BNL--45208

BNL--45208

DE91 000896

A THEORETICAL COMPARISON OF THE EFFECTS OF THE SHAPE
OF THE PINNING POTENTIAL AND A DISTRIBUTION OF
PINNING ENERGIES ON THE APPARENT PINNING ENERGY
AS MEASURED BY MAGNETIC FLUX CREEP

D. O. Welch
Brookhaven National Laboratory
Upton, NY 11973

Received by OSTI

OCT 18 1990

Abstract

In the analysis of magnetic flux creep experiments it is assumed that, at a given temperature, the pinning energy which must be overcome by thermal activation depends on the magnetic induction and its gradient by $U(B, \nabla B) \equiv U_p(B) [1 - \nabla B / \nabla B_{\max}]^n$, where U_p is the pinning well depth and $\nabla B_{\max}$ corresponds to the critical current density with no thermal activation. Customarily, n is assumed to be unity and any unusual temperature dependence of U_p is then ascribed to a distribution of well depths. However, realistic assumptions about the shape of the pinning potential yield $3/2 \leq n \leq 2$, which yields an apparent distribution of well depths in the conventional analysis. Simple models will be used to illustrate the characteristics of these two quite different origins for the apparent temperature dependence of well depth obtained from magnetic flux creep rates.

Introduction

The time-dependent decrease in the hysteresis of the magnetization of type-II superconductors (i.e., flux creep) has been widely used as an experimental probe of the strength of the pinning interaction between flux lines and pinning centers, especially in the high- T_c cuprate superconductors for which the flux creep rate can be quite large. Deductions about the pinning interaction are usually obtained using an analysis based on thermally-activated flux flow as described in the manner originally presented by Beasley et al.¹

$$D = -(\nabla B / \nabla B_0) B w v_0 \exp [-U(B, \nabla B) / kT] \quad (1)$$

where D is the magnetic flux-flow density, B is the magnetic induction (with a gradient ∇B proportional to the current density J), v_0 is the depinning attempt frequency of a pinned flux line, w is the distance of flux-bundle motion following depinning, and U is the effective pinning energy. [The time dependence of B is obtained from a solution of the continuity equation $\partial B / \partial t = -\nabla D$.]

In order to carry out the analysis it is necessary to know the explicit dependence of the pinning energy on the magnetic induction and its gradient. This has very often been assumed, following the work of Anderson and Kim,² to vary linearly with the driving force (in this case proportional to $B \nabla B$). This assumption leads to a very simple relationship between the depth of the pinning potential well and the flux creep rate which has been widely used. Applied to flux creep data for $YBa_2Cu_3O_x$ and other cuprates, the assumption of linearity leads to an apparent pinning well-depth U_0^* with an unusual temperature dependence, as shown in Fig. 1.

Based on conventional theories of type II superconductivity,⁴ the pinning potential energy is expected to be proportional to the square of the thermodynamic critical field, some power (from 1 to 3) of the coherence length, and perhaps a function of the elastic constants of the flux line lattice. Thus the pinning energy in a homogeneous superconductor with one type of pinning site is not expected to decrease to zero as the temperature is reduced, but rather to rise from zero at T_c to some constant value at low temperatures. Hence the temperature dependence shown in Fig. 1 is anomalous. Two possibilities (other than some exotic behavior of high- T_c cuprates) are: (1) the assumption of a linear relation between driving force and activation energy is incorrect; or (2) there is a distribution

Manuscript received September 24, 1990.

Figure 1. The temperature dependence of the apparent pinning energy U_0^* , obtained assuming a linear relation between activation energy and driving force, for melt-textured $YBa_2Cu_3O_7$. Data of Suenaga et al.³

of pinning energies, some of which have very low values, and only those pinning sites with well-depths which permit a thermally-activated escape from the well within a characteristic time "window" (which depends on the experimental technique used) are sampled at a given temperature. The first possibility, non-linearity caused by the shape of the pinning well was originally pointed out by Beasley et al.¹ and has recently been discussed in the context of high- T_c superconductors^{3,5-8} so we might call it the "BLW effect," while the second possibility has been championed by R. Griessen and co-workers⁹⁻¹¹ and an inversion scheme (based on the assumption of no BLW effect) to obtain the distribution has been proposed.⁹ [The work of Griessen et al. has utilized the assumption that the contributions of different types of pinning center in the distribution are independent, but A. Gurevich et al.¹² have recently presented a percolation model in which the effects of pinning centers of different strength are coupled, which also can yield results similar to Fig. 1.]

