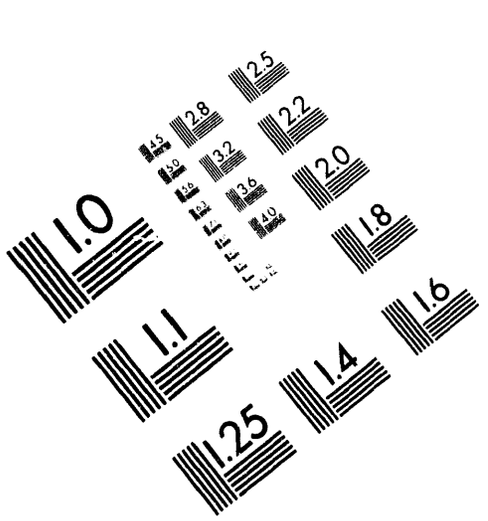

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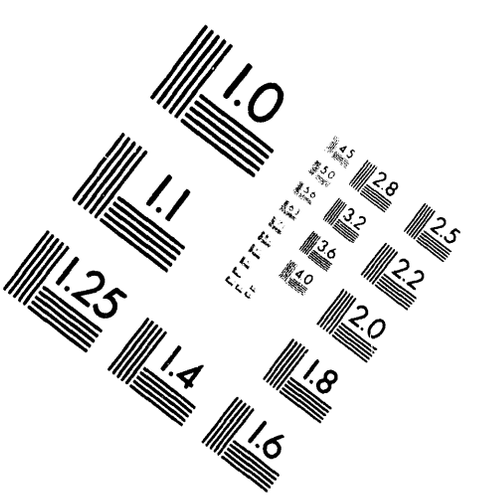

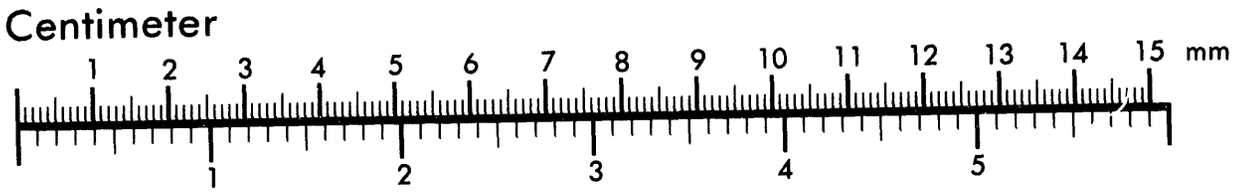

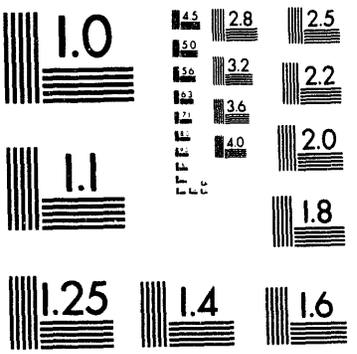

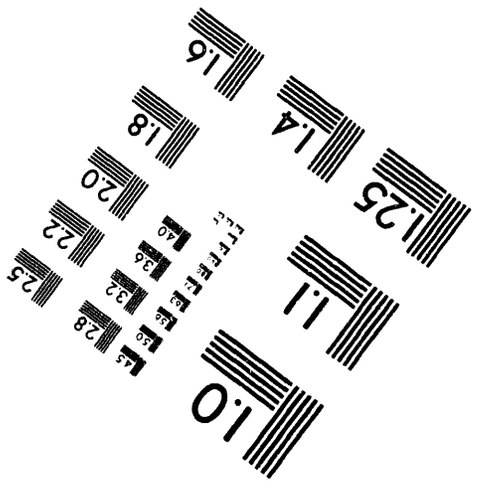

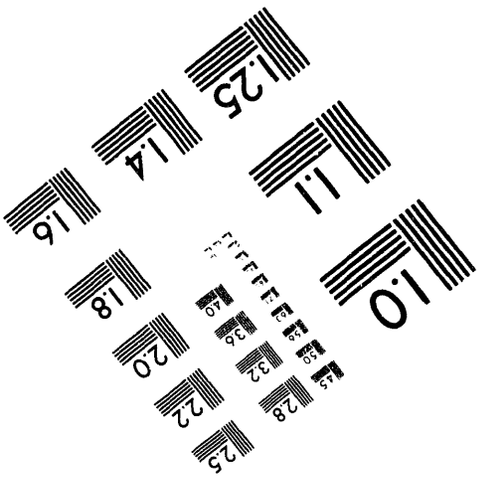

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Power-law resistivity, magnetic relaxation and ac susceptibility*

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Power-law resistivity, magnetic relaxation and ac susceptibility

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The nonlinear diffusion of magnetic flux into a superconducting sample can be studied by measuring the relaxation of the magnetisation after application of a step field or by measuring the ac susceptibility, χ_1 and its third harmonic, χ_3, or preferably both methods covering different time scales. Each has been analysed recently for a field-cooled sample of a material whose creep activation energy depends logarithmically on current density, J corresponding to a power-law relation between electric field, E and J. Here, results are compared, using a universal scaling depth. Maximum χ_1'' and $|\chi_3|$ values occur, and also the magnetisation has relaxed to half its initial value when the scaling depth is comparable to the sample half-thickness.

