	16:19:8	3.87	7.87	1.204	11	1196	103.6	101.5	4.45		
TP0230	16:20:7	4.34	8.81	1.003	11	1187	103.7	101.7	4.47	4.46	
TP0130	17:3:42	4.27	8.41	1.002	17	569	103.6	101.7	4.62		
TP0132	17:5:17	3.82	7.47	1.205	11	567	103.6	101.8	4.62	4.62	
TP0540	17:11:47	4.03	10.32	1.004	17	4514	139.6	136.7	4.16		
TP0542	17:13:21	3.63	9.17	1.203	11	4523	139.6	136.7	4.18	4.18	
TP0442	17:14:21	3.52	8.69	1.204	11	3341	139.2	136.5	4.03		
TP0440	17:15:20	3.94	9.79	1.003	11	3380	139.3	136.5	4.03	4.03	
TP0340	17:22:55	3.89	9.24	1.002	15	2261	139.0	136.5	4.09		
TP0342	18:0:40	3.45	8.17	1.203	9	2267	139.0	136.7	4.05	4.07	4.17 +/- 0.12
TP0242	18:1:31	3.54	7.72	1.204	11	1167	139.7	136.4	4.27		
TP0240	18:2:41	3.98	8.64	1.003	9	1162	139.7	136.5	4.30	4.29	
TP0140	18:10:16	3.87	8.41	1.004	15	565	139.6	136.4	4.29		
TP0142	18:11:41	3.46	7.46	1.204	11	571	139.6	136.5	4.28	4.28	
TP0550	18:18:6	3.78	9.97	1.003	18	4512	169.2	166.2	3.83		
TP0552	18:19:51	3.38	8.88	1.203	10	4509	169.2	166.2	3.83	3.83	
TP0452	18:20:55	3.33	8.52	1.203	9	3503	168.9	166.1	3.83		
TP0450	18:21:51	3.76	9.51	1.003	10	3373	168.9	166.2	3.87	3.85	
TP0350	18:5:18	3.63	8.94	1.003	18	2277	168.7	166.0	3.79		
TP0352	18:6:57	3.30	7.99	1.203	11	2244	169.7	166.1	3.86	3.83	3.81 +/- 0.08
TP0252	18:8:7	3.32	7.68	1.205	3	1218	168.4	165.9	3.87		
TP0250	18:9:3	3.68	8.58	1.004	10	1213	168.4	165.9	3.83	3.85	
TP0150	19:16:26	3.37	8.31	1.003	3	575	168.4	165.9	3.60		
TP0152	19:18:12	3.12	7.42	1.205	10	570	168.4	165.9	3.74	3.67	
TP0560	20:1:56	3.52	9.54	1.003	17	4524	205.0	202.7	3.54		
TP0562	20:3:39	3.16	8.45	1.203	9	4499	206.0	202.7	3.56	3.55	
TP0462	20:4:40	3.14	8.18	1.203	9	3463	205.7	202.5	3.59		
TP0460	20:5:29	3.51	9.15	1.003	11	3370	205.7	202.5	3.58	3.58	
TP0360	20:13:4	3.45	8.76	1.004	17	2234	205.5	202.4	3.61		
TP0362	20:14:48	3.10	7.83	1.203	9	2303	205.5	202.4	3.63	3.62	3.56 +/- 0.03
TP0262	20:15:45	3.06	7.59	1.205	10	1184	205.2	202.2	3.61		
TP0260	20:16:44	3.41	8.53	1.003	10	1184	205.3	202.3	3.60	3.60	
TP0160	21:0:15	3.42	8.15	1.003	17	533	204.9	202.0	3.57		
TP0162	21:1:54	3.01	7.18	1.205	10	531	204.9	202.0	3.51	3.54	

Table 2b. TPI3 Conductivity Results.

FILE	START TIME	COND	PWP	P.R.	#PTS	P	T(R1)	T(R5)	CDRR COND	P.R. AUG	P AUG
TP0212	20:16: 0	4.59	7.56	1.204	10	1138	28.3	26.8	4.99		
TP0210	20:17:29	5.00	8.18	1.002	5	1138	28.7	27.3	4.87	4.93	4.57
TP0110	21:10:35	4.23	7.86	1.002	16	543	28.6	27.3	4.22		
TP0112	21:12: 9	3.78	6.81	1.204	10	531	28.9	27.7	4.21	4.21	
TP0120	22:15:10	4.63	7.70	1.003	18	547	65.8	64.2	4.68		
TP0122	22:18: 4	4.15	6.80	1.203	8	536	65.9	64.3	4.68	4.68	4.68
TP0130	23: 0:21	4.39	8.37	1.004	17	549	102.1	99.9	4.76		
TP0132	23: 1:59	3.88	7.43	1.202	10	546	102.2	99.9	4.70	4.73	4.73
TP0242	23:11: 4	3.65	7.83	1.203	21	1181	137.3	134.6	4.41		
TP0240	23:13: 4	4.14	8.89	1.002	10	1168	137.4	134.6	4.48	4.45	4.52
TP0140	23: 8:25	4.14	8.57	1.003	17	556	137.2	134.4	4.60		
TP0142	23:10:14	3.69	7.63	1.203	8	554	137.2	134.4	4.58	4.59	
TP0150	23:22:39	4.13	8.86	1.003	16	576	167.1	164.0	4.46		
TP0152	24: 0:14	3.71	7.84	1.203	10	574	167.1	164.0	4.48	4.47	4.47
TP0160	24: 6:34	4.01	8.58	1.003	19	573	203.6	200.3	4.22		
TP0162	24: 8:20	3.62	7.62	1.204	10	564	203.5	200.3	4.26	4.24	4.24

Table 2c. TP14 Conductivity Results.

FILE	START TIME	COND	PWR	P.R.	#PIS	P	I(R1)	I(R5)	CORP COND	P.R. AVG	P AVG
TP0510	27:14:11	6.27	12.52	1.004	18	4498	30.9	28.8	5.70		
TP0512	27:16:0	5.61	10.74	1.204	10	4514	31.5	29.4	5.69	5.70	
TP0412	27:17:11	5.43	9.34	1.205	8	3341	31.2	29.6	5.61		
TP0410	27:18:10	6.20	10.41	1.004	8	3354	31.5	29.9	5.75	5.68	
TP0310	28:1:26	5.86	9.20	1.003	18	2257	30.7	29.3	5.66		
TP0312	28:3:15	5.23	8.02	1.204	9	2234	30.9	29.6	5.64	5.65	5.61 +/- 0.10
TP0212	28:4:25	5.14	6.97	1.203	7	1201	30.5	29.4	5.61		
TP0210	28:5:5	5.61	7.76	1.003	11	1189	30.6	29.5	5.48	5.55	
TP0110	28:12:44	5.41	7.49	1.003	17	574	30.1	29.0	5.45		
TP0112	28:14:30	4.89	6.55	1.202	8	577	30.3	29.3	5.50	5.47	
TP0520	28:23:25	5.04	11.48	1.003	19	4525	67.5	65.0	4.72		
TP0522	29:1:30	4.49	10.02	1.202	8	4522	67.7	65.4	4.70	4.71	
TP0422	29:2:37	4.49	9.18	1.202	7	3425	67.3	65.2	4.77		
TP0420	29:3:25	5.00	10.24	1.003	9	3325	67.3	65.3	4.76	4.77	
TP0320	29:11:0	4.71	9.41	1.003	15	2255	66.9	65.0	4.72		
TP0322	29:12:34	4.31	8.33	1.203	9	2253	66.9	65.1	4.82	4.77	4.65 +/- 0.14
TP0222	29:13:37	3.97	7.53	1.204	8	1185	66.6	64.9	4.49		
TP0220	29:14:39	4.51	8.49	1.003	8	1182	66.6	64.9	4.57	4.53	
TP0120	29:22:1	4.46	8.12	1.002	17	575	66.4	64.8	4.50		
TP0122	29:23:54	3.97	7.12	1.203	7	569	66.5	64.9	4.47	4.48	
TP0530	30:5:5	4.42	11.16	1.003	17	4518	103.9	101.1	4.38		
TP0532	30:7:45	3.94	9.91	1.204	10	4494	103.9	101.1	4.36	4.37	
TP0432	30:8:44	3.92	9.27	1.204	10	3401	103.5	100.9	4.24		
TP0430	30:10:5	4.36	10.30	1.002	6	3309	103.5	101.0	4.22	4.23	
TP0330	30:17:15	4.26	9.57	1.002	17	2245	103.2	100.8	4.29		
TP0332	30:18:54	3.78	8.45	1.202	10	2235	103.2	100.9	4.25	4.27	4.32 +/- 0.09
TP0232	30:20:10	3.70	7.86	1.206	7	1216	102.8	100.7	4.25		
TP0230	30:21:4	4.17	8.82	1.003	8	1211	102.9	100.8	4.29	4.27	
TP0130	31:4:26	4.11	6.60	1.003	17	575	102.7	100.6	4.44		
TP0132	31:6:14	3.67	7.66	1.204	8	566	102.7	100.7	4.43	4.44	
TP0540	31:12:25	4.07	10.46	1.004	18	4490	138.7	135.6	4.21		
TP0542	31:14:10	3.68	9.32	1.203	10	4492	138.6	135.6	4.25	4.23	
TP0442	31:15:20	3.58	8.83	1.204	8	3358	138.3	135.4	4.10		
TP0440	31:16:4	4.03	9.95	1.003	11	3405	138.3	135.5	4.13	4.11	
TP0340	31:23:30	3.98	9.44	1.004	6	2311	138.1	135.3	4.18		
TP0342	0:1:29	3.55	8.28	1.203	8	2249	138.1	135.4	4.17	4.18	4.26 +/- 0.13
TP0242	0:2:25	3.63	7.88	1.204	9	1190	137.8	135.3	4.39		
TP0240	0:3:20	4.05	8.85	1.003	10	1184	137.8	135.3	4.38	4.38	
TP0140	4:10:55	3.99	8.71	1.003	16	572	137.7	135.1	4.42		
TP0142	4:12:24	3.57	7.70	1.203	11	571	137.7	135.2	4.42	4.42	
TP0550	4:18:51	3.86	10.22	1.003	18	4534	168.5	165.1	3.91		
TP0552	4:20:44	3.44	9.01	1.203	8	4526	168.6	165.2	3.90	3.90	
TP0452	4:21:35	3.43	8.67	1.204	10	3401	168.3	165.0	3.95		
TP0450	4:22:34	3.91	9.79	1.002	10	3361	168.3	165.1	4.03	3.99	
TP0350	5:5:0	3.94	9.26	1.003	18	2283	168.0	164.8	4.14		
TP0352	5:7:45	3.56	8.28	1.204	10	2280	168.0	164.8	4.18	4.16	4.04 +/- 0.11
TP0252	5:8:47	3.42	7.94	1.203	10	1222	167.7	164.6	3.99		
TP0250	5:9:52	3.90	8.93	1.004	9	1219	167.7	164.7	4.07	4.03	
TP0150	5:17:17	3.85	8.62	1.004	17	574	167.6	164.6	4.15		
TP0152	5:18:5	3.42	7.63	1.204	8	569	167.6	164.6	4.11	4.13	
TP0560	6:1:16	3.74	9.84	1.002	18	4511	205.2	201.5	3.77		
TP0562	6:3:10	3.36	8.75	1.202	8	4462	205.2	201.5	3.79	3.78	
TP0462	6:4:0	3.42	8.51	1.203	10	3382	205.0	201.3	3.92		
TP0460	6:5:5	3.75	9.52	1.002	9	3365	205.0	201.2	3.84	3.88	
TP0360	6:12:24	3.69	9.15	1.003	18	2230	204.7	201.0	3.87		
TP0362	6:14:14	3.31	8.18	1.204	9	2318	204.7	201.1	3.89	3.88	3.86 +/- 0.05
TP0262	6:15:11	3.29	7.99	1.201	10	1205	204.4	200.8	3.90		
TP0260	6:16:5	3.71	8.99	1.003	11	1203	204.4	200.8	3.93	3.91	
TP0160	6:23:35	3.66	8.56	1.003	17	571	204.3	200.9	3.84		
TP0162	7:1:34	3.26	7.61	1.203	7	576	204.3	200.9	3.85	3.84	

Table 2d. TP15 Conductivity Results.

