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Saxena, Ram R.

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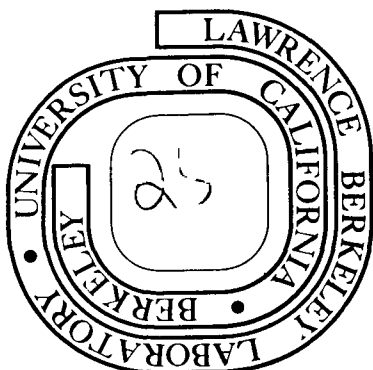
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ELECTRICAL CONDUCTION IN GLASSY CARBON

Ram R. Saxena* and Robert H. Bragg

Materials and Molecular Research Division, Lawrence Berkeley Laboratory
and Department of Materials Science and Engineering,
University of California, Berkeley, California 94720

ABSTRACT

The electrical conductivity and Hall Effect of a disordered carbon have been investigated in the temperature range 10-300^oK and magnetic fields up to 50KG. The structure of the material was changed by heat treating in the temperature range 1000-2800^oC. For heat treatment temperatures (HHT) greater than 2000^oC the conductivity was found to be the sum of a temperature independent contribution due to diffuse boundary scattering and a hopping contribution following a $T^{-1/4}$ law. For HHT less than 2000^oC, at the lowest measurement temperatures the conductivity exhibits a logarithmic temperature dependence characteristic of Kondo systems. An energy band structure for these disordered carbons is proposed in which the Fermi level is pinned by localized states.

*Current address: Varian Associates Solid State Laboratory
611 Hansen Way, Palo Alto, CA.

INTRODUCTION: In the last decade or so it has been possible to carefully decompose highly cross linked polymers to obtain what have been called "glassy", "glass-like" or "vitreous" carbons.¹ The nomenclature comes from the shiny black glass-like appearance and conchoidal fracture of these materials. These carbons retain their disordered structure up to the highest heat treatment temperature (HTT) ca. 3200°C, and are thus classified as non-graphitizing or hard carbons. Those carbons that develop a large crystallite size, well ordered graphitic structure on heat treatment to approximately 2500°C are called graphitizing or soft carbons. The prevalent model of the structure of glassy carbon (GC) is that of an entangled lath-like structure of graphitic ribbons cross-linked by sp^3 bonded atoms. Glassy carbon has a large porosity (about 40%) composed mainly of unconnected 10-20A voids. The void growth with HTT has been shown in the work of Bragg and Hammond², Biswal and Bragg³, and others⁴.

Whereas extensive review articles have been published on the electronic properties of single crystal graphite⁵ and graphitizing carbons⁶, comparatively little work has been done on non-graphitizing carbons. The electronic properties are relatively well-understood for near single crystal graphites, but even for soft carbons the understanding is far from complete. In the case of hard carbons there are even contradictions in the literature regarding the trends of the experimental data.

The electrical properties of soft carbons have been studied in considerable detail. Although elegant solutions and explanations have not always been possible, the work of Mrozowski⁷ and others following him has

been thorough. The temperature dependence of conductivity, σ , was studied in great detail by Mrozowski.⁷ The most important result was that - "In contrast with the infinite single crystal, systems of benzene rings of finite dimensions possess a finite energy gap between the filled and the conduction bands, the energy gap steadily decreasing with molecular size - from about 1 eV for molecules several benzene rings wide, to 0.2 - 0.3 eV for systems 30-40Å⁰ in diameter and down to .05 eV for graphite crystallites with diameters of the order 1000Å⁰." This, in conjunction with reasonable hypotheses regarding excess carriers and scattering from crystallite boundaries, can be considered to have explained $\sigma(T)$ in soft carbons.

Although all three, conductivity, σ , Hall Coefficient, R_H , and magnetoresistance, $\frac{\Delta\rho}{\rho}$, have been used to characterize soft carbons, the understanding of R_H and $\frac{\Delta\rho}{\rho}$ is far from complete. A qualitative understanding of R_H is possible and is usually presented in terms of the variations of the Fermi level, E_F , with HTT in a proposed band structure. Delhaes has written an excellent review article on the subject⁸ and has investigated $\frac{\Delta\rho}{\rho}$ in soft carbons quite thoroughly.⁹ For soft carbons $\frac{\Delta\rho}{\rho}$ is found to be both positive and negative. The explanation is as yet not satisfactory, although Delhaes⁹ has tried to employ all the available models to explain his data.

Only a few studies¹⁰⁻¹² of electronic properties of GC have been reported. The only two prior studies¹⁰⁻¹¹ of $\frac{\Delta\rho}{\rho}$ do not agree on the sign of $\frac{\Delta\rho}{\rho}$ over the range of HTT and ambient temperatures studied. No explanation of the magnetic field dependence of $\frac{\Delta\rho}{\rho}$ was offered in the one

reported study¹² in which the magnetic field H was varied. The conductivity and Hall Effect have not been carefully investigated either, but a recent ESR¹³ study of GC over a range of HTT has shown that both localized and extended electron states of comparable density exist at all HTT's studied.

We have studied the structure and the electrical properties of GC specially prepared by Polycarbon Company, North Hollywood, Ca. USA. The GC plates (8" x 2" x 1/16") as obtained had been heat treated at 1000°C for one hour. These were subsequently heat treated at higher temperatures and x-ray techniques were used to characterize the structure. For carbons, the crystallite size parameters L_c , L_a determined from the widths of (002) and (10) x-ray diffraction peaks represent average dimensions of the crystallite perpendicular and parallel to the graphitic layers respectively. For GC the parameters L_c and L_a grow from 10Å to 28Å and 26Å to 49Å respectively on heat treating GC at 1100°C to 2800°C for two hours each.¹⁴ The electrical properties studied included σ , R_H and $\frac{\Delta\rho}{\rho}$. Negative magnetoresistance is discussed elsewhere.¹⁵ Here we present the results of our conductivity and Hall Effect studies.

EXPERIMENTAL: Heat treatments of the GC samples were carried out in a graphite furnace with the samples enclosed in a cylindrical graphite crucible 3" diameter x 2 1/2" high and surrounded with GC wool. An optical pyrometer calibrated for the temperature range 1000° - 3000°C was used to measure the temperature. The proper heating rate was experimentally determined because too high heating rates caused the GC samples to crack. This cracking is probably due to the evolution of

gases trapped inside the specimen. The nomenclature for the heat treated samples is henceforth GC-HTT-time, e.g. GC-1500-2 means GC heat treated at 1500°C for two hours.

The low temperature facility used for the electrical measurements consists of a multi-chambered cryostat with a superconducting magnet and associated vacuum and electronic systems.* It produces a maximum 50KG field with better than 1% homogeneity in a 1 1/2" diameter x 2" region in the center. The sample probe used in our experiments consists of a hollow stainless steel tube with a Cu mounting block for samples and temperature sensors. A screw-on Cu cap is provided to maintain a thermal equipotential. The copper mounting block has a heater wire wrapped around it to control the temperature. A GaAs diode sensor was used in conjunction with the temperature controller, which also supplied current to the 100 heater for automatic temperature control.

The standard six-arm sample configuration was used for all the electrical measurements. To reduce noise, twisted pairs were used for current input to the sample, resistance leads and Hall leads. Two lock-in amplifiers were used to measure the low level resistance and Hall signals. All the measurements were done at a signal frequency of 100 Hz, with both the lock-in amplifiers in the band-pass mode. The precision of the data were determined to be $\pm .01\%$ for $H = 0$ and $\pm .05\%$ for $H \neq 0$. It was difficult to get accurate measurements of R_H , because the signal was typically $\sim 1\mu V$ and often the misalignment voltage was much larger than that.

