

THERMAL DIFFUSIVITY OF TWO RARE-EARTH SILICATE
GLASSES BETWEEN 100K AND 300K

By

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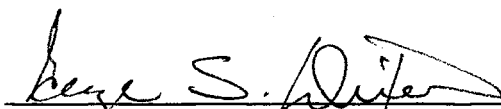
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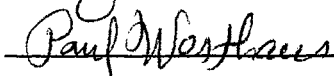
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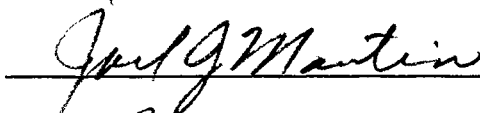
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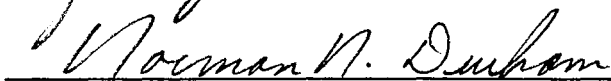
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The author feels pleased at this moment, after all, he gets his Master Degree from the field he is always interested in.

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CHAPTER I

INTRODUCTION

The solid is classified as crystal solid and amorphous solid according to their structures. The crystal solid has long range symmetric order while the amorphous solid does not. The crystal solid has been studied for over a century and the whole set of theories about its properties has been developed, while the studies over the amorphous solid has been remained in infancy. The reason is that the amorphous solids are complex structure which exhibit no symmetry characteristics of an orderly solid. It has been simply viewed as a short-range ordered liquid until recent years when it started to gain a increasing interest in the physical community and scientists in the related fields. There are two main factors for this reason: the advances of solid state physics and its numerous applications, and the fact that the disordered system are, in a way, systems of generic nature. The research over the disordered materials are challenging because this is a new field and many things can not be explained by the existing theory which depends to a great extent on the notion of the ideal structure of such systems and therefore can not applied to disordered system without substantial modification.

In the past decade, much progress has been made about the research over the disordered and amorphous materials, many new

ideas has been introduced and many new techniques has been employed, especially in the area of thermal conductivity which gained widespread attention in the solid state physics field in 1971 when Zeller and Pohl discovered that below 1K the thermal properties of amorphous solids were strikingly different from their crystalline counterparts. Since then, the phonon scattering and thermal conductance has remained one of the major topics for disordered and amorphous materials. Many experiments and observation have been done and we now have some pictures of the behavior of the thermal conductivity of the glass but the microscopic mechanism are not clear, the following is part of the summary written by A.C.Anderson and J.P.Wolfe for the Fifth International Conference over the Phonon Scattering in Condensed Matter V held in Urbana,Illinois, June 2-6,1986: "...The thermal conductivity of an amorphous solid, and of certain disordered crystals, varies as T^2 at low temperatures, exhibits a temperature independent plateau between roughly 1 and 10K, then increases again at higher temperatures. The phonon mean free path L as a function of wavelength λ is remarkably similar for all these materials. At temperature below 1k the phonons are scattered by "two-level states" (TLS) which are believed to arise from quantum tunneling of atoms or molecules. But there is no microscopic description of the TLS, nor an explanation of the universal dependence of L on λ . In the plateau, L appears to be dominated by Rayleigh scattering. But the source of this scattering has not been identified. At temperatures above 10K, even a description of the thermal excitation responsible for thermal transport has not

been identified..."

Not only in the theoretical research field there is so many uncertainties around the thermal conductivity of the amorphous materials but also in the experiment research field few experimental data are available, especially in the high temperature region where the radiative heat transport causes difficulty in making good measurements. Our research is concentrated in the measurements of the thermal conductivity of some glasses in the temperature above the liquid nitrogen temperature. In order to overcome the problem of the radiative heat loss, we measure the thermal diffusivity which related to the thermal conductivity in a simple way since it is less sensitive to radiative problem, we will discuss this in more detail when we discuss the technique in Chapter II. So far, this is the best systematic study of thermal transport in glasses above liquid nitrogen temperature.

Theory of Thermal Conductivity of Crystals

The first step in understanding the thermal properties of glasses is to review the thermal properties of crystals. The total internal energy of the phonons at temperature in a crystal may be written as the sum of the energies over all phonon modes

$$U = \sum_q \sum_p U_{(q,p)} = \sum_q \sum_p \langle n_{(q,p)} \rangle \hbar \omega_{(q,p)} \quad (1.1)$$

where q refers to the wavevector, p the polarization and $\langle n_{(q,p)} \rangle$ is the average excitation quantum number of a phonon of wavevector q and polarization p . From Planck's distribution we know that:

$$\langle n \rangle = 1 / (\exp(E/kT) - 1) \quad (1.2)$$

so the total energy of a collection of oscillators with energy $\hbar \omega_{(q,p)}$ is then

$$U = \sum_q \sum_p \hbar \omega_{(q,p)} / (\exp(\hbar \omega_{(q,p)} / kT) - 1) \quad (1.3)$$

for large quantity of oscillators, from statistical point of view we have

$$U = \sum_\lambda \int d\omega D_\lambda(\omega) \hbar \omega / (\exp(\hbar \omega / kT) - 1) \quad (1.4)$$

Where $D(\omega)$ is the density of the states within ω to $\omega + d\omega$. The lattice heat capacity is found by differentiating the above equation with respect to the temperature:

$$\partial U / \partial T = \sum_\lambda \int d\omega D_\lambda(\omega) \hbar^2 \omega^2 \exp(\hbar \omega / kT) / (\exp(\hbar \omega / kT) - 1)^2 kT^2 \quad (1.5)$$

Letting $x = \hbar\omega/kT$ this simplifies to

$$\partial U / \partial T = k \Sigma_{\lambda} \int d\omega D_{\lambda}(\omega) x^2 e^x / (e^x - 1)^2 \quad (1.6)$$

In calculating the density of states the standard way is to use the Debye model which treat the crystal as a continuous isotropic medium. for three dimensional periodic boundary condition:

$$\exp[i(q_x x + q_y y + q_z z)] = \exp[i(q_x(x+L) + q_y(y+L) + q_z(z+L))] \quad (1.7)$$

whence

$$q_x, q_y, q_z = 0, \pm 2\pi/L, \dots, \pm 2n\pi/L \quad (1.8)$$

therefore in K space there is one allowed value of q per volume $(2\pi/L)^3$ or $V/8\pi^3$ allowed values of q per unit volume thus the total number of modes with wavevector between q and q+dq is found to be

$$N = (L/2\pi)^3 (4\pi q^3/3) \quad (1.9)$$

In the Debye approximation the velocity of sound is taken as constant for each polarization type, as would be the case for a true elastic continuum. The dispersion relation is

$$\omega = vq \quad (1.11)$$

where v is the constant velocity of sound. substitute this into (1.9) we get:

$$D(\omega) = V\omega^2 / 2\pi^2 v^3 \quad (1.12)$$

this expression is applicable to any one of the three polarization modes. Assuming that the phonon velocity is independent of polarization the density of states will be

$$D(\omega) = 3V\omega^2 / 2\pi^2 v^3 \quad (1.13)$$

To normalize $D(\omega)$, The Debye frequency ω_D is introduced so that the total number of modes is $3N$

$$3N = \int_0^{\omega_D} D(\omega) d\omega = V \omega_D^3 / 2\pi^2 v^3 \quad (1.14)$$

so

$$\omega_D = (6N\pi^2/V)^{1/3} v \quad (1.15)$$

Let

$$\theta = \hbar(6N\pi^2/V)^{1/3} v/k \quad (1.16)$$

inserting (1.15), (1.16) into (1.6), we get:

$$C_v = 9Nk(T/\theta)^3 \int_0^{\omega_D} dx x^3 e^x / (e^x - 1)^2 \quad (1.17)$$

at very low temperature $x \gg 1$, so the upper limit of the integral can be treated as infinity, thus the integral becomes

$$\int_0^{\infty} dx x^3 / (e^x - 1) = \pi^4/15 \quad (1.18)$$

so the heat capacity becomes:

$$C_v = 234Nk(T/\theta)^3 \quad (1.19)$$

(1.19) is called Debye's T^3 law which has an excellent

agreement between experiment and theory for nonmetal crystals at all low temperature and metals when above 3K.

The mechanism of the thermal conductivity in crystalline dielectrics is well understood. Heat is transported by phonons which are the elementary excitations of the system. The thermal conductivity K is defined with respect to the steady state heat flow down a rod with a temperature gradient dT/dx

$$j_u = -KdT/dx \quad (1.20)$$

where j is the energy transmitted across unit area per unit time.

The form of (1.20) implies a random process in which the energy diffuses through the solid suffering frequent collisions. Considering the phonons as particles the flux of particles is

$$f_x = 1/2n \langle |v_x| \rangle \quad (1.21)$$

where n is the concentration of particles and $\langle v_x \rangle$ is the thermal average of the particle velocity. In moving from a region of temperature $T+dT$ to a region of temperature T a particle with heat capacity c will give up an amount of energy cdT . dT between the ends of the mean free path of the particle is

$$dT = (dT/dx)l_x = (dT/dx)v_x \tau \quad (1.22)$$

where τ is the average time between collisions. The net flux

of the energy is therefore

$$j_u = -n \langle v_x \rangle c \Delta T = -n \langle v_x^2 \rangle c \tau dT/dx = -1/3 n \langle v^2 \rangle c \tau dT/dx \quad (1.23)$$

for phonons v is a constant and Eq.1.23 becomes

$$j_u = -1/3 C_v l dT/dx \quad (1.24)$$

where $l = v\tau$ and $C = nc$.

compare this with Eq.1.20 the thermal conductivity is found

$$K = 1/3 C_v l \quad (1.25)$$

it is found in Eq.1.19 that the Debye approximation the heat capacity was proportional to T^3 . thus the thermal conductivity will display the same behavior

$$K \propto T^3 \quad (1.26)$$

this prediction fits extremely well for crystals below 20K.

Thermal conductivity of glasses at low temperature

Unlike the conductivity of crystalline solids, there is much less understanding of amorphous solids. A typical temperature dependence of $K(T)$ for an amorphous solid is displayed by curve II of Fig. II. In region A the curve decreases slowly with the decreasing temperature. Around 10K the thermal conductivity is only weakly dependent on temperature leading to the so called "plateau" of region B. In region C $K(T)$ decreases roughly as T^2 . The behaviour of curve II depends more on the amorphous state than chemical composition. This property of glasses received little attention until 1971 when Zeller and Pohl published a paper containing careful measurements of $K(T)$ in the T^2 region. They suggested that this behavior might be associated with the specific heat of glassy material which at low temperature is in excess of that expected for phonons and having a roughly linear temperature dependence.

Zeller and Pohl's paper stimulated the investigation of the low temperature properties of amorphous materials both in the experimental field and theoretical field. experimentally we now have some basic facts suggest that: 1) thermal phonons alone transport heat, 2) λ is essentially the same for both phonon polarizations, and 3) there exist additional states or excitations which contribute to the excess T term in the specific heat and which are localized. They do not transport heat. theoretically we now have a phenomenological model developed by Phillips and Anderson et al independently

describes the experimental results most successfully. The model is based upon the assumption that in a amorphous network small groups of atoms can tunneling between two positions of equilibrium. Thus two-level tunneling states are formed which give rise to the enhanced specific heat and which scatter phonons strongly.

The two-level-system theory proposes that an atom or group of atoms in the solid can arrange themselves into two possible equilibrium configurations. Fig.3 is a representation of the two-well system with the energy difference E . the energy levels of the particle are calculated by using as the starting point the solutions to the single well problem. The interaction Hamiltonian is:

$$H_{int} = -\left(-\frac{1}{2}\mu\sigma_z + \mu'\sigma_x\right)\xi - \left(\frac{1}{2}D\sigma_z + M\sigma_x\right)e \quad (1.27)$$

The interaction between the tunneling states of the TLS and the phonons can be expressed using a rate-equation approach

$$\dot{P}_+ = -P_+\omega_{+-} + P_-\omega_{-+} \quad (1.28)$$

$$\dot{P}_- = P_+\omega_{+-} - P_-\omega_{-+} \quad (1.29)$$

Where P_+ and P_- are the populations of states + and -, \dot{P}_+ and \dot{P}_- are the change in population per unit time, ω_{+-} is the transition probability from state + to state -. The population is assumed normalized so that $P_+ + P_- = 1$ in thermal equilibrium

$$\dot{P}_+ = \dot{P}_- = 0 \quad (1.30)$$

so that

$$P'_+ \omega_{+-} = P'_- \omega_{-+} \quad (1.31)$$

where P'_+ and P'_- are the equilibrium values of P_+ and P_- . From statistical mechanics the ratio of the populations is given by the Boltzmann factor

$$P'_-/P'_+ = \exp(E/kT) \quad (1.32)$$

where E is the energy difference between states $+$ and $-$. substitute eq.(1.31) into it, we get:

$$P'_+/P'_- = \omega_{-+}/\omega_{+-} = \exp(-E/kT) \quad (1.33)$$

Replacing p_+ in Eq.(1.29) with $1-P_-$ gives

$$P'_- = -P_-(\omega_{+-} + \omega_{-+}) + \omega_{+-} \quad (1.34)$$

This defines a relaxation time τ where

$$\tau^{-1} = (\omega_{+-} + \omega_{-+}) = \omega_{-+}(1 + \exp(E/kT)) \quad (1.35)$$

This relaxation time is referred to as T_1 the spin-lattice relaxation time.

