MAGNETIC AND THERMAL INSTABILITIES OBSERVED IN COMMERCIAL Nb_3Sn SUPERCONDUCTORS*

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INTRODUCTION

Instabilities of both magnetic and thermal type have been reported in the literature mostly in connection with fundamental studies of pure type II superconductors. In this paper we are presenting the results of experiments made using commercially available Nb_3Sn fabricated by the Radio Corporation of America and the General Electric Company. Samples of their products were made available to us[1] in the form of ribbon 0.5 in. wide; each sample was characterized by a given substrate material and different thicknesses depending on the type and quantity of the so-called "stabilizing" and mechanical reinforcing materials used in their fabrication. The following products were studied: General Electric 65A900000, 22CY030, and 65A900001; RCA 60304 and RCA 60299. Their compositions are available in the commercial literature; also a brief description appears in Table I.

This paper is divided into two parts. Part I is an isothermal study. This represents the most common operation of a superconductor, i.e., in a liquid helium bath. The second part is oriented towards the understanding of some fundamental questions related to flux jumps. It is a study of the behavior of these samples in semiadiabatic conditions. One cannot rule out, however, the possibility of operating a coil in such conditions.

I. ISOTHERMAL STUDY

All samples were cut one inch long and matched pairs of each material were attached to a perforated phenolic plate, thus making a one square inch split plate. Two such plates of the same material were used in each test as shown in Fig. 1A. The plates were located between the pole pieces of a magnet in such a manner that the external field was normal to the plates. The magnetic induction in the gap was measured by five magnetoresistance microprobes[2] located halfway along the plates and at the center of the gap. The separation between the plates was 0.1875 in.

Each run consisted of increasing the external magnetic field at a constant rate of about 6 G/sec, from zero up to 5.2 kG and back to zero. In some occasions runs were taken reversing the external field to further develop the instabilities. The magnetic induction between the plates was measured at five spots and recorded in a five-channel recorder. Tests were made on virgin (no magnetic history) and nonvirgin samples. Finally, the external field was increased by hand to 9 kG and suddenly decreased at an average rate of about 1 kG/sec. This part of the test was labeled as "power failure."

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1. Thanks are due to Dr. C.H. Rosner of the General Electric Company and Mr. J.H. Crowe of RCA for supplying the samples used in this work.

2. G. del Castillo and R.W. Fast, J. Appl. Phys. 36, 1973 (1965).

A typical example of the five-probe recording is shown in Fig. 2. The vertical scale represents the magnetic induction between plates, and the horizontal is the external magnetic field. The top traces (A) correspond to the case when the magnetic flux penetrates smoothly into the superconductor. The recording is consistent with what is expected from the magnetic properties of the superconductor. Magnetic probes 2 and 4 which are located at the center of the strips see little change in field as maximum shielding is provided by the samples, whereas probes 1, 3, and 5 follow the changes of the external field. This is especially clear for probe 3 which is located at the joint of the strips; its trace, as one can see in the picture, shows a fast increase in field, which may be interpreted as due to the superposition of macroscopic currents running in opposite directions at the four edges of the strips. These currents do not provide shielding against the external field; in fact, they may even add to it. The possible relation between smooth flux penetration and macroscopic currents was suggested by the authors.[3]

Traces (B) illustrate the case of flux jumps observed in a sample when the external field decreased. The mixing of the traces is clear and becomes evident in case (C) which represents the magnetic behavior after reversing the external field. One can see a large flux jump that reverses the magnetization of the sample, then the smooth penetration in all five probes. Probes 4 and 5, which did not register the initial flux jump, show a smooth cancellation of the local magnetization. Probe 3, however, follows the external field as before, in spite of the strong perturbation caused by the flux jump.

The magnetic field sensitivity of our probes varied, depending on the external field, but an average value of about 1 V/A-kG can be considered as representative of all of them. No particular effort was made to preorient the bismuth crystals to maximize the sensitivity.

The results obtained from these samples at three different temperatures are summarized in Table I. The figures that appear under the temperature columns represent the number of flux jumps observed within the external field interval mentioned above, either increasing (up) or decreasing (down) the field. These figures are the results of only a few runs; they do not represent statistical averages. They are, however, consistent with the results of our previous statistical study.[3]

The first sample GE 65A900000 showed no flux jumps except one at 2.5°K when the external field was changing rapidly. The field penetrated smoothly into this material.