FILE	START TIME	COND	PWP	P.R.	#PIS	P	T(R1)	T(R5)	CORR COND	P.R. AVG	P AVG
TP0510	11:20:55	4.31	11.82	1.003	14	4501	30.9	26.2	3.86		
TP0512	11:22:20	3.82	10.24	1.204	8	4507	31.2	26.7	3.82	3.84	
TP0412	11:23:35	3.60	9.02	1.204	5	3380	31.0	27.9	3.66		
TP0410	12: 0:20	4.05	10.12	1.003	9	3439	31.3	27.2	3.68	3.67	
TP0310	12: 7:35	3.88	8.92	1.002	19	2262	30.0	26.2	3.66		
TP0312	12: 9:25	3.43	7.77	1.204	10	2293	30.4	26.6	3.64	3.66	3.60 +/- 0.19
TP0212	12:10:45	3.16	6.70	1.205	6	1200	30.2	26.8	3.38		
TP0210	12:11:34	3.54	7.47	1.003	8	1186	30.4	27.0	3.39	3.39	
TP0110	12:19:29	3.48	6.82	1.003	11	569	30.0	27.0	3.43		
TP0112	12:20:44	3.10	5.88	1.202	8	571	30.2	27.3	3.42	3.43	
TP0520	13:17:25	3.92	10.84	1.003	13	4499	67.1	62.3	3.63		
TP0522	13:18:48	3.99	9.56	1.202	9	4531	67.3	62.5	3.62	3.62	
TP0422	13:19:54	3.36	8.74	1.203	8	3414	66.9	62.4	3.53		
TP0420	13:20:43	3.78	9.73	1.003	10	3322	66.9	62.5	3.55	3.54	
TP0320	14: 4:34	3.24	9.43	1.003	13	2274	66.3	61.8	3.60		
TP0322	14: 5:52	3.23	8.28	1.204	10	2218	66.4	61.9	3.57	3.59	3.51 +/- 0.11
TP0222	14: 7: 0	3.05	7.45	1.204	8	1192	66.0	61.9	3.41		
TP0220	14: 7:57	3.40	8.41	1.003	9	1185	66.1	61.9	3.40	3.40	
TP0120	14:15:43	3.40	7.94	1.003	13	573	65.9	61.9	3.38		
TP0122	14:17:11	3.05	7.00	1.203	8	573	65.9	62.1	3.40	3.39	
TP0530	14:23:59	3.63	10.96	1.002	11	4495	103.2	97.8	3.56		
TP0532	15: 1: 7	3.16	9.61	1.203	10	4495	103.2	97.7	3.47	3.52	
TP0432	15: 2: 1	3.14	9.06	1.204	11	3454	102.8	97.6	3.37		
TP0430	15: 3:16	3.53	10.13	1.002	8	3334	102.8	97.6	3.38	3.37	
TP0330	15:11: 1	3.45	9.50	1.003	12	2288	102.7	97.8	3.44		
TP0332	15:12:15	3.06	8.40	1.203	10	2223	102.7	97.8	3.41	3.42	3.46 +/- 0.07
TP0232	15:13:21	3.02	7.82	1.204	9	1200	102.3	97.8	3.44		
TP0230	15:14:15	3.38	8.79	1.003	10	1187	102.4	97.8	3.44	3.44	
TP0130	15:21:59	3.32	8.46	1.002	15	575	102.2	97.7	3.55		
TP0132	15:23:24	2.95	7.55	1.204	8	578	102.1	97.7	3.53	3.54	
TP0540	16: 6: 5	3.33	10.53	1.002	14	4519	138.3	132.4	3.40		
TP0542	16: 7:49	3.00	9.28	1.204	6	4526	138.5	132.6	3.43	3.42	
TP0442	16: 8:29	2.96	8.60	1.203	10	3446	138.1	132.6	3.36		
TP0440	16: 9:35	3.31	9.33	1.003	9	3320	138.1	132.5	3.35	3.36	
TP0340	16:17: 0	3.27	9.36	1.003	17	2261	137.7	132.3	3.40		
TP0342	16:18:39	2.93	8.30	1.203	10	2285	137.7	132.4	3.41	3.41	3.42 +/- 0.05
TP0242	16:19:40	2.85	7.84	1.204	10	1186	137.3	132.3	3.41		
TP0240	16:20:39	3.22	8.81	1.004	10	1172	137.4	132.4	3.44	3.42	
TP0140	17: 4:19	3.19	8.50	1.003	15	581	137.3	132.4	3.50		
TP0142	17: 6: 3	2.86	7.55	1.203	7	563	137.3	132.5	3.51	3.50	
TP0550	17:12: 5	3.23	10.17	1.004	19	4522	168.0	161.9	3.24		
TP0552	17:13:54	2.90	8.98	1.203	10	4534	168.0	162.0	3.25	3.25	
TP0452	17:15: 4	2.90	8.60	1.203	8	3407	167.7	162.0	3.31		
TP0450	17:15:59	3.22	9.65	1.003	9	3343	167.7	161.9	3.28	3.30	
TP0350	17:23:43	3.22	9.08	1.004	13	2296	167.4	162.1	3.34		
TP0252	18: 1: 7	2.86	8.04	1.204	9	2310	167.5	162.2	3.35	3.35	3.35 +/- 0.10
TP0252	18: 2:13	2.87	7.88	1.204	8	1207	167.2	162.1	3.32		
TP0250	18: 3: 7	3.25	8.63	1.004	9	1194	167.3	162.2	3.36	3.34	
TP0150	18:10:57	3.29	8.33	1.004	13	565	167.1	162.1	3.51		
TP0152	18:12:11	2.94	7.38	1.204	10	573	167.1	162.2	3.51	3.51	
TP0560	18:18:32	3.21	9.59	1.003	18	4521	204.7	198.6	3.21		
TP0562	18:20:21	2.85	8.53	1.203	9	4534	204.7	198.6	3.19	3.20	
TP0462	18:21:22	2.88	8.26	1.203	9	3420	204.4	198.6	3.27		
TP0460	18:22:16	3.24	9.28	1.002	10	3322	204.4	198.6	3.29	3.28	
TP0360	18: 6: 2	3.18	8.89	1.003	14	2311	204.3	198.6	3.32		
TP0362	18: 7:31	2.85	7.90	1.204	9	2248	204.2	198.6	3.34	3.33	3.32 +/- 0.09
TP0262	18: 8:28	2.81	7.70	1.203	10	1203	203.9	198.3	3.30		
TP0260	18: 9:27	3.24	8.69	1.003	10	1194	204.0	198.5	3.41	3.36	
TP0160	18:17: 7	3.30	8.50	1.003	15	564	203.9	198.6	3.44		
TP0162	18:18:41	2.95	7.57	1.204	9	571	203.9	198.6	3.44	3.44	

Table 2e. TP15 Conductivity Results (Repeat Cycle).

FILE	START TIME	COND	PWR	P.R. #PIS	P	T(R1)	T(R5)	CORP COND	P.R. AVG	P AVG
TP0520	22:16:30	3.79	11.20	1.003	7	4492	67.4	62.2	3.85	
TP0522	22:17:27	3.35	9.90	1.204	8	4503	67.5	62.3	3.82	3.83
TP0422	22:18:18	3.27	9.06	1.203	10	3408	67.1	62.3	3.81	
TP0420	22:19:15	3.60	10.08	1.003	10	3333	67.2	62.3	3.75	3.78
TP0320	23: 3:28	3.51	9.23	1.003	9	2270	66.7	62.2	3.78	
TP0322	23: 4:35	3.11	8.14	1.202	8	2222	66.7	62.2	3.74	3.76
TP0222	23: 5:42	2.96	7.30	1.205	7	1180	66.3	62.2	3.65	
TP0220	23: 6:21	3.34	8.20	1.003	5	1165	66.4	62.2	3.65	3.65
TP0120	23:14:25	3.31	7.80	1.003	11	563	66.0	62.1	3.80	
TP0122	23:15:43	2.91	6.92	1.203	8	562	66.1	62.1	3.73	3.76
TP0540	24: 3:10	3.29	10.25	1.003	15	4509	138.2	132.4	3.42	
TP0542	24: 4:43	2.93	9.11	1.204	9	4497	138.2	132.4	3.40	3.41
TP0442	24: 5:56	2.93	8.68	1.204	6	3483	137.9	132.4	3.52	
TP0440	24: 6:36	3.28	9.73	1.002	10	3388	137.9	132.4	3.52	3.52
TP0340	24:14: 7	3.18	9.08	1.003	18	2279	137.5	132.3	3.51	
TP0342	24:15:48	2.82	8.04	1.204	10	2242	137.5	132.3	3.48	3.48
TP0242	24:17: 9	2.82	7.57	1.204	6	1198	137.2	132.3	3.51	
TP0240	24:17:54	3.18	8.57	1.002	9	1183	137.2	132.4	3.54	3.53
TP0140	25: 1:48	3.17	8.31	1.003	11	576	137.2	132.5	3.61	
TP0142	25: 2:56	2.81	7.37	1.203	10	579	137.2	132.5	3.58	3.60
TP0560	25:13:37	3.10	9.16	1.003	10	4529	204.4	198.6	3.12	
TP0562	25:14:50	2.81	8.12	1.204	8	4511	204.4	198.7	3.17	3.14
TP0462	25:15:46	2.75	7.85	1.202	9	3363	204.1	198.5	3.18	
TP0460	25:16:47	3.11	8.87	1.003	9	3433	204.2	198.6	3.21	3.20
TP0360	26: 0:21	3.04	8.38	1.003	16	2261	203.9	198.4	3.13	
TP0362	26: 1:53	2.70	7.42	1.203	10	2277	204.0	199.5	3.11	3.12
TP0262	26: 3: 9	2.75	7.19	1.204	7	1159	203.7	198.4	3.18	
TP0260	26: 3:54	2.95	8.08	1.002	10	1129	203.8	198.1	3.04	3.11
TP0160	26:14:31	3.10	8.06	1.003	15	553	203.4	198.2	3.21	
TP0162	26:16: 0	2.70	7.11	1.204	10	523	203.5	198.2	3.12	3.17

Table 2f. TPX (Pyroceram 9606) Conductivity Results.