It is clear that one can always find a suitable distribution of pinning energies to describe results such as those shown in Fig. 1, but is it possible that the BLW effect itself can account for such results? It seems desirable to include the BLW effect in an inversion scheme such as that of Hagen and Griessen⁹ to get the distribution of pinning energies, but is it possible to do so in a general and simple manner? These matters will be considered below.

The Beasley-Labusch-Webb (BLW) Nonlinearity Effect

Consider a pinned flux bundle of volume V ; the energy $E(x)$ depends on both the interaction with the pinning site $u(x)$ and the Lorentz force due to the current density J (proportional to the gradient ∇B):

$$E(x) = u(x) - JB \nabla x \quad (2)$$

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

where x is the location of flux bundle relative to its location in the absence of the force. The activation energy U required for thermally-activated depinning can be obtained from the maximum and minimum values of $E(x)$ as shown in Fig. 2. The dependence of U on $J/J_c(0)$, for several different functional forms of the pinning interaction $u(x)$, is shown in Fig. 3. Also shown is the dependence on J of the apparent well depth U_{apparent} which one would obtain by assuming that, in a small range of J , the U -versus- J relation was linear. Note that U_{apparent} rises infinitely steeply at $J_c(0)$ and is concave downward over the whole range of J for all of the potential forms shown. Note also that for all of these forms, a reasonably good approximation to $U(J)$ is given by:

$$U(J) \equiv U_p [1 - J/J_c(0)]^n \quad \text{for } \frac{3}{2} \leq n \leq 2 \quad (3)$$

[This is possibly because it can be shown that for any continuous, differentiable form $u(x)$, the lowest order Taylor expansion around $J = J_c(0)$ yields $U \sim [1 - J/J_c(0)]^{3/2}$, provided d^3u/dx^3 at the inflection point of $u(x)$ remains finite.]

The results shown in Figs. 2 and 3 suggest that for a wide range of reasonably short-ranged pinning interactions U_{apparent} , which one would obtain from an analysis based on the assumption of linearity of the U -versus- J relation, rises steeply from a value of zero at $J = J_c(0)$ and is concave downward as J decreases. [In a magnetic flux creep experiment, the value of J around which the analysis is centered decreases as the temperature increases, from $J_c(0)$ at zero temperature.] The data for $\text{YBa}_2\text{Cu}_3\text{O}_x$ shown in Fig. 1 also rise from approximately zero at zero temperature, but the shape is concave upward rather than downward which intuitively suggests that perhaps the temperature dependence of these data reflect a distribution of activation energies rather than the BLW nonlinearity effect. Indeed, preliminary data for flux creep in Nb_3Sn of Suenaga et al.⁶ show a temperature dependence more like that of U_{apparent} in Fig. 2 than that of $\text{YBa}_2\text{Cu}_3\text{O}_x$. The discussion here (as well as that of BLW¹) has been rather intuitive,

Figure 2. Evaluation of the activation energy U for thermally-activated depinning from the position-dependence of the energy given by Eq 2. Arrows denote the location of the maximum and minimum. Curves are shown for several values of current $J/J_c(0)$, where $J_c(0)$ is the value at which U goes to zero. In this example $u(x) = (x/x_0)^{20}/[1 + (x/x_0)^{20}]$.

Figure 3. Depinning activation energy U (scaled by the value at $J = 0$) versus current density for several functional forms of the pinning interaction $u(x)$. The solid curve is for the form used in Fig. 2; the dashed curve corresponds to an inverted Gaussian; the single-dot/dash curve and double-dot/dash curves correspond to double-well potentials of the form $u(x) = -c_2 n x^{2n} + c_2 m x^{2m}$, with (n, m) equal to $(3, 6)$ and $(1, 2)$ respectively. Also shown for each of these forms is the value of the intercept U_{apparent} obtained by extrapolating the tangent to the curves, at a given value of J , to $J = 0$. The points, circle and triangle, correspond to $[1 - J/J_c(0)]^n$ with $n = 3/2$ and 2 , respectively.

since the dependence of the effective operating value of J on temperature is somewhat vague. However, we can use a simple model, to be described later, to investigate this more precisely.

The Logarithmic Dependence of Zeldov et al.