*The cryostat, superconducting magnet and the magnet power supply were bought from Oxford Instruments, England.

To achieve reliable contact to the sample various techniques were tried.¹⁴ The technique found to be most successful was coating the contacts with silver paint and using a Be-Cu alloy strip as the pressure contact, screwed down into the Cu mounting block. This method was used for all the data presented in this work.

RESULTS AND ANALYSIS: Hall Effect: Reliable data could be obtained only for a few samples, and low field R_H data could not be obtained for enough samples to allow proper analysis of the temperature dependence. The magnetic field and temperature dependence of R_H for one sample is shown in Fig. 1. A weak dependence on temperature can be seen at low fields. The data of Fig. 1 can be plotted against $1/T$ to obtain an activation energy of 0.4 meV. At high fields R_H saturates and the temperature dependence disappears. The saturation in R_H is related to the low mobility conduction of the carriers at the fermi level. The variation in the number of carriers calculated from the saturation R_H value, using the simple formula $n = \frac{1}{e R_H}$ is shown in Fig. 2. A maxima in n is seen to occur around a HTT of 2000°C . A separation into HTT regimes above and below 2000°C is also evident in conductivity studies and other parameters studied.

Conductivity σ : The room temperature conductivity for the isochronally heat treated specimens were all found to be around $2000\ \Omega^{-1} \cdot \text{cm}^{-1}$. The change in σ with measurement temperature at the lowest temperatures studied ($\sim 10^\circ\text{K}$) is found to be $< 25\%$. Based upon the behavior of σ with T the results are classified in two different HTT regimes. Typical dependence of σ on T in the high HTT region ($\text{HTT} > 2000^\circ\text{C}$) is shown in

Fig. 3. For GC samples with $\text{HTT} < 2000^\circ\text{C}$ the low temperature behavior of σ is markedly different as also shown in Fig. 3.

From the ESR studies of Orszesko and Yang¹³, it is known that densities of localized and conduction spins are comparable over a broad range of heat treatment temperatures (HTT) in GC. It was anticipated that due to small crystallite size in GC a boundary scattering mechanism should dominate for extended states at all temperatures, which is expected to give a temperature independent contribution to σ .⁷ For localized states hopping conduction is expected which should follow a $1/T^{1/n}$ law at low temperatures.¹⁶

In our attempts to separate the two contributions it was found that plots of $\ln\sigma$ against T were straight lines over a large range of temperatures. At low measurement temperatures for the two HTT regimes different characteristics were evident: (i) a temperature independent σ for $\text{HTT} > 2000^\circ\text{C}$ and (ii) a sharp decrease in σ for $\text{HTT} < 2000^\circ\text{C}$. Typical plots are shown in Fig. 4. For the higher HTT material the intercept of the straight line of $\ln\sigma$ versus T is found to be equal to (within the measurement accuracy) the temperature independent value of σ . Clearly then, for $\text{HTT} > 2000^\circ\text{C}$, σ_0 is the temperature independent boundary scattering contribution. For the lower HTT regime the same interpretation of σ_0 is not self-evident, but shall be seen to be so from the analysis of the low temperature dependent of σ . The variation of σ_0 with HTT is shown in Fig. 5. The error bars result largely from the dimensional measurements of the samples.

Assuming σ_0 as determined above to be the independent contribution for the lower HTT regime as well, the temperature dependence of

$(\sigma - \sigma_0)$ was analyzed. Plots of $\ln(\sigma - \sigma_0)$ vs $1/T^{1/4}$ were found to be straight lines for all the samples as shown in Figs. 6 and 7. This is expected temperature dependence for variable range hopping conduction σ_{hop} in the localized states.¹⁹ The variation in the slopes of these plots is small, but the trend is toward increasing slope at lower HTT. This separation of σ into σ_0 and σ_{hop} is valid over the entire temperature range for GC samples in the higher HTT regime. For the lower HTT samples it is applicable over a limited range of temperatures only (linear portion in Fig. 4). Having identified the hopping conduction we can now analyze the temperature dependence of $\sigma_K = \sigma - \sigma_{hop}$ and understand the meaning of σ_0 in the lower HTT regime.

For the low HTT material ($HTT < 2000^\circ\text{C}$) σ at low temperatures exhibits a sharp decrease. The decrease in σ becomes more pronounced as the HTT is lowered. To analyze the temperature dependence at these low temperatures the hopping contribution to conductivity σ_{hop} extrapolated from Fig. 7 was subtracted. The remainder σ_K was found to follow a logarithmic dependence on temperature as shown in Fig. 8. The slope of σ_K vs $\log T$ line reduces with increasing HTT. The logarithmic temperature dependent contribution saturates at σ_0 as the temperature is increased to about 100°K . Thus the intercept σ_0 is the temperature independent boundary scattering contribution for all the samples, but for the lower HTT regime an extra resistance is added at low temperatures. This logarithmic temperature dependent term which eventually saturates arises from the 'Kondo Effect' phenomenon in these disordered carbons.

DISCUSSION: The temperature dependence of the electrical conductivity is found to consist of three contributions: (i) a temperature independent

σ_0 , (ii) variable range hopping $\sigma_{hop} \propto \exp(-B/T^{1/4})$, and (iii) an anomalous contribution at low temperatures in lower HTT material σ_K .

A temperature independent contribution due to boundary scattering in carbon has been found earlier in the work of Mrozowski⁷, who analyzed the temperature dependence of resistivity in terms of a model where an energy gap between valence and conduction bands was assumed. Excess holes were postulated which were considered to be the result of trapping of resonance π electrons by carbon atoms on the periphery of crystallites. The temperature dependence was successfully explained by assuming a temperature independent boundary scattering contribution and a phonon scattering term linear with T. Klein⁶ also found a temperature independent boundary scattering contribution in his study of electrical properties of pyrolytic graphites.

To check the consistency of the assumption of a temperature independent boundary scattering to conductivity, we calculate σ_0 using

$$\sigma = \frac{ne^2}{m^*}$$

where n is the number of the carriers, τ is the mean scattering time given by

$$\tau = l/v$$

l = mean free path

v = velocity of carriers

and m^* is the effective mass of carriers.

We take n to be the value obtained from R_H in the high HTT range. The quantity n is not expected to change appreciably with temperature, as seen in the weak dependence of R_H on temperature in our data and that

of Yamaguchi.¹⁰ Other studies on carbons^{11,12} also seem to indicate that when negative magnetoresistance similar to ours is observed, R_H does not vary much with temperature. As will be discussed later, this is a natural consequence if the fermi level is pinned down by localized states. We take n to be $7 \cdot 10^{19} \text{ cm}^{-3}$, a mean value from Fig. 2.

The mean free path, l , would be of the order of the crystallite size L_a . The value taken here is 30 \AA .¹⁴ The velocity of carriers is taken to be the same as in graphite. The justification comes from the observed closeness of GC and graphite K-emission bands in our work¹⁷ and the photoemission studies of Shirley et al.¹⁸ Little change is expected in the velocity with regard to temperature since the fermi level is pinned down by localized states. Klein⁶ has also concluded that v is only weakly dependent on temperature. We take v to be $2 \times 10^7 \text{ cm/sec}$ (Ref. 5), and m^* to be $0.5 \times m$, where m is the mass of the free electrons, as deduced by Mrozowski⁷, for carbons with crystallites of about 30 \AA diameters. The calculated σ_0 is $590 \Omega^{-1} \text{ cm}^{-1}$. This value is about three times larger than measured which could be due to a too large value of n calculated from R_H . The order of magnitude comparison is satisfactory, and the σ_0 vs HTT plot (Fig. 5) is seen to be qualitatively similar to n vs HTT graph (Fig. 2). The broader maxima seen in the variation of σ_0 with HTT could be the result of a gradual increase in L_a with HTT.¹⁴

The contribution of the localized states to conductivity, σ_{hop} , is via the hopping conduction mechanism. At low temperatures, when tunneling to farther than the nearest neighbour is possible, the hopping conductivity varies as¹⁹

$$\ln \sigma_{\text{hop}} = A - B/T^{1/4}$$

where

$$B \approx 2.1 \left(\frac{\alpha^3}{kN} \right)^{1/4}$$

α = decay parameter of localized wave function with distance $R(e^{-\alpha R})$

k = Boltzman's constant

N = Density of states per cm^3 per eV.

