MASTER

Y/DA-7013

**THERMAL CONDUCTIVITY OF HALITE
USING A PULSED LASER**

D. D. Smith

**UNION
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ABSTRACT

A pulsed laser technique was used for obtaining experimental thermal conductivities of salts and steel based on the thermal diffusivity, heat capacity, and density relationship.

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SUMMARY

A feasibility study of the experimental determination of thermal conductivities of salts (NaCl) and a steel casing material using a pulsed laser technique are presented. Optically transparent materials such as salt were effectively coated with an opaque layer of aluminum or silver to satisfy test boundary conditions. Thermal conductivities for the three specimens were obtained from the thermal diffusivity, heat capacity and density relationship. Based on measurements from room temperature to 923 K, single crystal halite yielded values ranging from 6.5 to 1.5 W/m-K versus 5.5 to 1.2 W/m-K for Avery Island Bed Salt. AISI 106-Grade B steel gave values of 46 to 29 W/m-K. While these measurements may be no better than $\pm 10\%$, it is possible with appropriate equipment and technique to generate data of engineering quality, $\pm 5\%$ error, provided adequate test specimens can be fabricated.

Attributes of this technique include the generation of data very quickly which is more applicable to testing large numbers of specimens relative to steady state methods. The use of penny-sized specimens can be a problem from the fabrication requirement, especially for friable and anisotropic geological materials. The quality of the data rests on the adherence of the experimental design to the mathematical model.

INTRODUCTION

The purpose of this study was to assess the applicability of the laser flash thermal diffusivity method as a quick and reliable approach for assessing the thermal conductivity of geologic media. This work was undertaken at the request of the Office of Waste Isolation.

Stable geologic formations, such as salt beds, have been proposed as terminal repositories for high-level radiation reactor wastes by the Office of Waste Isolation. Computer modeling of storage array parameters and associated temperature distributions within the array require reliable thermal transport properties of the particular stored materials and the associated geologic media. Convergence of modeled arrays and experimental pilot plant operations is needed to assure aspects such as safety, confinement, quality and retrievability for this type of program.

Efficient and accurate methods for the determination of the thermophysical properties of materials associated with storage facilities are needed because of the possible use of a wide variety of different types of media. Candidates include salt, shale, or granite and various kinds of canister and containment materials such as steels.

The thermal conductivity of a use material is one of the more important properties of interest in such an elevated temperature system. Most experimental methods of evaluating thermal conductivity are steady state, requiring rather large specimens and long test times for the generation of reasonable data. Such tests, being inherently expensive, are not appealing in a situation where a large number of samples are to be tested. Experimental techniques using a transient method of analysis should have an overall advantage in the screening of a large number of specimens.

Advantages of the laser flash method include small sample size and generation of large amounts of data rather quickly. With computerized data reduction, experimental points can be generated as fast as a specimen temperature can be changed and thermal equilibrium reestablished, usually about one hour per 100 K temperature difference with five replicate determinations at temperature. Disadvantages to the technique include the rigid enforcement of a precise set of boundary conditions required in the experimental setup, including the coating of translucent or transparent materials such as salt with thin opaque layers, and the necessity of appropriate corrections for this modification. Also, small specimen sizes may show results that are related to localized variations in structure, density or anisotropy relative to a larger test specimen which would tend to average out such fluctuations.

DETERMINATION OF THERMAL CONDUCTIVITY

LASER DIFFUSIVITY TECHNIQUE

The technique was originated by Parker, et al,⁽¹⁾ who devised the scheme for measuring thermal diffusivity by a flash technique. With the laser technological growth of the past few years, the technique has been used by increasing numbers of experimentors for obtaining thermal diffusivity and derived thermal conductivity measurements.⁽²⁻⁵⁾

The flash diffusivity method is based mathematically on the time dependence of a unidirectional pulse of heat traveling axially through a thin disk of material. This heat pulse is generated by the deposition of radiant energy on the front surface of the material. By monitoring the rear surface of the specimen with a small gauge thermocouple or other suitable temperature transducer, a characteristic thermal wave form is produced. At the time at which the temperature rise at the rear surface is one-half its maximum the relationship for thermal diffusivity at a particular temperature is:

$$\alpha = \frac{0.139 \ell^2}{t_{1/2}} \quad (1)$$

where α is thermal diffusivity in cm^2/sec , ℓ is specimen thickness in centimeters and $t_{1/2}$ is the half time for maximum temperature in seconds.

The use of Equation 1 requires that a well defined pulse of laser energy be uniformly deposited on the front face of the homogeneous specimen. The incident pulse time must be small relative to the transit time of the thermal pulse through the specimen, requiring a thin specimen, so as to minimize radial conduction losses or gains (at elevated temperature) to or from the specimen holder or thermocouple sensor. Taylor and Cape⁽⁶⁾ have shown that Equation 1 is good to about 1% if the pulse width of the laser is less than two percent of that of the rise time, $\ell^2/\pi \alpha$, where ℓ is the thickness in cm and α is thermal diffusivity in cm^2/sec . This form assumes no perturbing heat losses. They have shown such finite pulse width errors tend to lower measured thermal diffusivity values. The geometric shape of the pulse is also an important parameter.