The discussion above made use of pinning interactions $u(x)$ which were reasonably short range, in the sense that the range of the potential was a few times the displacement at its inflection point, i.e. the point beyond which the restoring force due to the pinning interaction decreases below its maximum value [corresponding to the depinning of the flux bundle under the effect of the Lorentz force at $J_c(0)$]. Recently Zeldov et al.⁷ proposed that the thermal depinning activation energy varies logarithmically with current density:

$$U \equiv U_J \ln[J/J_c(0)] \quad (4)$$

These authors claim that such a form arises from a potential $u(x)$ which rises linearly with displacement, as (ax/x_0) , out to a displacement x_0 , beyond which there is a long-range tail, varying as $a[\ln(x/x_0) + 1]$. Although the empirical form of Eq 4 works quite well for $\text{YBa}_2\text{Cu}_3\text{O}_x$,^{7,8} there are some problems. First of all, the activation energy diverges as J approaches zero and the interpretation of U_J is somewhat mysterious. Second, the linear energy-vs-displacement relation is somewhat unphysical in that it corresponds to an infinite restoring force unless the Lorentz force exceeds the critical value at $J_c(0)$. [This linear form $u(x) \equiv -U_p + ax$ for $x \leq x_0$ corresponds to a "bond" with an infinite restoring force-constant but a finite breaking strength when the driving force equals $-a$.] The behavior of the relation of Zeldov et al., Eq 4, is contrasted with that of the shorter-ranged, but more physically realistic, pinning interactions in Fig. 4. As well as the unphysical divergence of Eq 4 as J goes to zero, notice the quite different behavior of U_{apparent} as J approaches $J_c(0)$. This latter is a consequence of the physically unrealistic "on-off" behavior of the linear core of the potential of Zeldov et al.

Figure 4. Comparison of the current-density dependence of the thermal-depinning activation energy U and the resulting U_{apparent} given by the relation of Zeldov et al.⁷ (dashed lines) and those given by the potentials of Fig. 3 which lie between the solid lines corresponding to $U = [1 - J/J_c(0)]^n$ with $n = 3/2$ (upper) and 2 (lower). The pinning energy for these potentials is normalized to unity at $J = 0$, while two values of U_J in Eq 4 are chosen to match the two points as shown.

In view of the apparent usefulness of Eq 4 as an empirical form^{7,8} for U vs J (although Griessen¹¹ points out that a distribution of activation energies works just as well), it is perhaps worthwhile to eliminate some of the unphysical aspects of the potential of Zeldov et al. while retaining the long-range tail in order to examine its effects. This can be done by eliminating the linear core of the potential and replacing it with a quadratic plus cubic form $u(x) = -U_p + c[(x/x_0)^2 - (4/9)(x/x_0)^3]$ which joins smoothly at x_0 onto a logarithmic tail $u(x) = (2c/3)\ln(x/x_c)$. Beyond the cut-off distance x_c the potential is zero. [The constant c is given by $9U_p/[5 + 6\ln(x_c/x_0)]$.] This new core has a finite restoring force-constant and a well-behaved critical force, which occurs at a displacement of $3x_0/4$, thus eliminating the previous unphysical behavior at the critical current density. The cut-off at x_c eliminates the divergence of U at zero current density. There now are two parameters, U_p and x_c/x_0 , to be determined empirically. It is easily shown that the following activation-energy-vs-current-density relation is obtained from the "modified Zeldov" pinning interaction:

$$U = \frac{U_p}{(6\ln\xi_c + 5)} \left\{ \frac{6\ln\xi_c + 5 - (27/4)F(\xi_c - \xi_a)}{(3/2)\xi_a^2 - (2/3)\xi_a^3} \right\} \quad (5a)$$

$$\text{for } 0 \leq F \leq 8/(9\xi_c)$$

$$= \frac{U_p}{(6\ln\xi_c + 5)} \left\{ \frac{6\ln(8/9F) - 1 + (27/4)F\xi_a}{9\xi_a^2[1 - (4\xi_a/9)]} \right\} \quad (5b)$$

$$\text{for } 8/(9\xi_c) < F \leq 8/9$$

$$= \frac{U_p}{(6\ln\xi_c + 5)} \left\{ (27/4)(1 - F)^{1/2} \right\} \quad (5c)$$