FILE	START TIME	COND	PWR	P.R.	#PTS	P	T(R1)	T(R5)
TP0510	22:18:15	4.43	10.09	1.004	19	4516	32.1	29.3
TP0512	22:20:06	3.99	8.79	1.202	9	4499	32.3	29.6
TP0412	22:21:21	3.87	7.90	1.204	6	3390	32.0	29.7
TP0410	22:22:16	4.39	8.85	1.003	7	3398	32.1	29.8
TP0310	23:05:30	4.17	8.53	1.003	17	2263	30.6	28.3
TP0312	23:07:25	3.75	7.55	1.203	7	2334	30.7	28.4
TP0212	23:08:27	3.70	6.54	1.203	7	1189	30.2	28.3
TP0210	23:09:20	4.12	7.34	1.004	8	1175	30.3	28.3
TP0110	23:17:47	4.01	6.88	1.003	15	577	29.7	28.0
TP0112	23:19:12	3.58	6.01	1.204	10	573	29.9	28.3
TP0520	24:16:10	4.10	9.94	1.002	17	4501	68.2	65.2
TP0522	24:18:11	3.71	8.75	1.202	6	4489	68.2	65.3
TP0422	24:18:46	3.63	8.16	1.205	11	3442	67.9	65.2
TP0420	24:19:56	4.07	9.02	1.004	9	3325	67.9	65.3
TP0320	25:03:26	3.89	8.30	1.004	16	2248	67.5	65.2
TP0322	25:05:00	3.42	7.32	1.205	10	2281	67.5	65.1
TP0222	25:06:12	3.42	6.71	1.204	8	1201	67.1	64.9
TP0220	25:06:55	3.79	7.53	1.004	11	1198	67.2	65.0
TP0120	25:14:42	3.80	7.11	1.002	15	574	66.9	65.0
TP0122	25:16:10	3.44	6.31	1.202	10	580	66.9	65.1
TP0530	25:22:31	3.79	10.00	1.002	17	4497	104.5	101.5
TP0532	26:00:30	3.36	8.80	1.203	7	4487	104.6	101.6
TP0432	26:01:26	3.44	8.35	1.203	8	3501	104.3	101.5
TP0430	26:02:10	3.87	9.33	1.003	11	3408	104.3	101.5
TP0330	26:09:45	3.75	8.66	1.002	18	2311	103.8	101.3
TP0332	26:11:31	3.36	7.66	1.204	9	2273	103.8	101.4
TP0232	26:12:31	3.25	7.14	1.203	9	1189	103.5	101.3
TP0230	26:13:25	3.64	8.01	1.003	10	1178	103.5	101.3
TP0130	26:21:10	3.46	7.71	1.002	15	573	103.7	101.5
TP0132	26:22:35	3.10	6.84	1.202	10	579	103.6	101.6
TP0540	27:05:06	3.55	9.70	1.002	16	4488	139.6	136.7
TP0542	27:06:40	3.15	8.61	1.203	10	4489	139.6	136.7
TP0442	27:07:41	3.19	8.28	1.204	10	3490	139.3	136.6
TP0440	27:08:35	3.56	9.27	1.003	11	3380	139.3	136.6
TP0340	27:16:36	3.53	8.72	1.002	12	2302	138.9	136.5
TP0342	27:17:48	3.06	7.60	1.205	10	2237	139.0	136.6
TP0242	27:18:59	3.02	7.17	1.204	8	1186	138.7	136.4
TP0240	27:19:49	3.39	8.17	1.004	10	1173	138.8	136.5
TP0140	28:03:48	3.32	7.61	1.003	12	575	138.7	136.6
TP0142	28:04:53	2.94	6.75	1.203	11	580	138.7	136.5
TP0550	28:11:34	3.53	9.44	1.001	15	4503	169.6	166.7
TP0552	28:13:13	3.16	8.40	1.203	8	4571	169.6	166.8
TP0452	28:14:14	3.10	8.03	1.203	8	3388	169.4	166.7
TP0450	28:15:04	3.49	9.06	1.004	10	3358	169.4	166.7
TP0350	28:22:34	3.41	8.61	1.003	17	2266	169.3	166.7
TP0352	29:00:08	3.05	7.69	1.204	11	2266	169.3	166.8
TP0252	29:01:15	3.08	7.38	1.203	10	1189	169.0	166.5
TP0250	29:02:14	3.42	8.29	1.003	10	1178	169.0	166.6
TP0150	29:09:46	3.33	7.90	1.002	17	573	168.9	166.5
TP0152	29:11:28	2.98	7.01	1.203	9	581	168.9	166.6
TP0560	29:17:48	3.49	9.48	1.004	17	4495	206.7	203.5
TP0562	29:19:33	3.08	8.39	1.204	9	4521	206.7	203.6
TP0462	29:20:28	3.06	8.14	1.204	10	3466	206.5	203.5
TP0460	29:21:29	3.42	9.15	1.003	10	3382	206.6	203.6
TP0360	30:05:09	3.34	8.92	1.003	15	2264	206.7	203.8
TP0362	30:06:49	2.98	7.86	1.205	8	2264	206.7	203.8
TP0262	30:07:51	2.97	7.67	1.203	8	1198	206.5	203.7
TP0260	30:08:45	3.30	8.67	1.002	5	1187	206.6	203.8
TP0160	30:16:31	3.33	8.20	1.003	13	574	206.1	203.5
TP0162	30:17:50	3.00	7.33	1.204	10	566	206.1	203.5

Table 2g. TPX (Pyroceram 9606) Conductivity Results (Repeat Cycle).

FILE	START TIME	COND	PWR	P.R.	#PTS	P	T(R1)	T(R5)
TP0520	3: 0:22	3.72	10.02	1.003	19	4504	68.1	65.3
TP0522	3: 2:10	3.34	8.81	1.204	10	4512	68.1	65.4
TP0422	3: 3:14	3.27	8.15	1.204	9	3425	67.8	65.3
TP0420	3: 4:10	3.68	9.17	1.003	10	3372	67.8	65.4
TP0320	3:11:40	3.53	8.29	1.003	17	2254	67.2	65.2
TP0322	3:13:19	3.20	7.39	1.205	10	2290	67.3	65.2
TP0222	3:14:26	3.08	6.69	1.204	9	1184	66.8	65.0
TP0220	3:15:15	3.49	7.56	1.003	11	1180	66.9	65.1
TP0120	3:22:50	3.34	7.13	1.003	17	572	66.6	64.8
TP0122	4: 0:29	2.98	6.30	1.205	10	580	66.7	64.9
TP0540	4: 8:44	3.50	9.68	1.003	17	4520	139.3	136.5
TP0542	4:10:33	3.10	8.57	1.202	8	4509	139.4	136.5
TP0442	4:11:24	3.01	8.19	1.203	10	3456	139.1	136.4
TP0440	4:12:19	3.38	9.19	1.003	11	3395	139.1	136.4
TP0340	4:20: 0	3.28	8.57	1.003	16	2237	138.9	136.4
TP0342	4:21:43	2.94	7.65	1.203	8	2325	138.9	136.4
TP0242	4:22:34	2.89	7.23	1.203	10	1219	138.6	136.3
TP0240	4:23:39	3.27	8.19	1.002	7	1208	138.6	136.4
TP0140	5: 7:20	3.16	7.67	1.002	14	572	138.4	136.3
TP0142	5: 8:44	2.57	6.84	1.202	10	575	138.4	136.3
TP0560	5:11:50	3.46	9.37	1.003	17	4511	206.3	203.3
TP0562	5:20:38	3.07	8.33	1.204	8	4514	206.3	203.3
TP0462	5:21:29	3.01	8.01	1.204	10	3445	206.1	203.2
TP0460	5:22:29	3.35	8.96	1.003	10	3327	206.2	203.2
TP0360	6: 5:52	3.34	8.68	1.004	17	2266	206.2	203.4
TP0362	6: 7:48	3.03	7.78	1.200	8	2246	206.2	203.4
TP0262	6: 8:39	2.99	7.57	1.204	10	1200	206.0	203.4
TP0260	6: 9:33	3.39	8.55	1.002	11	1189	206.0	203.4
TP0160	6:17:26	3.37	8.27	1.003	14	553	205.8	203.4
TP0162	6:18:49	2.95	7.32	1.204	10	548	205.9	203.4

EXPLANATION OF TABLE 3

In the following tables, the column heads are defined as:

FILE	Name of the raw data file, coded by pressure (third digit from the right: 1 = 3.8 MPa, 2 = 7.8 MPa, 3 = 15.5 MPa, 4 = 23.3 MPa, and 5 = 31.0 MPa) and temperature (second digit from the right: 1 = 303 K, 2 = 338 K, 3 = 373 K, 4 = 408 K, 5 = 438 K).
DIFFUSIVITY	In units of $10^{-6} \text{ m}^2/\text{s}$
RAW	As calculated by the iterative data reduction routine (Durham et al., 1983).
CORR	Raw Diffusivity corrected for Pyroceram results (see text). These are the values plotted in Figure 8.
P AVG	Average and one standard deviation of Corr Diffusivity over the (usually) five values at fixed T. These are the values used to plot the curves in Figure 13.

Table 3a. TP12 Diffusivity Results.

FILE	RAW	DIFFUSIVITY	
		CORR	P AVG
TK0510	1.83	2.74	
TK0410	1.71	2.57	
TK0310	1.61	2.46	2.56 +/- 0.13
TK0210	1.53	2.40	
TK0110	1.63	2.61	
TK0520	1.43	2.14	
TK0420	1.41	2.12	
TK0320	1.35	2.06	2.06 +/- 0.13
TK0220	1.36	2.13	
TK0120	1.15	1.84	
TK0530	1.30	1.95	
TK0430	1.28	1.92	
TK0330	1.25	1.91	1.94 +/- 0.03
TK0230	1.24	1.94	
TK0130	1.24	1.98	
TK0540	1.23	1.84	
TK0440	1.18	1.77	
TK0340	1.16	1.77	1.77 +/- 0.04
TK0240	1.11	1.74	
TK0140	1.09	1.74	
TK0550	1.04	1.56	
TK0450	1.10	1.65	
TK0350	1.11	1.69	1.66 +/- 0.06
TK0250	1.07	1.68	
TK0150	1.06	1.70	
TK0560	1.08	1.62	
TK0460	1.04	1.56	
TK0360	0.99	1.51	1.53 +/- 0.07
TK0260	0.97	1.52	
TK0160	0.89	1.42	

Table 3b. TP13 Diffusivity Results.

FILE	RAW	DIFFUSIVITY	
		CORR	P AUG
TK0210	3.05	4.78	
TK0110	2.45	3.92	4.35
TK0120	2.14	3.42	3.42
TK0130	2.34	3.74	3.74
TK0240	1.94	3.04	
TK0140	1.88	3.01	3.03
TK0150	1.80	2.88	2.88
TK0160	1.26	2.02	2.02

Table 3c. TP14 Diffusivity Results.

FILE	RAW	DIFFUSIVITY	
		CORR	P AVG
TK0510	1.97	2.95	2.88 +/- 0.08
TK0410	1.88	2.83	
TK0310	1.95	2.98	
TK0210	1.80	2.82	
TK0110	1.77	2.83	
TK0520	1.59	2.38	2.26 +/- 0.10
TK0420	1.55	2.33	
TK0320	1.45	2.21	
TK0220	1.35	2.12	
TK0120	1.40	2.24	
TK0530	1.46	2.19	2.21 +/- 0.03
TK0430	1.44	2.17	
TK0330	1.46	2.23	
TK0230	1.44	2.26	
TK0130	1.38	2.21	
TK0540	1.37	2.05	2.01 +/- 0.04
TK0440	1.30	1.95	
TK0340	1.33	2.03	
TK0240	--	--	
TK0140	1.25	2.00	
TK0550	1.21	1.81	1.87 +/- 0.03
TK0450	1.25	1.88	
TK0350	1.23	1.88	
TK0250	1.20	1.88	
TK0150	1.19	1.90	
TK0560	1.17	1.75	1.74 +/- 0.01
TK0460	1.15	1.73	
TK0360	1.13	1.73	
TK0260	--	--	
TK0160	1.09	1.74	

Table 3d. TP15 Diffusivity Results.