For a weak strain field the transition probability for a one-phonon process can be calculated from time-dependent perturbation theory. The probability per unit time that the TLS in state Φ_- absorbs a phonon and jumps to state Φ_+ is given by

$$\omega_{-+} = 2\pi/\hbar \sum_{\alpha} |\langle \Phi_f | H_{int} | \Phi_i \rangle|^2 g(E) \delta(\hbar\omega - E) \quad (1.36)$$

where the sum over α is to account for all phonon polarizations and $g(E)$ is the phonon density of states. By evaluating the local strain we can calculate the matrix element and get:

$$\omega_{-+} = 2\pi/\hbar \sum_{\alpha} \Lambda_{\alpha}^2 \gamma_{\alpha}^2 \hbar q_{\alpha}^2 n_{\alpha} g(E) \delta(\hbar\omega - E) / E^2 2\rho\omega_q \quad (1.37)$$

substitute into the dispersion relation $q = \omega/v$ and Debye density of states per unit volume

$$g(E) = \omega^2 / 2\pi^2 \hbar v^3 \quad (1.38)$$

the Eq(1.36) becomes

$$\omega_{-+} = \sum_{\alpha} r_{\alpha}^2 E \Lambda_{\alpha}^2 (\exp(E/kT) - 1)^{-1} \delta(\hbar\omega - E) / v^5 2\pi\rho\hbar^4 \quad (1.39)$$

thus the spin-lattice relaxation rate is given by

$$\tau^{-1} = \sum_{\alpha} r_{\alpha}^2 E \Lambda_{\alpha}^2 \coth(E/2kT) / v^5 2\pi\rho\hbar^4 \quad (1.40)$$

The interaction between the TLS and phonons reduces the mean free path of the phonons. The above procedure can be utilized to determine the scattering rate of the phonons. Beginning with a detailed balance between the energy lost by the phonons and the energy gained by a single TLS gives

$$Eg(E)n_{\text{ph}} = EP \quad (1.41)$$

which reduce to

$$n_{\text{ph}} = P / g(E) \quad (1.42)$$

where $g(E)$ is still the phonon density of states and n_{ph}

refers to the total number of phonons in the system. Using Eq.(1.29) for P_- gives

$$n_{ph} = (P_+ \omega_{+-} - P_- \omega_{-+}) / g(E) \quad (1.43)$$

Expressing ω_{-+} and ω_{+-} as

$$\omega_{+-} = 2\pi M^2 g(E) n_{ph}(E) / \hbar \quad (1.44)$$

$$\omega_{-+} = \omega_{+-} (n_{ph} + 1) / n_{ph} \quad (1.45)$$

Eq.1.43 becomes

$$n_{ph} = -2\pi M^2 n_{ph} (P_- - P_+) / \hbar + 2\pi M^2 P_+ / \hbar \quad (1.46)$$

this gives a phonon scattering rate of

$$\tau^{-1} = 2\pi M^2 (P_- - P_+) / \hbar \quad (1.47)$$

This can be simplified with the following expressions

$$P_- / P_+ = (n_{ph} + 1) / n_{ph} \quad (1.48)$$

$$P_+ = 1 / (\exp(E/kT) + 1) \quad (1.49)$$

This gives a phonon scattering rate from Eq.1.47 which is equal to

$$\tau^{-1} = 2\pi M^2 \tanh(E/2kT) / \hbar \quad (1.50)$$

inserting M^2 from Eqs.1.44 and 1.39 into the above equation we get the phonon scattering rate of

$$\tau^{-1} = \pi r_{\alpha}^2 \omega_{\alpha}^2 \tanh(E/2kT) / \rho v_{\alpha}^2 E^2 \quad (1.51)$$

assume that Λ is very small and the tunneling-parameter distribution function P is uniformly distributed approximately we get the phonon mean free path due to one-phonon process is

$$l_{\alpha}^{-1} = \pi \omega r_{\alpha}^2 P \tanh(\hbar\omega/2kT) / \rho v_{\alpha}^3 \quad (1.52)$$

for a phonon of polarization α and angular frequency ω .

The definition for the thermal conductivity of glasses is

$$K(T) = 1/3 \sum_{\alpha} \int_0^{\omega_D} C_{\alpha}(\omega) v_{\alpha} l_{\alpha}(\omega) d\omega \quad (1.53)$$

where $C_{\alpha}(\omega)$ is the specific heat predicted by the Debye model for a phonon of polarization α . $C_{\alpha}(\omega)$ is related to the Debye heat capacity by

$$C_{\alpha}(\omega) = C_V / 3V \quad (1.54)$$

substitute Eqs. 1.52, 1.54 into 1.53 and changing variables to solve the integral, the thermal conductivity becomes

$$K(T) = \rho K^3 (\sum_{\alpha} v_{\alpha} / \rho r_{\alpha}^2) T^2 / 6\pi \hbar^2 \quad (1.55)$$

this is the source of the T^2 term below the 'plateau'.

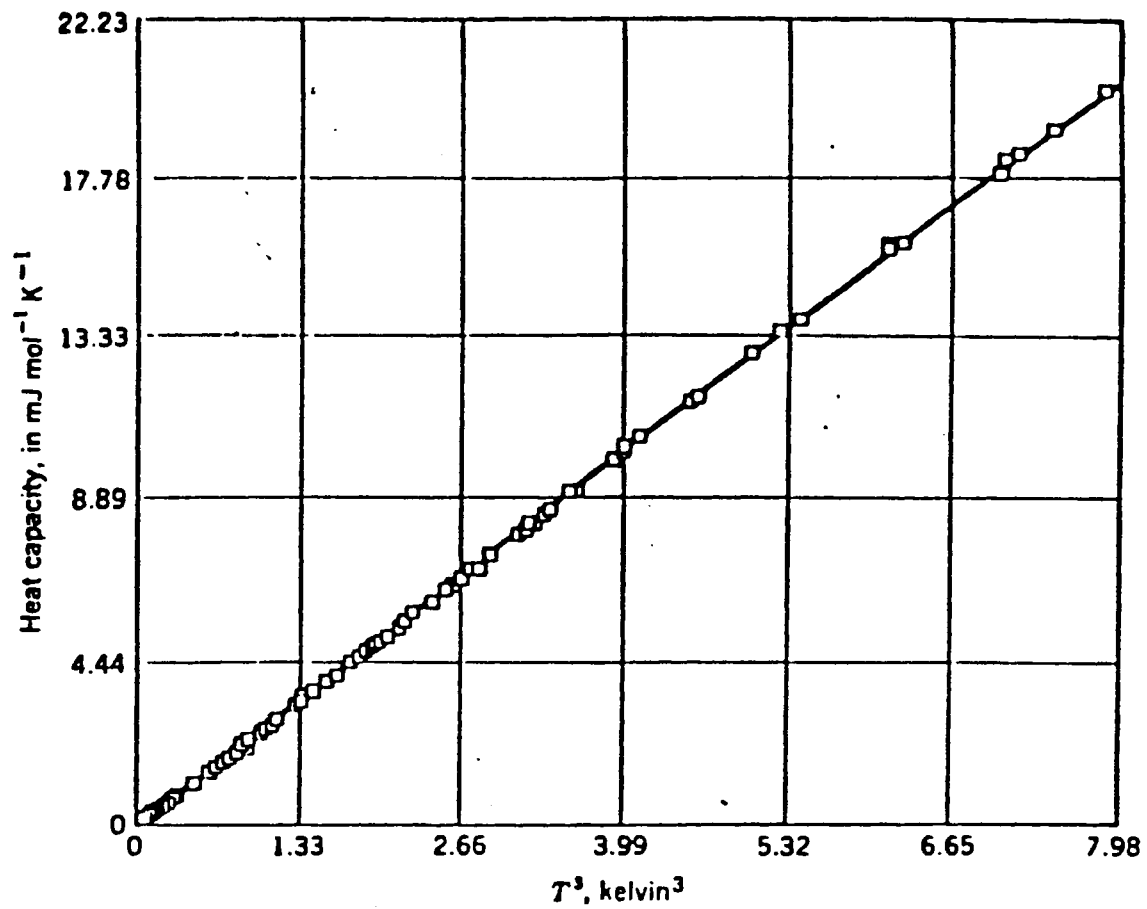


Fig.1 Low temperature heat capacity of solid argon, plotted against T^3 . In this region the experimental results are in excellent agreement with the Debye T^3 law with $\theta = 92.0\text{K}$.

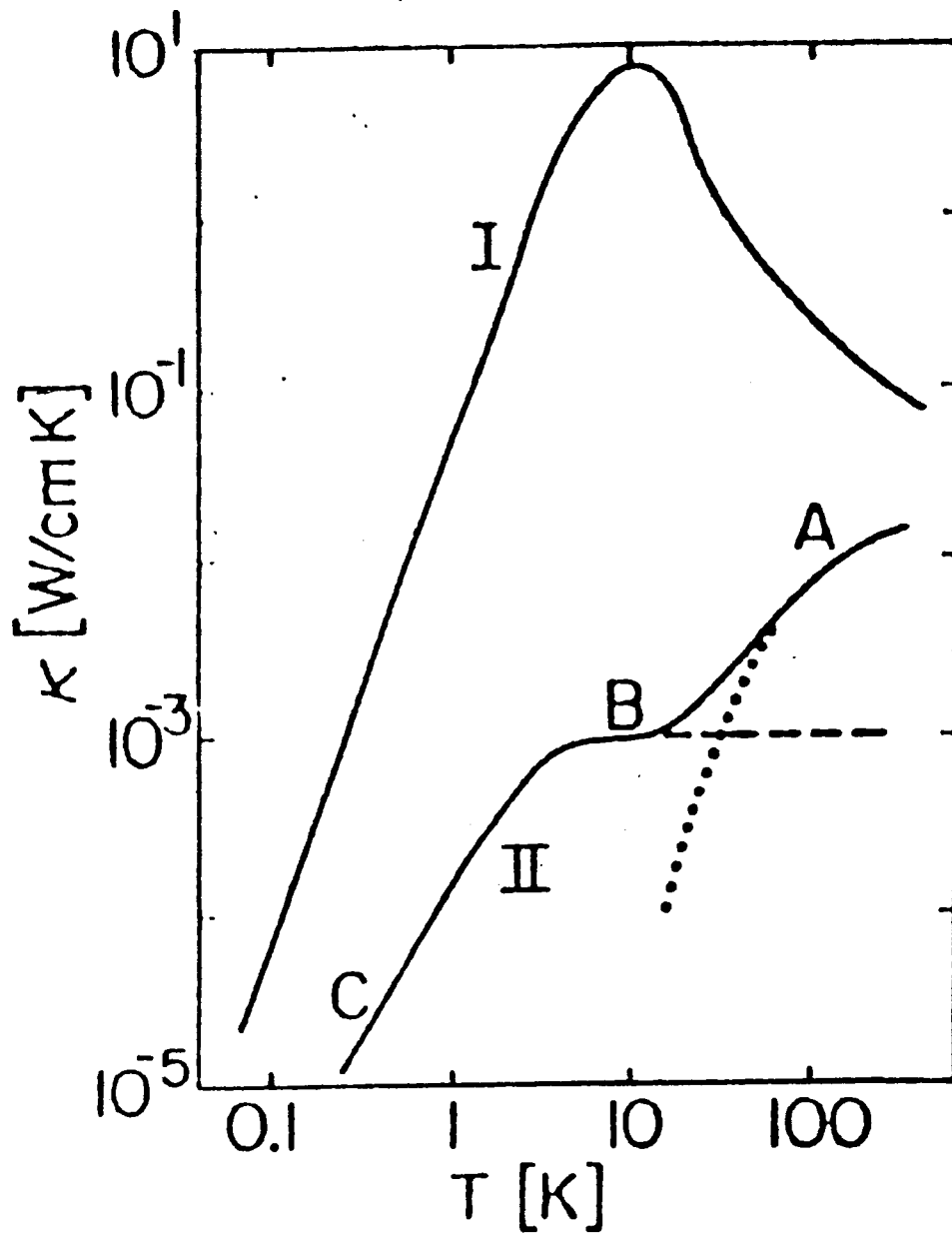


Fig.2 Thermal conductivity of crystalline quartz (I) and fused quartz (II).