$$\text{for } 8/9 < F \leq 1$$

where $F = J/J_c(0)$, $\xi_c = x_c/x_0$, $\xi_a = (3/4)[1 - (1 - F)^{1/2}]$, and U_p is the depth of the pinning well (at $J = 0$). This is illustrated in Fig. 5, where it may be seen that the behavior of U_{apparent} near $J_c(0)$ now resembles that of Fig. 3 and the divergence of U near $J = 0$ has been eliminated. Note that for a range of parameters where the first term of Eq 5b dominates, one obtains the original relation of Zeldov et al., Eq 4. This permits us to identify the parameter U_J of that relation as $6U_p/(6\ln\xi_c + 5)$ and to note that the $J_c(0)$ which is obtained from Eq 4 is $8/9$ of the true $J_c(0)$ appropriate to the pinning potential. This allows us to analyze the data of Zeldov et al. for epitaxial $\text{YBa}_2\text{Cu}_3\text{O}_x$ films to obtain $J_c(0) = 4.4 \times 10^6 \text{ Acm}^{-2}$, $U_p > 0.95 \text{ eV}$, and $\xi_c \geq 990$. It may be seen in Fig. 5 that for very long-range tails (e.g. $\xi_c = x_c/x_0 = 100$), even though U_{apparent} rises rapidly and is concave downward near $J_c(0)$ (equivalent to temperatures near $T=0$) as is the case for the short-range pinning potentials of Fig. 2, there is a substantial range of J for which, unlike the behavior of the short-range potentials, the U_{apparent} -vs- J relation is concave upward, similar to the data shown in Fig. 1. Thus it is not clear whether the shape of those data arises from pinning potentials with long-range tails or from a distribution of activation energies.

Figure 5. Depinning activation energy U and apparent well depth U_{apparent} versus current density for the "modified Zeldov" pinning potential.

A Simple Model for Flux Creep Kinetics

The discussion of the effect of nonlinearity in the relation between the activation energy for depinning and the current density, especially the temperature dependence of the apparent pinning energy, has been somewhat vague because we have not yet developed an explicit description of flux-creep kinetics. A simple illustrative model which demonstrates the effects of nonlinear potentials in a concrete way may be derived using a simple analytical model of Hagen et al.¹³ for the flux distribution in a slab of type II superconductor evolving from the critical state under the influence of thermally activated depinning. The model considers explicitly only the flux density in two regions: at the surface, where it is fixed by the applied field, and near the center of the slab, where it is initially determined by the critical state and then evolves by thermally-activated flux flow from the surface region. The model, though quite simple, reproduces the results of Monte Carlo simulations (assuming linearity) which treat the flux density in many pinning regions. We shall assume here that the applied field is so large

that it has fully penetrated the sample. Furthermore, we assume that the pinning potentials are of the short-range type discussed in connection with Fig. 3, so that the activation energy for depinning can be approximated adequately by $U_p[1 - J/J_c(0)]^n$ with $3/2 \leq n \leq 2$. It then follows from the model of Hagen et al.,¹³ that when the flux gradient is still large enough or the temperature low enough that only thermally activated jumps from the surface to the interior need be considered:

$$\int_0^{\epsilon^{(1/n)}} |\Delta M|/M_0 e^{x^n} dx = \frac{t}{\epsilon^{(1-1/n)} \tau_0} \quad (6)$$

where $\epsilon = U_p/kT$, M_0 is the initial value of the magnetization before thermally-activated depinning begins, $\Delta M = M_0 - M(t)$ is the decrease in magnetization caused by flux creep, and τ_0 is a characteristic time scale. Thus finding $M(t)$ is simply a matter of integrating (numerically for $n > 1$) the left-hand side of the equation.

For $n = 1$ (i.e. linearity), Eq 6 yields the familiar case of ΔM proportional to ϵt , after a transient period of length τ_0 , as discussed by Hagen et al.¹³ This is shown in Fig. 6, together with results for $n = 3/2$ and 2. Note in the latter two cases (nonlinearity) that the $\Delta M \propto \epsilon t$ behavior is never obtained exactly, but is approximately correct over a restricted period of time. This may be seen more clearly by considering the creep rate $dM(t)/d\ln t$, which is constant when $\Delta M \propto \epsilon t$, shown in Fig. 7. Since M_0 is difficult to obtain experimentally, $(dM(t)/d\ln t)/M(t)$, which is more easily obtained experimentally, is also shown. Note that a maximum in the magnitude of the normalized creep rate $|dM(t)/d\ln t|/M(t)$ occurs, followed by long plateau, in the case of nonlinearity ($n=3/2$) but not in the linear case ($n=1$). This type of behavior has been observed experimentally⁶ for melt-textured $YBa_2Cu_3O_x$, as shown in Fig. 8, which suggests that BLW nonlinearity is manifesting itself in this material.