Beedham and Dalrymple⁽⁷⁾ have shown that because of varying spatial intensity of their laser beam, similar to the one used in this study, thermal diffusivity data on graphite specimens could vary as much as eight percent. Areas where the beam was hotter gave positive (higher) and where colder gave negative (lower) biased values of thermal diffusivity.

The thermal conductivity is related to the diffusivity by the equation:

$$\kappa = \alpha \rho C_p \quad (2)$$

where κ is the thermal conductivity in W/m-K , α is the thermal diffusivity in cm^2/sec , ρ is the density in kg/m^3 and C_p is the heat capacity in cal/g-K ; all variables being for a common temperature. Thus, heat capacity data also have to be experimentally obtained or approximated in order for conductivities to be calculated. Because density is another variable

in this equation, thermal expansion data would allow correction for the variation of density with temperature. Over small temperature ranges correction for expansion is normally not accounted for.

Apparatus Description

An in-depth presentation of the laser thermal diffusivity apparatus and computerized data acquisition and reduction systems used in this study have been reported previously.⁽⁸⁾ Briefly, system hardware includes a Hadron Model 8512 ruby rod laser for generating the radiant pulse, a wire wound resistance furnace for elevated temperature testing, and an evacuable quartz envelope containing the sample, specimen holder and temperature sensor. The specimen holder is a fired lavite assembly which when screwed together sandwiches the specimen against 30 gauge chromel-alumel wires, forming an intrinsic thermocouple. This thermocouple is also used for elevated temperature monitoring. The specimen is 12.7 mm diameter by approximately 2.5 mm thick. Temperature transient signals from the thermocouple are read through a Tektronix R564B oscilloscope, amplified with a Tektronix 3A9 differential amplifier and stored in a Biomation 802 transient recorder. A prototype solar cell pulse generator, triggered by the laser's xenon flash lamps, initiates the storage of signals in the transient recorder. Thermal transient data and temperature along with the specimen's pertinent physical data are used by the computer program to calculate the thermal diffusivity.

Optical alignment of the laser pulse on the specimen surface is quite critical. Cowan⁽⁹⁾ has shown that as little as 0.3% of the surface area being unheated can cause detectable measurement errors. To insure that the entire front surface of the sample is totally illuminated, a converging lens focuses the output to a spot size slightly larger than the front surface of the specimen. By maintaining the spot size slightly larger than the sample area, small movements caused by the heating of the furnace and expansion of the sample assembly are not a source of error caused by lack of total surface illumination.

All tests in this study were conducted in a vacuum of 6.7 Pa (50×10^{-3} torr) to reduce conduction errors and limit the occurrence of chemical reactions. In elevated temperature tests, thermal equilibrium was achieved by visually observing the differentially amplified oscilloscope trace of the intrinsic thermocouple voltage using a sensitive resolution level (10^{-5} volt f.s.) on the oscilloscope. Specimens were tested with approximate square waves of ruby radiation (694.3 nm) of one millisecond pulse duration. Beam energies were varied between 10 and 30 joules and specimen temperature excursions of less than 5 K were maintained so that the characteristic half time $t_{1/2}$, was maintained at a relatively constant value.

Heat capacity measurements were obtained using a Perkin-Elmer differential scanning calorimeter, Model DSC-2. This method determines the energy required to heat a specimen at a given rate over a small temperature range. Two calorimetric standards, α - Al_2O_3 and Armco iron, were used to correlate experimental conditions between the samples and standards.

Densities of the steel and salts were obtained at room temperature by measuring the mass-volume parameters. These values agreed reasonably with handbook data.

Sample Preparation

Specimens of AISI-106 Grade B steel, single crystal halite from Lyons, Kansas, and bed salt from Avery Island, Louisiana were prepared with the following geometry: 12.7 mm diameter by nominally 2.5 mm thickness with the two disk surfaces parallel and smooth. The steel specimens were machined from a section of an eight-inch casing. Several specimens of the halite were successfully cleaved along crystallographic planes, sanded and ground to the required diameter. The bed salt samples had to be rough sawn, filed, and sanded to the appropriate geometry. Successively finer grades of sandpaper were used without wetting agents until suitable surfaces were obtained. This technique was not entirely satisfactory, since some of the specimen grain sizes had dimensions on the order of the required specimen thickness. Such material fractured under very little mechanical pressure. Thicker specimens, 3.6 mm, were found more satisfactory.

The problem of finding a suitable material and method of coating the salt samples to make them opaque was addressed in several ways. Other experimenters have had good success using colloidal graphite coatings to prevent "shine through." This approach was abandoned because of a lack of reproducibility and required coating thicknesses which were not consistently obtained on the smooth salt surfaces. The graphite coatings were found to degrade to the point of being unusable after a single test shot.