The mean experimental value of the slope B is about $14^\circ \text{K}^{1/4}$. As an estimate of N we divide n (obtained from our R_H data) by the width (in eV) of the localized state band, taken to be 0.25 eV from the energy gaps observed by Mrozowski.⁷ This estimate of the energy gap is reliable because it was obtained from conductivity studies up to a measurement temperature of 1100°C . Taking n to be $7.10^{19} \text{ cm}^{-3}$ the calculated value of α is $3.6 \times 10^6 \text{ cm}^{-1}$ or $1/\alpha = 28\text{\AA}$. Thus a localized state seems to extend over a distance of the order of the crystallite size L_a . The trend of increasing slope B at lower HTT seen in Figs. 6 and 7 is consistent with stronger localization (larger α) expected in the structurally less perfect material.

To obtain a further check on the consistency of our results we estimate the temperature T_0 below which $T^{-1/4}$ law is obeyed. Realizing that we are in the $(\alpha a) < 1$ (a -lattice parameter) regime, the expression for T_0 is²⁰

$$T_0 = \frac{\alpha^3}{kN} = \left(\frac{B}{2.1} \right)^4 = 1975^\circ \text{K}$$

The calculated value is much larger than 300°K for all cases and is extremely sensitive to the value of B chosen and the exact value of the numerical constant because of the fourth power. The inappropriateness of Mott's theory when the $T^{-1/4}$ law is valid up to high temperatures has been discussed by various authors^{21,22}. Percolation treatments of hopping conduction also predict $T^{-1/4}$ dependence, and they may be more appropriate^{22,23}. It should be pointed out that the exact hopping mechanism cannot be determined by conductivity studies alone, because as discussed by Hill¹⁶, a straightline fit to $1/T^{1/3}$ and $1/T^{1/7}$ would be equally possible.

The logarithmic dependence of the sharp decrease in σ at low temperatures for GC heat treated below 2000°C is known to be a characteristic of Kondo systems when $T > T_k$, where T_k is the Kondo temperature. The saturation effect is discussed by Rivier and Zlatic.²⁴ To observe the other regimes of the temperature dependence of the resistivity discussed by Rivier and Zlatic²⁴, one would have to go down to temperatures closer to T_k . If we consider the expression for T_k ,²⁰

$$kT_k \propto \exp(-1/JN)$$

(where J is a coupling constant) the reduction in the number of spins seen in our R_H data and the ESR studies¹³ would lead to lower T_k with higher HTT. This is also evident from the reduced slope $(\propto JN)$ ²⁰ of σ vs $\log T$ line with HTT. Thus with increasing HTT one would have to go down to lower and lower measurement temperatures to observe the logarithmic temperature dependence of σ_k .

The Kondo phenomenon also leads to an anomalous peak in the specific heat at $T \approx T_k$.²⁰ The anomalous peak and the expected antiferromagnetic coupling between spins has been shown in the low temperature heat studies on various carbons including GC.^{25, 26} Strong correlation between the density of spins as seen in the ESR studies¹³ and the parameters characterizing the excess specific heat were also found.²⁶ Vagh and Mrozowski²⁶ studied the low temperature specific heat of GC heat treated in the temperature range 1000-3200°C for one hour each. Indications of a peak were seen for GC heat treated up to 2200°C, and the location of the peak moves down to lower temperatures with HTT. For GC 2700, 3000, and 3200 no indication of a peak was seen down to 0.4°k. These results are in agreement with our observations.

The temperature dependence of σ found in this work is similar to that seen previously in other studies, although the prior analyses have not been as thorough. Bucker²⁷ found only a $T^{-1/4}$ dependence for $\ln \sigma$ for a glassy carbon (thermally degraded phenol-formaldehyde resin) up to $HTT = 1200^\circ C$. This might be due to the poor crystallinity of his material. It seems that his material might have been like amorphous carbon films which have crystallites of size $\approx 10A^\circ$, and a $T^{-1/4}$ law is obeyed over a long range of temperatures.²⁸ A linear dependence of $\log \sigma$ on T or $\log T$ has been found by some workers for amorphous carbon films.²⁹ It seems likely that an analysis similar to ours might be applicable in these cases.

Our Hall Effect data are in agreement with Yamaguchi's¹⁰ data on GC A. The variation in the number of carriers with HTT shown in Fig. 2 is also in qualitative agreement with the results of the ESR study of Orszesko and Yang¹³ on GC. Their data are replotted in Fig. 9. The maximum in the number of carriers occurs at a slightly lower HTT, which could be due to the differences in the preparation of the GC's used. Bückner³⁰ has deduced number of carriers $\sim 10^{20} \text{ cm}^{-3}$ in his studies of the electronic properties of a glassy carbon in agreement with our numbers in Fig. 2. He has also pointed out the difficulties in obtaining and interpreting Hall Effect data in amorphous semiconductor systems.

BAND MODEL FOR CARBONS: The earliest band model for carbons is due to Mrozowski⁷, who envisages a decreasing band gap with HTT, eventually resulting in the overlap of the valence and conduction bands. A similar model has been suggested by Klein⁶ for pyrolytic graphites. Recent work of Carmona, Delhaes et al³¹ suggested a nonmetal-metal transition in carbons around a HTT of 700°C. This is also seen in Mrozowski's⁷ work and the study of Bückner²⁷ on GC. Whereas the possibility of nonmetal-metal transition in carbon seems to be quite clearly demonstrated by the change in conductivity by many orders of magnitude, it should be pointed out that it differs strongly from more common examples of metal-insulator transitions, e.g., in V_2O_3 . For V_2O_3 the transition occurs as a function of temperature, T , and is reversible.²⁰ The transition in carbons is an irreversible process. Matters are further complicated by the inhomogeneous structure of carbons heat treated at lower temperatures. These carbons have small crystallite sizes and the C-C bonding at the boundaries

of these crystallites is expected to be diamond (sp^3) like compared to the graphitic (sp^2) bonding within a crystallite.¹⁷

We believe that nonmetal-metal transition does take place in carbons, although considerably more work is needed to understand this phenomenon. On the insulator side of the transition the fermi level is expected to be in the middle of the energy gap or at least a mobility gap. On the metallic side of the transition the fermi level lies inside the valence band. That it is indeed so is supported by the positive sign of R_H found in many studies of transport properties of carbons.^{9, 11} Bucker³⁰ has also concluded that holes are the carriers in GC for $HTT > 600^\circ C$. On the metallic side an Anderson transition due to disorder is also expected. There would be localized states in the tails of valence and conduction band. Thus, a mobility gap would exist,¹⁹ and these would be the energy gaps observed by Mrozowski.⁷

Based upon these ideas, the band model for carbons should be as shown in Fig. 10. The fermi level lies on the high mobility side of the mobility shoulder inside the valence band. As heat treatment progresses, the mobility gap is reduced. The fermi level moves closer to the center still situated near the top of the extended states inside the valence band. For soft carbons the mobility gap finally closes, the fermi level moves near the center, a graphitic overlapping band structure is formed, and the conductivity becomes metallic. For hard carbons the structural disorder is preserved up to the highest HTT, and the conductivity retains its semi-conducting nature. Thermodynamic evidence for the stability of the disordered structure of GC is available in the study of Das.³²