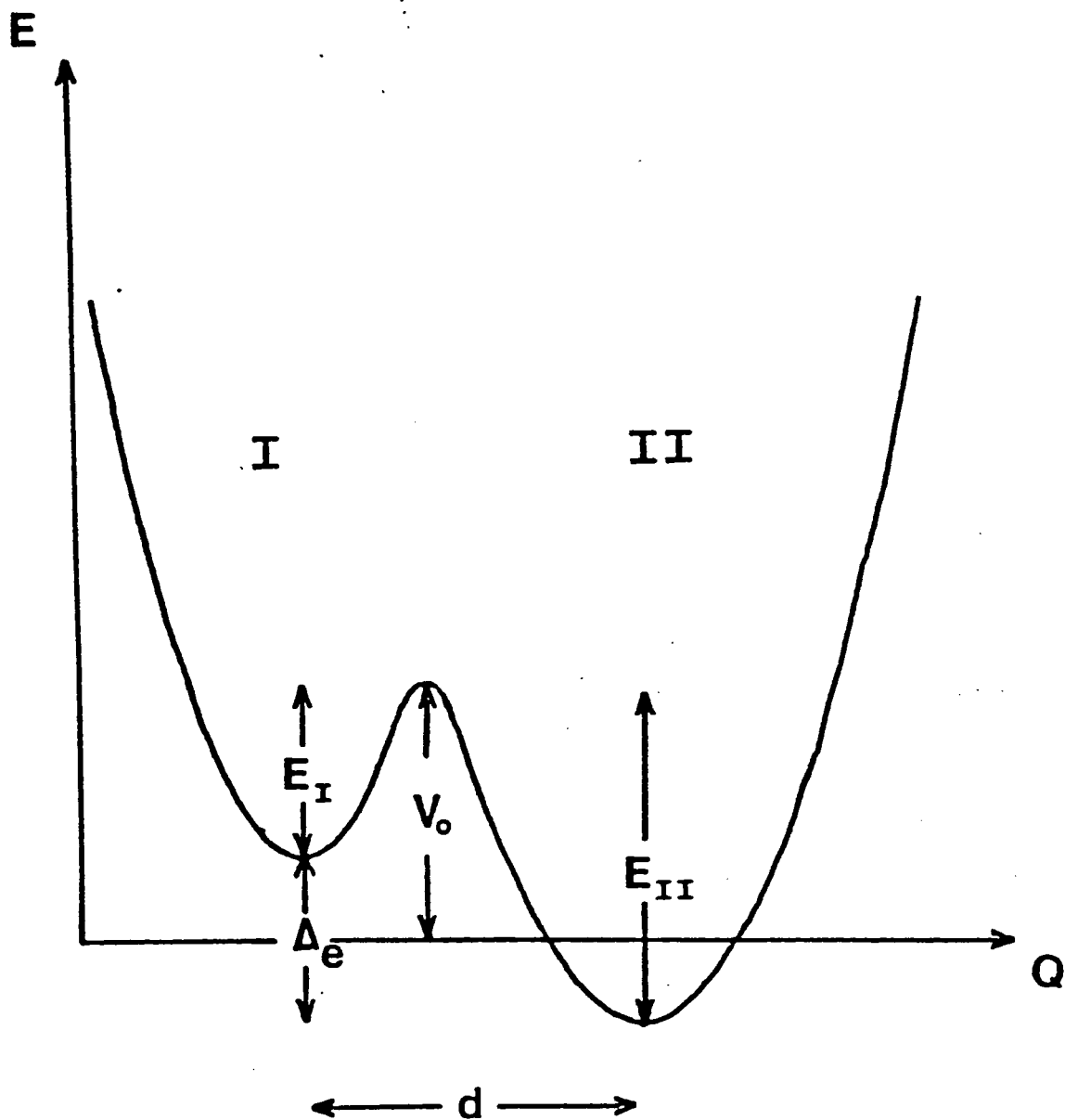


Fig.3 Double-minima potential well.

CHAPTER II

EXPERIMENTAL PROCEDURE

There are two equations which govern the thermal transport property of solids. One is the Fourier's law which defines thermal conductivity

$$J = -\lambda \nabla T \quad (2.1)$$

the another is the thermal diffusion equation

$$\partial T / \partial t = \eta \nabla^2 T \quad (2.2)$$

which determines the thermal diffusivity. They are related by

$$\eta = \lambda / \rho c \quad (2.3)$$

The thermal conductivity is the most widely used thermal transport coefficient. However, determining the thermal conductivity require a determination not only of the temperature profile in the sample, but also the thermal current density J . Since J and ∇T must be held constant over the measurement volume, the experiment must be conducted under rigorously steady-state conditions to obtain accurate results. With poorly conducting materials such as glass it is particularly difficult to hold J constant because of radiative heat loss through the boundaries of the sample.

Thermal equilibrium times can be of the order of hours, limiting the rate of data collection. On the other hand, measuring the thermal diffusivity does not require a knowledge of J or steady state conditions. So the experiment is much easier to conduct, is less influenced by radiation losses, and the data are collected much faster. In this work, the thermal transport property is measured in terms of thermal diffusivity and conducted by a pulse method.

Apparatus

The sample is prepared in a shape of rectangular bar with the length of 20 mm, width of 2 mm and thickness of 2 mm, there are three slots cut near one end with the separation of 0.5 cm which allow the thermal couples to put in. The separation is chosen such that the three thermal couples response to the heat pulse quickly. the sample is mounted on a sample shelf as shown in Fig.4. and the shelf is mounted on the cold finger inside a metal dewar, there are two heaters around, both constructed by thin wire with the resistance 50Ω . heater I, which located around the cold finger, is controlled by an outside voltage source and used to maintain the background temperature while the heater II, which located on the other end of the sample shelf, is controlled by a microcomputer controlled relay device and used to generate the heat pulse during the measurement. The low temperature source is provided by the liquid nitrogen in the metal dewar. A block diagram of the whole setting of the

experiment apparatus is shown in Fig.5. The thermometers used are type K thermocouples and electronic ice points are used as the reference points. The thermocouples are monitored, under computer control, by digital voltmeters (HP 3478A), with a sensitivity of 0.1uV. This gives a temperature measurement sensitivity of 3mK near room temperature.

Procedure

First we pour the liquid nitrogen into the dewar, then choose the voltage of the power supply for heater I so as to maintain the equilibrium of the sample at a desired temperature. After the sample is brought to steady-state conditions, The computer triggers the voltmeters and records the initial readings of the thermometers. It then closes the relay to turn the heater II on. A transient heat pulse now flows through the sample, and the temperature is recorded as a function of time. To do this, the computer simultaneously collects the readings of the three thermometers every 0.5 seconds and stores them. Data are collected for a time interval of 40 seconds, during which the temperature at the thermometer nearest the heater II rises by 5 to 7 K, this can be done by adjust the voltage of the power supply for heater II.when the computer finishes taking the data, it turn off the heater II and waits 45 minutes to allow the sample to reach a state of equilibrium, then it repeats the process again.

During the time between measurements, The computer

reduces the data it has stored during the process of data acquisition and displays the results on the monitor screen. The one dimensional diffusion equation

$$\partial T / \partial t = \eta \partial^2 / \partial x^2 \quad (2.4)$$

applies to the region of interest which is the part of the sample between the lowerest and the highest thermocouples. A plot of $\partial T / \partial t$ versus $\partial^2 T / \partial x^2$ for the middle-plane between these two thermocouples is made. the thermal diffusivity is given by the slope of the least squares regression line for this plot.

A typical graph of the temperature change versus the time elapsed for the three thermocouples is shown on Fig.6. The top curve which rises the most represents the thermocouple closest to the heater. The next curve is the second thermocouple (middle-plane) and the lowest curve is the thermocouple farthest away from the heater. The curves are done by first converting the readings of the voltmeters into temperature using an interpolation formula for the thermocouple tables and then substrate the initial readings to eliminate the small mismatch between the thermocouples. The $\partial T / \partial t$ can be got by applying a least squareed line to a group of ten consecutive points and the slope of that line is the derivative for the midpoint of those points.

The $\partial^2 T / \partial x^2$ can be got using the following approximation formula for finite difference relation:

$$\partial^2 T / \partial x^2 = \{ [T_1(t) - T_2(t)] - [T_2(t) - T_3(t)] \} / (\Delta x)^2 \quad (2.5)$$

where Δx is the distance between adjacent thermometers and the subscripts 1, 2 and 3 refer to the upper, middle and lower thermometers respectively. by this way, a set of values for $\partial T / \partial t$ and the corresponding $\partial^2 T / \partial x^2$ are obtained for the middle-plane, so a new graph of the temperature derivative with respect to time versus the second temperature derivative with respect to spacing is obtained as shown on Fig.7. This is linear curve. by applying the least square method to the curve which close to a straight line, we can get a strict regression line with the slope equal to the thermal diffusivity η .

When the computer finishes reducing the data, it displays four parameters on the monitor screen, they are: 1) temperature, 2) thermal diffusivity, 3) ETA , 4) standard deviation.

Because the experiment is conducted at the low temperature and the signals in the experiment such as current and temperature rise are small and weak compare to the noises in the enviorement, there is some disturbance and errors in the experiment, So the data need to be selected. The data we selected are based on two factors: 1) the disturbance in the curve on graph $\partial T / \partial t$ versus $\partial^2 T / \partial x^2$ should be small, 2) the standard deviation in that specific measurement is less than 2%. This is done by the DBASE III PLUS program. After that, the data are typed into Harvard Graphics and get the graph

for the thermal diffusivity versus temperature.

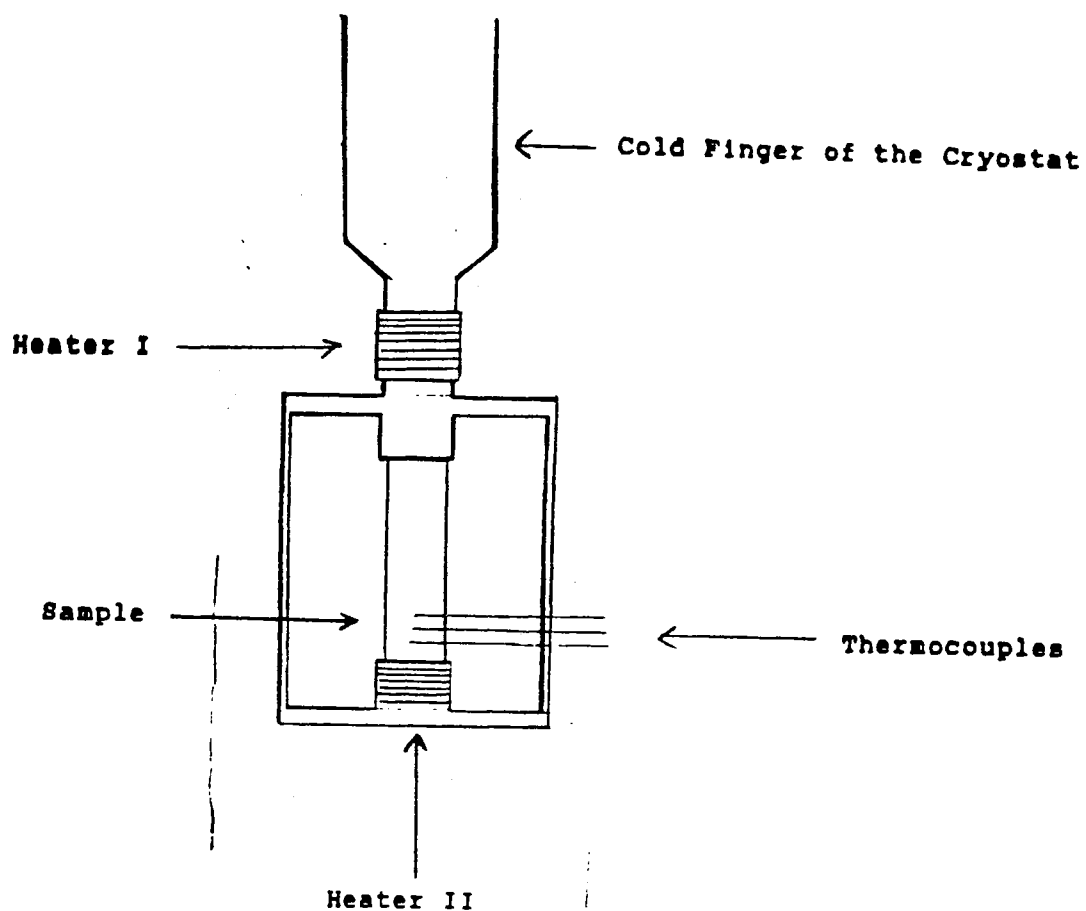


Fig.4 Schematic diagram of the mounting of the sample and the positions of the heaters.