Different approaches were tried (with varying amounts of success) in an attempt to find a material which would not degrade severely during the energy deposition process. Specimen surfaces were coated with the following materials: Silver Print alone; aluminum foil (0.025 mm) bonded with Silver Print; and aluminum foil bonded with Eastman-910 cement. Coatings of Silver Print alone, laid down by swabbing the specimen then wiping it over the surface with a microscope slide, was the predominate method used on the salt specimens at elevated temperature tests.

Results

Heat capacity, thermal diffusivity and derived thermal conductivity for the steel are shown in Figures 1, 2, and 3 with the experimental data points at discrete temperatures indicated as circles and a second order fit of the experimental data as a smooth line. Data on the steel are listed in Tables B1, B2, and B3 respectively, Appendix B. The steel was found to have heat capacity values quite similar to those of Armco iron. The steel gave slightly higher heat capacities at the higher test temperatures. Heat

capacity data is accurate to within $\pm 2\%$ of experimental values based on standards of aluminum oxide and Armco iron.

Thermal diffusivity for the steel, Figure 2 decreased a factor of three over the temperature test range. Data appears to be low by as much as 10% at room temperature and perhaps 2% low at 500 K as this trend was observed using an Armco iron test standard of identical geometry. One reason for this condition is the heat sinking effect of the alumina rod which maintains contact between the specimen and holds the thermocouple lead wires in place. The 30 gauge chromel-alumel bare wire should have a short enough response time to negate the effect of the laser's one millisecond pulse width with the chosen specimen thickness, i.e. the half-time of the samples varied between 50 and 70 milliseconds. However, the response time of the thermocouple assembly including axial heat losses through the alumina must be less than one millisecond for the constant, 0.139, in Equation 1 to be correct. Heat losses or gains to the sample holder were minimized by testing in a vacuum and spot welding three tiny chromel beads on the front side of the steel so that a standoff from the lavite holder was maintained. Thermal conductivity of the steel, from Equation 2, was obtained using smoothed heat capacity and diffusivity data and a constant density of 7.84 g/cm^3 .

The single crystal and bed salt were found to have identical values of heat capacity within the limits of experimental error. The equation form and graphical presentation of data are the same as those for the steel. Thermal data for the salt specimens are shown in Figures 4-9 (tabulated in Appendix B, Tables B-4-9). Using coatings of aluminum foil for tests near room temperature and of Silver Print at elevated temperatures required two different sets of corrections. The experimental determination of these constants consisted of evaluating the typical response time on a single specimen of steel at room temperature with and without the coatings. A thin film of Silver Print on the back surface of the specimen was used to maintain electrical contact across the thermocouple wires. Since contributions to response time, because of the silver surfaces, ranged between 17 and 22 msec, an averaged value of 20 msec was used as a correction in the calculations. It was assumed that this correction was a constant factor over the entire temperature range of testing, although this is probably not the actual case. The aluminum foil correction was about half that of the Silver Print (10 msec). Although these values were significant in calculations involving the steel, the lower diffusivity and increased specimen thicknesses of the salts resulted in corrections of less than 5% of the characteristic response times. The silver coatings degraded after a few shots especially at elevated temperatures and the specimens had to be recoated or discarded and replaced with new ones.

Thermal diffusivity for the single crystal and bed salt (Figures 6,7) decreased by a factor of three over the temperature range. Differences between the materials were more significant at room temperature, about 15%, than at elevated temperatures where values were more nearly identical. Calculated thermal conductivities (from smoothed heat capacity and diffusivity data constant density (Figures 8,9) of 2.17 g/cm^3) revealed a room temperature single crystal salt conductivity about fifteen percent greater

than the bed salt; but at 923 K both materials had nearly the same conductivity value.

DIRECT THERMAL CONDUCTIVITY MEASUREMENT

An alternative approach to thermal conductivity measurements by the thermal diffusivity, heat capacity, and density relationship is that of the direct or known absorption method. If the amount of energy absorbed by a material can be reproduced, the thermal conductivity can be obtained from the mathematical relationships shown in Appendix A. This technique requires a reproducible amount of energy both generated by the laser and absorbed by the specimen.

Direct thermal conductivity measurements were made on the single crystal salt and steel specimens at room temperature. Because of the constant energy absorption requirement, both the variation in laser output intensity and condition of degradation of the specimens' opaque surface were found to be important variables. Table 1 shows the energy output of the laser with a given set of charging conditions. Laser energy was quantitatively determined using a Quantronix 501 calorimeter as the detector. Qualitative evaluation of the energy distribution can be done by impinging the laser burst on a piece of totally exposed photo paper. Figure 10 shows significant areas of varying intensity, the lighter areas being hotter and the darker being cooler, which will also contribute to variations in boundary conditions. Maximum detected temperatures and thus thermal diffusivity and conductivity values are affected by such perturbations.