FILE	RAW	DIFFUSIVITY CDRR	P AVG
TK0510	2.47	3.70	
TK0410	2.61	3.92	
TK0310	2.47	3.77	3.80 +/- 0.11
TK0210	--	--	
TK0110	--	--	
TK0520	--	--	
TK0420	2.56	3.85	
TK0320	2.91	4.44	3.71 +/- 0.81
TK0220	--	--	
TK0120	1.77	2.83	
TK0530	2.55	3.82	
TK0430	--	--	
TK0330	--	--	3.70 +/- 0.18
TK0230	--	--	
TK0130	2.23	3.57	
TK0540	2.24	3.35	
TK0440	1.95	2.93	
TK0340	2.35	3.59	3.33 +/- 0.26
TK0240	2.08	3.26	
TK0140	2.21	3.54	
TK0550	1.74	2.60	
TK0450	1.75	2.63	
TK0350	--	--	2.67 +/- 0.09
TK0250	1.77	2.77	
TK0150	--	--	
TK0560	1.63	2.44	
TK0460	1.65	2.48	
TK0360	1.49	2.27	2.49 +/- 0.19
TK0260	1.78	2.79	
TK0160	1.55	2.48	

Table 3e. TP15 Diffusivity Results (Repeat Cycle).

FILE	RAW	DIFFUSIVITY CDRR	P AVG
TK0520	--	--	
TK0420	--	--	
TK0320	--	--	3.78 +/- 0.37
TK0220	2.04	3.52	
TK0120	2.35	4.04	
TK0540	1.89	2.89	
TK0440	2.18	3.33	
TK0340	2.07	3.18	3.13 +/- 0.22
TK0240	--	--	
TK0140	--	--	
TK0560	1.70	2.54	
TK0460	1.75	2.65	
TK0360	--	--	2.58 +/- 0.06
TK0260	1.63	2.55	
TK0160	--	--	

Table 3f. TPX Diffusivity Results.

FILE	DIFFUSIVITY
TK0510	1.30
TK0410	1.23
TK0310	1.19
TK0210	1.20
TK0110	1.15
TK0520	1.17
TK0420	1.16
TK0320	1.09
TK0220	1.06
TK0120	1.09
TK0530	1.00
TK0430	1.09
TK0330	1.01
TK0230	0.95
TK0130	1.05
TK0540	0.93
TK0440	0.96
TK0340	--
TK0240	--
TK0140	1.02
TK0550	0.93
TK0450	0.88
TK0350	0.93
TK0250	--
TK0150	0.79
TK0560	0.87
TK0460	0.90
TK0360	0.91
TK0260	0.89
TK0160	0.85

Table 3g. TPX Diffusivity Results (Repeat Cycle).

FILE	DIFFUSIVITY
TK0520	1.05
TK0420	1.08
TK0320	0.98
TK0220	0.98
TK0120	1.03
TK0540	0.95
TK0440	0.99
TK0340	0.96
TK0240	0.91
TK0140	0.94
TK0560	0.91
TK0460	0.89
TK0360	0.88
TK0260	0.84
TK0160	0.82

Table 4a. Conductivity (λ) Data, Sample LP1 (Anhydrite).

P (MPa)	Probe Power (W)	λ (W/m·K)	Vessel Temp (K)	Linear Range (s)
30.0	5	5.42	Room T	65 - 200
22.5	5	5.51	Room T	80 - 200
15.0	5	5.22	Room T	80 - 200
15.0	5	5.39	Room T	60 - 200
7.5	5	5.40	Room T	60 - 200
3.0	5	6.84	Room T	80 - 200
0.1	5	5.22	Room T	60 - 140
22.5	5	5.03	333	60 - 175
15.0	5	4.79	333	60 - 140
7.5	5	4.78	333	60 - 200
3.0	5	5.14	333	60 - 200
0.1	5	4.90	333	60 - 195
30.0	5	4.45	359	90 - 190
30.0	10	4.11	359	115 - 225
30.0	10	4.64	358	60 - 200
30.0	5	5.51	358	115 - 285
22.5	5	4.77	359	85 - 240
22.5	10	4.65	359	60 - 200
15.0	5	4.73	359	60 - 200
15.0	10	4.63	359	60 - 200
7.5	5	4.79	359	60 - 200
7.5	10	4.61	359	60 - 200
3.0	5	4.83	359	60 - 200
3.0	10	4.58	359	60 - 200
0.1	5	4.94	359	60 - 200
0.1	10	4.51	359	60 - 200

Table 4b. Conductivity (λ) Data, Sample LP2 (Dolomite).

P (MPa)	Probe Power (W)	λ (W/m·K)	Vessel Temp (K)	Linear Range (s)
30.0	5	2.05	308	75 - 245
30.0	10	2.47	307	75 - 245
22.5	5	2.84	306	75 - 245
22.5	10	2.54	306	75 - 245
15.0	5	2.99	306	75 - 245
30.0	5	1.98	299	75 - 245
30.0	10	2.51	299	75 - 245
15.0	10	2.55	299	90 - 245
7.5	5	2.64	299	90 - 245
7.5	10	2.48	299	90 - 245
3.0	5	2.64	299	75 - 245
3.0	10	2.52	299	75 - 245
0.1	5	2.67	299	75 - 245
0.1	10	2.50	299	75 - 245
30.0	5	2.38	333	75 - 245
30.0	10	2.37	333	75 - 245
22.5	5	2.44	333	75 - 245
22.5	10	2.39	333	75 - 245
15.0	5	2.43	333	75 - 245
15.0	10	2.43	333	75 - 245
7.5	5	2.43	333	75 - 200
7.5	10	2.37	333	90 - 245
3.0	5	2.46	333	60 - 200
3.0	10	2.41	333	60 - 200
0.1	5	2.43	333	75 - 245
0.1	10	2.38	333	60 - 200
30.0	5	2.31	358	60 - 200
30.0	10	2.45	358	75 - 245
22.5	5	2.35	358	75 - 245
22.5	10	2.41	358	75 - 245
15.0	5	2.38	358	60 - 200
15.0	10	2.34	358	75 - 200
7.5	5	2.25	358	75 - 180
7.5	10	2.32	358	75 - 245
3.0	5	2.39	358	75 - 245
3.0	10	2.36	358	75 - 245
0.1	5	2.37	358	75 - 245
0.1	10	2.30	358	75 - 200

Table 4c. Conductivity (λ) Data, Sample LP3 (Anhydrite).

P (MPa)	Probe Power (W)	λ (W/m·K)	Vessel Temp (K)	Linear Range (s)
30.0	5	4.05	297	60 - 200
30.0	10	5.25	297	60 - 200
22.5	5	6.04	297	60 - 200
22.5	10	5.22	297	60 - 200
15.0	5	5.66	297	60 - 200
15.0	10	5.37	297	60 - 200
7.5	5	5.16	297	60 - 200
7.5	10	5.10	297	60 - 200
3.0	5	5.27	297	60 - 200
3.0	10	5.14	297	60 - 200
0.1	5	5.15	297	60 - 195
0.1	10	5.09	297	60 - 200
30.0	5	4.22	333	60 - 200
30.0	10	4.40	333	60 - 200
22.5	5	4.75	333	60 - 200
22.5	10	4.42	333	60 - 200
15.0	5	4.76	333	60 - 200
15.0	10	4.42	333	60 - 200
7.5	5	4.63	333	60 - 200
7.5	10	4.37	333	60 - 200
3.0	5	4.59	333	60 - 200
3.0	10	4.48	333	60 - 200
0.1	5	4.60	333	60 - 200
0.1	10	4.47	333	60 - 200
30.0	5	3.53	358	90 - 145
30.0	10	3.94	358	90 - 135
22.5	5	4.24	358	60 - 200
22.5	10	3.96	358	60 - 200
15.0	5	4.42	358	60 - 200
15.0	10	4.22	358	120 - 200
7.5	5	4.53	358	60 - 200
7.5	10	4.08	358	60 - 200
3.0	5	4.47	358	60 - 200
3.0	10	4.03	358	60 - 200
0.1	5	4.26	358	60 - 200
0.1	10	4.01	358	60 - 200

Table 4d. Conductivity (λ) Data, Sample LP4 (Dolomite).

<u>P (MPa)</u>	<u>Probe Power (W)</u>	<u>λ(W/m·K)</u>	<u>Vessel Temp (K)</u>	<u>Linear Range (s)</u>
30.0	5	3.42	298	200 - 400
30.0	10	3.43	298	200 - 400
22.5	5	3.44	298	190 - 400
22.5	10	3.23	298	200 - 400
15.0	10	3.25	298	200 - 400
7.5	5	3.41	298	200 - 400
7.5	10	3.28	298	200 - 400
3.0	5	3.32	298	200 - 400
3.0	10	3.19	298	200 - 400
0.1	5	3.19	298	200 - 400
0.1	10	3.21	298	200 - 400
30.0	5	3.16	333	200 - 400
30.0	10	3.20	333	200 - 400
22.5	5	3.14	333	200 - 400
22.5	10	3.12	333	200 - 400
15.0	5	3.25	333	200 - 400
15.0	10	3.13	333	200 - 400
7.5	5	3.20	333	200 - 400
7.5	10	3.09	333	200 - 400
3.0	5	3.13	333	200 - 400
3.0	10	3.11	333	200 - 400
0.1	5	3.07	333	200 - 400
0.1	10	3.04	333	200 - 400
30.0	5	3.12	358	200 - 400
30.0	10	3.20	358	200 - 400
22.5	5	3.07	358	200 - 400
22.5	10	3.09	358	200 - 400
15.0	5	3.08	358	200 - 400
15.0	10	3.09	358	200 - 400
7.5	5	3.10	358	200 - 400
7.5	10	3.06	358	200 - 400
3.0	5	3.05	358	200 - 400
3.0	10	2.85	358	200 - 400
0.1	5	2.94	358	200 - 400
0.1	10	2.93	358	200 - 400

Table 4e. Conductivity (λ) Data, Pyroceram Code 9606.

P (MPa)	Probe Power (W)	λ (W/m $\cdot$ K)	Vessel Temp (K)	Linear Range (s)	T _{probe at 300 s} (K)
30.0	10	4.04	299	75 - 300	309
30.0	5	3.72	299	75 - 300	309
30.0	5	3.81	299	75 - 300	303
22.5	5	4.32	299	75 - 300	303
22.5	10	3.79	298	75 - 300	308
15.0	5	3.75	298	75 - 300	302
15.0	10	3.72	298	75 - 300	308
7.5	5	3.79	299	75 - 300	305
7.5	10	3.86	299	75 - 250	311
3.0	5	3.82	299	75 - 300	305
3.0	10	3.75	299	75 - 300	311
0.1	5	3.71	299	75 - 300	305
0.1	10	3.66	299	75 - 300	311
30.0	5	3.48	333	75 - 300	339
30.0	10	3.52	333	75 - 300	347
22.5	5	3.53	333	75 - 300	340
22.5	10	3.53	333	75 - 300	347
15.0	5	3.56	333	75 - 300	340
15.0	10	3.57	333	75 - 300	347
7.5	5	3.53	333	75 - 300	339
7.5	10	3.56	333	75 - 300	347
3.0	5	3.56	333	75 - 300	340
3.0	10	3.59	333	75 - 300	347
0.1	5	3.53	333	75 - 300	340
0.1	10	3.58	333	75 - 300	347
30.0	5	3.25	358	75 - 300	365
30.0	10	3.46	358	75 - 300	372
22.5	5	3.52	358	75 - 300	366
22.5	10	3.50	358	75 - 300	373
15.0	5	3.56	358	75 - 300	366
15.0	10	3.50	358	75 - 300	373
7.5	5	3.49	358	75 - 300	365
7.5	10	3.46	358	75 - 300	373
3.0	5	3.46	358	75 - 300	366
3.0	10	3.50	358	75 - 300	373
0.1	5	3.46	358	75 - 300	365
0.1	10	3.48	358	75 - 300	372

Table 5a. Diffusivity (κ) Data, Sample KP1 (Anhydrite).