THERMAL DIFFUSIVITY APPARATUS

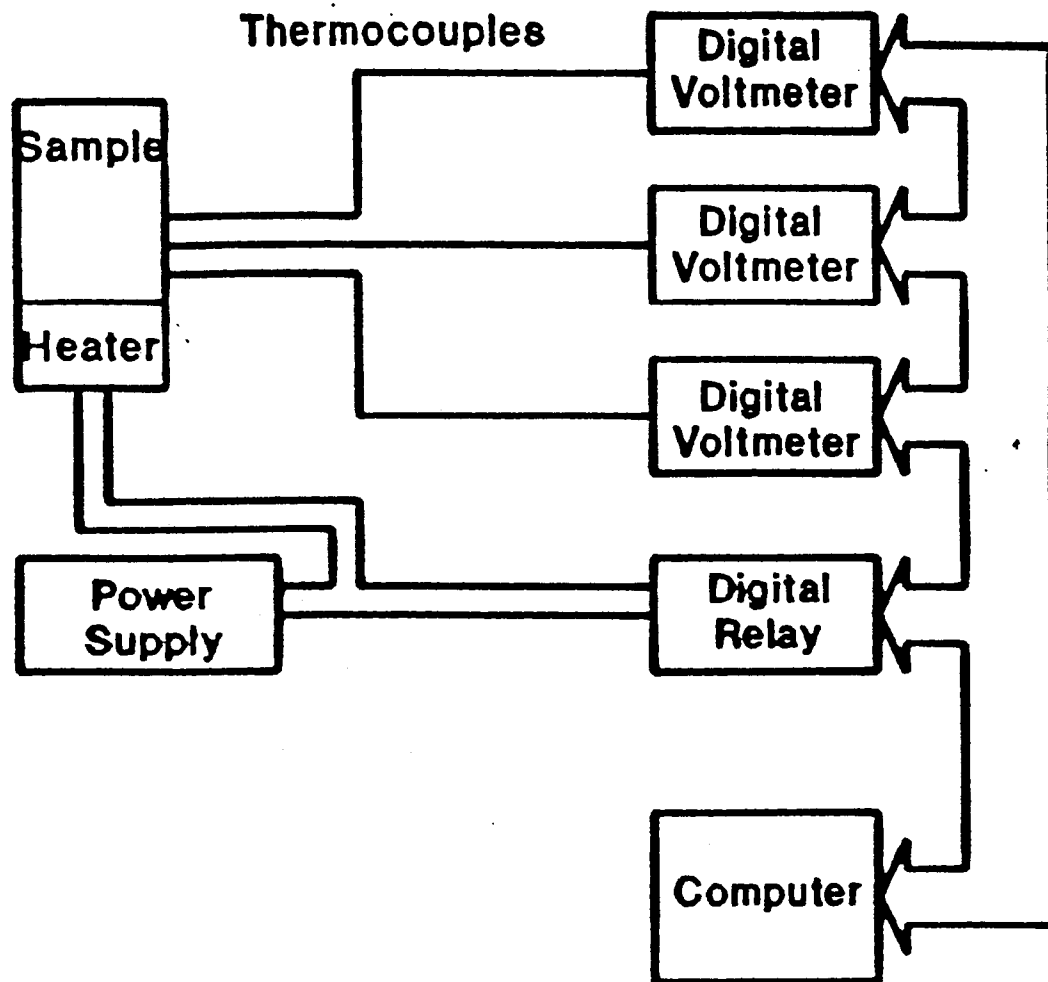


Fig.5 Block diagram of the setup of the apparatus. The sample and the heater are mounted on the cold finger of a cryostat which is not shown.

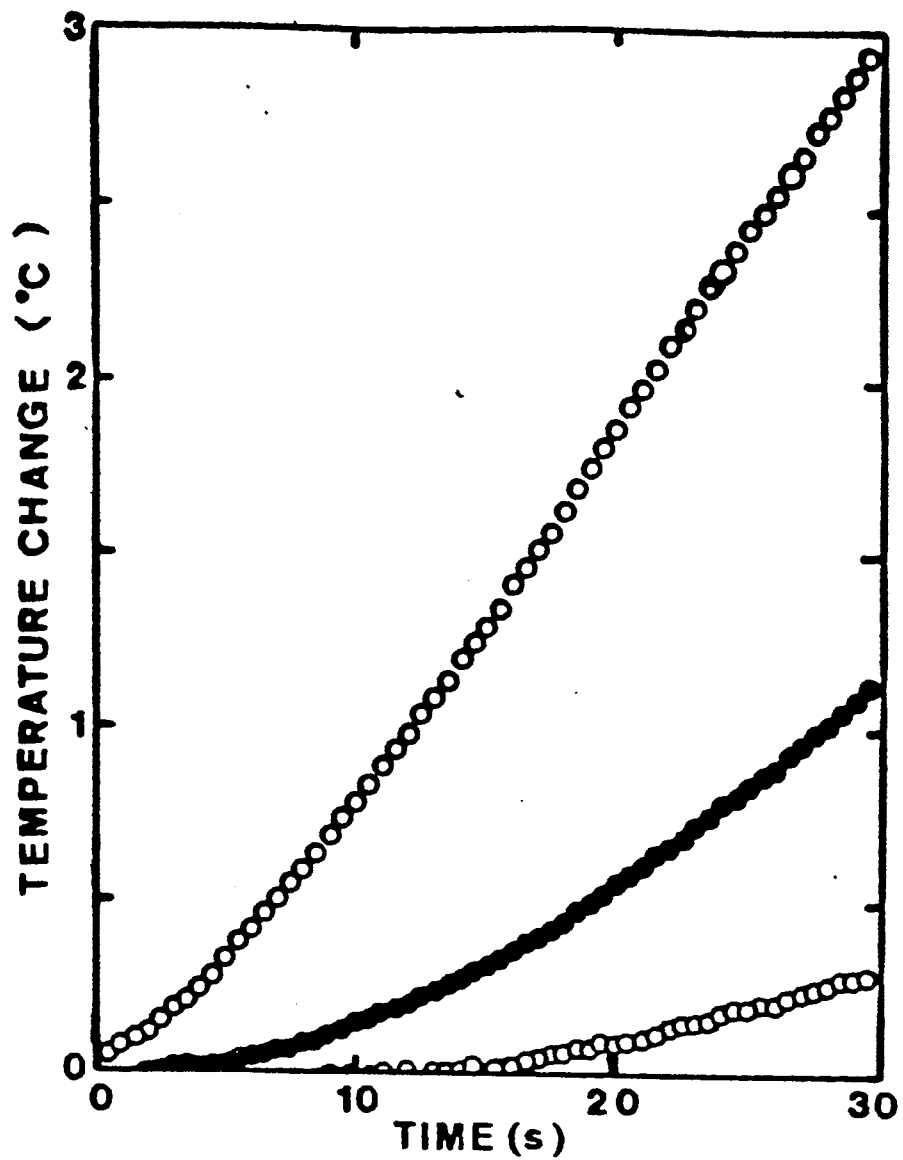


Fig.6 Typical temperature vs. time curves for the three thermocouples.

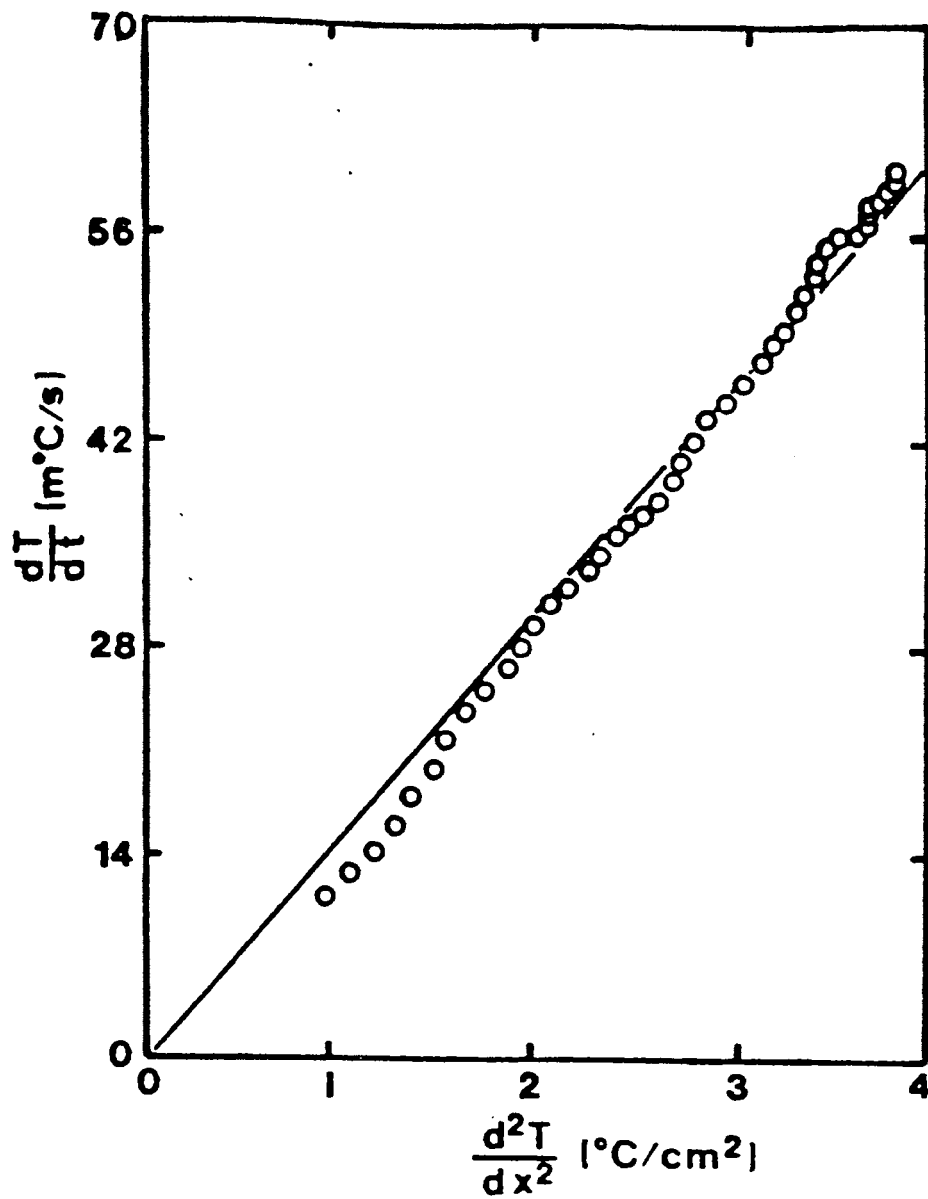


Fig.7 Rate of change of temperature vs. its second space derivative calculated from the data in Fig.IV. The slope of the regression line is the thermal diffusivity.

CHAPTER III

EXPERIMENT RESULTS AND DISCUSSION

The samples used in the experiment were Lisio and Nasio glass with the mol% composition of 70 SiO₂, 15 MO, 5 BaO, 5 ZnO and 5 Eu₂O₃, where M=Li and Na. Fig.8 and Fig.9 are the results of the experiments data shown the relationship between the thermal diffusivity and the temperature from liquid nitrogen up to room temperature. The experimental data curves show a linear relationship between the thermal diffusivity and the temperature. Because the experiment was conducted in the low temperature, the sensitivity of the thermocouples is greatly reduced, therefore sometimes electronic noise was picked up and caused the standard deviation of the experiment data to be bigger than that in the room temperature. This is the reason why some data points are scattered away from the regression line. Still the tendency of the experimental data is clearly a linear function, and the deviation is within the experiment error. Fig.10 are the experimental data combined with the experimental data provided by Brent Gault so the temperature rises up to 400K. because the two experiments are conducted on two different samples (with the same chemical composition) and two different experimental apparatus, there is a

discontinuity at the joint point. This discontinuity is slightly larger than the experimental uncertainties of the measurements. We consider the excess caused by small compositional difference in the different samples (The glass is not a homogenous structure). Most of the discontinuity results from the system experimental error involved two different apparatus. Therefore, through the temperature range that it has been measured, we can see that the thermal diffusivity increases proportionally with the temperature.

As mentioned before, there is no existing widely-accepted theory about the thermal transport in amorphous materials. Experiments suggested that it is the phonons in the amorphous material that transport the heat at temperatures below 1K. This is thought to be so in the present temperature region also. The explanation for the behavior of the thermal conductance above the 'plateau' is not quite satisfactory. Two models have been developed that predict a linear temperature dependence of the thermal diffusivity at high temperatures. These are the Karpov and Parshin model and Alexander et al's "fracton" model.

Karpov and Parshin introduced anharmonic modes that carry the heat by scattering off the two level system which are common to amorphous structures. At temperatures above the plateau temperature, the relative population of the TLS is inversely proportional to temperature. Thus the scattering of the anharmonic modes decreases linearly with increasing temperature. Hence this model ascribes the linear temperature

dependence of K above the plateau temperature to a linear decrease in the scattering rate of these heat-carrying states.

In 1982, Alexander and Orbach put forward a "fracton" model suggested that below a certain length scale there exists a fractal geometry whose quantized anomalous vibrational states, called fractons, would be responsible for the properties in the disordered system. They introduced a fracton dimensionality of the relevant reciprocal space in addition to the Euclidean dimensionality and anomalous dimensionality to describe the disordered system. The fractons are localized vibrational modes have a density of states and a dependence of their frequency on localization length of a specific form that is determined by the fracton dimensionalities that characterize the structure of the disordered system. This model gained a lot attention in the disordered system research field because in the middle 80's Alexander et al have developed the fracton theory to explain a variety phenomena in the disordered system. So far some behavior of the disordered system can be understood on the basis of fracton model, but the complicated mathematical concepts and arbitrary parameters makes it uneasy to be accepted as a clear and true representation of the disordered system. In particular there is no direct evidence of fractal structure in ordinary inorganic glasses such as those studied here.