Results

Figure 11 shows the time-temperature response of a specimen of single crystal salt using Silver Print as the opaque after various numbers of "shots". After six tests, response is shown to be significantly altered, thus the specimen no longer yields information of any value. Due to this degradation, several specimens had to be coated and "used up" during the course of the experiment. Maximum temperatures were determined by calibrating the output of the transient recorder onto a Y-time plotter using one millivolt reference voltage source relative to thermocouple output at these temperatures.

Absorbed energy, Q , was calculated by testing a specimen of "Armco iron" and determining the energy absorbed by knowing its mass, heat capacity and experimental maximum temperature excursion. For five separate determinations a Q value of $1.483 \text{ joules} \pm 0.135 \text{ joules}$ was obtained. (App. A, eq. (A-2)). Then, using Equation A-7 in Appendix A, the room temperature thermal conductivity of the steel was found to be $46 \pm 6.0 \text{ W/m-K}$ and the single crystal salt $8.2 \pm 0.91 \text{ W/m-K}$ as compared to the values of 46 and 6.5 W/m-K obtained above. Significant variations in diffusivity and maximum temperature excursions, on the order of $\pm 10\%$ were observed in the data due to the interacting variables of beam intensity, uniformity, degradation of the opaque silver layer and error associated with the maximum temperature measurement.

RECOMMENDATIONS

The laser flash technique for the determination of thermal diffusivity and conductivity of geologic materials is viable provided several criteria can be successfully met. Thermal conductivity data of engineering quality (within $\pm 5\%$ error) should be possible with an appropriate system.

Criteria for such a system depends on the adherence to the experimental boundary conditions of the technique and the preparation of samples of suitable quality for testing purposes. Some of these criteria have been stated in the body of the study. A brief review of salient features is iterated.

Sample preparation should be of such means as to provide thin disk specimens with uniform geometry, parallel faces and determinable surface quality. In the case of transparent or translucent materials like salt, the evaporation of thin, adherent, and opaque films of a metal such as silver, aluminum, or gold should provide an adequate means of obtaining the requirement of energy absorption on the specimen's front surface.

Test samples should have an approximate 10:1 ratio of diameter to thickness to minimize skewing of the thermal pulse shape traveling through the material by radial conduction losses. Heat losses both to or from the sample holder and temperature sensor should be minimized. Appropriate means of maintaining low conduction losses to the sample holder, while assuring that all of the front surface is irradiated, should be considered in fabricating a specimen holder. Three point contact of the samples with the holder should provide stability and minimize losses.

Since even small heat sinks affect the waveform of the thermal pulse, precise control of furnace temperatures and gradients is most important. The visual monitoring of the response of the intrinsic specimen thermocouple on high sensitivity oscilloscope voltage level has been quite helpful in determining when the specimen reaches thermal equilibrium.

The pulse of energy from the laser should be uniform and constant in geometry, though controllable in total power. These considerations should result from a well-engineered system that is capable of providing enough energy to raise the temperature of the specimen 1 to 3 K above its quiescent value. A system, laser plus optical elements, capable of yielding pulses constant in spatial energy density to perhaps 5% and total power to 1% should be more than adequate. The laser system used in the present study is thus inadequate, especially in the spatial energy density requirement.

In terms of data acquisition and reduction systems, computerized techniques are deemed almost necessary. With such a measurement system, and with reasonable care and technique, thermal conductivities on geologic materials such as salt, rock or shale can be generated rather efficiently provided the materials have physical characteristics to allow them to be made into small disks for testing.

A basis of three specimens per week over a temperature range from ambient to 1000 K for heat capacity and thermal diffusivity measurements is not unreasonable. The accuracy of the measurements will be dependent on many variables, however, data of engineering quality can be attained with appropriate instrumentation and technique.

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ACKNOWLEDGMENTS

The author wishes to acknowledge the aid of J. F. McLaughlin of the Laboratory Development Department for cleaving the salt crystals and vacuum evaporating the metal films on the salt specimens.

Table 1

Energy Variation of Hadron Ruby Pulsed Laser
at 4.2 KV and 1.0 millisecond Pulse Width

<u>Shot No.</u>	<u>Net Energy (joules)</u>
1	8.97
2	10.08
3	9.59
4	9.22
5	8.78
6	8.65
7	8.88
8	8.81
9	9.40
10	9.49
11	9.14
Average	9.18
Std. Dev.	0.43

Figure 1: Heat Capacity of AISI 106 Grade B Steel

Figure 2: Thermal Diffusivity of AISI 106 Grade B Steel

Figure 3: Thermal Conductivity of AISI 106 Grade B Steel

Figure 4: Heat Capacity of Single Crystal Salt

Figure 5: Heat Capacity of Avary Island Bed Salt

Figure 6: Thermal Diffusivity of Single Crystal Salt

Figure 7: Thermal Diffusivity of Avary Island Red Salt

Figure 8: Thermal Conductivity of Single Crystal Salt

Figure 9: Thermal Conductivity of Avary Island Bed Salt

7X

Figure 10: Photograph of Qualitative Spatial
Energy Distribution of Laser Beam 4.2 KV,
1 millisecond pulse width.