<u>P (MPa)</u>	<u>T (K)</u>	<u>$\kappa(\times 10^{-6} \text{ m}^2/\text{s})$</u>	<u>No. of Measurements</u>
30.0 $\pm$ 1.0	319.0	2.13 $\pm$.01	10
22.5 $\pm$ 1.0	319.0	2.13 $\pm$.02	15
15.4 $\pm$ 0.2	316.0	2.14 $\pm$.03	5
7.8 $\pm$ 0.2	313.0	2.14 $\pm$.01	6
3.2 $\pm$ 0.2	328.5	2.00 $\pm$.04	9
29.7 $\pm$ 0.3	338.5	1.95 $\pm$.03	13
22.7 $\pm$ 0.1	338.5	1.94 $\pm$.02	5
15.4 $\pm$ 0.1	336.5	1.93 $\pm$.04	7
7.8 $\pm$ 0.3	339.0	1.92 $\pm$.04	5
2.8 $\pm$ 0.3	344.0	1.95 $\pm$.01	13
0.1 ^a	339.5	1.92 $\pm$.01	8
30.3 $\pm$ 0.3	363.5	1.75 $\pm$.02	5
22.6 $\pm$ 0.1	363.0	1.73 $\pm$.02	5
15.1	363.5	1.73 $\pm$.01	4
7.5	365.0	1.74 $\pm$.01	5
3.0	363.5	1.80 $\pm$.01	12
0.1	362.0	1.84 $\pm$.01	10

^aNo indicated limits means P was steady to ± 0.05 MPa.

Table 5b. Diffusivity (κ) Data, Sample KP2 (Dolomite).

<u>P (MPa)</u>	<u>T (K)</u>	<u>$\kappa(\times 10^{-6} \text{ m}^2/\text{s})$</u>	<u>No. of Measurements</u>
29.7 $\pm$ 0.3	311.5	1.30 $\pm$.02	5
22.4 $\pm$ 0.3	315.5	1.29 $\pm$.01	6
15.0 ^a	316.5	1.29 $\pm$.01	8
7.5 $\pm$ 0.1	317.5	1.30 $\pm$.01	17
2.5 $\pm$ 0.5	335.0	1.18 $\pm$.01	18
30.2 $\pm$ 0.5	338.5	1.20 $\pm$.03	4
22.5 $\pm$ 0.3	338.5	1.21 $\pm$.01	5
15.2 $\pm$ 0.1	338.5	1.23 $\pm$.02	5
7.6	339.5	1.20 $\pm$.01	6
3.0 $\pm$ 0.1	341.0	1.19 $\pm$.02	4
0.1	343.5	1.18 $\pm$.01	10
29.5 $\pm$ 0.5	364.5	1.13 $\pm$.01	5
22.6 $\pm$ 0.4	363.5	1.13 $\pm$.02	6
15.0	365.0	1.13 $\pm$.02	7
7.5	364.5	1.11 $\pm$.02	5
3.1	366.0	1.11 $\pm$.01	5
0.1	367.0	1.10 $\pm$.01	25

^aNo indicated limits means P was steady to ± 0.05 MPa.

Table 5c. Diffusivity (κ) Data, Sample KP3 (Anhydrite).

<u>P (MPa)</u>	<u>T (K)</u>	<u>$\kappa(\times 10^{-6} \text{ m}^2/\text{s})$</u>	<u>No. of Measurements</u>
27 $\pm$ 2	309.5	2.37 $\pm$.02	4
22.5 $\pm$ 2	311.5	2.38 $\pm$.02	11
15.0 $\pm$ 1.5	315.0	2.32 $\pm$.02	7
7.8 ^a	311.0	2.22 $\pm$.02	7
3.2	330.0	2.25 $\pm$.01	5
30.0 $\pm$ 1.2	338.0	2.10 $\pm$.04	5
22.9 $\pm$ 0.3	338.0	2.11 $\pm$.02	5
15.0	337.0	2.13 $\pm$.02	5
7.5	335.5	2.17 $\pm$.06	4
3.3	339.0	2.18 $\pm$.02	5
0.1	341.5	2.07 $\pm$.01	5
29.8 $\pm$ 0.8	364.0	1.87 $\pm$.05	5
22.8 $\pm$ 0.3	364.0	1.87 $\pm$.02	4
14.9 $\pm$ 0.1	364.5	1.87 $\pm$.03	5
7.6	362.0	1.92 $\pm$.02	5
3.0 $\pm$ 0.1	363.5	1.93 $\pm$.03	5
0.1	363.0	1.91 $\pm$.04	18

^aNo indicated limits means P was steady to ± 0.05 MPa.

Table 5d. Diffusivity (κ) Data, Sample KP4 (Dolomite).

<u>P (MPa)</u>	<u>T (K)</u>	<u>$\kappa(\times 10^{-6} \text{ m}^2/\text{s})$</u>	<u>No. of Measurements</u>
30.4 $\pm$ 0.4	312.0	1.43 $\pm$.01	4
22.7 ^a	313.0	1.44 $\pm$.01	5
15.1 $\pm$ 0.1	313.0	1.43 $\pm$.01	5
7.7 $\pm$ 0.2	310.5	1.43 $\pm$.01	10
3.5 $\pm$ 0.1	333.0	1.28 $\pm$.01	17
30.0 $\pm$ 0.2	338.0	1.28 $\pm$.01	5
22.4 $\pm$ 0.1	340.5	1.27 $\pm$.04	4
15.4	340.0	1.24 $\pm$.04	4
7.6	341.5	1.24 $\pm$.03	8
3.1	340.5	1.25 $\pm$.01	10
0.1	344.0	1.24 $\pm$.01	10
30.2	366.0	1.17 $\pm$.01	4
22.7	364.0	1.17 $\pm$.01	3
15.2 $\pm$ 0.2	365.0	1.17 $\pm$.02	6
7.6	364.5	1.15 $\pm$.02	4
2.9 $\pm$ 0.1	367.0	1.13 $\pm$.01	7
0.1	366.0	1.14 $\pm$.01	10

^aNo indicated limits means P was steady to ± 0.05 MPa.

Table 5e. Diffusivity (κ) Data, Pyroceram Code 9606.

<u>P (MPa)</u>	<u>T (K)</u>	<u>$\kappa(\times 10^{-6} \text{ m}^2/\text{s})$</u>	<u>No. of Measurements</u>
30.8 $\pm$ 1.6	314.0	1.88 $\pm$.02	6
23.0 $\pm$ 1.3	313.0	1.93 $\pm$.02	5
15.0 $\pm$ 0.7	307.0	1.82 $\pm$.04	7
7.8 $\pm$ 0.3	308.5	1.90 $\pm$.04	9
2.5 $\pm$ 0.5	333.0	1.89 $\pm$.03	6
31.2 $\pm$ 1.5	338.0	1.88 $\pm$.03	5
22.4 $\pm$ 0.8	337.5	1.87 $\pm$.03	5
15.4 $\pm$ 0.2	337.0	1.88 $\pm$.02	5
7.9 $\pm$ 0.5	341.0	1.89 $\pm$.03	5
3.0 $\pm$ 0.2	343.5	1.92 $\pm$.01	5
0.1 ^a	347.5	2.01 $\pm$.01	10
2.5 $\pm$ 0.5	344.0	1.88 $\pm$.03	4
29.7 $\pm$ 2.6	363.5	1.71 $\pm$.02	5
23.6 $\pm$ 2.0	364.5	1.69 $\pm$.02	5

^aNo indicated limits means P was steady to ± 0.05 MPa.

Table 6. Coefficient of Thermal Linear Expansion (in units of 10^{-6} K^{-1}).

Anhydrite						
Sample	T (K)	P (MPa)				
		30	22.5	15.0	7.5	3.0
XP1	308	6.6	6.6	6.6	11.4	16.2
XP3	309	9.4	10.2	10.2	10.2	15.5
XP1	338	9.4	8.7	8.7	5.6	6.4
XP3	339	5.8	8.7	12.2	14.4	13.0
XP1	373	6.3	6.8	5.7	3.0	4.1
XP3	374	5.1	6.8	7.4	11.3	12.4
Dolomite						
XP2	307	5.0	5.7	4.3	5.7	10.1
XP4	307	2.2	3.8	5.8	5.8	8.6
XP2	338	3.6	4.3	4.3	5.8	9.7
XP4	338	5.8	6.5	8.7	8.7	7.2
XP2	373	4.0	5.7	7.4	6.8	11.2
XP4	373	7.9	6.8	6.3	10.7	12.9

Table 7. Coefficient of Thermal Linear Expansion (in units of 10^{-6} K^{-1}).

Sample	T (K)	P		
		25 MPa	10 MPa	3 MPa
XP5	309	28.8	30.9	30.6
XP6	308	34.6	35.9	34.7
XP7	308	14.9	33.7	35.5
XP8	307	35.1	42.3	39.6
AVERAGE		28.4 ± 8.2	35.7 ± 4.2	35.1 ± 3.2
XP5	338	35.3	33.5	37.4
XP6	338	35.3	30.3	33.3
XP7	340	30.6	35.2	39.5
XP8	338	30.2	39.0	35.6
AVERAGE		32.9 ± 2.5	34.5 ± 3.2	36.5 ± 2.3
XP5	373	36.4	35.3	37.3
XP6	373	34.2	34.9	36.0
XP7	374	432.9	45.9	32.2
XP8	373	39.8	40.4	36.9
AVERAGE		35.8 ± 2.6	39.1 ± 4.5	35.6 ± 2.0
XP5	413	34.4	35.1	34.9
XP6	413	31.0	31.9	32.3
XP7	413	43.0	52.7	40.5
XP8	413	36.3	33.9	29.6
AVERAGE		36.2 ± 4.4	38.4 ± 8.3	34.3 ± 4.0
XP5	453	35.5	36.4	36.4
XP6	454	38.0	27.8	32.9
XP7	453	33.4	40.7	39.4
XP8	453	28.5	34.9	29.5
AVERAGE		33.9 ± 3.5	35.0 ± 4.6	34.6 ± 3.7
XP5	493	35.8	30.7	40.1
XP6	493	32.5	33.4	34.1
XP7	493	30.0	32.2	39.7
XP8	493	34.0	33.1	33.3
AVERAGE		33.1 ± 2.1	32.4 ± 0.9	36.8 ± 3.1

1983). In the Durham et al. (1983) study, where the reader is referred to the definitions of "apparent conductivity" and "correction factor," only five different correction factors could be resolved, one for each pressure (Table A1, Durham et al., 1983). We now resolve a clear effect of temperature on the accuracy of the raw measurement, so in the application of the correction factor (Step 2 of the recipe in Appendix A, Durham et al., 1983), we use a different value for each of the 30 points in (P,T) space. As discussed in Chapter 5, Calibration and Measurement Error, we resolved a different set of correction factors for a second cycle through (P,T) space.