The model above can be used to show how BLW nonlinearity ($n > 1$) causes U_{apparent} , the apparent pinning-well depth obtained if the flux-creep data are analyzed assuming linearity ($n=1$), to vary with temperature even if the temperature is low enough that the true well-depth U_p is sensibly independent of temperature. We find from the model that the true well-depth is related to the maximum isothermal creep rate $|dM/d\ln t|_{\text{max}}$ at a given temperature by:

$$U_p = \frac{kT}{[c_n |dM/d\ln t|_{\text{max}} / M_0]^n} \quad (7)$$

where c_n is a constant near unity which depends on n (e.g., $c_1=1$, $c_{3/2} \approx 1.65$, etc.). Consequently:

$$U_{\text{apparent}} = c_n U_p^{1/n} (kT)^{(n-1)/n} \quad (8)$$

Thus U_{apparent} goes to zero, even for U_p constant, as T goes to zero, since $n > 1$ in the non-linear case. Furthermore, U_{apparent} rises rapidly (infinitely so at $T=0$) as T increases from zero and is concave-downward. Thus, the qualitative conclusions based on the behavior of U_{apparent} -versus- J curves in the previous sections are borne out by this analysis of the explicit temperature dependence.

Figure 6. Time-dependent magnetization for varying degrees of non-linearity calculated with Eq 6.

Figure 7. Calculated values of $dM(t)/d\ln t$ at two temperatures for $n = 1$ and $n = 3/2$. (The pinning energy $U_p \equiv E = 0.2$ eV.) Two different normalizations are used: $M(t)$ (solid lines and dashed lines) and $M(t) = 0$ (dotted lines and dot-dash lines.)

Figure 8. Experimental data for the slope of M vs tnt , normalized by $M(t)$, for melt-textured, bulk $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$. Data of M. Suenaga.⁶

The Simple Model Including a Distribution of Activation Energies

The simple model of flux creep kinetics described above also lends itself readily to an investigation of the effect of a distribution of activation energies on flux creep kinetics, and it is not necessary to make the assumption of a linear U -vs.- J relation. A full investigation of the interplay between the effects of BLW non-linearity and a distribution of activation energies will not be given here, but a framework, based on the simple, analytical two-region model of Hagen et al.,¹³ for such an investigation will be sketched out.

The basic kinetic equation of the model describes the rate at which flux enters the central region by thermally-activated depinning. On the assumption that the contribution of pinning wells of different strength contribute independently, this becomes:

$$\frac{dB_1}{dt} = f_0 B_s \int_0^\infty \int_0^\infty P(U_p, J_c(O)) e^{-U_p F(J/J_c(O))/kT} dU_p dJ_c(O) \quad (9)$$

where B_1 and B_s are the magnetic induction in central region and surface region (where it is fixed by the applied field) respectively, f_0 is an attempt frequency, U_p is the pinning-well depth (at zero current), and F is a function describing how the activation energy depends on $J/J_c(O)$. For example, F might be $\ln(J/J_c(O))$ or $(1-J/J_c(O))^n$ as discussed above. The probability distribution function P describes the probability that a given pinning well has a given depth U_p and maximum pinning force, i.e. $J_c(O)$. After particular functions are chosen for F and P , and the right-hand-side of Eq 9 integrated over the distribution function, the resulting equation for dB_1/dt may simply be integrated over time to obtain $B_1(t)$ and hence the sample magnetization $M(t)$.

Consider a simple example in which only the well depth, but not the maximum pinning force, varies over the ensemble of pinning sites. Thus, the integral on the rhs of Eq 9 is only taken over U_p and not $J_c(O)$. As an example, suppose that $P(U_p)$ consists simply of two delta functions:

$$P(U_p) = f\delta(U_{p1}) + (1-f)\delta(U_{p2}) \quad (10)$$

where f is the fraction of the pinning sites with well-depth U_{p1} . If we choose the current-dependence of U to be of the form $U = U_p[1 - J/J_c(O)]^n$, then Eqs 9 and 10 yield (after relating J and M to the magnetic inductions of the two regions $B_1(t)$ and B_s):

$$\int_0^\infty e^{(1/n) \Delta M/M_0} \frac{dx}{[f e^{-rx^n} + (1-f)e^{-x^n}]} = \frac{t}{\tau_0 \epsilon^{(1-1/n)}} \quad (11)$$

where $\epsilon \equiv U_{p2}/kT$ and $r \equiv U_{p1}/U_{p2}$. When f goes to zero, one recovers Eq 6. This simple example illustrates how one might explore the inter-relation between the effects on non-linearity and a distribution of pinning site properties using the two-region model of Hagen et al.¹³