We believe that the fermi level is pinned down by defects (e.g., voids) characteristic to the material. These defects act as traps and can also be described as localized states. These states are expected to lie in the inhomogeneous part of the structure, most likely on the boundary of the crystallites. That E_f could be held down inside the valence band by localized states is supported by the work of Ball³³ who contends that localized and extended states are different in nature and could be infinitesimally apart in energy, and in the study of Inglis and Williams³⁴ where extended and localized states are found to exist in different regions in space for an inhomogeneous system. These localized states trap electrons from the valence band leaving holes behind and would be responsible for the excess holes postulated by Mrozowski.⁷ Thus there should be a close correspondence between localized and conduction states, as can be seen in the ESR data from Ref. 13, replotted in Fig. 9. Similar correspondence between localized and conduction spins has been seen in the studies of carbon films, and one localized state per crystallite is suggested which could also be true in our case.²⁸

The localized spins in the disordered forms of carbon constitute a Kondo system with a low Kondo temperature $T_k < 1^{\circ}\text{K}$. The Kondo temperature reduces with increasing structural order and annealing of spins. On the metallic side the localized spins are also expected to be highly correlated with neighbouring extended states.²⁰ This could give rise to effective magnetic moment per spin μ_{eff} larger than μ_B . This highly correlated state and μ_{eff} is expected to increase with decreasing structural disorder at first because of the possibility of overlapping a large

number of extended states with weaker localization. Eventually this state disappears as the structural disorder is annealed out and the graphitic overlapping band structure is attained.

CONCLUSIONS: The electrical properties of GC are found to be affected by heat treatment. Two regimes can be identified above and below HTT 2000°C. For the higher HTT regime the electrical conductivity has been explained as a sum of two contributions: (i) temperature independent diffuse boundary scattering and (ii) hopping conduction varying as $A \exp(-B/T^{1/4})$. For GC heat treated below 2000°C there is an anomalous contribution at low temperatures following a logarithmic temperature dependence characteristic of Kondo systems, the previous decomposition of conductivity remaining valid over the rest of the temperature range. The number of carriers deduced from a simplified analysis of the Hall Effect data exhibit a maximum around HTT 2000°C and are in agreement with the results of related studies. Based upon our results, an energy band model for carbons is proposed which consists of a pseudogap (with mobility shoulders) arising from localization of states due to disorder. The fermi level is pinned down near the top of the extended states inside the valence band due to localized states in the inhomogeneous part of the structure.

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FIGURE CAPTIONS

1. Magnetic field and temperature dependence of R_H for GC 2300-2.
2. The variation in the number of carriers with HTT.
3. Typical temperature dependence of the electrical conductivity in the two HTT regimes (above and below 2000°C).
4. Linear dependence of $\ln\sigma$ on T in the two HTT regimes.
5. Variation in σ_0 with HTT.
6. Hopping conduction in GC following $T^{-1/4}$ law; $\text{HTT} > 2000^\circ\text{C}$.
7. Hopping conduction in GC following $T^{-1/4}$ law; $\text{HTT} < 2000^\circ\text{C}$.
8. Logarithmic temperature dependence of σ_K for GC heat treated below 2000°C .
9. Variation in spins/gm with HTT. (from Orzesko and Yang - Ref. 13).
10. Energy band model for carbons.