Figure 11: Characteristic Waveforms resulting from Degradation of Opaque Silver Layer on Salt

APPENDIX A

DIRECT THERMAL CONDUCTIVITY MEASUREMENT

The measurement of thermal conductivity by the thermal diffusivity, heat capacity, and density relationship requires two and preferably three separate measurements. A technique which would reduce the number of measurable quantities to a single test situation would be desirable. One approach to such a simplification is the direct or constant energy absorption method.

di Novi⁽¹⁰⁾ has addressed one form, getting engineering quality data on 347 stainless steel. If the requirement that the radiant energy be absorbed immediately in a small depth, g , of a disk specimen whose thickness is ℓ , then a series expansion of the unidirectional heat flow that expresses the temperature of the back surface as shown by Parker is:

$$T(\ell, t) = \frac{Q}{\rho C_p \ell} \left\{ 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left(\frac{-\pi^2 \alpha t n^2}{\ell^2} \right) \right\} \quad (A-1)$$

Assuming no heat losses:

$$\text{For } g < x < L \quad T(x, 0) = 0 \text{ and for } 0 < x < g \quad T(x, 0) = \frac{Q}{\rho C_p g} \quad (A-2)$$

where Q = energy density, (cal/cm²)

ρ = density, (g/cm³)

C_p = heat capacity, (cal/g-K)

g = absorption thickness (cm)

absorbed heat is:

$$Q = \Delta T_{\text{exc.}} \rho C_p \ell \quad (A-3)$$

in (cal/cm²) for a perfectly insulated material. From the heat capacity, (C_p) thermal diffusivity (α) and density (ρ) relationship,

$$\kappa = \alpha \rho C_p \quad (A-4)$$

$$C_p = \frac{\kappa}{\alpha \rho} \quad (A-5)$$

$$C_p = \frac{Q}{\Delta T_{\text{exc.}} \rho \ell} \quad (A-6)$$

$$\text{such that} \quad \kappa = \frac{Q}{\Delta T_{\text{exc.}} \ell} \quad (A-7)$$

- (1) Parker, W. J. et al; "Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity," J. App. Physics 32, pp. 1679-84 (1961).
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where κ = thermal conductivity, (cal/sec-cm-K)

Q = Energy density, (cal/cm²)

α = Thermal diffusivity, (cm²/sec)

$\Delta T_{exc.}$ = temperature excursion, K

ℓ = Sample thickness, (cm)

Thus the primary problem becomes one of determining the heat input to a specimen. The applicability of this modification depends on the variability of net power from the laser and the reproducibility and consistency of the coatings used to make the salt materials opaque, and thus the absorption of energy a constant value. di Novi used the well-known properties of Armco iron to evaluate the Q absorption factor, by coating the surfaces of the steel and Armco iron with colloidal graphite. Thus

$$Q = \ell \rho C_p \Delta T_{exc.} \quad (A-8)$$

or total energy,

$$Q = m C_p \Delta T_{exc.} \quad (A-9)$$

A working curve of absorbed energy as a function of test temperatures should be used because of varying absorption as a function of temperature.

Our experimental arrangement of coating specimens of Armco iron and steel with a layer of Silver Print to evaluate the absorption factor, Q , was used instead of graphite. By determining the temperature excursion of a specimen whose mass and heat capacity are known, the energy absorbed at the front surface of a specimen can be obtained, provided all specimens have the same surface coating to absorb identical amounts of energy and the laser energy output and optical alignment are constants.

APPENDIX B

This appendix contains a listing of experimental heat capacity, thermal diffusivity and calculated thermal conductivity data for AISI-106 Grade B steel, single crystal halite and Avery Island bed salt.

A general purpose curve fitting program, GENFIT, was used to smooth the data to a polynomial of the form

$$Y = A + BT + CT^{-2} \quad (B-1)$$

where Y is the smoothed value of heat capacity in cal/g-K, thermal diffusivity in cm²/sec or thermal conductivity in W/m-K. A, B, and C are constants in the equation which are listed in each table respectively under the coefficients title. T is Kelvin temperature for the polynomial form. In each table $\bar{x}$ represents the test temperature in Kelvin temperature, Y the experimental property under consideration, YCALC the smoothed value of the property, DIFF the difference between the experimental and smoothed property and SLOPE the slope of the equation at each test temperature.

(1) Instructions for Running GENPLT, GENFIT, and SOECIN Programs.
Memorandum, C. M. Davenport, April 21, 1975.

DATA POINTS = 14

STANDARD DEVIATION:
2.88943E-03

COEFFICIENTS:
4.93394E-02
1.41359E-01
1.60974E-03

COMPARISON TABLE?