Conclusions

We have seen that the shape of the flux pinning potential, naturally gives rise to a non-linearity in the dependence of the activation energy for thermal depinning U on the current density J . (This effect was first noted by Beasley, Labusch, and Webb.¹) It was seen that the apparent activation energy U_0 , which one obtains if flux-creep data are analyzed assuming the U -vs.- J relation to be linear as did Anderson and Kim,² goes to zero as the temperature of the experiment decreases to zero, even when the true pinning-well depth U_p is independent of temperature. It was found that for constant U_p the apparent activation energy U_0 rises steeply as T increases from zero, and the U_0 -vs.- T curve near $T=0$ is concave downward for all well-behaved pinning potentials. However, while it was found that for short-range pinning potentials, U_0 -vs.- T is always concave downward, a pinning potential with a very long range logarithmic tail can produce an upward concavity in U_0 -vs.- T for some range of T not too near zero. A suitable distribution of pinning potential-well depths can cause a temperature dependence of U_0 which goes to zero at $T=0$ and any sort of slope and curvature of the U_0 -vs.- T curve can be obtained with a suitably chosen distribution function. The experimental data for U_0 -vs.- T for bulk $\text{YBa}_2\text{Cu}_3\text{O}_x$ show U_0 going to zero at $T=0$ with apparently upward curvature (but with some scatter) all the way to $T=0$. This suggests the dominant effect of a distribution of pinning-well depths for this material. Further experimental studies of flux-creep in presumably more well-behaved superconductors such as Nb_3Sn and Nb-Ti may be helpful in distinguishing between the effects of non-linearity and distributions of pinning strength. The theoretical analysis was facilitated by the use of a simple model of flux creep kinetics, and more analysis using this model should help to clarify the inter-relation between effects due to non-linear U -vs.- J relations and those due to a distribution of pinning-site properties.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences under Contract No. DE-AC02-76CH00016. I would like to thank M. Suenaga for many useful discussions and for the use of his data.

References

1. M. R. Beasley, R. Labusch, and W. W. Webb, *Phys. Rev.*, 181, 682, 1969.
2. P. W. Anderson and Y. B. Kim, *Rev. Mod. Phys.*, 36, 39, 1964.
3. M. Suenaga, D. O. Welch, Y. Xu, Y. Zhu, A. K. Ghosh, and A. R. Moodenbaugh, in *Superconductivity and Applications*, H. S. Kwok and D. T. Shaw, Eds., Plenum Press, New York, 1990.
4. M. Tinkham, *Introduction to Superconductivity*, McGraw-Hill, New York, 1975.
5. Y. Xu, M. Suenaga, A. R. Moodenbaugh, and D. O. Welch, *Phys. Rev. B*, 40, 10822, 1989.
6. D. O. Welch, M. Suenaga, Y. Xu, and A. R. Ghosh, in *Advances in Superconductivity II*, T. Ishiguro and K. Kajimura, Eds., Springer-Verlag, Tokyo, 1990.
7. E. Zeldov, N. N. Amer, G. Koren, A. Gupta, M. W. McElfresh, and R. J. Gambino, *Phys. Rev. Lett.*, 62, 3093, 1989; *Appl. Phys. Lett.*, 56, 680, 1990.
8. M. P. Maley, J. O. Willis, H. Lessure, and M. E. McHenry, *Phys. Rev. B*, 42, 2639, 1990.
9. C. W. Hagen and R. Griessen, *Phys. Rev. Lett.*, 62, 2857, 1989.
10. C. W. Hagen and R. Griessen, in *Studies of High Temperature Superconductors*, Vol. 3, A. V. Narlikar, Ed., Nova Science, Commack, NY, 1989.
11. R. Griessen, *Phys. Rev. Lett.*, 64, 1674, 1990.
12. A. Gurevich, H. Küpfer, and C. Keller, unpublished.
13. C. W. Hagen, R. Griessen, and E. Salomons, *Physica C*, 157, 199, 1989.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

END

DATE FILMED

11 / 02 / 90