In 1987, Alexander et al suggested that in fractal

glasses phonons are responsible for the thermal conduction at low temperatures. There are two kinds of phonon state in the phonon spectrum of fracton model: Debye phonons with the long wavelength and the fractons with the dimensionality shorter than the length scale of the disorder. The quadratic temperature dependence of the thermal conductivity at the lowest temperatures is thereby associated with phonon scattering off the two-level systems. The "plateau" is caused by the saturation of the Debye phonons. For higher temperatures, the thermally excited vibrational excitations crossover from phononlike to fractonlike at a temperature $T = \hbar\omega(c)/k(B)$, where $\omega(c)$ is the crossover frequency separating phonon from fracton excitations. At high temperature $kT \gg \hbar\omega$, two-fracton-one-phonon anharmonic processes lead to fracton hopping which dominates the thermal transport, generating a thermal conductivity which increases linearly with increasing temperature.

Our results coincide with the suggestion of Alexander et al, thus provide some support for the fracton model. But it does not provide information about the structure of the localized modes, nor the fracton dimensionality. Rather, we think it would be more appropriate to put forward some simple explanations about the result itself instead of developing complicated models at this stage of research. We shall generalize the arguments of Alexander et al to conduction by localized phonon hopping on non-fractal glasses. We shall see that the the linear temperature dependence is characteristic

of hopping transport by a broader class of localized phonons as we shall discuss below.

We know that in the glasses the phonon alone transport heat. Because of the disorder structure of the glasses, the high frequency phonons which have the shorter wavelength have the tendency to be trapped in a local region. The origin of the localization could be the disorder inherent analogous to Anderson localization of electrons in amorphous conductors. This argument is supported by the computer simulation done by Bell and Dean which indicate that weak phonon localization and the existence of a phonon mobility edge may be a common occurrence in glasses.

When a localized phonon decays, it reappears in some other mode at another place in the glass, because there is few other modes in the glass have the exact same frequency in the glass, it must emit or absorb a low frequency phonon to keep the energy conserved from the donor mode to acceptor mode. propagating modes will be the most likely low frequency facilitating modes since every one of these modes has access to the entire sample. The lowest order hopping process is a two-localized-phonon-one-propagating-phonon anharmonic process and the thermal diffusivity due to the hopping processes can be write as:

$$\eta = \langle R^2 \rangle / \tau \quad (3.1)$$

where $\langle R^2 \rangle$ is a thermal averaged square hopping distance and τ is the mean lifetime of the localized phonon modes.

Using the above model, we can estimate the mean hopping distance and the lifetime of the localized phonon modes at the mobility edge with the data already available with the assumption that the Debye approximation of the density of states is valid both for the propagating and localized phonon modes.

A localized phonon at the mobility edge ω_c can hop, assisted by a propagating phonon, to states in the range $\omega_c < \omega < 2\omega_c$.

The number of propagating phonons available to assist the hopping will be, between ω and $\omega+d\omega$, when ($\hbar\omega_c \ll kT$)

$$N(\omega)d\omega = V \omega^2 d\omega / 2\pi^2 v^3 (e^{\hbar\omega/kT} - 1)^{-1} \approx kT V \omega d\omega / \hbar 2\pi^2 v^3 \quad (3.2)$$

The number of states per unit volume that are available is

$$D(\omega_1)d\omega = (\omega + \omega_c)^2 d\omega / 2\pi^2 v^3 \quad (3.3)$$

The total states per unit volume that can be reached by phonon assisted hopping from the localization edge will be

$$\int_{\omega_c}^{2\omega_c} \omega^2 d\omega / 2\pi^2 v^3 = 7\omega_c^3 / 6\pi^2 v^3 \quad (3.4)$$

Then the volume per state in this range will be

$$\Omega = 6\pi^2 v^3 / 7\omega_c^3 \quad (3.5)$$

We know that in the solid $v = 3000\text{m/s}$ and from the experimental data provided by Powell and Gang we know that the ω_c for our sample is about $\hbar\omega = 17\text{cm}^{-1}$, that is $\omega_c = 3 \times 10^{12}$ rad/s, then:

$$\Omega = 6\pi^2 (3 \times 10^3)^3 / 7 (3 \times 10^2)^3 \approx (2 \times 10^{-9} \text{ m})^3 \quad (3.6)$$

thus there should be an acceptor state within 20A of any donor state and the wave length of the assisting phonon $\lambda = v/\nu = 6 \times 10^{-9} \text{ m}$ this will be comparable to the localization length near the mobility edge. Thus one can then expect the typical jump to be 20A or $2 \times 10^{-9} \text{ m}$.

At the room temperature, we have that $\approx 2 \times 10^{-3} \text{ cm}^2/\text{s}$ from our experiment. So the lifetime of the localized phonon can be estimated as:

$$\tau = \langle R^2 \rangle / \eta = (2 \times 10^{-7} \text{ cm})^2 / 2 \times 10^{-3} \text{ cm}^2/\text{s} = 2 \times 10^{-11} \text{ s} \quad (3.7)$$

The life time is comparable to that for Debye phonons in a crystal at room temperature.

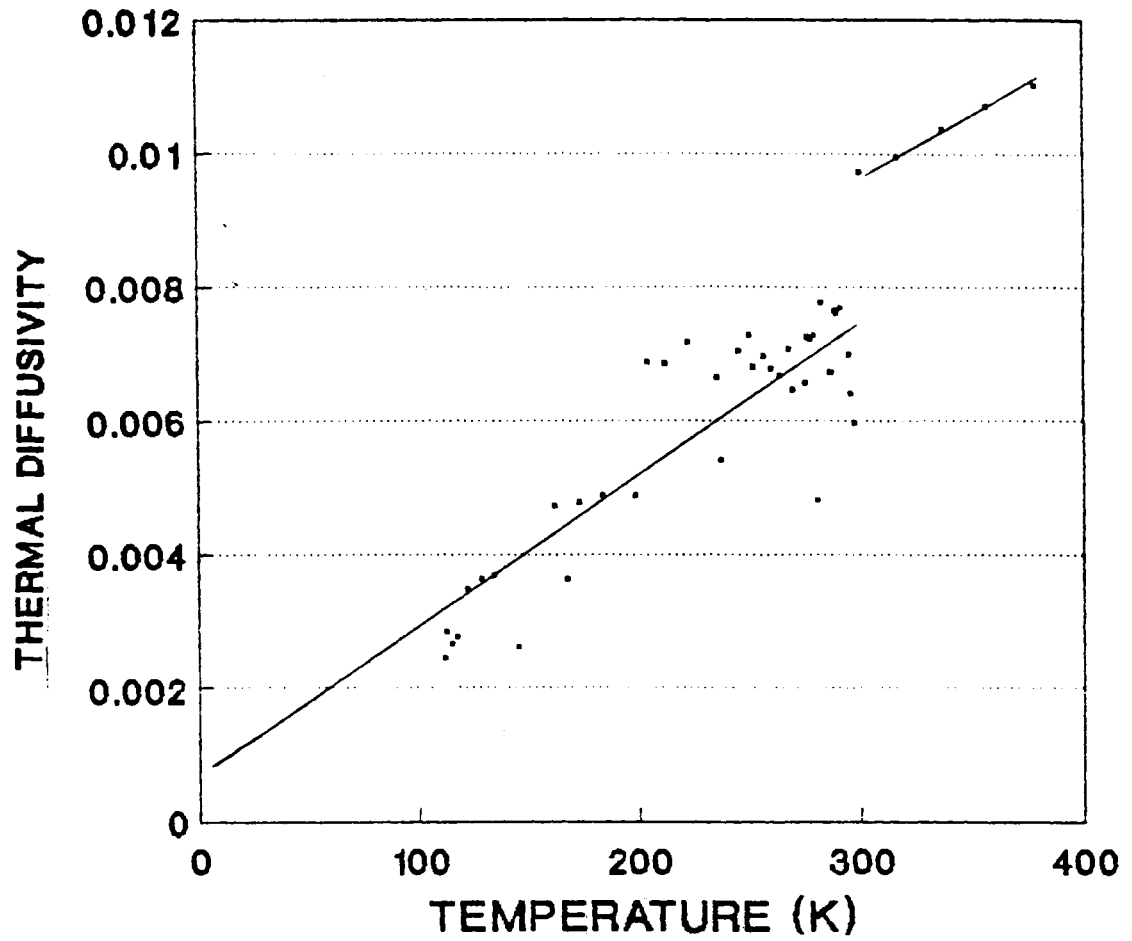


Fig.8 The thermal diffusivity of LiSiO glass vs. temperature from 100K to 300K.

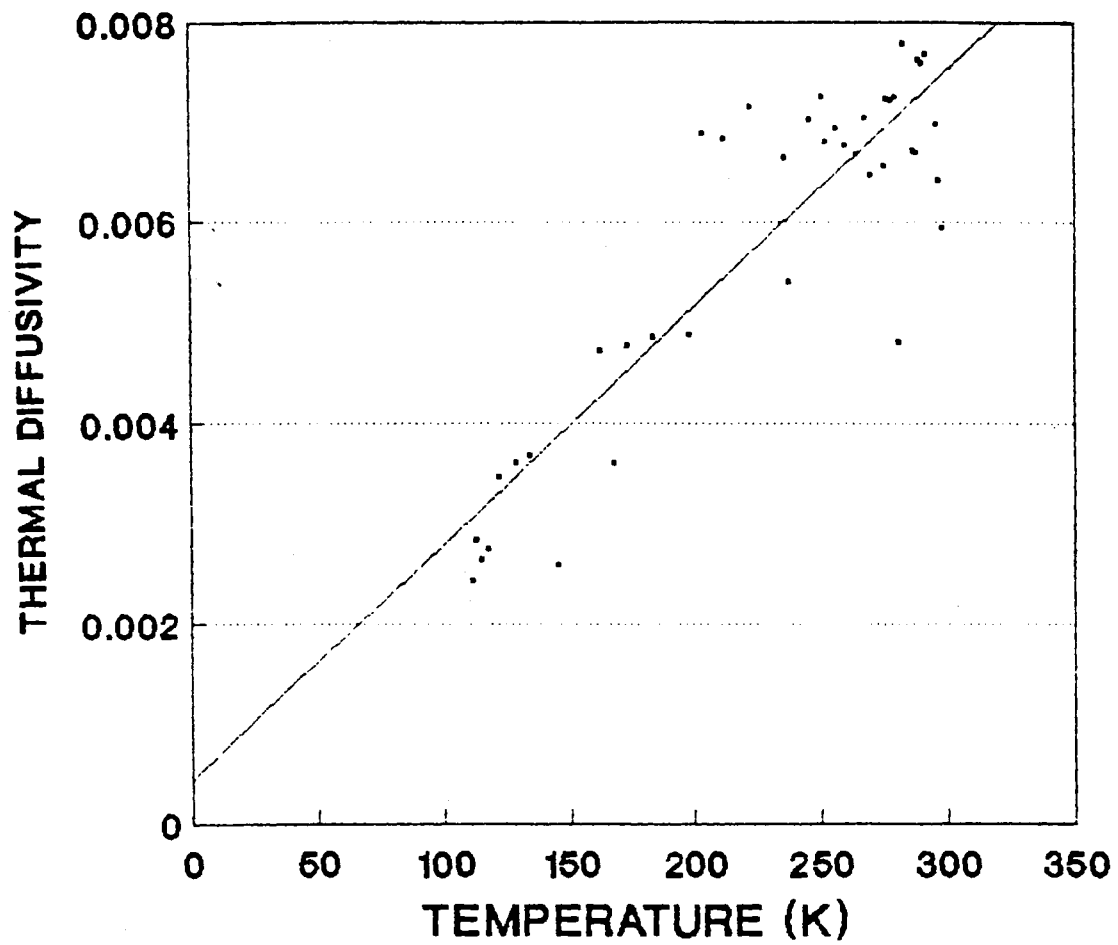


Fig.9 The thermal diffusivity of NaSiO glass vs. temperature from 100K to 300K.