In the second sample we see a very peculiar behavior at 4.2°K and 2.5°K, where the field penetrated smoothly but was expelled by flux jumps (see also Fig. 2). At 1.9°K no jumps were observed in the regular run. The origin of this behavior is puzzling, as in the past our experiments indicated that under the same conditions the mode of penetration remained the same for increasing or decreasing external fields. We had observed, however, a distinct difference in the frequency-extension distribution of flux jumps originated presumably by the sign reversal of $(dH/dt)_{ext}$.

One is tempted to speculate about the origin of these observations. If one assumes that vortex filaments of positive vorticity populate the superconductor when it enters into the mixed state, a change of the sign of dH/dt could create vortex motion of opposite vorticity.[4] A turbulent mixing of fluids may result with the possible annihilation of vortex motion which will, as a consequence, decrease the magnetic induction in the sample.

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3. G. del Castillo and R.W. Fast, unpublished.

4. G. del Castillo, Bull. Am. Phys. Soc. 11, 709 (1966).

Annihilation of flux quanta is a concept that was introduced before[5] but always related to the reversal of the sign of H_{ext}. Our results seem to fit better to the idea that the reversal of the sign of the time derivative is sufficient to cause the instability leading to flux annihilation.

The third sample was RCA vapor deposited Nb_3Sn which showed flux jumps at 4.2 and 2.5°K for field either increasing or decreasing, but no jumps were observed at 1.9°K.

Next, GE 65A900001 showed somewhat similar behavior as the previous sample, and finally RCA 60299 ahowed flux jumps in large numbers all the time.

We can see that, except for the last sample, the number of flux jumps after reversal of the sign of dH/dt is always greater than for field going up.

The power failure test was omitted in many cases where during the normal run flux jumps were observed. Experience demonstrated that a larger dH/dt will produce more jumps.

As the purpose of this study is to see if this method can be used for selecting a given material for a particular application, one may draw some tentative conclusions from the results shown in the table. Knowing that high critical currents are related to strong pinning[6] and that materials showing flux jumps are strong pinners,[3] one should select RCA 60299 as the best, as far as critical current is concerned. Next should come RCA 60304 followed by GE 65A900001, GE 22CY030, and GE 65A900000.

These findings are consistent with the current rating of the RCA materials, i.e., 1200 A and 600 A at 100 kG, respectively. There is also consistency between the critical currents of the RCA and GE superconductors; the latter group is rated at 300 A at 100 kG. However, the commercial literature does not establish any difference between the three GE materials, and according to our results GE 65A900001 should have a higher critical current than the other two.

On the other hand, let us look into the stability question. If flux jumps are responsible for producing premature normal transitions (quenches) in a coil, one should select as the more stable material GE 65A900000 following the others in vertical order to the most unstable — the RCA 60299.

There are indications[7] that coils wound with GE 22CY030 can be energized without any indications of instability, but premature quenches appear when the current is decreased; this supports the stability argument as mentioned above. For pulsed field application GE 65A900000 should be the best at 4.2°K. All the first four should be good at 1.9°K.

Whether this criterion is valid to select a given material remains to be seen; further comparison of our results with observations made by other investigators that have used such materials is needed.

There is still a fundamental question that has to do with the physical reasons for the different behavior of these samples. Outside the well-known differences that result from the GE and RCA production processes, the influence of the additional materials

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5. J. Silcox and R.W. Rollins, Rev. Mod. Phys. 36, 52 (1964).
6. R.W. Meyerhoff and B.H. Heise, J. Appl. Phys. 36, 137 (1965).
7. J. Purcell, private communication.

in modifying the magnetic behavior is not clear. An indication that the thermal conductivity of the composite (superconductor plus extra materials) is playing a role can be concluded from data obtained at 2.5°K; nevertheless, more work is needed in this direction.