4.2 Diffusivity, salt. Thermal diffusivities for the four salt samples range from about 4 to $1.5 \times 10^{-6} \text{ m}^2/\text{s}$. As is the case with conductivity, diffusivities have a negative monotonic temperature dependence and no measurable pressure dependence. If we calculate a single diffusivity for each temperature (Table 3), we can compare the four samples in a single plot (Figure 14). TP12 and TP14 again exhibit similar diffusive behavior. TP15 is considerably more diffusive, and the values after (P,T) cycling are indistinguishable from those before. The peculiar sigmoidal shape of its temperature dependence is apparently real. For the reasons discussed above, however, we can't put much confidence on the values of diffusivity for TP13, the leaky single crystal.

The measured values for Pyroceram are typically 30% lower than the true values for this material. This contrasts with the earlier results by Durham et al. (1983) that found the diffusivity measurements to be accurate but rather badly scattered. The diffusivity in its "improved" mode in this study seems to give results that are much better resolved, as we had hoped, but much less accurate. We have not succeeded in identifying the cause of the inaccuracy, despite detailed but not exhaustive examination of the data reduction routine. However, since the inaccuracy is reproducible and fairly uniform throughout (P,T) space, we reduced the rock salt data by multiplying raw results by the ratio of true-to-measured Pyroceram values at each temperature. We could not distinguish a change in the correction factor with temperature. As with conductivity, we used a different set of correction factors for the repeat cycle of TP15, based on the repeat cycle on Pyroceram.

4.3 Conductivity, nonsalt. Although there were nominally three temperatures tested, the duplicate measurements at 5 and 10 W in fact gave six different temperatures because of the slight additional warming produced at 10 W. The six temperatures plotted in Figure 9 are 304.0 and 309.5 K (from a start at a vessel temperature of 299 K), 340.0 and 347.0 K (from a start at 333 K), and 365.5 and 372.5 K (from a start at 358 K) and were based on the measurements on Pyroceram (Table 4e).

Measured values of conductivity fall between 2 and about $6 \text{ W/m}\cdot\text{K}$. The anhydrites are considerably more conductive than the dolomites. All four rocks show a decreasing conductivity with increasing temperature, and none shows any obvious dependence on pressure. In sample LP4, the more conductive of the two dolomites, the distribution of conductivities as a function of pressure appears to be nonrandom, but the range of conductivity vs pressure at fixed temperature is comparable to our estimates of random measurement error.

Figure 13. Thermal conductivity vs temperature of the four Permian Basin rock salts measured in this study.

Figure 14. Thermal diffusivity vs temperature of the four Permian Basin rock salts measured in this study.

Error is discussed more fully below. Again, because of the lack of pressure dependence we can compare the conductivities of the samples on a single plot (Figure 15).

For the Pyroceram 9606 reference standard (Figure 9e), measured values of conductivity fall consistently below expected values, but only by about 5%. Given the level of uncertainty (see below), this disagreement is not significant. Figure 9e therefore demonstrates that the straight-line approximation is met for our sample geometry for Pyroceram (conductivity = $4 \text{ W/m}\cdot\text{K}$) in the time interval 75 to 300s.

4.4 Diffusivity, nonsalt. As with the conductivity results, the anhydrites show a higher diffusivity than the dolomites, all four rocks show an inverse relationship between diffusivity and temperature, and no rock shows a dependence of diffusivity upon pressure. Diffusivities of the four samples are compared in Figure 16.

Measured values for diffusivity are slightly above literature values, but may again fall within a distance comparable to measurement error (see below). There is excellent agreement between our present measurements and measurements made by us two years earlier on the same piece of Pyroceram (Mirkovich et al., 1983), assuring evidence that minor hardware changes and major electronic upgrades have not altered the quality of the measurements. [We note that the values plotted in Figure 10e from Mirkovich et al. (1983) are different from the values published by those authors. Since publication of the earlier values, we have measured the distance between thermocouple holes at $b = 11.02 \text{ mm}$ rather than the nominal 11.2 mm used by Mirkovich et al. The published values have been corrected downward by a factor of $(11.02/11.2)^2$. Data in the present work in Figure 10e and Table 5e were calculated on the basis of $b = 11.02 \text{ mm}$.]

4.5 Expansivity, nonsalt. Note that because a temperature change is required to determine expansivity, data were taken at four temperatures, approximately 293, 323, 353, and 393 K; but only three values of expansivity are given in Figure 11 and Table 6 for any given pressure.

The anhydrite samples show broad similarities in behavior. The range of values for expansivity generally decreases with temperature from $6\text{--}16$ and $9\text{--}16 \times 10^{-6} \text{ K}^{-1}$ at 308 K, to $6\text{--}4$ and $5\text{--}12 \times 10^{-6} \text{ K}^{-1}$ at 373 K for samples XP1 and XP3, respectively. The latter sample indicates a marked pressure effect on expansivity with higher expansivity values at the lowest pressures. In sample XP1, the above observation seems to hold only the lowest temperature; at 338 to 373 K, expansivity decreases with pressure. Although both effects have been noted in crystalline igneous rocks identically tested (Heard, 1980; Page and Heard, 1981; Heard and Page, 1982), an increase in expansivity with temperature and a decrease with pressure is the most common pattern. In those earlier studies, grain boundary cracking and the opening (and closing) of such cracks can dominate the expansivity behavior at pressure and temperature. Data are not available from the literature concerning expansivity as a function of crystal direction in single crystals of anhydrite or in expansivity as measured on porous aggregates.

Figure 15. Summary of thermal conductivity measurements for anhydrite and dolomite. The solid lines are estimated fits to the data in Figure 9. The error bars depict the estimated $\pm 5\%$ random measurement error. The absolute uncertainty has not yet been fully quantified (see text).

Figure 16. Summary of thermal diffusivity measurements for anhydrite and dolomite. The solid lines are estimated fits to the data in Figure 10. The error bars depict the analysis in Table 9. The absolute (total systematic) uncertainty is $\pm 4\%$, but the relative systematic uncertainty among the four rocks here is only $\pm 2.4\%$ because the thermocouple positions were not switched (Item 6, Table 9). The total amount of uncertainty in any single measurement includes an additional scatter of $\pm 5.6\%$, which is not included in these error bars.

The two dolomites also behave similarly: Expansivity shows a slight to moderate increase with temperature (note this is the inverse of the anhydrite). Considering the overall pressure range, values of expansivity range from 2-9 and 5-10 $\times 10^{-6} \text{ K}^{-1}$ at 307 K, to 8-13 and 4-11 $\times 10^{-6} \text{ K}^{-1}$ at 373 K for samples LP4 and LP2, respectively. Both samples show a similar pressure effect: The higher expansivity values occur at the lower pressures. This overall behavior is consistent with cracks opening with increasing temperature but closing with increasing pressure. The points indicated by an "X" in Figure 11 illustrate the only literature value which could be found for a dolomite aggregate (porosity unknown) tested at 0.1 MPa pressure and 293 to 373 K (Cheng and Liaw, 1967). This observation seems consistent with the present data taken at higher pressures.

4.6 Expansivity, Cycle 5 Salt. Displacement measurements were taken at seven temperatures at each of three pressures: 25, 10, and 3 MPa. These results then allowed six thermal expansion values to be calculated at the average temperature between adjacent temperatures. These data are summarized in Table 7 for each of the four salt samples tested: XP5, XP6, XP7, and XP8. The averages of these thermal expansion values at any pressure or average temperature are plotted in Figure 12. The deviation bar in this figure represents the average deviation (as calculated as 1 STD) of all values listed in Table 7. Generally, values for α do not appear to be influenced by pressure and are approximately constant at about 32 to 38 $\times 10^{-6} \text{ K}^{-1}$ over the 308- to 493-K range. Values for pure salt (Skinner, 1966) are also shown as "X's" at 333 to 483 K. Thermal expansion of the pure material at 0.1 MPa is about 15 to 30% greater than for the Cycle 5 salt at comparable temperatures and is slightly temperature dependent. These differences are consistent in magnitude and sign with the effect of the presence of clay and other impurities in the Cycle 5 salt and with the fact that pressure increases in the 0.1- to 3-MPa range can be expected to decrease α from that of the pure salt. Additional thermal expansion measurements have been reported for salt at about the 750-m depth from the Palo Duro salt dome, Randall and Swisher Counties, Texas (Lagedrost and Capps, 1983). These measurements were made at 0.1 MPa and 298 to 598 K. Calculation of α from their data yielded values of 40 $\times 10^{-6} \text{ K}^{-1}$ near 350 K and 44 $\times 10^{-6} \text{ K}^{-1}$ near 475 K, which are between the present results and those from Skinner (1966).

5.0 CALIBRATION AND MEASUREMENT ERROR

5.1 Conductivity and diffusivity, salt (TP experiment). Empirical examination of the results of the same experiment by Durham et al. (1983) led to the conclusion that for conductivity the measurement scatter was less than ± 0.25 W/m $\cdot$ K and the inaccuracy of second-order, because of a calibration standard of conductivity similar to that of the unknowns. After the standard was run a second time and the set of correction factors was improved, the scatter band, as evidenced by the range of values for salt at any temperature, seems to have been reduced to nearly ± 0.10 W/m $\cdot$ K, which is at the theoretical limit of our ability to resolve temperatures, power, and power ratio (Durham et al., 1983). In the case of TP13, we have almost no basis for estimating resolution.

Two separate runs on the Pyroceram also provide us with a measure of the systematic effects of changing samples in the apparatus. Values measured under similar conditions are compared in Table 8. The agreement is impressive: Of the 56 points in (P, T, Power Ratio) space where a comparison is possible, the disagreement between old and new values of conductivity exceeds 5% in only 14 cases, and, as discussed in Chapter 4, Results, most of the 5% disagreements seem to be anomalies in old rather than in new data. Rerunning the same piece of Pyroceram did not test the effect of rejacketing (which theoretically should have no effect) or of the ± 1 -mm inaccuracy in the location of thermocouple holes. The position error was determined by Durham et al. (1983) and was found to be capable of deflecting conductivity by no more than 7%. On the basis of the second Pyroceram run and the identification of thermocouple position error as the only source of systematic error not tested by rerunning the Pyroceram, we estimate the system produces conductivity measurements which are accurate to $\pm 10\%$.

The matter of the effect of (P,T) cycling is a curiosity. The before and after cycling measurements on Pyroceram differ by far more (as much as 10%) than before cycling measurements made nearly two years apart (Table 8). There is no theoretical basis for suspecting that (P,T) cycling over the conditions in this experiment causes a permanent change in Pyroceram. In fact, a large volume of experimental evidence (e.g., Mirkovich et al., 1983), including our own rerunning of the same Pyroceram sample, indicates that Pyroceram doesn't change. Furthermore, the differences in TP15 before and after (P,T) cycling agree almost perfectly with the changes in Pyroceram before and after (P,T) cycling. The suggestion clearly is that the measurement system is deflected by the (P,T) cycling rather than by the salt or Pyroceram itself, but that, at least for the salt and Pyroceram, the systematic deflection is the same.

As regards diffusivity in the TP experiment, there is a serious systematic error of 30% that arose between the old and new runs on the Pyroceram (see Chapter 4, Results). We suspect, for the reasons discussed in Results, that the part of the "system" in which the problem lies is the postmeasurement data reduction. However, the deflection seems sufficiently predictable that we can make a valid adjustment to the salt data. We lack a good basis, therefore, for determining final system accuracy. The diffusivity data in Figure 8 are probably accurate to $\pm 20\%$, and could easily be as accurate as the conductivity data.

Table 8. Comparison of Conductivity Measurements on Pyroceram.