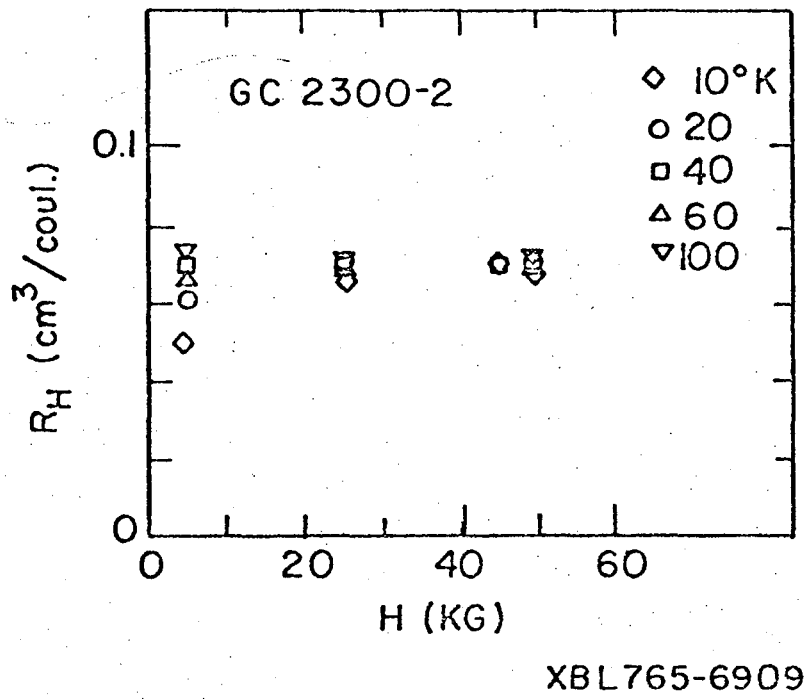


FIG. 1

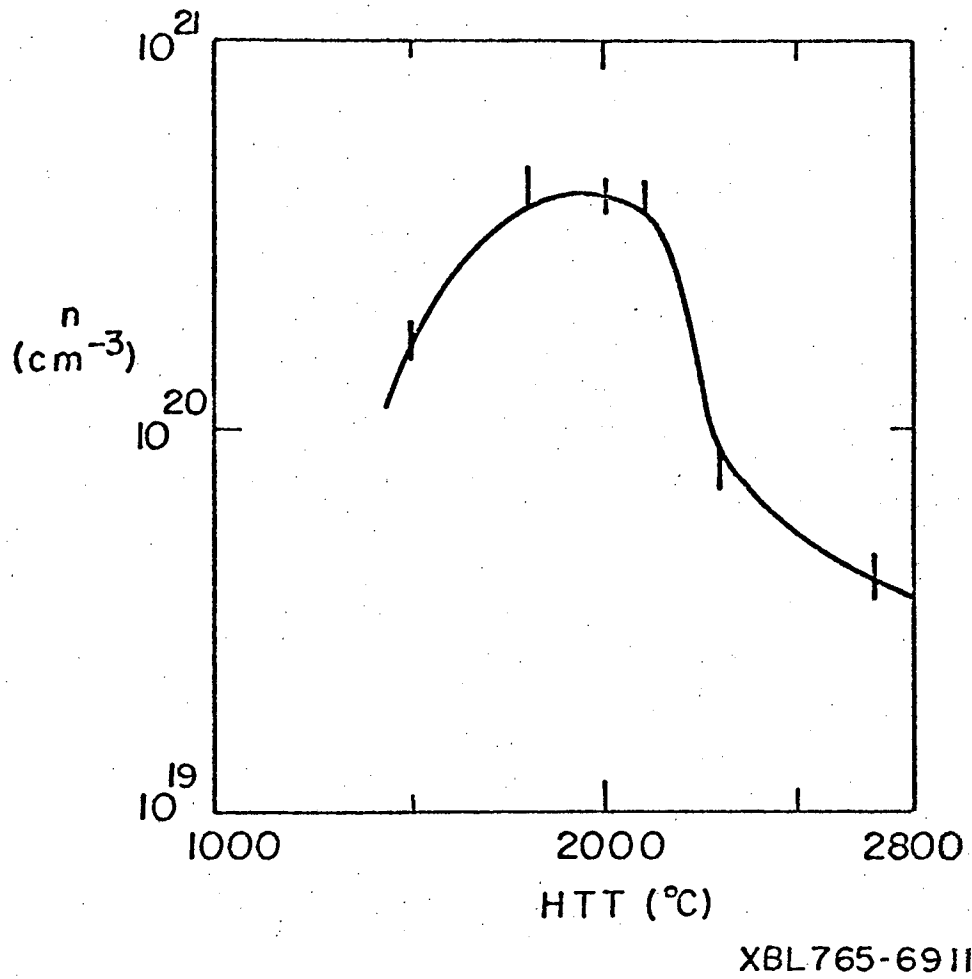
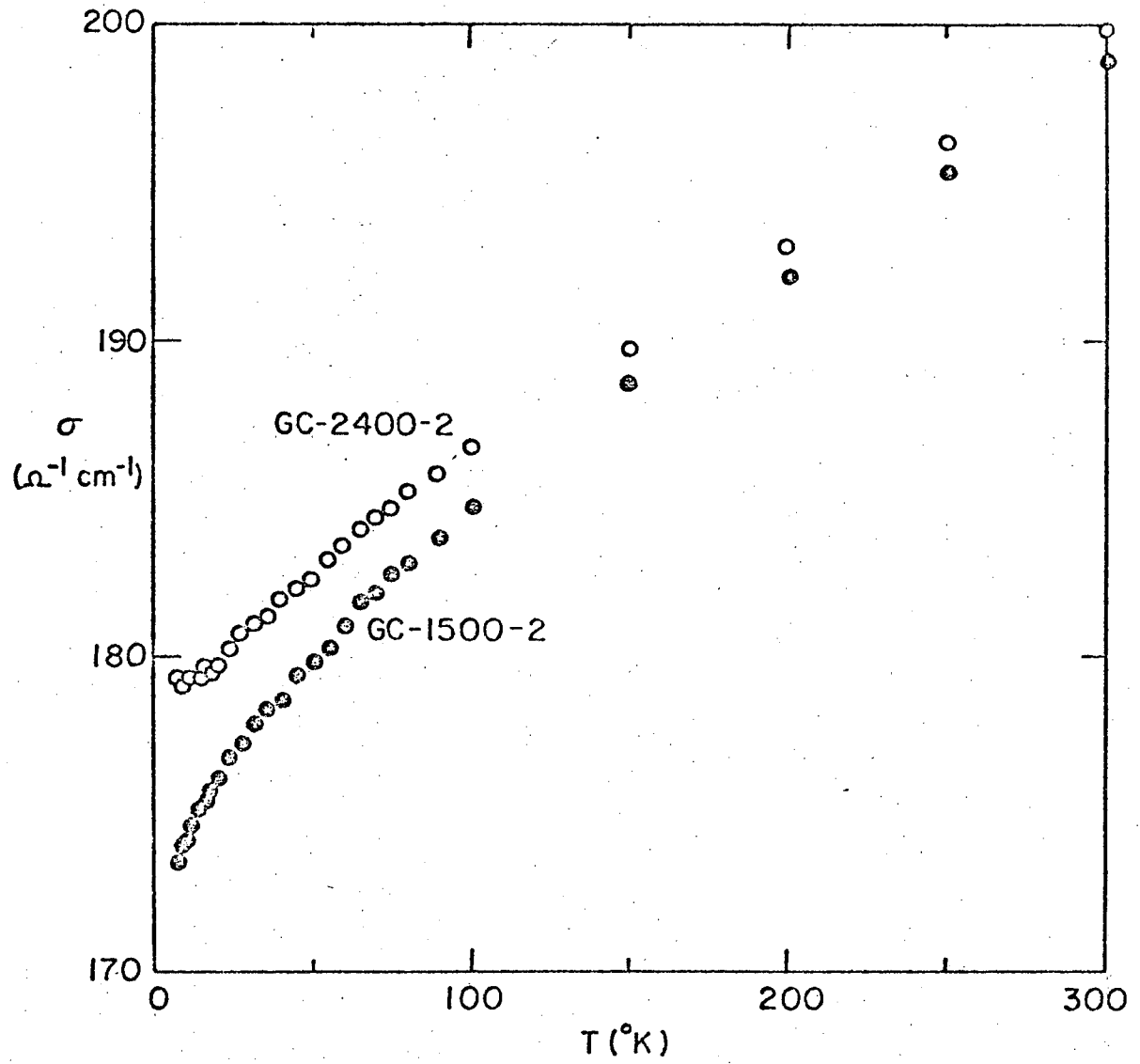
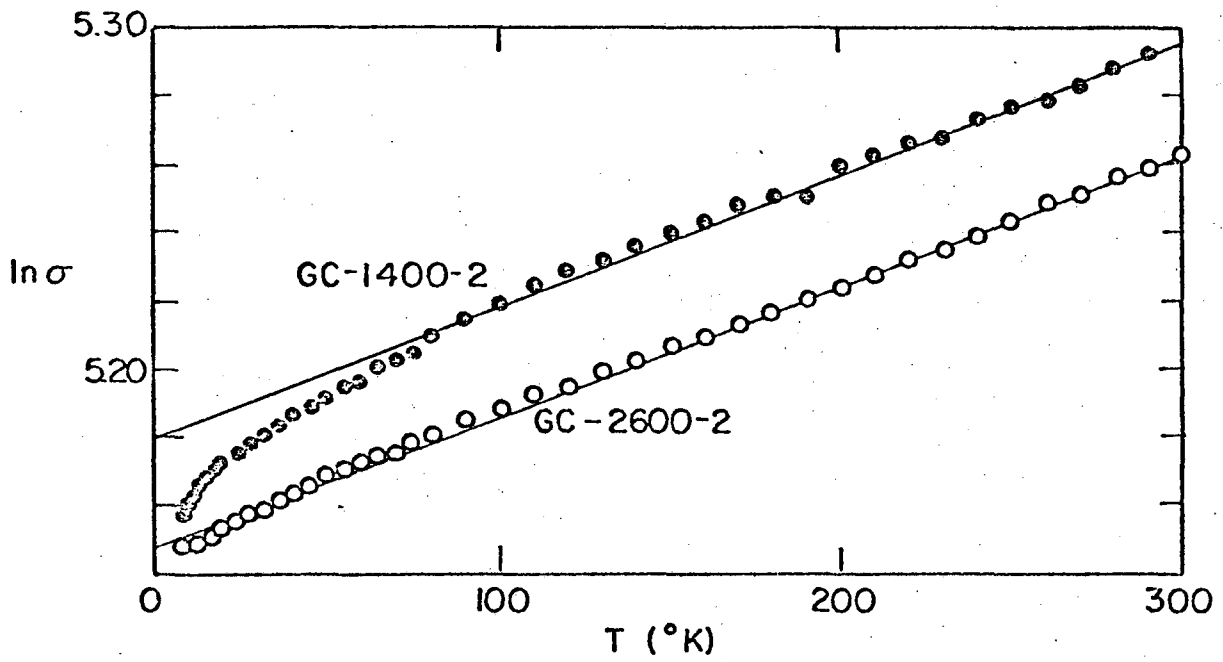