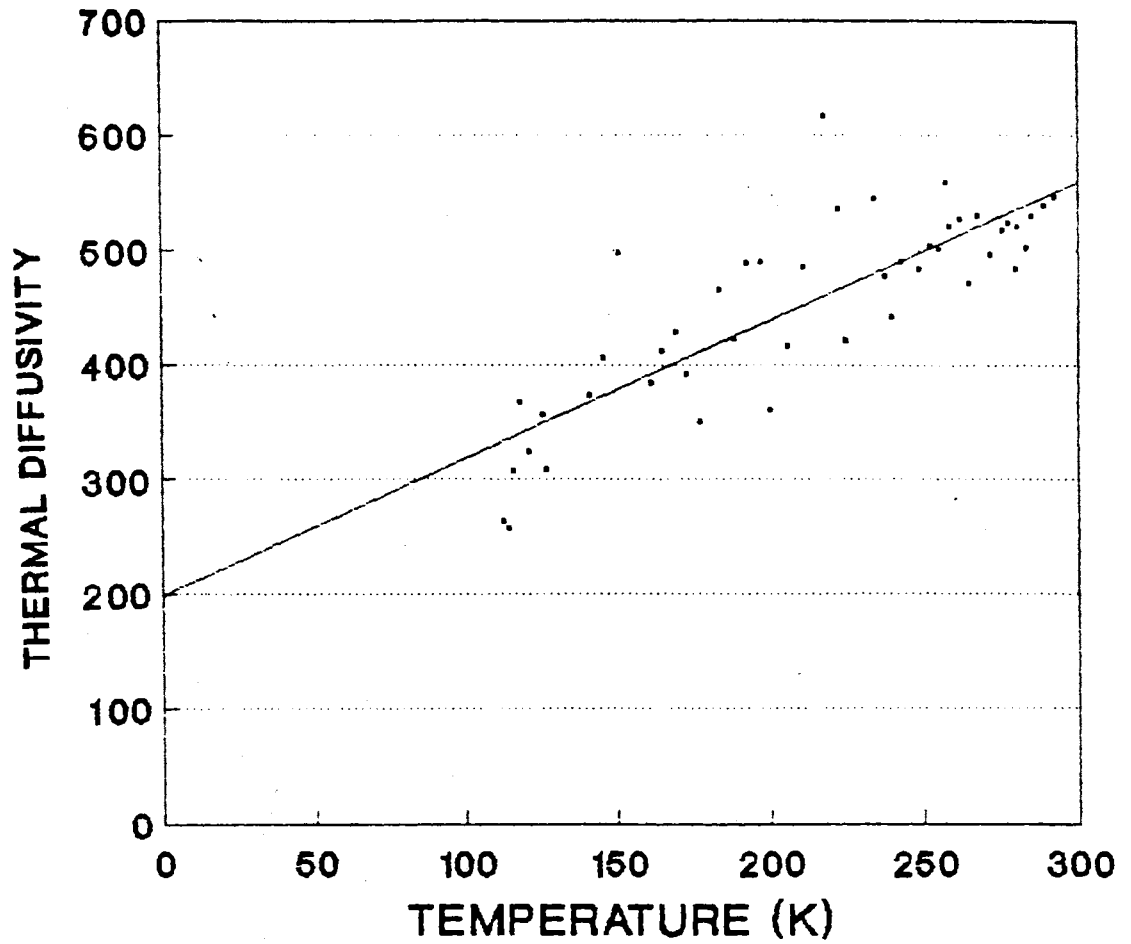


Fig.10 The thermal diffusivity of LiSiO glass vs. temperature from 100K to 500K. The data above 300K are provided by B. Gault.

CHAPTER IV

SUMMARY AND CONCLUSIONS

The research of the thermal conductivity of the disordered system has been an active research field in solid state physics for over a decade. But because of the radiative heat transport factor involved in the experiment measurement, few good experimental data are available at high temperature. To avoid the radiative heat loss of the sample, we choose to measure the thermal diffusivity which related to thermal conductivity in a simple relationship. The experiment is done by a pulse method which is an adaptation of transient technique of Danielson and Sidles, and carried out under computer control.

The thermal diffusivities of two silicate glasses (mol % composition 70 SiO₂ , 15 M O, 5 BaO, 5 ZnO, 5 Eu₂O₅, M=Li and Na) have been measured as a function of temperature from about 100K to 300K. In each case the thermal diffusivity increased linearly with temperature in this range.

In this paper, we have discussed the Debye theory of the thermal conductivity of the crystal and Two-level-system (TLS) theory of the thermal conductivity of amorphous material below 10K. In the temperature range we measured, there is no widely-accepted theory of the mechanism of thermal transport.

Two models are available, they are Karpov and Parshin's model and Alexander et al's "fracton" model. Our experiment results provide some support for the fracton model. But it does not provide information about the structure of the localized modes and fracton dimensionality which the theory based on. As an interpretation of the experiment results, we generalized the arguments of Alexander et al to conduction by localized phonon hopping on non-fractal glasses and shown that the linear temperature dependence is characteristic of hopping transport by a broader class of localized phonons. We estimated the average square hopping distance and the localized phonon lifetime. The estimation shown that a typical jump of the localized phonon is about $20A$ and the lifetime is comparable to that for Debye phonons in the crystal at room temperature.

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APPENDIX

CONTROL, SAMPLING AND DATA ACQUISITION PROGRAMS

```
10 ! THERMAL DIFFUSIVITY -- MAIN PGM
20 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
30 COM eta(200),xs(200),yx(200),tc(50),tbar(200)
40 COM runum,jr,tint,dti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
50 COM tau,b
100 DISP "Enter a descriptive title for the experiment" @ INPUT titles
110 DISP "Enter additional information" @ INPUT subtitles$
120 !
130 DISP "Choose a file name for data storage."
140 DISP " USE THE SPECIAL FUNCTION KEYS"
150 ON KEY# 1,"CONOCO" GOTO 800
160 ON KEY# 2,"OTHER" GOTO 900
170 KEY LABEL
180 GOTO 180
190 OFF KEY#
200 ! 200-299 are reserved for alarms
300 WAIT 2000
310 CLEAR
320 DISP "*** CHOOSE THE TYPE OF EXPERIMENT *** "
330 DISP " "
340 DISP "      <f1> Single temperature only"
350 DISP "      <f2> N specified temperatures"
360 DISP "      <f3> Range of temperatures at regular intervals"
365 DISP "      <f4> Several temperatures, manual control"
366 DISP "      <f5> Auto"
370 ON KEY# 1,"SINGLE" GOTO 500
380 ON KEY# 2,"N TEMP" GOTO 600
390 ON KEY# 3,"T RANGE" GOTO 700
395 ON KEY# 4,"MANUAL" GOTO 550
396 ON KEY# 5,"AUTODATA" GOTO 580
400 KEY LABEL
410 GOTO 410
420 OFF KEY#
430 GOTO 1000
500 runtyp$="singlet"
505 runtyp=1
510 GOTO 420
550 runtyp$="singlet"
560 runtyp=4
570 GOTO 420
580 runtyp$="AUTO"
581 runtyp=5
582 GOTO 420
600 runtyp$="ntemp"
605 runtyp=2
610 GOTO 420
700 runtyp$="trange"
705 runtyp=3
710 GOTO 420
800 ! set up Conoco file
810 D$=VAL$(DATE)
820 L$="CONOCO"&D$
830 DISP "The data will be stored as ";L$
840 GOTO 190
900 D$=VAL$(DATE)
```



```

910 DISP "Enter the file name (up to 5 characters)" @ INPUT L$
920 L$=L$&D$
930 DISP " The data will be stored as ";L$
940 GOTO 190
999 !
1000 ! Enter the experimental parameters
1010 CLEAR @ DISP "SET THE PARAMETERS FOR THE DIFFUSIVITY MEASUREMENT"
1020 DISP " "
1030 DISP "Time between temperature measurements (msec)" @ INPUT tint
1040 DISP "Total time for a diffusivity measurement (msec)" @ INPUT deti
1050 DISP "Time delay before starting data acquisition (msec)" @ INPUT dlay
1060 DISP "Distances between thermocouples: x12,x23 (cm)" @ INPUT x12,x23
1070 runum=0
1080 tau=2*tint
1099 !
1100 IF runtyp$="singlet" THEN 1110 ELSE 1200
1102 IF runtyp=1 THEN 1110
1105 CLEAR @ DISP " INSTRUCTIONS FOR A MANUAL RUN"
1106 DISP " " @ GOTO 1120
1110 CLEAR @ DISP "INSTRUCTIONS FOR A SINGLE TEMPERATURE RUN " @ DISP " "
1120 DISP " 1. Set the temperature controller manually to the desired "
1121 DISP " temperature. NOTE THAT THE SETTINGS ARE IN DEG C."
1122 DISP " "
1130 DISP " 2. Wait for the system to equilibrate. "
1131 DISP " "
1140 DISP " 3. Press CONT <f4> when equilibrium has been reached."
1141 DISP " "
1150 DISP " 4. If the desired temperature is room temperature, you may"
1151 DISP " press CONT at once." @ DISP " "
1160 PAUSE
1170 runs=1
1180 GOTO 1500
1200 IF runtyp$="ntemp" THEN 1210 ELSE 1300
1210 CLEAR @ DISP " INSTRUCTIONS FOR SETTING N TEMPERATURES "
1211 DISP " "
1220 DISP " 1. Enter the number of temperatures. " @ INPUT NT
1230 DISP " 2. Enter the ";NT;" temperatures as prompted" @ DISP " "
1240 FOR jt=1 TO NT @ DISP " Temp #";jt;" (deg C) "; @ INPUT tc(jt)
1250 NEXT jt
1260 runs=NT
1270 GOTO 1500
1300 IF runtyp$="trange" THEN 1305 ELSE 1400
1305 CLEAR @ DISP " INSTRUCTIONS FOR SETTING A RANGE OF TEMPERATURES "
1310 DISP " "
1320 DISP " 1. Enter the lowest temperature. (deg C)" @ INPUT tl
1330 DISP " "
1340 DISP " 2. Enter the highest temperature. (deg C)" @ INPUT th
1350 DISP " "
1360 DISP " 3. Enter the temperature interval between points. (deg C)"
1370 INPUT dt
1380 runs=(th-tl)/tint+1
1390 GOTO 1500
1400 runs=1
1410 GOTO 1500
1499 !
1500 ! Set up storage for the experiment.
1510 NR=6

```

```
1520 IF runtyp$="ntemp" THEN NR=NR+NT+1
1530 IF runtyp$="trange" THEN NR=NR+1
1540 LL$=L$&".TX"
1542 MASS STORAGE IS "/vol1"
1545 ON ERROR GOTO 2000
1550 CREATE LL$,NR,256
1560 ASSIGN# 1 TO LL$
1565 PRINT# 1 ; runs
1570 PRINT# 1 ; title$
1580 PRINT# 1 ; subtitle$
1590 PRINT# 1 ; runtyp$
1600 PRINT# 1 ; L$
1610 PRINT# 1 ; tint,deti,dlay
1620 PRINT# 1 ; x12,x23
1630 IF runtyp$="trange" THEN PRINT# 1 ; t1,th,dt
1640 IF runtyp$="ntemp" THEN 1650 ELSE 1700
1650 PRINT# 1 ; NT
1660 FOR jt=1 TO NT @ PRINT# 1 ; tc(jt) @ NEXT jt
1700 ASSIGN# 1 TO * @ ! Close the file
1705 MASS STORAGE IS "/mstr/shi"
1710 ASSIGN# 1 TO "name"
1720 PRINT# 1 ; L$
1730 ASSIGN# 1 TO *
1800 CLEAR @ DISP USING 1810
1810 IMAGE " TEMP " ,3X," DFSVTY " ,3X," ETA " ,3X,"STD DEV"
1900 CHAIN runtyp$
2000 OFF ERROR
2010 IF ERRN=63 THEN 2020 ELSE 2200
2020 ASSIGN# 1 TO LL$
2030 READ# 1 ; oldruns
2040 READ# 1 ; oldtitle$
2050 ASSIGN# 1 TO *
2060 DISP " File: ";L$
2070 DISP title$
2080 DISP oldruns
2090 DISP "Increment number of runs? (y/n)" @ INPUT qm$
2100 IF qm$="y" THEN 2110 ELSE 2200
2110 runs=runs+oldruns
2120 IF title$=oldtitle$ THEN 1560
2200 ERRM
2210 IF ERRN<>63 THEN 2300
2220 DISP "Old title: ";oldtitle$
2230 DISP "New title: ";title$
2240 DISP "Use old title? (y/n)" @ INPUT qm$
2250 IF qm$="y" THEN title$=oldtitle$ ELSE 2300
2260 GOTO 1560
2300 DISP "This action will DESTROY data."
2310 DISP "Execution of this program is terminated."
2320 BEEP @ GOTO 2320
```

```

10 1AUTO
20 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
30 COM eta(200),xs(200),ys(200),tc(50),tbar(200)
40 COM runum,jr,tint,deti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
50 COM tau,b
70 ASSIGN 7 TO "hpib"
90 ASSIGN 3 TO "bcd.b"
95 RESET 3
100 ASSIGN# 1 TO "name"
110 READ# 1 ; L$
120 ASSIGN# 1 TO *
121 LL$=L$&".TX" @ MASS STORAGE IS "/vol1"
122 ASSIGN# 1 TO LL$
123 READ# 1 ; runs
124 READ# 1 ; title$
125 ASSIGN# 1 TO *
130 DISP "SAMPLE # ";title$
140 DISP "STORED AS ";L$
150 DISP "SET TIME IN MINUTES BETWEEN OBSERVATIONS"
160 INPUT TOBS
170 TOBS=TOBS*60000
175 MASS STORAGE IS "/mstr/shi"
180 FINDPROG "TAKEDATA"
190 FINDPROG "TDREDUCE"
200 FINDPROG "TDSTORE"
210 ! ASSIGN 7 TO "hpib"
220 MASS STORAGE IS "/mstr/shi"
230 CALL "TAKEDATA"
232 MASS STORAGE IS "/vol1"
235 runum=runum+1 @ TB$=TIMES
240 CALL "TDREDUCE"
250 CALL "TDSTORE" (L$)
255 ON TIMER# 1,TOBS GOTO 220
260 OFF KEY# @ ON KEY# 1,"PARMS" GOTO 300
270 ON KEY# 16,"STOP" GOTO 880
290 GOTO 290
300 OFF KEY#
310 ON KEY# 1,"PLOT" GOTO 410
320 ON KEY# 2,"TOBS" GOTO 710
330 ON KEY# 3,"TINT" GOSUB 750
340 ON KEY# 4,"DETI" GOSUB 790
350 ON KEY# 5,"DELAY" GOSUB 840
360 ON KEY# 8,"RESUME" GOTO 1800
370 GOTO 370
410 rn$=VAL$(runum) @ LL$=L$&". "&rn$
420 ! Set plotting options
425 tbar=tbar(runum) @ tdfs=tdfs(runum) @ OFF KEY#
430 LT$=L$&".TX"
440 ASSIGN# 1 TO LT$
450 READ# 1 ; runs
460 READ# 1 ; title$
470 ASSIGN# 1 TO *
480 ON KEY# 1,"TMP/TIM" GOTO 570
490 ON KEY# 2,"DERIVS" GOTO 610
500 ON KEY# 8,"RETURN" GOTO 300
510 KEY LABEL

