To be submitted for publication
in Journal of Applied Physics

THE TEMPERATURE DEPENDENCE OF CRITICAL FIELDS OF A SUPERCONDUCTING Pb-Tl ALLOY*

S. T. Sekula and R. H. Kernohan
Solid State Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

Using a conventional ballistic technique, magnetization curves of a superconducting Pb-27% Tl alloy have been obtained from the transition temperature $T_c = 6.43^{\circ}K$ down to $1.70^{\circ}K$. The thermodynamic critical curve is reasonably well fitted by the two-fluid model although small deviations indicate that this alloy is of the strong coupling type. The Ginzburg-Landau parameters deduced from several features of the magnetization curves are given and their temperature dependence is compared to theoretical models.

* Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

DISCLAIMER

INTRODUCTION

The bulk magnetic behavior of Type II superconductors as predicted by the Ginzburg-Landau-Abrikosov[1] theory has been verified by much recent work.[2] As is well known the theory predicts that

$$H_{c2}(t) = \sqrt{2}\,\varkappa_1(t) H_c(t) \tag{1}$$

where $H_{c2}(t)$ is the value of magnetic field at complete flux penetration at reduced temperature $t = \frac{T}{T_c}$, H_c is the thermodynamic critical field, and $\varkappa_1(t)$ is a temperature dependent Ginzburg-Landau parameter which can be conveniently written as[3]

$$\varkappa_1(t) = a(t)\,\varkappa_1(1), \tag{2}$$

where $\varkappa_1(1)$ is the value of the Ginzburg-Landau parameter at the critical temperature, $T_c(t = 1)$. Extensions of the theory to temperatures below T_c assume a parabolic temperature dependence of $H_c(t)$ and predict for $a(t)$:

$$\text{Gor'kov}^4\text{:}\quad a(t) = 1.25 - 0.30t^2 + 0.05t^4 \tag{3}$$

$$\text{Ginzburg}^5\text{:}\quad a(t) = \frac{2}{1 + t^2} \tag{4}$$

$$\text{Bardeen}^6\text{:}\quad a(t) = \left(\frac{2}{1 + t^2}\right)^{1/2} \tag{5}$$

More recent calculations[7,8] predict a temperature dependence not too dissimilar from the Gor'kov formulation with $\frac{\varkappa_1(t)}{\varkappa_1(1)}$ attaining a value of 1.2 in the limit $T = 0$.

The slope of the magnetization curve at H_{c2} is also related to a Ginzburg-Landau parameter $\varkappa_2(t)$[1,8] and is given by:

$$4\pi \left(\frac{dM(t)}{dH}\right)_{H = H_{c2}} = \frac{1}{1.18(2\varkappa_2^2(t)-1)} \tag{6}$$

In general, $\kappa_1(t)$ may not equal $\kappa_2(t)$ except near the transition temperature where the Ginzburg-Landau theory is valid.[8]

We have studied in detail the magnetic properties of a Pb-27% Tl alloy and our results are compared with the above predictions.

EXPERIMENTAL

The specimens consisted of bundles of wires with a small demagnetization factor as well as cast spheres 1/4" diameter. All samples were annealed in a furnace under a helium atmosphere for 25 hours at a temperature no more than $10^{o}C$ below the melting point. The samples were mounted on a nylon rod which could be moved from one coil to another wound in opposition to give a ballistic signal. A Pb sample of similar geometry was used for calibration purposes. The longitudinal field was supplied by a sixth-order superconducting solenoid. The sensitivity of the apparatus was found to correspond to a flux density of 0.2 gauss. The assembly of coils, sample, and rod could be isolated from the helium bath and temperatures above $4.2^{o}K$ were obtained by supplying power to a Pt-Rh heater. Temperatures were measured by means of a Ge-thermometer to an accuracy of $0.05^{o}K$. As has been commonly observed, the resultant magnetization curves were not completely reversible. However, the resultant frozen-in-flux upon restoring the field to zero was quite small and there are indications that an interaction between flux filaments and the surface preclude complete reversibility.[9] Figure 1 shows a typical magnetization curve obtained by cycling in a magnetic field. Magnetization curves thus obtained yield values of $H_c(t)$ by integration. It is interesting to note that while the annealed sphere sample shows a similar irreversibility, integration of the curves for the sphere leads to the same value of $H_c(t)$ as obtained from the data on the wire samples.