FIG. 2



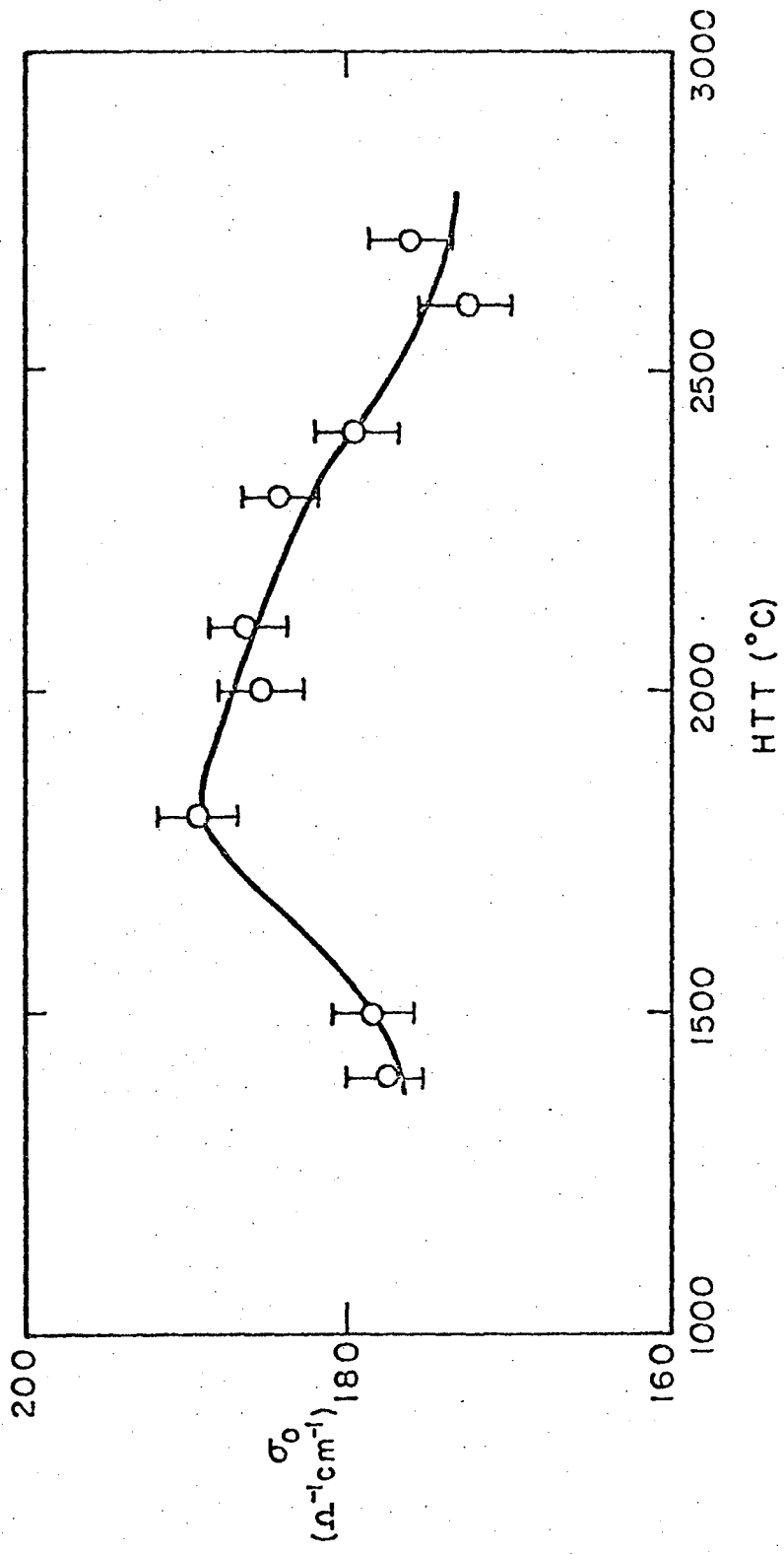
XBL 765-6908 A

FIG. 3.