Pressure (MPa)	Temperature (K)	Power Ratio	Conductivity (M/m·K)		
			TPX (this study)	TPD (B. 1983*)	TPX After (T,P cycling)
31.0	303	1.0	4.43	4.33	
31.0	303	1.2	3.98	3.86	
23.3	303	1.2	3.87	3.75	
23.3	303	1.0	4.39	4.24	
15.5	303	1.0	4.17	3.95	
15.5	303	1.2	3.75	3.35	
7.8	303	1.2	3.70	3.39	
7.8	303	1.0	4.12	3.83	
3.8	303	1.0	4.01	3.73	
3.8	303	1.2	3.58	3.28	
31.0	338	1.0	4.10	--	3.72
31.0	338	1.2	3.71	3.67	3.34
23.3	338	1.2	3.63	3.61	3.27
23.3	338	1.0	4.07	--	3.68
15.5	338	1.0	3.89	3.45	3.53
15.5	338	1.2	3.42	3.48	3.20
7.8	338	1.2	3.42	3.42	3.08
7.8	338	1.0	3.79	3.29	3.49
3.8	338	1.0	3.80	3.46	3.34
3.8	338	1.2	3.44	3.48	2.98
31.0	373	1.0	3.79	--	
31.0	373	1.2	3.36	3.41	
23.3	373	1.2	3.44	3.57	
23.3	373	1.0	3.87	--	
15.5	373	1.0	3.75	3.62	
15.5	373	1.2	3.36	3.14	
7.8	373	1.2	3.25	2.74	
7.8	373	1.0	3.64	3.06	
3.8	373	1.0	3.46	3.66	
3.8	373	1.2	3.10	3.25	
31.0	408	1.0	3.55	3.50	3.50
31.0	408	1.2	3.15	3.16	3.10
23.3	408	1.2	3.19	3.07	3.01
23.3	408	1.0	3.56	3.50	3.38
15.5	408	1.0	3.53	3.35	3.28
15.5	408	1.2	3.06	2.97	2.94
7.8	408	1.2	3.02	3.14	2.89
7.8	408	1.0	3.39	3.52	3.27
3.8	408	1.0	3.32	3.80	3.16
3.8	408	1.2	2.94	3.28	2.87
31.0	438	1.0	3.53	3.58	
31.0	438	1.2	3.16	3.24	
23.3	438	1.2	3.10	3.13	
23.3	438	1.0	3.49	3.44	
15.5	438	1.0	3.41	3.45	
15.5	438	1.2	3.06	3.06	
7.8	438	1.2	3.06	2.98	
7.8	438	1.0	3.42	3.39	
3.8	438	1.0	3.33	3.53	
3.8	438	1.2	2.98	3.18	
31.0	473	1.0	3.49	3.54	3.46
31.0	473	1.2	3.08	3.16	3.07
23.3	473	1.2	3.06	3.06	3.01
23.3	473	1.0	3.42	3.40	3.35
15.5	473	1.0	3.34	3.41	3.34
15.5	473	1.2	2.98	3.06	3.03
7.8	473	1.2	2.97	2.96	2.98
7.8	473	1.0	3.30	3.32	3.39
3.8	473	1.0	3.33	3.04	3.37
3.8	473	1.2	3.00	2.98	2.99

*Durham et al., 1983

We note that the curiosity seen in the (P,T) cycling effect on conductivity is reproduced in the diffusivity as well, and the Pyroceram and TP15 are in lockstep agreement on the magnitude of the effect.

5.2 Conductivity, nonsalt (LP experiment). Empirically, the measurements are scattered $\pm 5\%$ for the measurements at 10 W. Some, but not all, of the 5-W measurements show the same scatter. Notable exceptions are the high-conductivity anhydrite samples LP1 and LP3 for which the scatter approaches $\pm 10\%$ at 5 W, with one or two points even farther away. The absolute error in the Pyroceram measurement of -5% (Figure 9) may be significant, but corrections have not been applied to the measurements on LP1 to LP4 pending a better understanding of the causes of measurement error. A possible explanation of the 5% error is that the contact resistance at the probe-rock interface varies during a test. However, it would take considerable effort to determine if such a change actually occurs. We saw no obvious signs of changes in the probe-rock contact. For instance, at the end of the measurements on each rock and on the standard we were able to withdraw the probe with no more effort than was required to insert it.

Relative errors in P, T_{vessel} and probe power (all given in Chapter 3, Experimental Techniques) have a total effect on conductivity of $< \pm 1\%$, a small percentage of the observed scatter. The rest of the scatter lies in the resolution of the slope of the straight-line portion of the run curve. The thermocouple measurement resolution limit of $1 \mu\text{V}$ or about 0.02 K is an important factor. Because this round-off error is most pronounced where ΔT_{probe} is smallest, i.e., at low probe power and high sample conductivity, it is a plausible explanation for the large scatter in, say, sample LP3 at 5 W (Figure 9c). Over the linear portion of the curve, 60 to 200 s for most of the points in Figure 9c, ΔT_{probe} is typically about 0.5 K . At the other extreme, for the low conductivity sample LP2 at 10 W, ΔT_{probe} is over 3 K over the linear portion, usually 75 to 245 s. (The linear portion for LP2 starts and ends later because of the lower thermal diffusivity of LP2.) There is, of course, some error resulting from misidentification by the operator of the straight-line portion of the curve. In order to minimize the arbitrariness of this selection from point to point, considerable importance was given to the selection of time intervals typical for a given sample. In fact, as can be seen from the data (Table 4), the interval was usually the same for nearly all points taken on a given sample. Hence, errors in the identification of the straight-line portion would tend to be systematic, i.e., common to all the results from a given sample, rather than random.

5.3 Diffusivity, nonsalt (KP experiment). An error analysis for our diffusivity measurement is detailed in Table 9. The greatest source of error in the measurement arises from uncertainty in the distance between thermocouples in the sample (Items 2 and 5 in Table 9). The separation of random drift of the thermocouples in their holes (Item 2 in Table 9) from the standard deviation of repeat measurements (Item 1) reflects our assertion that any such drift took place after any given series of repeat measurements, either as a result of (P,T) changes or of handling of the thermocouples by the operator. The effect of interchanging thermocouples (Item 6) can probably be traced to differing diffusivities between thermocouples. The error of 1.6% is

Table 9. Diffusivity Measurement Error.

Point-to-point resolution (random error)

- 1) Standard deviation in κ (from Table 3): $\pm(0.03/2.00)$ = $\pm 1.5\%$
(contains totality of electronic noise, round-off error, etc.)
- 2) *Maximum side-to-side movement of thermocouples (0.51 mm diam)
in thermocouple holes (0.74 mm):

$$\pm \frac{0.74 - 0.51}{2} \text{ mm/hole} \times 2 \text{ holes} = \pm 0.23 \text{ mm}; \frac{11.2^{\dagger} \pm 0.23}{11.2} - 1 = \pm 4.1\% = \pm 5.6\%$$

Sample-to-sample accuracy (systematic error)

- 3) Pressure accuracy: $\pm 1 \text{ MPa}$; $\frac{d\kappa}{dP} \sim 0$ ± 0
 - 4) Temperature accuracy: $\pm 1.5 \text{ K}$ per thermocouple;
 $\frac{d\kappa}{dT} \sim -0.004 \times 10^{-6} \text{ m}^2/\text{s}\cdot\text{K}$ (from Figure 6)
 $\pm 1.5 \text{ K (sample)} \pm 1.5 \text{ K (ref. jcn.)} = \pm 3 \text{ K}; \pm \frac{3 \times 0.004}{2.00} = \pm 0.6\%$
 - 5) ^bPosition of thermocouple holes: $\pm 0.05 \text{ mm/hole}$
 $\pm 0.05 \text{ mm/hole} \times 2 \text{ holes} = \pm 0.10 \text{ mm} \rightarrow \frac{11.2^* \pm 0.2}{11.2} - 1 = \pm 1.8\%$
 - 6) **Effect of interchanging thermocouples $\pm 1.6\%$
 4.0%
-

* $\kappa \propto \frac{1}{b^2}$, where b is the distance between thermocouples (Mirkovich, 1977).

[†] $b = 11.2 \text{ mm}$ (distance between thermocouples).

** Based on parameter sensitivity tests using sample KP1. This error does not apply to the relative error of samples KP0 to KP4 because thermocouples were not interchanged in these runs (i.e., the same thermocouple was always in the center).

specific to the single pair of thermocouples used in our measurements here. In the past, we have occasionally been able to screen thermocouples in order to find a "matched pair" that gave the same measured value for diffusivity regardless of which thermocouple was in the center and which was on the outside. This has led us to the conclusion that the source of the uncertainty is within the thermocouples themselves rather than some effect of rock-thermocouple interaction.

The total random plus systematic error from Table 9 is $\pm 9.6\%$, which is the size of the error bar in Figure 10e. The random error alone, $\pm 5.6\%$, is the size of the error bars in Figure 10a-d.

5.4 Expansivity. Cycle 5 salt and nonsalts (XP experiment). The apparatus was calibrated by measuring the apparatus plus sample response using fused silica and Carpenter 883 tool steel samples. By subtracting the known expansivity of these quite different materials from that of the total, apparatus distortion could be calculated. Response of the apparatus based on the two measurements agreed within 11%. This corresponds to an uncertainty of less than $\pm 0.5 \times 10^{-6} \text{ K}^{-1}$ for the anhydrite, the dolomite, and the Cycle 5 salt. Scatter among the three displacement measurements on the unknown samples at any pressure and temperature was also generally less than $\pm 0.5 \times 10^{-6} \text{ K}^{-1}$.

6.0 DISCUSSION

6.1 Salt. The conductivities and diffusivities of the four Permian Basin rock salt samples measured here are compared to the values for other samples measured under pressure and to those for pure halite in Figures 17 and 18. The strong variation among rock salt samples seen in the past seems to continue with the latest results. TP12 and TP14 seem to lie near the median of rock salt samples. TP15 is, however, anomalous. Its conductivity is distinctly lower than that of any other rock salt, and its diffusivity is distinctly higher. The explanation presumably lies in the particular mineralogy of TP15, so any further analysis is deferred. We have already found TP10, a Permian Basin rock salt measured in the earlier study (Durham et al., 1983), to have similar indications of an anomalous chemical and/or physical makeup.

The measurements of rock salt in this study and those of the earlier study (Durham et al., 1983) form, for the most part, a harmonious study of Permian Basin rock salt. One point of disharmony stands out: We found the diffusivity of samples from the earlier study to have a pressure dependence at lowest pressures. Arguing from the simple relationship between conductivity (λ) and diffusivity (κ):

$$\kappa = \frac{\lambda}{\rho C_p} \quad (3)$$

where ρ is the density and C_p the specific heat at constant pressure, we concluded that the pressure effect on diffusivity must be an experimental artifact, caused perhaps by the strong thermal gradients (in conjunction with the high expansivity of salt) imposed during the diffusivity test. With good confidence, however, we do not see that pressure dependence in this study, even though steeper thermal gradients were imposed in this study. Thus, the explanation for the apparent pressure effect in the earlier work is cast in doubt, but the fact that the four rock salts measured here don't exhibit a pressure dependence of diffusivity makes strong the conclusion that the pressure effect is not present.

There appears to be no discernible effect of pressure on thermal expansivity of salt, consistent with the results from the transport properties, diffusivity and conductivity. This observation is in contradiction with an appreciable pressure effect noted in the anhydrite and dolomite. Because salt is weak and ductile compared to the nonsalt rocks, any cracks or pores could be expected to close elastically or plastically in the salt at low pressure, as compared to the nonsalt. We would expect any pressure effect on expansivity to appear at pressures < 3 MPa in salt, whereas it continues to be much higher pressures in the nonsalt rocks where cracks and pores are more difficult to close.