RESULTS AND DISCUSSION

Figure 2 shows the thermodynamic critical field of the alloy as determined from the magnetization data plotted against the square of the reduced temperature. Extrapolation of the data to $T = 0^oK$ yields a value of $H_0 = 757$ oersteds. The transition temperature of the alloy determined from the magnetic data was found to be $T_c = 6.43^oK$ and this value was corroborated by earlier resistive measurements. In the latter case the extrapolation of critical current versus magnetic field data in the region where the current abruptly decreases serves to define H_{c2}. The consistency of these data is shown in Fig. 3 where H_{c2} determined both magnetically and resistively is plotted against the reduced temperature. Also shown in Fig. 2 is the two-fluid model temperature dependence of the critical field, i.e., $H_c = H_0(1 - t^2)$. While the agreement is good, a detailed analysis of the data reveals that the experimental points consistently lie above the two-fluid curve which would indicate that this alloy is a strong coupling superconductor. Some degree of confidence has been established in this statement in that we have analyzed critical field data for pure lead obtained from integration of the experimental magnetization curves and find a deviation from the two-fluid curve which is in agreement with that first observed by Decker and co-workers.[10] An exact quantitative discussion of this deviation must be held in abeyance until an experimental difficulty is corrected. This difficulty consists of the generation of small heat pulses during motion of the rod, which smears out the transition and deteriorates our relative accuracy near the transition temperature.

From the experimental values of $H_c(t)$ and $H_{c2}(t)$ one can determine $\kappa_1(t)$, and a linear extrapolation to t = 1 yields a value of $\kappa_1(1)$ = $3.8 \pm .05$ for this alloy. Differentiating equation 1 with respect to temperature one obtains

$$\left(\frac{dH_{c2}}{dT}\right)_{T = T_c} = \frac{\sqrt{2}\,\kappa_1(1)}{T_c}\left(\frac{d\,H_c(t)}{dt}\right)_{t = 1} \qquad (7)$$

The value of the derivative on the right hand side of the equation becomes $-2\,H_0$ for the two-fluid model and is the same to within 10% for both weak and strong coupling superconductors. Using the two-fluid approximation and the experimental value of $\left(\frac{dH_{c2}}{dT}\right)_{T = T_c} = 1.28 \times 10^3$ oe./°K as determined from the data shown in Fig. 3, we obtain a value for the Ginzburg-Landau parameter $\kappa_1(1) = 3.84$ which is in good agreement with the above extrapolation.

According to the relation due to Goodman,[11] $\kappa = \kappa_0 + 7.5 \times 10^{-3}\,\gamma^{\frac{1}{2}}\rho$ where γ is the electronic specific heat coefficient in c.g.s. units, ρ is the normal resistivity in μΩ-cm, and κ_0 the Ginzburg-Landau parameter for the pure solvent metal. The value of γ can be calculated from the thermodynamic relationship $\gamma = .14\,\frac{H_o^2}{T_c^2}$ using our experimental values for this alloy. (The numerical constant is obtained from experimental values[10] for Pb and the assumption that the strong coupling character for the alloy is identical to that of lead). Using Goodman's estimate of $\kappa_o = 0.4$ for Pb, $\gamma_{calc.} = 1898$ erg cm^{-3} deg^{-2}, and the experimental value for ρ found to be 14.9 μΩ-cm, the calculated value becomes $\kappa_1(1) = 5.3$.

In Fig. 4 a plot of the experimental determination of $\frac{\kappa_1(t)}{\kappa_1(1)}$ is given along with the several theoretical models for purposes of comparison. It is evident that for this particular alloy the best agreement is obtained with the Bardeen model. Also shown in Fig. 4 are experimental values of $\frac{\kappa_2(t)}{\kappa_2(1)}$ as determined from the slopes of the tails of the magnetization curves near H_{c2} (equation 6). The extrapolation of this curve indicates that $\kappa_1(1) = \kappa_2(1)$ to within 2% but below the transition temperature $\kappa_2(t) > \kappa_1(t)$, which is at variance with the prediction of Maki.[8] A least squares fit to these data gives the relation:

$$\kappa_2(t) = \kappa_2(1)\ (1.73 - .86\ t^2 + .10\ t^4) \tag{8}$$

An attempt was made to obtain the Ginzburg-Landau parameter $\kappa_3(t)$ related to the field of first penetration H_{c1}, following the work of Harden and Arp.[12] The data in this case are widely scattered, this probably being due to the generation of heat pulses previously mentioned and perhaps the phenomenon of delayed flux penetration. The temperature dependence of $\kappa_3(t)$ is not as large as that of $\kappa_1(t)$ and $\kappa_2(t)$ and the value of $\kappa_3(1)$ is lower than $\kappa_1(1)$ and $\kappa_2(1)$ by about 10%.

ACKNOWLEDGMENTS

A debt of gratitude is acknowledged to P. G. Huray and J. B. Sanders for their able assistance during the course of this work. We also wish to thank M. Strongin and co-workers for a pre-print of their work.

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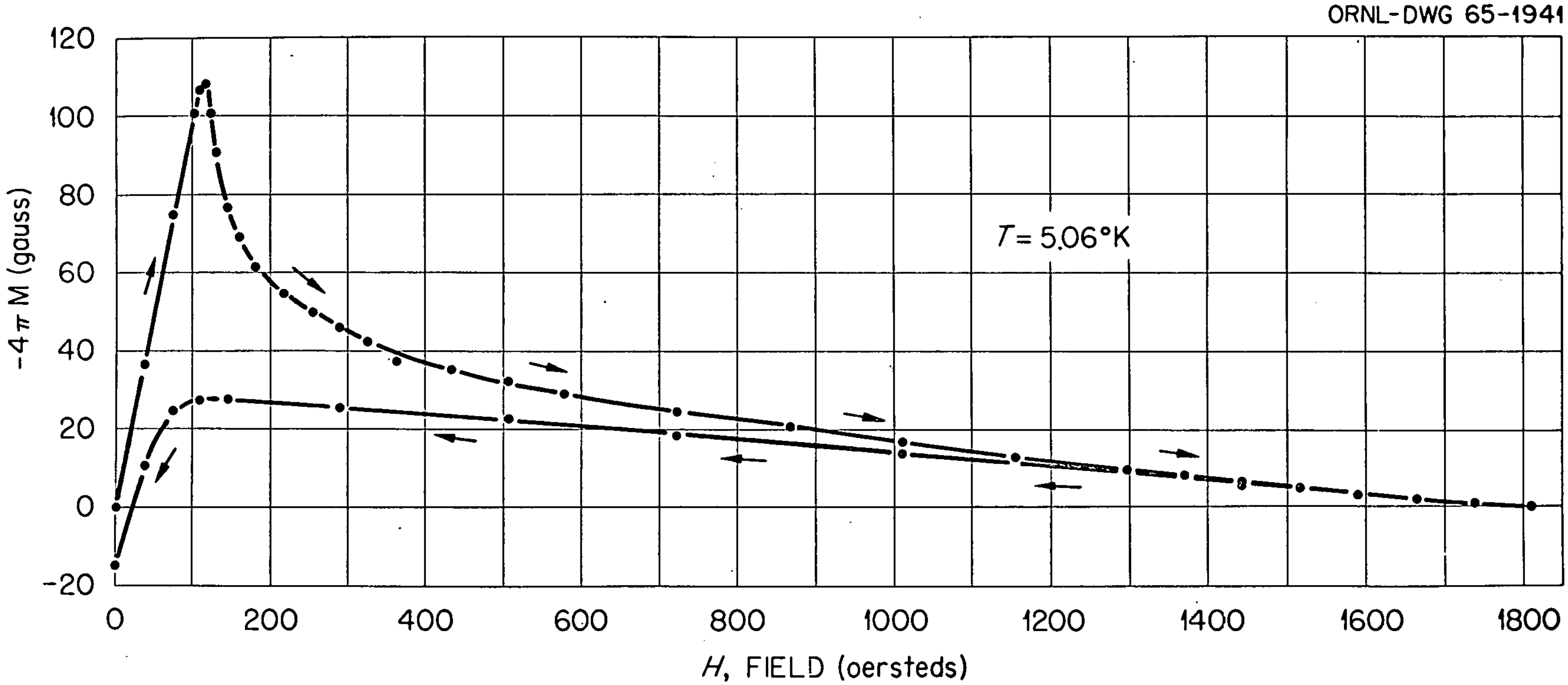
LIST OF FIGURES