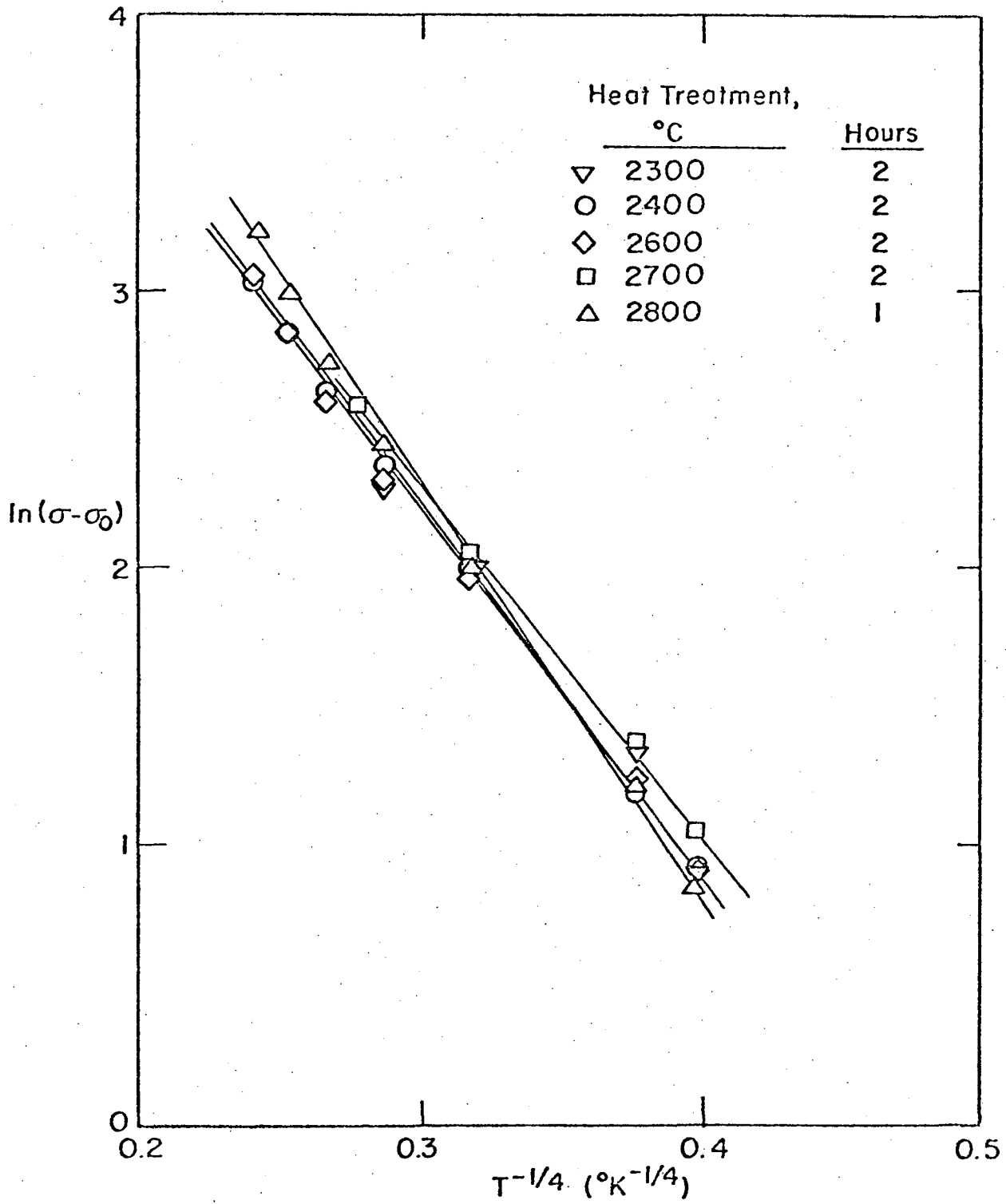
XBL765-6916A

FIG. 4



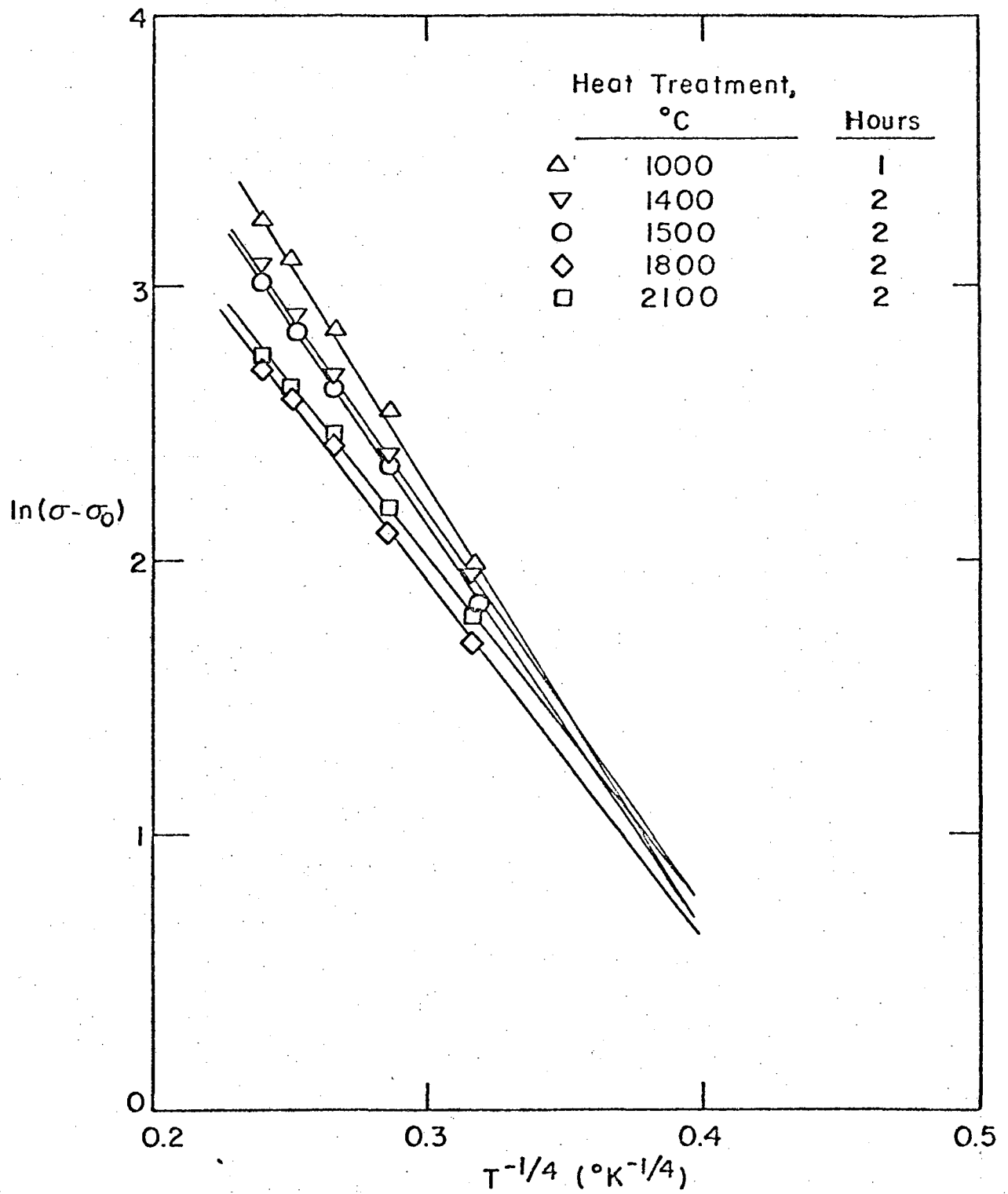
XBL 7611-7818

Fig. 5



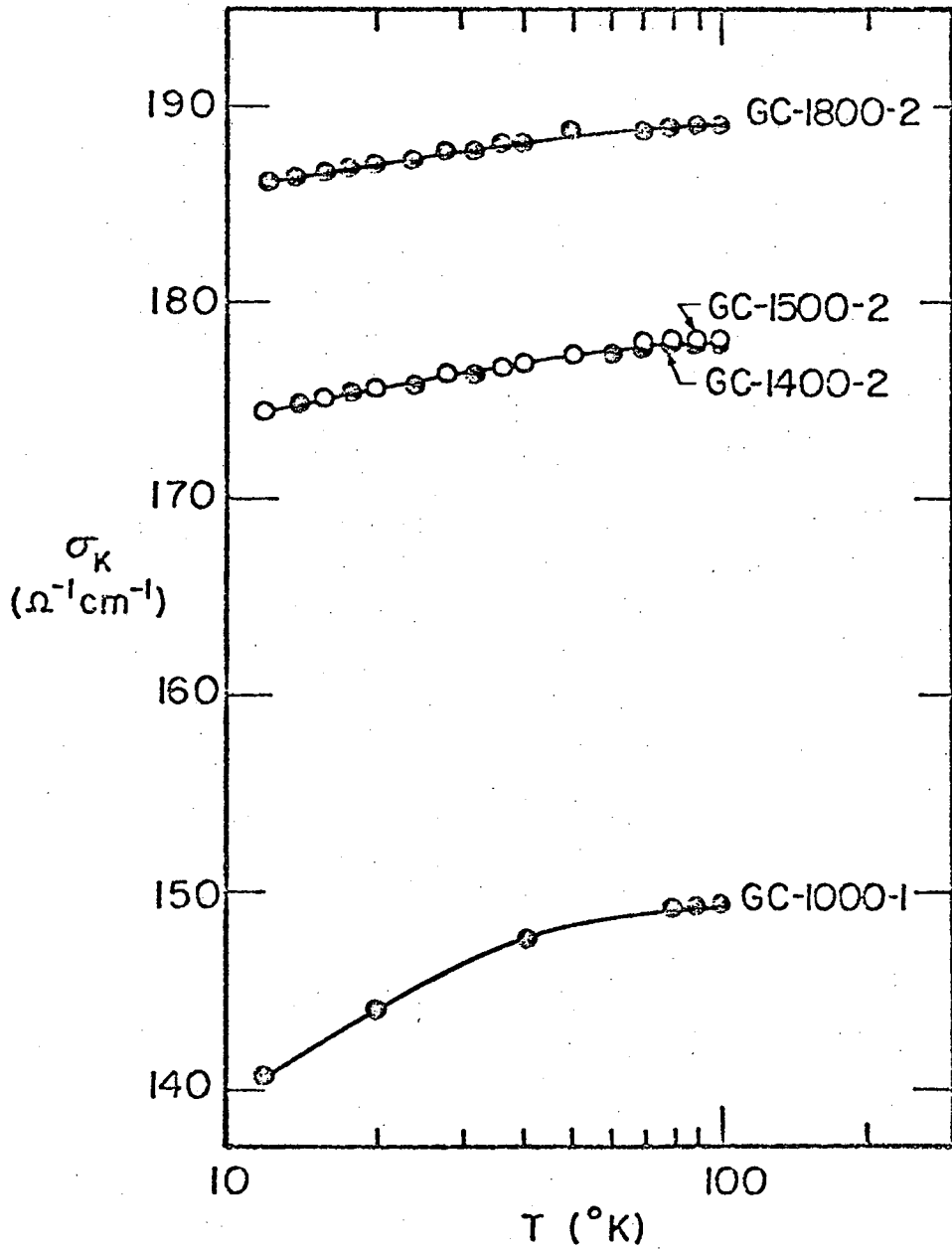
XBL 765-6918

FIG. 6



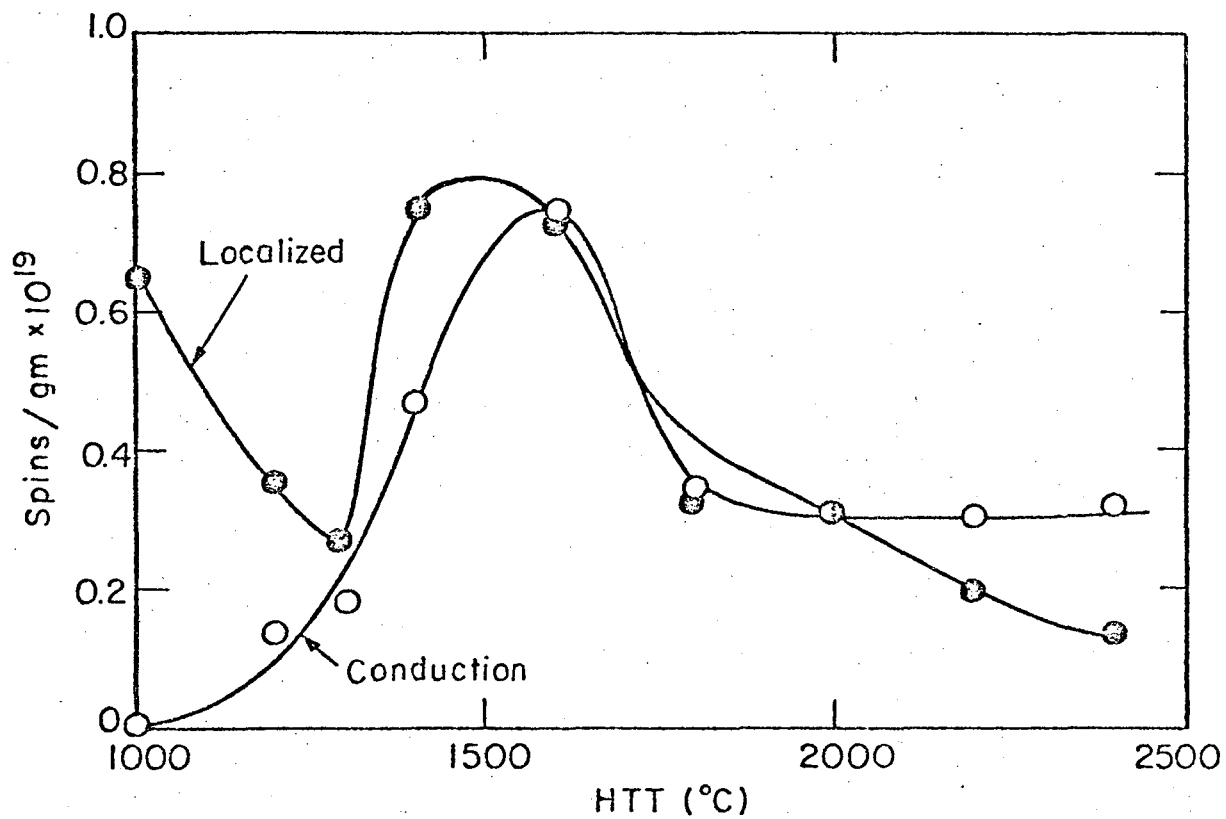