```

```

520 CLEAR @ DISP " SELECT THE TYPE OF PLOT USING THE FUNCTION KEYS" @ DISP "
530 DISP "      <f1> Temperatures vs. time "
540 DISP "      <f2> dT/dt vs. d2T/dx2 "
550 DISP " " @ DISP "      <f8> Return to main menu."
560 GOTO 560
570 ymax=INT(t1(jr)) @ xmax=deti/1000 @ fl=1
580 IF ymax=0 THEN ymax=1
590 xlbl$="TIME (sec)" @ ylbl$="TEMP. CHANGE (C)"
600 GOTO 900
610 ymax=MAXAB(ys) @ xmax=MAXAB(xs) @ xmax=INT(xmax)+1 @ fl=2
620 IF ymax<1 THEN 630 ELSE 680
630 za=1
640 za=10*za
650 IF za*ymax<1 THEN 640
660 ymax=INT(za*ymax+1)/za
670 GOTO 690
680 ymax=INT(ymax+1)
690 xlbl$="d2T/dx2" @ ylbl$="dT/dt"
700 GOTO 900
710 DISP "SET TIME IN MINUTES BETWEEN OBSERVATIONS"
720 INPUT TOBS
730 TOBS=TOBS*60000
740 OFF KEY# @ GOTO 255
750 DISP "SET TINT"
760 DISP "OLD TINT = ";tint
770 INPUT tint
780 RETURN
790 DISP " SET DETI -- TIME FOR EXPERIMENT"
800 DISP "OLD DETI = ";deti
810 INPUT deti
820 RETURN
830 END
840 DISP "SET DELAY"
850 DISP " OLD DELAY = ";dlay
860 INPUT dlay
870 RETURN
880 MASS STORAGE IS "/mstr/shi"
890 END
900 ! plotting routine
910 GCLEAR @ DEG @ CSIZE 4,0.6
920 LOCATE 0,200,0,100
930 SCALE (-0.5)*xmax,1.05*xmax,(-0.2)*ymax,1.15*ymax
940 CLIP 0,xmax,0,ymax
950 AXES xmax/5,ymax/5,0,0 @ AXES xmax/5,ymax/5,xmax,ymax
960 LDIR 0 @ LORG 2
970 y=(-0.05)*ymax
980 FOR x=0 TO xmax STEP xmax/5
990 MOVE x,y
1000 LABEL x
1010 NEXT x
1020 MOVE xmax/2,(-0.12)*ymax
1030 LABEL xlbl$
1040 x=0.32*xmax @ LORG 8
1050 FOR y=0 TO ymax STEP ymax/5
1060 MOVE x,y
1070 LABEL y
1080 NEXT y
1090 LDIR 90 @ LORG 5

```

```

1100 MOVE (-0.1)*xmax,0.6*ymax
1110 LABEL y1b1$
1120 LDIR 0 @ LORG 2
1130 MOVE 0.05*xmax,1.04*ymax
1140 LABEL title$
1150 MOVE 0.05*xmax,0.9*ymax
1160 LABEL "T = "
1170 MOVE 0.1*xmax,0.9*ymax
1180 tbar=INT(100*tbar)/100
1190 LABEL tbar
1200 IF f1=1 THEN 1230
1210 GOTO 1590
1220 ! Plot the temperature vs. time data
1230 FOR j=1 TO jr
1240 x=j*tint*0.001
1250 y=t1(j)
1260 MOVE x,y @ GOSUB 1670
1270 y=t2(j)
1280 MOVE x,y @ GOSUB 1700
1290 y=t3(j)
1300 MOVE x,y @ GOSUB 1670 @ GOSUB 1700
1310 NEXT j
1320 ! Add additional data to the plot
1330 LDIR 0 @ LORG 2 @ CSIZE 4,0.6
1340 MOVE (-0.4)*xmax,1.04*ymax
1350 LABEL "DATA"
1360 CSIZE 3,0.6
1370 MOVE (-0.5)*xmax,0.9*ymax @ LABEL "DELAY = "
1380 MOVE (-0.4)*xmax,0.9*ymax @ LABEL dlay
1390 MOVE (-0.5)*xmax,0.8*ymax @ LABEL "T-INT = "
1400 MOVE (-0.4)*xmax,0.8*ymax @ LABEL tint
1410 MOVE (-0.5)*xmax,0.7*ymax @ LABEL "TDFSVTY = "
1420 tdfs=INT(tdfs*100000)/100000
1430 MOVE (-0.38)*xmax,0.7*ymax @ LABEL tdfs
1440 MOVE (-0.5)*xmax,0.6*ymax @ LABEL "L$ = "
1450 MOVE (-0.42)*xmax,0.6*ymax @ LABEL LL$
1460 MOVE (-0.5)*xmax,0.5*ymax @ LABEL "x12 = "
1470 MOVE (-0.4)*xmax,0.5*ymax @ LABEL x12
1480 MOVE (-0.5)*xmax,0.4*ymax @ LABEL "x23 = "
1490 MOVE (-0.4)*xmax,0.4*ymax @ LABEL x23
1500 MOVE (-0.5)*xmax,0.3*ymax @ LABEL "TIME CONST. ="
1510 MOVE (-0.3)*xmax,0.3*ymax @ LABEL tau
1520 MOVE (-0.5)*xmax,0.2*ymax @ LABEL "STD. DEV. ="
1530 sd=INT(sd(runum)*1000000)/1000000
1540 MOVE (-0.3)*xmax,0.2*ymax @ LABEL sd
1550 MOVE (-0.5)*xmax,0.1*ymax @ LABEL "ETA ="
1560 etabar=INT(etabar*1000000)/1000000
1570 MOVE (-0.4)*xmax,0.1*ymax @ LABEL etabar
1580 CLEAR @ GOTO 420
1590 ! dtdt vs d2tdx2 plots
1600 FOR jp=2 TO jr-1
1610 MOVE xs(jp),ys(jp) @ GOSUB 1670
1620 NEXT jp
1630 ! Draw the regression line
1640 MOVE 0,b @ y=tdfs*xmax+b
1650 LINE TYPE 1 @ DRAW xmax,y

```

```
1660 GOTO 1330
1670 ! plus symbol
1680 SETGU @ IDRAW 1,0 @ IDRAW -2,0 @ IDRAW 1,0 @ IDRAW 0,1 @ IDRAW 0,-2 @ I
0,1
1690 SETUU @ RETURN
1700 ! x symbol
1710 SETGU @ IDRAW 1,1 @ IDRAW -2,-2 @ IDRAW 1,1 @ IDRAW -1,1 @ IDRAW 2,-2 @
AW -1,1
1720 SETUU @ RETURN
1800 !UPDATE THE DISPLAY
1810 CLEAR @ DISP "SAMPLE # ";title$
1820 DISP "STORED AS ";L$
1830 DISP "TIME BETWEEN MEASUREMENTS ";TOBS/60000
1835 DISP "LAST MEASUREMENT ENDED AT ";TB$
1840 DISP USING 1850
1850 IMAGE " TEMP ",3X," DFSVTY ",3X," ETA ",3X,"STD DEV"
1860 FOR JU=1 TO runum
1870 DISP USING 1890 ; tbar(JU);tdfs(JU);eta(JU);sd(JU)
1880 NEXT JU
1890 IMAGE DDDD.DD,3(3X,DD.5D)
1900 GOTO 260
```

```

10 SUB "TAKEDATA"
20 !last adjustment at 14/07/88 ,GOING BACK TO THE NEW SYS.
30 ! 19/1/88 ADJUSTING THE PROG. TO THE FACILITIES
40 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
50 COM eta(200),xs(200),ys(200),tc(50),tbar(200)
60 COM runum,jr,tint,deti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
70 COM tau,b
80 COM SIN1(2000),COS1(2000),SIN2(2000),COS2(2000),TA1(2000),TA2(2000)
85 COM TA3(2000),V$(2000)
90 DIM T3(100),T4(100)
100 INTEGER dummy,Tint
110 LOADBIN "timer"
120 Tint=tint
130 ON KYBD dummy,"~027T" GOSUB TIMEDOUT
140 GOTO 230
150 GOTO 150
160 TIMEDOUT: TRIGGER vm1,vm2,vm3 @ jr=jr+1
170 ENTER vm1 ; t1(jr) @ ENTER vm2 ; t2(jr) @ ENTER vm3 ; t3(jr)
175 OUTPUT pwr ; V$(jr)
180 RETURN
190 OFF TIMER# 3 @ GOTO 390
200 CALLBIN "offtimer" (0)
210 OFF TIMER# 1 @ GOTO 420
220 CONTROL 3,2 ; 1 @ GOTO 420
230 ! Set up instruments
240 dac=709 @ vm1=723 @ vm2=724 @ vm3=725 @ !hpib addresses
250 ! set up voltmeters
260 FOR ji=0 TO 2 @ vm=vm1+ji @ OUTPUT vm ; "F1R-2T4Z0N5" @ NEXT ji
270 CONTROL 3,2 ; 1
280 ! get the temperature baseline
290 TRIGGER vm1,vm2,vm3
300 ENTER vm1 ; t1(0)
310 ENTER vm2 ; t2(0)
320 !PRINT "START TIME=",TIME$,TIME
330 ENTER vm3 ; t3(0)
340 jr=0
350 CONTROL 3,2 ; 0
360 IF dlay<10 THEN 390
370 ON TIMER# 3,dlay GOTO 190
380 GOTO 380
390 ON TIMER# 1,deti GOTO 200
400 CALLBIN "on_timer" (500)
410 LOOP: GOTO LOOP
420 FOR ji=0 TO 2 @ vm=vm1+ji @ OUTPUT vm ; "T1" @ NEXT ji
430 !DT21=VAL(T2$(1))-VAL(T1$(1))
440 !DT31=T3(1)-VAL(T1$(1)) @ DT32=T4(1)-T3(1) @ DT33=VAL(T2$(1))-T4(1)
450 !DISP USING 490 ; runum,jr
460 !IMAGE "Run number",3X,2D,3X,"Has ",3X,3D,3X,"Sampling points."
470 SUBEND
500 SUBEND