6.2 Nonsalt. The thermal conductivities and diffusivities of the four nonsalt rocks are compared in Figures 15 and 16. We have noted already that the two anhydrites have considerably higher conductivity and diffusivity than

Figure 17. Comparison of thermal conductivities of various salts. The bold lines are from this study. The other curves are compiled in Durham et al. (1983).

Figure 18. Comparison of thermal diffusivities of various salts. The bold lines are from this study. The other curves are compiled in Durham et al. (1983).

do the dolomites and that both conductivity and diffusivity decrease with increasing temperature in all four rocks. The thermal transport properties are also related to one another in the expected way in the four rocks. Applying Equation (3), Figures 15 and 16 indicate values for the thermal capacity, ρC_p , of 2.0 to $2.5 \times 10^6 \text{ W} \times \text{s/m}^3 \times \text{K}$, very comfortably in the expected range for most rocks of $2.3 \times 10^6 \text{ W} \times \text{s/m}^3 \times \text{K} \pm 20\%$ (Touloukian and Ho, 1981).

Acceptable values of the thermal transport properties of anhydrites and dolomites are not well constrained by previous research. In compilations by Clark (1966) and Touloukian and Ho (1981), conductivity for dolomites ranges from 3 to about 6 W/m·K. Acton (1978) found for southeastern New Mexico anhydrite values of conductivity from 1.5 to 6 W/m·K. Laboratory measurements on these evaporites are apparently affected by relatively small amounts of ancillary minerals such as calcite and halite. The present measurements may be no exception. We have purposely avoided petrologic descriptions of our rock samples because that work is presumably being done elsewhere. cursory examination of our samples reveals significant petrologic complexity. Only sample LPI presents a macroscopic impression of uniformity.

An intriguing aspect of the combined thermal property measurements on nonsalt rocks in the present work is the distinct effect of confining pressure on expansivity, but not on the transport properties, diffusivity, and conductivity. Measurable effects of pressure upon diffusivity and conductivity have been observed in some low-porosity rocks (for instance, on granite, Durham, 1982), and the diffusivity technique employed here easily detected 5 to 15% effects of pressure upon diffusivity in three other low-porosity igneous rocks (Mirkovich et al., 1983). Given that we have reproduced so closely the earlier measurements on Pyrocera 9606 (Figure 1), we are confident that pressure effects are absent in the present rock samples. However, we are equally confident that confining pressures in the range 0.1 to 30 MPa cause the pore volumes to change in our samples XPI to XP4, based on the detection of a pressure-dependent linear expansivity. Walsh and Decker (1966) have shown that the effect of porosity on thermal conductivity depends on pore structure (for instance, 1% porosity arranged as round pores has less of an impeding effect than the same porosity arranged as flat cracks). However, Walsh and Decker do show on theoretical grounds that compressibility and conductivity ought to show similar pressure dependencies for a given pore structure. Heard and Page (1982) argued for similar pressure dependence of compressibility and thermal linear expansion. The present study, showing dissimilar pressure effects upon expansivity and diffusivity, leads to a closure error in the circle of logical argument. It would be illuminating to compare the pore structure of dolomite and anhydrite to that of low-porosity crystalline igneous rocks.

7.0 CONCLUSIONS

We have measured the thermal conductivity (λ), diffusivity (κ), and coefficient of linear expansion (α) of eight rock salts, two dolomites, and two anhydrites associated with Cycles 4 and 5 of the Permian Basin bedded salt formations in Texas. Test conditions were $0.1 < P < 30$ MPa, $303 < T < 493$ K for the salts, and the same pressure range and $308 < T < 373$ K for the nonsalts. We found the following:

1. Neither conductivity nor diffusivity changed with pressure over the range investigated for any of the samples. The resolution of the zero-pressure effect is somewhat better than the measurement scatter of about $\pm 5\%$ for any given sample.
2. For the salts, both λ and κ showed a monotonic negative dependence on temperature. The two salts from Cycle 4 had nearly identical properties: Over $303 < T < 473$ K, λ decreased from about 5.5 to 3.75 W/m·K, and κ decreased from about 2.7 to 1.7×10^{-6} m²/s. One of the Cycle 5 samples was a single crystal that encountered experimental difficulties. The other had properties which were anomalous compared to other salts: λ was low and only weakly temperature dependent, approximately 3.4 W/m·K, but κ was relatively high and strongly temperature dependent, decreasing from 3.8 to 2.5×10^{-6} m²/s over the experimental temperature range.
3. For the nonsalts, both conductivity and diffusivity also showed a negative temperature dependence in all samples. Over 308 to 373 K, the anhydrites measured $\lambda = 5.4$ to 4.4 W/m·K, and $\kappa = 2.3$ to 1.8×10^{-6} m²/s. Over the same range the dolomites showed $\lambda = 3.0$ to 2.8 W/m·K, and $\kappa = 1.4$ to 1.1×10^{-6} m²/s. Figures 14 and 15 give more exact results. Absolute measurement uncertainty was about $\pm 10\%$.
4. In all four nonsalt samples, the value of α showed a pronounced pressure effect, in strong contrast to λ and κ . Typically, where $\alpha = 4 \times 10^{-6}$ K⁻¹ at pressure = 30 MPa, it measured 10 to 16×10^{-6} K⁻¹ at 3.0 MPa. For the two anhydrites, α was slightly negatively temperature dependent. It showed a positive temperature dependence for one of the dolomites and little temperature dependence for the other.
5. Thermal expansivity of four Cycle 5 salt samples indicated no appreciable effects of either pressure or temperature ranging from 3 to 25 MPa and 308 to 493 K. Thermal linear expansion average 35×10^{-6} K⁻¹, 15 to 30% lower than that for pure salt at 0.1 MPa.

8.0 REFERENCES

- Acton, R. U. (1978), "Thermal Conductivity of S.E. New Mexico Rock Salt and Anhydrite," Thermal Conductivity 15 (Proc. 15th Int. Conf. Thermal Conductivity), V. V. Mirkovich, Ed. (Plenum Press, New York, NY), pp. 263-276.
- Blackwell, J. H. (1954), "A Transient-Flow Method for Determination of Thermal Constants of Insulating Materials in Bulk," J. Appl. Phys., **25**, pp. 137-144.
- Blackwell, J. H. (1956), "The Axial-Flow Error in the Thermal-Conductivity Probe," Canadian J. Phys., **34**, pp. 412-417.
- Carpenter (1977), Matched Tool and Die Steels Handbook (Carpenter Technology Corp., Reading, PA), p. 97.
- Carslaw, H. S., and J. C. Jaeger (1959), Conduction of Heat in Solids, 2nd Ed. (Oxford University Press, Oxford), p. 345.
- Cheng, T. Y., and C. T. Liaw (1967), Kung Ch' Eng., **40**, p. 8.
- Clark, S. P., Jr. (1966), "Thermal Conductivity," in Handbook of Physical Constants, Geol. Soc. Am. Memoir 97, S. P. Clark, Jr., Ed. (Geol. Soc. Am., NY), pp. 459-482.
- Durham, W. B. (1982), Thermal Properties of Climax Stock Quartz Monzonite to 523 K and 50-MPa Confining Pressure, UCRL-53349, Lawrence Livermore National Laboratory, Livermore, CA.
- Durham, W. B., and A. E. Abey (1983), "Thermal Conductivity and Diffusivity of Climax Stock Quartz Monzonite at High Pressure and Temperature," Thermal Conductivity 17 (Proc. 17th Int. Conf. Thermal Conductivity), J. Hust, Ed. (Plenum Press, New York, NY), pp. 459-468.
- Durham, W. B., C. O. Boro, J. M. Beiriger, and D. N. Montan (1983), Thermal Conductivity and Diffusivity of Permian Basin Bedded Salt at Elevated Pressure and Temperature, UCRL-53476, Lawrence Livermore National Laboratory, Livermore, CA.
- Flieger, H. M. (1963), "The Thermal Diffusivity of Pyroceram at High Temperatures," Proc. 3rd Conf. Thermal Conductivity (Oak Ridge National Laboratory, Oak Ridge, TN), (Gatlinburg, TN, Oct. 16-18, 1963), Vol. II, pp. 769-783.
- Flynn, D. R., H. E. Robinson, and I. L. Martz (1964), "Present Status of Pyroceram Code 9606 as a Thermal Conductivity Reference Standard," Proc. 4th Conf. Thermal Conductivity (U.S. Naval Radiological Defense Laboratory, San Francisco, CA, Oct. 13-16, 1964), pp. 1-F-1 to 1-F-27.
- Heard, H. C. (1980), "Thermal Expansion and Inferred Permeability of Climax Quartz Monzonite to 300°C and 27.6 MPa," Int. Rock. Mech. Min. Sci., **17**, pp. 289-296.

- Heard, H. C., and L. Page (1982), "Elastic Moduli, Thermal Expansion and Inferred Permeability of Two Granites to 350°C and 55 MPa," J. Geophys. Res., **87**, pp. 9340-9348.
- Koski, J. A., and D. F. McVey (1983), "Application of Parameter Estimation Techniques to Thermal Conductivity Probe Data Reduction," Thermal Conductivity 17 (Proc. 17th Int. Conf. Thermal Conductivity), J. Hust, Ed. (Plenum Press, New York, NY), pp. 587-600.
- Lagedrost, J. F., and W. Capps (1983), Thermal Property and Density Measurements of Samples Taken from Drilling Cores from Potential Geologic Media, FMI/ONWI-522, prepared by Fiber Materials, Inc. for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.
- Mirkovich, V. V. (1977), "Thermal Diffusivity Measurement of Armco Iron by a Novel Method," Rev. Sci. Instrum., **48**, pp. 560-565.
- Mirkovich, V. V., W. B. Durham, and H. C. Heard (1983), "Measurements of Thermal Diffusivity of Rocks at High Pressure," Proc. 8th European Conf. Thermophysical Properties (Baden-Baden, Federal Republic of Germany, 1982), pp. 255-264.
- Page, L., and H. C. Heard (1981), "Elastic Moduli, Thermal Expansion and Inferred Permeability of Climax Quartz Monzonite and Sudbury Gabbro to 500°C and 55 MPa," Proc. 22nd U.S. Symp. on Rock Mech. (MIT Press, Cambridge, MA), pp. 97-104.
- Plummer, N. A., D. E. Campbell, and A. A. Comstock (1962), "Method of Measurement of Thermal Diffusivity to 1000°C," J. Am. Cer. Soc., **45**, pp. 310-316.
- Powell, R. W., C. Y. Ho, and P. E. Liley (1966), Thermal Conductivity of Selected Materials, NSRDS-NBS 8, National Bureau of Standards, U.S. Government Printing Office, Washington, D.C.
- Rudkin, R. L. (1963), Thermal Diffusivity Measurements on Metals and Ceramics at High Temperatures, Office of Technical Services, U.S. Dept. of Commerce, Washington, D.C., Technical Documentary Report No. ASD-TDR-62-24, part II.
- Skinner, B. J. (1966), "Thermal Expansion," in Handbook of Physical Constants, Geol. Soc. Am. Mem. 97, S. P. Clark, Jr., Ed. (Geol. Soc. Am., NY), pp. 75-96.
- Touloukian, Y. S., and C. Y. Ho., Eds. (1981), Physical Properties of Rocks and Minerals, McGraw-Hill/CINDAS Data Series on Material Properties (McGraw-Hill, New York, NY), Vol. II-2, Ch. 12.
- Walsh, J. B., and E. R. Decker (1966), "Effect of Pressure and Saturating Fluid on the Thermal Conductivity of Compact Rock," J. Geophys. Res., **71**, pp. 3053-3061.