Y

Table B-1
Heat Capacity of AISI - 106 Steel

X	Y	YCALC	DIFF	SLOPE
0.2980E+00	0.1075E+00	0.1096E+00	-0.2091E-02	0.1970E-01
0.3230E+00	0.1100E+00	0.1104E+00	-0.4277E-03	0.4582E-01
0.3730E+00	0.1151E+00	0.1136E+00	0.1464E-02	0.7932E-01
0.4230E+00	0.1217E+00	0.1181E+00	0.3569E-02	0.9882E-01
0.4730E+00	0.1254E+00	0.1234E+00	0.2003E-02	0.1109E+00
0.5230E+00	0.1304E+00	0.1292E+00	0.1245E-02	0.1189E+00
0.5730E+00	0.1349E+00	0.1352E+00	-0.3408E-03	0.1242E+00
0.6230E+00	0.1405E+00	0.1416E+00	-0.1053E-02	0.1280E+00
0.6730E+00	0.1452E+00	0.1480E+00	-0.2828E-02	0.1308E+00
0.7230E+00	0.1510E+00	0.1546E+00	-0.3621E-02	0.1328E+00
0.7730E+00	0.1584E+00	0.1613E+00	-0.2904E-02	0.1344E+00
0.8230E+00	0.1660E+00	0.1681E+00	-0.2054E-02	0.1356E+00
0.8730E+00	0.1765E+00	0.1749E+00	0.1642E-02	0.1365E+00
0.9230E+00	0.1871E+00	0.1817E+00	0.5397E-02	0.1373E+00

DATA POINTS = 9

STANDARD DEVIATION:
2.43611E-03

COEFFICIENTS:
1.27651E-01
-9.11025E-02
2.43554E-03

Table B-2
Thermal Diffusivity of AISI-106 Grade B Steel

COMPARISON TABLE?

Y

X	Y	YCALC	DIFF	SLOPE
0.2950E+00	0.1287E+00	0.1288E+00	-0.6229E-04	-0.2808E+00
0.4163E+00	0.1030E+00	0.1038E+00	-0.8260E-03	-0.1588E+00
0.4830E+00	0.9421E-01	0.9449E-01	-0.2826E-03	-0.1351E+00
0.5352E+00	0.9180E-01	0.8742E-01	0.4380E-02	-0.1229E+00
0.6053E+00	0.7787E-01	0.7919E-01	-0.1318E-02	-0.1131E+00
0.7010E+00	0.6552E-01	0.6874E-01	-0.3224E-02	-0.1052E+00
0.7730E+00	0.6116E-01	0.6161E-01	-0.4498E-03	-0.1018E+00
0.8750E+00	0.5294E-01	0.5112E-01	0.1823E-02	-0.9837E-01
0.9223E+00	0.4648E-01	0.4652E-01	-0.3947E-04	-0.9732E-01

DATA POINTS = 14

STANDARD DEVIATION:
6.55928E-01

COEFFICIENTS:
4.71147E+01
-2.05021E+01
3.87513E-01

Table B-3
Thermal Conductivity of AISI-106 Grade B Steel

COMPARISON TABLE?

Y

X	Y	YCALC	DIFF	SLOPE
0.2980E+00	0.4603E+02	0.4536E+02	0.6675E+00	-0.4977E+02
0.3230E+00	0.4423E+02	0.4420E+02	0.2904E-01	-0.4349E+02
0.3730E+00	0.4156E+02	0.4225E+02	-0.6873E+00	-0.3543E+02
0.4280E+00	0.3979E+02	0.4060E+02	-0.8130E+00	-0.3074E+02
0.4780E+00	0.3866E+02	0.3914E+02	-0.4844E+00	-0.2782E+02
0.5230E+00	0.3773E+02	0.3780E+02	-0.7411E-01	-0.2592E+02
0.5730E+00	0.3677E+02	0.3654E+02	0.2273E+00	-0.2462E+02
0.6280E+00	0.3582E+02	0.3534E+02	0.4842E+00	-0.2371E+02
0.6780E+00	0.3482E+02	0.3417E+02	0.6521E+00	-0.2304E+02
0.7280E+00	0.3366E+02	0.3303E+02	0.6313E+00	-0.2255E+02
0.7780E+00	0.3242E+02	0.3191E+02	0.5092E+00	-0.2218E+02
0.8280E+00	0.3105E+02	0.3081E+02	0.2407E+00	-0.2189E+02
0.8780E+00	0.2938E+02	0.2972E+02	-0.3406E+00	-0.2167E+02
0.9280E+00	0.2760E+02	0.2864E+02	-0.1042E+01	-0.2149E+02

DATA POINTS = 14

STANDARD DEVIATION:
7.18411E-04

Table B-4
Heat Capacity of Single Crystal Halite

COEFFICIENTS:
2.06429E-01
2.82741E-02
-1.09445E-03

COMPARISON TABLE?