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1400
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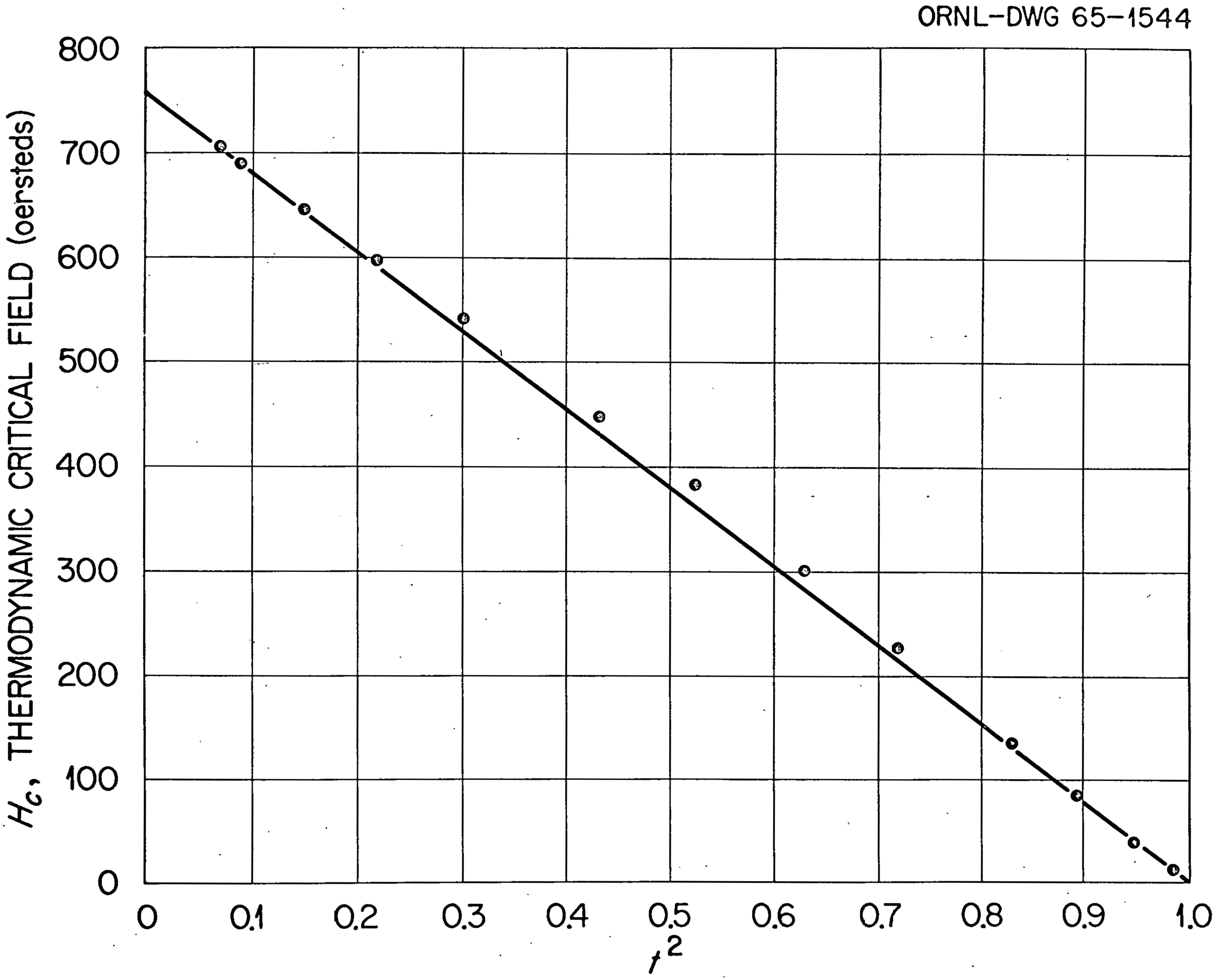
1800
H, FIELD (oersteds)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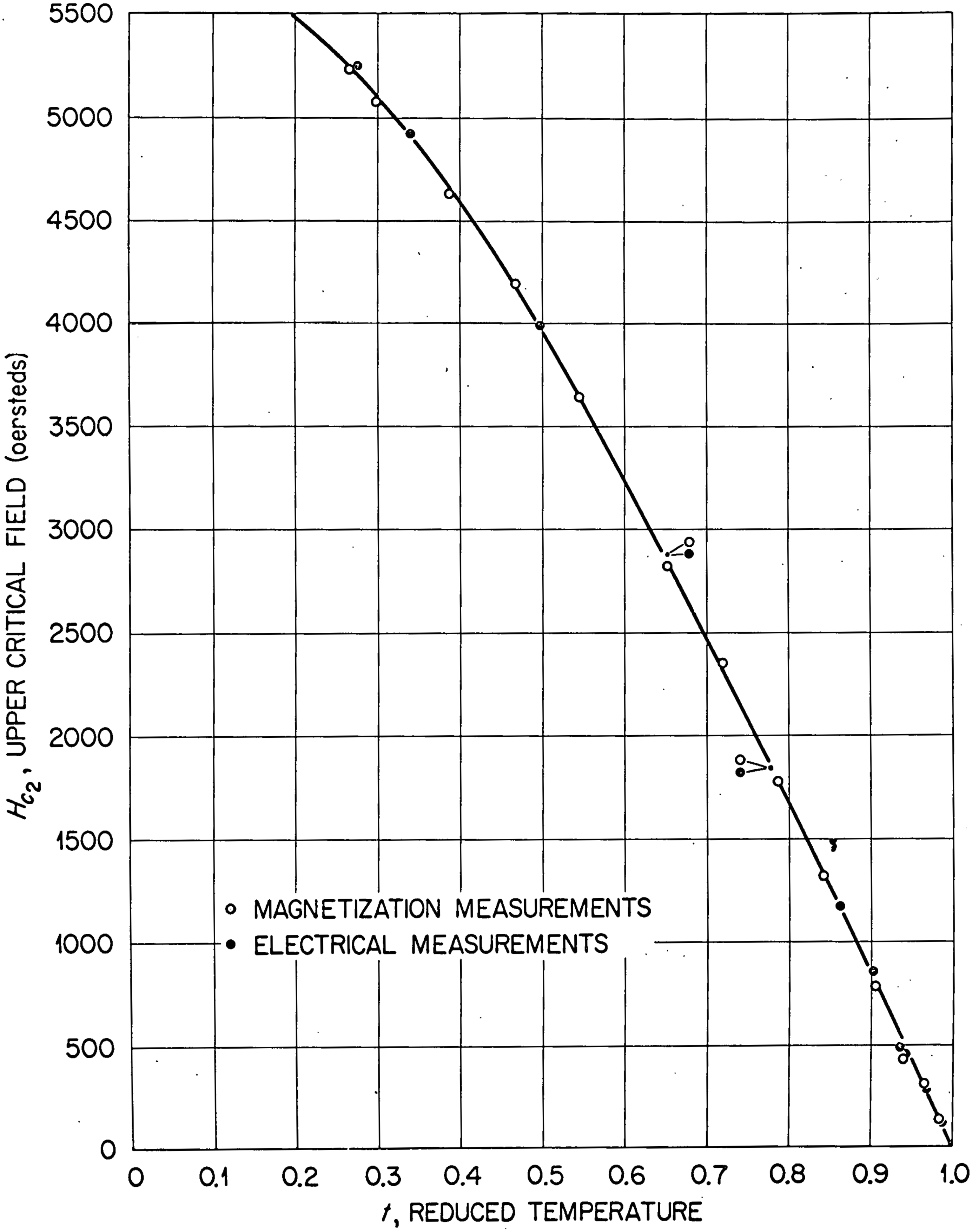
t^2
H_c, THERMODYNAMIC CRITICAL FIELD (oersteds)



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0.3
0.4
0.5
0.6
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0.8
0.9
1.0
t, REDUCED TEMPERATURE
○ MAGNETIZATION MEASUREMENTS
● ELECTRICAL MEASUREMENTS

ORNL-DWG 65-1546