```

```

10 SUB "TDREDUCE"
20 ! tdreduce
30 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
40 COM eta(200),xs(200),ys(200),tc(50),tbar(200)
50 COM runum,jr,tint,deli,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
60 COM tau,b
70 xbar=0.5*(x12+x23)
80 a1=25.334 @ a2=-0.4575 @ a3=0.08744 @ a4=-7.68e-005 @ a5=-0.0031 @ a6=-0.00
81 a7=0.000266 @ a8=1.08e-005 @ a9=-8.06e-006 @ a10=7.8e-008 @ a11=1.03e-007 @
12=-5.96e-009
90 ! Convert voltages to temperatures
100 FOR j=0 TO jr
110 tt=t1(j)*1000
111 t1(j)=tt*(a1+tt*(a2+tt*(a3+tt*(a4+tt*(a5+tt*(a6+tt*(a7+tt*(a8+tt*(a9+tt*(a
+tt*(a11+tt*a12))))))))))
120 tt=t2(j)*1000
121 t2(j)=tt*(a1+tt*(a2+tt*(a3+tt*(a4+tt*(a5+tt*(a6+tt*(a7+tt*(a8+tt*(a9+tt*(a
+tt*(a11+tt*a12))))))))))
130 tt=t3(j)*1000
131 t3(j)=tt*(a1+tt*(a2+tt*(a3+tt*(a4+tt*(a5+tt*(a6+tt*(a7+tt*(a8+tt*(a9+tt*(a
+tt*(a11+tt*a12))))))))))
140 NEXT j
150 ! Calculate the time derivatives of t2
160 n=8
170 sj=0 @ sj2=0 @ st=0 @ sjt=0
180 FOR j=1 TO 2*n+1
190 sj=sj+j @ sj2=sj2+j*j
200 st=st+t2(j) @ sjt=sjt+j*t2(j)
210 NEXT j
220 dtdt(n+1)=1000*((2*n+1)*sjt-sj*st)/(tint*((2*n+1)*sj2-sj*sj))
230 FOR j=n+2 TO jr-n
240 sj=sj+n*n+1 @ sj2=sj2-(j-n-1)*(j-n-1)+(j+n)*(j+n)
250 st=st-t2(j-n-1)+t2(j+n) @ sjt=sjt-(j-n-1)*t2(j-n-1)+(j+n)*t2(j+n)
260 dtdt(j)=1000*((2*n+1)*sjt-sj*st)/(tint*((2*n+1)*sj2-sj*sj))
270 NEXT j
280 ! Get the delta t's and the laplacian
290 FOR j=1 TO jr
300 t1(j)=t1(j)-t1(0) @ t2(j)=t2(j)-t2(0) @ t3(j)=t3(j)-t3(0)
310 d2tdx(j)=((t3(j)-t2(j))/x23-(t2(j)-t1(j))/x12)/xbar
320 NEXT j
330 ! Get the thermal diffusivity by least squares
340 sx=0 @ sx2=0 @ sy=0 @ sxy=0 @ st=0 @ set=0 @ sy2=0 @ sbx=0
350 FOR j=n+1 TO jr-n
360 x=(d2tdx(j-1)+d2tdx(j)+d2tdx(j+1))/3
370 xs(j)=x
380 y=dtdt(j)
390 ys(j)=y
400 sxy=sxy+x*y
401 sx=sx+x
402 sy=sy+y
403 sbx=sbx+1/x
410 sx2=sx2+x*x
420 sy2=sy2+y*y
430 st=st+t2(j)
440 eta(j)=y/x
450 set=set+y/x

```



```

460 NEXT j
470 tdfs(runum)=(sxy-sx*sy/(jr-2*n))/(sx2-sx*sx/(jr-2*n))
471 tdfs=tdfs(runum)
472 b=(sy-tdfs*sx)/(jr-2*n)
480 tbar(runum)=st/(jr-2*n)+t2(0)
490 etabar=(set-sbx*b)/(jr-2*n)
500 sd=SQR((sy2-2*tdfs*sxy-2*b*sy+tdfs*tdfs*sx2+2*tdfs*b*sx+(jr-2*n)*b*b)/(,
n-2)/(sx2-sx*sx/(jr-2*n)))
501 sd(runum)=sd
505 ON ERROR GOTO 530
510 DISP USING 520 ; tbar(runum);tdfs(runum);etabar;sd(runum)
520 IMAGE DDDD.DD,3(3X,DD.5D)
530 eta(runum)=etabar
535 OFF ERROR
540 SUBEND

```

```

10 SUB "TDSTORE" (L$)
20 ! tdstore
30 COM t1(200),t2(200),t3(200),dtdt(200),d2tdx(200),tdfs(200)
40 COM eta(200),xs(200),ys(200),tc(50),tbar(200)
50 COM runum,jr,tint,deti,dlay,x12,x23,t1,th,dt,NT,runtyp,etabar,sd(200)
60 COM tau,b
70 sd=sd(runum)
100 rn$=VAL$(runum)
110 LL$=L$&"."&rn$
120 CREATE LL$,jr+8,40
130 ASSIGN# 1 TO LL$
140 PRINT# 1 ; LL$
150 PRINT# 1 ; tbar(runum),tdfs(runum),etabar,sd
160 PRINT# 1 ; x12,x23
170 PRINT# 1 ; tint,deti,dlay,tau,b
180 PRINT# 1 ; jr
190 FOR js=0 TO jr
200 PRINT# 1 ; t1(js),t2(js),t3(js),xs(js),ys(js)
210 NEXT js
220 ASSIGN# 1 TO *
230 LL$=L$&".TX"
240 ASSIGN# 1 TO LL$
250 READ# 1 ; RUNS
260 READ# 1 ; TITLE$
270 ASSIGN# 1 TO *
280 ASSIGN# 1 TO LL$
290 PRINT# 1 ; runum
300 PRINT# 1 ; TITLE$
310 ASSIGN# 1 TO *
320 SUBEND

```

```

i0 ! tdplot
20 MASS STORAGE IS "/vol1"
999 CLEAR
1000 DISP " THIS PROGRAM READS THERMAL DIFFUSIVITY DATA FILES"
1001 DISP " AND MAKES PLOTS ON THE SCREEN"
1005 DIM t1(200),t2(200),t3(200),xs(200),ys(200),yx(200)
1006 DIM ylbl$(130)
1010 DISP " "
1020 DISP "The file names have the form FFFFFFFFFF.##"
1030 DISP " Enter FFFFFFFFFF" @ INPUT LL$
1031 LT$=LL$&".TX" @ ASSIGN# 1 TO LT$ @ READ# 1 ; runs
1032 READ# 1 ; title$
1033 ASSIGN# 1 TO *
1035 DISP "Enter ##" @ INPUT rn
1036 rn$=VAL$(rn)
1040 L$=LL$&". "&rn$
1050 ASSIGN# 1 TO L$
1160 READ# 1 ; L$
1170 READ# 1 ; tbar,tdfs,eta,sd
1180 READ# 1 ; x12,x23
1190 READ# 1 ; tint,deti,dlay,tau
1200 READ# 1 ; jr
1320 FOR j=0 TO jr
1330 READ# 1 ; t1(j),t2(j),t3(j),xs(j),ys(j)
1340 NEXT j
1350 ! Set plotting options
1360 ON KEY# 1,"TMP/TIM" GOTO 1450
1370 ON KEY# 2,"DERIVS" GOTO 1500
1375 ON KEY# 5,"NEW FILE" GOTO 1530
1376 ON KEY# 8,"QUIT" GOTO 1700
1380 KEY LABEL
1390 CLEAR @ DISP " SELECT THE TYPE OF PLOT USING THE FUNCTION KEYS" @ DISP
1400 DISP "      <f1> Temperatures vs. time "
1410 DISP "      <f2> dT/dt vs. d2T/dx2 "
1420 DISP " " @ DISP "      <f5> Change file"
1430 DISP " " @ DISP "      <f8> Quit"
1440 GOTO 1440
1450 ymax=INT(t1(jr)) @ xmax=deti/1000 @ f1=1
1455 IF ymax=0 THEN ymax=1
1460 xlbl$="TIME (sec)" @ ylbl$="TEMP. CHANGE (C)"
1470 GOTO 2000
1500 ymax=MAXAB(ys) @ xmax=MAXAB(xs) @ xmax=INT(xmax)+1 @ f1=2
1510 IF ymax<1 THEN 1512 ELSE 1518
1512 za=1
1513 za=10*za
1514 IF za*ymax<1 THEN 1513
1515 ymax=INT(za*ymax+1)/za
1516 GOTO 1519
1518 ymax=INT(ymax+1)
1519 xlbl$="d2T/dx2" @ ylbl$="dT/dt"
1520 GOTO 2000
1530 OFF KEY#
1540 DISP "The file names have the form FFFFFFFFFF.##"
1550 ON KEY# 1,"FFFFF" GOTO 1590
1560 ON KEY# 2,"##" GOTO 1610
1570 KEY LABEL
1580 GOTO 1580
1590 OFF KEY#

```

```

1600 GOTO 1030
1610 OFF KEY#
1620 GOTO 1035
1700 END
2000 ! plotting routine
2010 GCLEAR @ DEG @ CSIZE 4,0.6
2020 LOCATE 0,200,0,100
2030 SCALE (-0.5)*xmax,1.05*xmax,(-0.2)*ymax,1.15*ymax
2050 CLIP 0,xmax,0,ymax
2060 AXES xmax/5,ymax/5,0,0 @ AXES xmax/5,ymax/5,xmax,ymax
2070 LDIR 0 @ LORG 2
2080 y=(-0.05)*ymax
2090 FOR x=0 TO xmax STEP xmax/5
2100 MOVE x,y
2110 LABEL x
2120 NEXT x
2130 MOVE xmax/2,(-0.12)*ymax
2140 LABEL x1b1$
2150 x=0.32*xmax @ LORG 8
2160 FOR y=0 TO ymax STEP ymax/5
2170 MOVE x,y
2180 LABEL y
2190 NEXT y
2200 LDIR 90 @ LORG 5
2210 MOVE (-0.1)*xmax,0.6*ymax
2220 LABEL y1b1$
2230 LDIR 0 @ LORG 2
2240 MOVE 0.05*xmax,1.04*ymax
2250 LABEL title$
2260 MOVE 0.05*xmax,0.9*ymax
2270 LABEL "T = "
2280 MOVE 0.1*xmax,0.9*ymax
2285 tbar=INT(100*tbar)/100
2290 LABEL tbar
2900 IF f1=1 THEN 3000
2910 GOTO 3500
2999 ! Plot the temperature vs. time data
3000 FOR j=1 TO jr
3010 x=j*tint*0.001
3020 y=t1(j)
3030 MOVE x,y @ GOSUB 4500
3040 y=t2(j)
3050 MOVE x,y @ GOSUB 4530
3060 y=t3(j)
3070 MOVE x,y @ GOSUB 4500 @ GOSUB 4530
3080 NEXT j
3090 ! Add additional data to the plot
3100 LDIR 0 @ LORG 2 @ CSIZE 4,0.6
3110 MOVE (-0.4)*xmax,1.04*ymax
3120 LABEL "DATA"
3130 CSIZE 3,0.6
3140 MOVE (-0.5)*xmax,0.9*ymax @ LABEL "DELAY = "
3150 MOVE (-0.4)*xmax,0.9*ymax @ LABEL dlay
3160 MOVE (-0.5)*xmax,0.8*ymax @ LABEL "T-INT = "
3170 MOVE (-0.4)*xmax,0.8*ymax @ LABEL tint
3180 MOVE (-0.5)*xmax,0.7*ymax @ LABEL "TDFSUTY = "

```

```
3185 tdfs=INT(tdfs*100000)/100000
3190 MOVE (-0.38)*xmax,0.7*ymax @ LABEL tdfs
3200 MOVE (-0.5)*xmax,0.6*ymax @ LABEL "L$ = "
3210 MOVE (-0.42)*xmax,0.6*ymax @ LABEL L$
3220 MOVE (-0.5)*xmax,0.5*ymax @ LABEL "x12 ="
3230 MOVE (-0.4)*xmax,0.5*ymax @ LABEL x12
3240 MOVE (-0.5)*xmax,0.4*ymax @ LABEL "x23 = "
3250 MOVE (-0.4)*xmax,0.4*ymax @ LABEL x23
3260 MOVE (-0.5)*xmax,0.3*ymax @ LABEL "TIME CONST. ="
3270 MOVE (-0.3)*xmax,0.3*ymax @ LABEL tau
3280 MOVE (-0.5)*xmax,0.2*ymax @ LABEL "STD. DEV. ="
3285 sd=INT(sd*1000000)/1000000
3290 MOVE (-0.3)*xmax,0.2*ymax @ LABEL sd
3300 MOVE (-0.5)*xmax,0.1*ymax @ LABEL "ETA ="
3305 eta=INT(eta*100000)/100000
3310 MOVE (-0.4)*xmax,0.1*ymax @ LABEL eta
3390 CLEAR @ GOTO 1350
3500 ! dtdt vs d2tdx2 plots
3510 FOR jp=2 TO jr-1
3520 MOVE xs(jp),ys(jp) @ GOSUB 4500
3530 NEXT jp
3540 ! Draw the regression line
3550 MOVE 0,0 @ y=tdfs*xmax
3560 LINE TYPE 1 @ DRAW xmax,y
3570 GOTO 3100
4500 ! plus symbol
4510 SETGU @ IDRAW 1,0 @ IDRAW -2,0 @ IDRAW 1,0 @ IDRAW 0,1 @ IDRAW 0,-2 @ ID
0,1
4520 SETUU @ RETURN
4530 ! x symbol
4540 SETGU @ IDRAW 1,1 @ IDRAW -2,-2 @ IDRAW 1,1 @ IDRAW -1,1 @ IDRAW 2,-2 @
AW -1,1
4550 SETUU @ RETURN
```

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