Y

X	Y	YCALC	DIFF	SLOPE
0.2980E+00	0.2025E+00	0.2025E+00	-0.3023E-04	0.1110E+00
0.3230E+00	0.2050E+00	0.2051E+00	-0.71 5E-04	0.9323E-01
0.3730E+00	0.2092E+00	0.2091E+00	0.9131E-04	0.7045E- 1
0.423 E+00	0.21""E+00	0.2123+	-0.7217E-04	0.5719E-01
0.4730E+00	0.2148E+00	0.2149E+00	-0.1107E-03	0.4896E-01
0.5230E+00	0.2184E+00	0.2172E+00	0.1185E-02	0.4358E-01
0.5730E+00	0.2190E+00	0.2193E+00	-0.2966E-03	0.3991E-01
0.6230E+00	0.2201E+00	0.2212E+00	-0.1124E-02	0.3733E-01
0.6730E+00	0.2234E+00	0.2230E+00	0.3590E-03	0.3546E-01
0.7230E+00	0.2243E+00	0.2248E+00	-0.4774E-03	0.3407E-01
0.7730E+00	0.2262E+00	0.2267E+00	-0.2532E-03	0.3301E-01
0.8230E+00	0.2295E+00	0.2281E+00	0.1417E-02	0.3220E-01
0.8730E+00	0.2290E+00	0.2297E+00	-0.6762E-03	0.3156A-01
0.9230E+00	0.2313E+00	0.2312E+00	0.5876E-04	0.3106E-01

DATA POINTS = 14

STANDARD DEVIATION:
1.03374E-03

COEFFICIENTS:
2.05688E-01
2.96259E-02
-1.11503E-03

COMPARISON TABLE?

Y

Table B-5
Heat Capacity of Bed Salt

X	Y	YCALC	DIFF	SLOPE
0.2980E+00	0.2020E+00	0.2020E+00	0.3976E-04	0.1139E+00
0.3230E+00	0.2037E+00	0.2046E+00	-0.8693E-03	0.9580E-01
0.3730E+00	0.2095E+00	0.2087E+00	0.7761E-03	0.7260E-01
0.4230E+00	0.2125E+00	0.2120E+00	0.5121E-03	0.5909E-01
0.4730E+00	0.2150E+00	0.2147E+00	0.2830E-03	0.5070E-01
0.5230E+00	0.2169E+00	0.2171E+00	-0.2057E-03	0.4521E-01
0.5730E+00	0.2201E+00	0.2193E+00	0.8326E-03	0.4148E-01
0.6230E+00	0.2210E+00	0.2213E+00	-0.2719E-03	0.3885E-01
0.6730E+00	0.2226E+00	0.2232E+00	-0.5642E-03	0.3694E-01
0.7230E+00	0.2237E+00	0.2250E+00	-0.1274E-02	0.3553E-01
0.7730E+00	0.2275E+00	0.2267E+00	0.7774E-03	0.3445E-01
0.8230E+00	0.2272E+00	0.2284E+00	-0.1224E-02	0.3363E-01
0.8730E+00	0.2293E+00	0.2301E+00	-0.7882E-03	0.3298E-01
0.9230E+00	0.2337E+00	0.2317E+00	0.1976E-02	0.3246E-01

STANDARD DEVIATION:
2.55145E-03

COEFFICIENTS:
5.98971E-02
-9.47659E-02
4.13954E-02

Table B-6
Thermal Diffusivity of Single Crystal Halite

COMPARISON TABLE?

Y

X	Y	YCALC	DIFF	SLOPE
0.2970E+00	0.3158E-01	0.3540E-01	-0.3823E-02	-0.7018E-01
0.2980E+00	0.3712E-01	0.3533E-01	0.1787E-02	-0.7009E-01
0.3010E+00	0.3693E-01	0.3512E-01	0.1807E-02	-0.6985E-01
0.3020E+00	0.3553E-01	0.3505E-01	0.4767E-03	-0.6976E-01
0.4400E+00	0.2407E-01	0.2621E-01	-0.2144E-02	-0.5834E-01
0.5270E+00	0.2609E-01	0.2145E-01	0.4638E-02	-0.5114E-01
0.5540E+00	0.1860E-01	0.2010E-01	-0.1502E-02	-0.4890E-01
0.6590E+00	0.1389E-01	0.1542E-01	-0.1534E-02	-0.4021E-01
0.7760E+00	0.1135E-01	0.1129E-01	0.6393E-04	-0.3052E-01
0.9020E+00	0.8340E-02	0.8098E-02	0.2423E-03	-0.2009E-01
0.9230E+00	0.7682E-02	0.7694E-02	-0.1209E-04	-0.1835E-01

DATA POINTS = 13

STANDARD DEVIATION:
1.70142E-03

Table B-7
Thermal Diffusivity of Bed Salt

COEFFICIENTS:
1.77877E-02
-1.44067E-02
1.40541E-03

COMPARISON TABLE?