Non-linear diffusion is a topic of wide general interest in physics (hydrodynamics, interface growth, chemical reactions, fractals, self-organised criticality). Magnetic flux diffuses non-linearly in a superconductor exhibiting flux creep and a high T_c material might provide a good practical example. To avoid unnecessary complications a monocrystalline platelet would be needed, with the applied field in its plane. The width, transverse to the field would need to be so much greater than the thickness as to overcome the intrinsic anisotropy of the material and allow the flux to penetrate from the broad faces rather than the edges. Bearing in mind these limitations, it is particularly profitable to analyse the case of a power-law E(J), as Vinokur et al did [1], assuming for simplicity a field-cooled sample with prior existing flux density B_o ($>> \mu_o H_{c1}$) and an increment δB ($<< B_o$) caused by switching on an additional field. Numerical work [2] has shown that the results are qualitatively similar if an exponential E(J) law is assumed. The analogous problem with an alternating perturbation of amplitude δB has only been solved numerically [3,4].

Flux creep consists of a series of hops (of bundles or individual lines) and a complete analysis would be a stochastic one. In the references cited [1-4], E(J) was combined with Maxwell's equations to obtain a deterministic differential equation, and effectively the material, and the flux-line lattice treated as a continuum. This limits the validity to space and time scales large compared with the elementary hopping distance or hopping time, ignores noise and disallows any elastic response.

Putting $E = |J/J_c|^{\sigma}\rho J$ introduces two independent constants, the index σ and the coefficient $J_c^{-\sigma}\rho$. ρ is equivalent to $Bu\,\omega_m/J_c$ of ref. 1, but only the product $J_c^{-\sigma}\rho$ is relevant to the flux diffusion problem. This E(J) law evidently interpolates between Ohm's ($\sigma = 0$) and Bean's ($\sigma \to \infty$).

There are basic similarities between the step field and the alternating field problems. For all $\sigma > 0$ the perturbation is totally extinguished at a finite depth, δ_{ex}, which depends on its amplitude and duration (or period). Two cases arise according to whether or not δ_{ex} exceeds the sample half-thickness, h. The extinction is

abrupt if $\sigma >> 1$ but more gradual for low σ values, so that δ_{ex} does not always describe the amount of flux penetration accurately. It is preferable to use a scaling depth, δ_s which, for an alternating field is a hybrid between Bean's penetration depth and the Ohmic skin depth :

$$\delta_s^{2+\sigma} = (\delta B/\mu_o J_c)^{\sigma} 2\rho/\mu_o\omega \qquad (1)$$

For the step field, ω^{-1} should be replaced by the time, t since switch-on. Following Vinokur's analysis, but the present definition of δ_s, the ratio δ_{ex}/δ_s is expressible using Γ-functions, and is given for representative σ values in Table 1. Also given is the ratio of sample half-thickness to scaling depth at the moment when the magnetisation has fallen to half the value, M(0) it would in principle have had immediately after δB was switched on. These values were obtained using a new numerical calculation and checked by an approximate analysis. In practice δB is more likely to be switched on with a finite ramp rate and M(0) deduced by extrapolation. The important point is that when $M(t)/M(0) = 1/2$, h/δ_s is always of order unity, which demonstrates that δ_s is a good measure of the flux penetration. σ could be obtained from the limiting slope $S_{t\to\infty} = -1/\sigma$, where $S = d(\ln|M|)/d(\ln t)$ [1]. $J_c^{-\sigma}\rho$ could then be deduced using table 1.

If an alternating δB is used, the same information is obtainable by noting when $\chi_1' = -1/2$ (where the fundamental susceptibility is $\chi_1' - i\chi_1''$), or when χ_1'' or $|\chi_3|$ is maximum. As Table 2 shows, all these conditions occur when h/δ_s is of order unity. If the third harmonic is used, a σ value cannot be extracted reliably from $|\chi_3|_{max}$ as this tends to be lower than the theoretical value on account of edge effects and nonuniformities. Preferably the amplitude δB for $|\chi_3|_{max}$ should be found at several frequencies and the scaling law (Eq.1) used.

Table 1
Ratio of total extinction depth to the time dependent scaling depth and ratio of sample half-thickness to scaling depth at the moment when the magnetisation has fallen to half its initial value. At this moment the whole sample has been penetrated, and $\delta_{ex} \geq h$.

σ	$\frac{\delta_{ex}}{\delta_s}$	$\frac{h}{\delta_s}$ for $\frac{M(t)}{M(0)} = \frac{1}{2}$
0	∞	1.59
1	2.08	1.54
2	1.77	1.49
4	1.53	1.39
6	1.42	1.33
10	1.30	1.25
∞	1.00	1.00

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Table 2
The analogue to table 1 for the case of an alternating applied field component. Except for $\sigma = 0$ and ∞ the data all come from ref. 4. Rationalised units are used in which χ_1 varies between -1 and 0. Each of the three landmarks occurs where $\delta_{ex} \geq h$ and the whole sample is penetrated.

σ	$\frac{\delta_{ex}}{\delta_s}$	$\frac{h}{\delta_s}$ for $\chi_1' = -\frac{1}{2}$	$\chi_1''_{max}$	$\frac{h}{\delta_s}$ for $\chi_1''_{max}$	$\lvert\chi_3\rvert_{max}$	$\frac{h}{\delta_s}$ for $\lvert\chi_3\rvert_{max}$
0	∞	1.25	0.417	1.13	0.00	-
1	3.49	1.22	0.375	1.06	0.0295	0.79
3	2.00	1.18	0.340	1.01	0.0470	0.74
7	1.50	1.12	0.305	0.95	0.0545	0.70
∞	1.00	1.00	0.239	0.75	0.0613	0.59

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