XBL 765-6919

FIG. 7



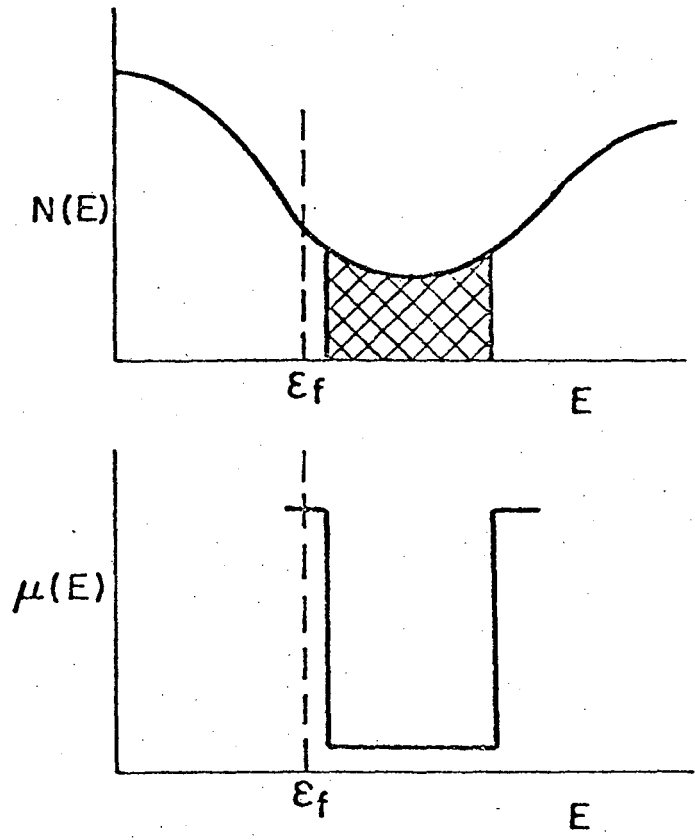
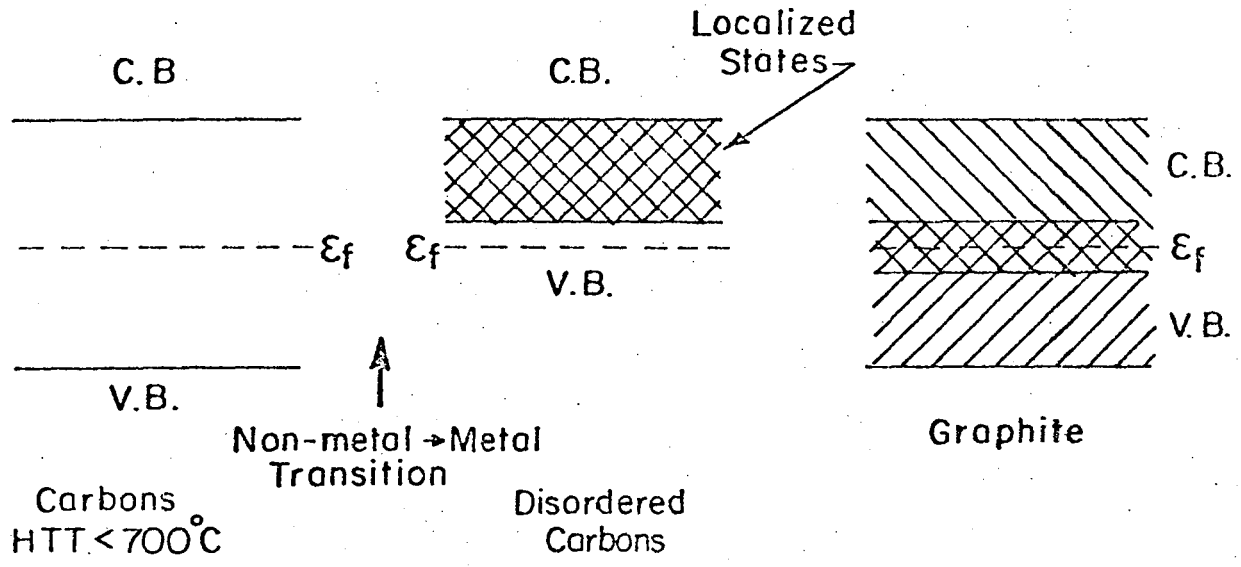
XBL 7611-7819

FIG. 8



XBL 765-6929

FIG. 9



XBL 765-6928

FIG. 10.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720