Y

X	Y	YCALC	DIFF	SLOPE
0.2980E+00	0.2719E-01	0.2932E-01	-0.2131E-02	-0.1206E+00
0.3020E+00	0.3050E-01	0.2885E-01	0.1654E-02	-0.1165E+00
0.4040E+00	0.1879E-01	0.2058E-01	-0.1788E-02	-0.5703E-01
0.3710E+00	0.2502E-01	0.2265E-01	0.2366E-02	-0.6945E-01
0.4520E+00	0.1925E-01	0.1815E-01	0.1095E-02	-0.4484E-01
0.4720E+00	0.1550E-01	0.1730E-01	-0.1796E-02	-0.4114E-01
0.5580E+00	0.1508E-01	0.1426E-01	0.8175E-03	-0.3058E-01
0.6570E+00	0.1266E-01	0.1158E-01	0.1082E-02	-0.2432E-01
0.7480E+00	0.7388E-02	0.9523E-02	-0.2135E-02	-0.2112E-01
0.7580E+00	0.1024E-01	0.9313E-02	0.9265E-03	-0.2086E-01
0.7630E+00	0.8374E-02	0.9272E-02	-0.8978E-03	-0.2081E-01
0.9180E+00	0.6455E-02	0.6230E-02	0.2250E-03	-0.1804E-01
0.9200E+00	0.6740E-02	0.6158E-02	0.5820E-03	-0.1799E-01

DATA POINTS = 14

STANDARD DEVIATION:
1.79023E-02

Table B-8
Thermal Conductivity of Single Crystal Halite

COEFFICIENTS:
7.01134E+00
-6.10812E+00
1.19718E-01

COMPARISON TABLE?

Y

X	Y	YCALC	DIFF	SLOPE
0.2980E+00	0.6512E+01	0.6539E+01	-0.2724E-01	-0.1516E+02
0.3230E+00	0.6213E+01	0.6186E+01	0.2707E-01	-0.1321E+02
0.3730E+00	0.5620E+01	0.5593E+01	0.2650E-01	-0.1072E+02
0.4230E+00	0.5091E+01	0.5097E+01	-0.5689E-02	-0.9272E+01
0.4730E+00	0.4646E+01	0.4657E+01	-0.1130E-01	-0.8371E+01
0.5230E+00	0.4230E+01	0.4254E+01	-0.2447E-01	-0.7782E+01
0.5730E+00	0.3869E+01	0.3876E+01	-0.7017E-02	-0.7381E+01
0.6230E+00	0.3515E+01	0.3514E+01	0.5685E-03	-0.7098E+01
0.6730E+00	0.3173E+01	0.3165E+01	0.8104E-02	-0.6894E+01
0.7230E+00	0.2839E+01	0.2824E+01	0.1480E-01	-0.6742E+01
0.7730E+00	0.2492E+01	0.2490E+01	0.1881E-02	-0.6627E+01
0.8230E+00	0.2170E+01	0.2161E+01	0.8892E-02	-0.6538E+01
0.8730E+00	0.1837E+01	0.1836E+01	0.9644E-03	-0.6468E+01
0.9230E+00	0.1501E+01	0.1514E+01	-0.1307E-01	-0.6413E+01

DATA POINTS = 14

STANDARD DEVIATION:
2.99856E-02

COEFFICIENTS:
3.89427E+00
-3.08398E+02
2.11185E-01

COMPARISON TABLE?

v

Table B-9
Thermal Conductivity of Bed Salt

X	Y	YCALC	DIFF	SLOPE
0.2980E+00	0.5377E+01	0.5353E+01	0.2365E-01	-0.1904E+02
0.3230E+00	0.4930E+01	0.4922E+01	-0.2237E-01	-0.1562E+02
0.3730E+00	0.4258E+01	0.4262E+01	-0.3859E-02	-0.1122E+02
0.4230E+00	0.3776E+01	0.3770E+01	0.5975E-02	-0.8664E+01
0.4730E+00	0.3353E+01	0.3379E+01	-0.2649E-01	-0.7075E+01
0.5230E+00	0.3051E+01	0.3053E+01	-0.2430E-02	-0.6036E+01
0.5730E+00	0.2758E+01	0.2770E+01	-0.1237E-01	-0.5329E+01
0.6230E+00	0.2576E+01	0.2517E+01	-0.1107E-01	-0.4831E+01
0.6730E+00	0.2371E+01	0.2285E+01	0.8598E-01	-0.4470E+01
0.7230E+00	0.2067E+01	0.2069E+01	-0.1564E-02	-0.4202E+01
0.7730E+00	0.1850E+01	0.1864E+01	-0.1379E-01	-0.3998E+01
0.8230E+00	0.1661E+01	0.1668E+01	-0.6952E-02	-0.3842E+01
0.8730E+00	0.1477E+01	0.1479E+01	-0.2061E-02	-0.3719E+01
0.9230E+00	0.1283E+01	0.1296E+01	-0.1265E-01	-0.3621E+01

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