II. SEMIADIABATIC STUDY

The same samples were used for studying their magnetic and thermal behavior in nearly adiabatic conditions. A calorimeter built for this purpose was first used to calibrate three carbon thermometers (1/8 W, 560 Ω at 300°K) against a germanium cryoresistor.[8] The temperature values were translated into galvanometer deflections of a multichannel recorder; in this manner the temperature measurements were made directly from the graph. The calibration curves for two temperature ranges are shown in Figs. 3 and 4. These curves remained the same during the time taken by the experiment (two months). Although the resistors went through many cooling cycles and handling, it was found that readings, reproducible within a few hundredths of a degree, could be obtained by adjusting the current through the carbon resistors to the same potential difference obtained at 4.2°K during their initial calibration. After calibration the three resistors were cemented using GE 7031 to the various samples of superconductor and assembled in the calorimeter as shown schematically in Fig. 1B.

For these tests two matched samples of superconductor were used. Each was 0.5 in. wide and 1.0 in. long. The same parallel plate arrangement normal to the external field was used. Besides the three carbon resistors that were attached to one of the plates, a manganin wire heater was used to select the operating temperature and to produce the superconducting to normal transition whenever a virgin sample run was desired. A single bismuth microprobe was used for measuring the field, and a small coil of fine wire was used as an induction probe. Except for some special cases that will be mentioned in what follows, the external field was increased (or decreased) at the same constant rate of 6 G/sec. All five signals (three temperature and two field) were fed into the five-channel recorder.

The samples were initially mounted in such a manner as to make a good thermal contact with their support; however, it was found that when the inner pressure in the calorimeter was only a few microns, the samples never reached the transition temperature except at the ends where the thermal contact was made. It was then decided to thermally insulate the samples from the support and to allow some helium gas to remain in the calorimeter for better heat exchange. Thus, all runs were made at 30 mm Hg helium pressure measured at room temperature.

In these samples we observed four types of magnetic and thermal activity. These are shown in Fig. 5. The ordinate represents either temperature for the upper trace or magnetic induction for the lower one. The abscissa is the external magnetic field, which as mentioned before is a function of time.

Type (C^2) behavior was perhaps the simplest and most commonly expected from theoretical grounds.[9] It consisted in a heat pulse that occurred at the same time of the flux jump. Experimentally, we found in Part I that thermal energy was released during the jump, as indicated by small increases of the inner pressure in the helium Dewar. But entropy considerations show that, under adiabatic conditions, the temperature of the material should decrease during the superconducting to normal transition. We have,

8. CryoCal Inc.. 1371 Avenue E, Riviera Beach, Florida.

9. P.W. Anderson and Y.B. Kim, Rev. Mod. Phys. 36, 39 (1964).

however, observed what might have been cooling pulses only in a very few cases — mostly at low temperature (below 4.2°K) where the sensitivity of the carbon thermometer was high. It is probable that any cooling that occurred in these materials was overshadowed by a heating pulse that presumably resulted from losses due to inductive currents originated during the flux rearrangement. Cooling has been reported to occur in pure samples of niobium in the mixed state.[10]

Type (C^1) activity looked like (C^2) with no magnetic jump. It may not necessarily represent a different type from the physics point of view, as it could always be attributed to a low sensitivity of the magnetic probe and the recording apparatus, which in our experiment was about 0.5 G at 2 kG. We will come back to discuss this point further.

Type (A) is unique. It was observed first in NbZr[11,12] and now in Nb_3Sn. It consisted in a thermal oscillation of low frequency (period $\approx$ 1 sec) and 40 to 100 millidegrees amplitude that always appeared before a temperature jump with magnetic signature (flux jump). A copy of the actual record is shown in Fig. 6. An effect not reported before in the literature was observed here, namely, the coherence of the thermal oscillations. Although the amplitude of the oscillation is very small, one can see in this figure that even small details are reproduced in all three traces. This represents temperature changes of the same phase that cover an area of at least 2 cm^2. The origin and coherent nature of the thermal oscillation is not yet understood. It could be interpreted as collective oscillation of the type already described in the literature.[13] The Type (A) activity terminated in a large temperature (6°-9°K) jump accompanied by a flux jump. This was followed by a quiet period where temperature dropped a few millidegrees, remaining the same until a new cycle was completed.

Type (B) consisted in heat spikes of increasing amplitude showing no magnetic signature until the last one that had a large amplitude and a longer decay time (1 sec).

Type (D) consisted of groupings of several incomplete Type (B); they were terminated by a heat and flux jump.

In all types, cessation of all thermal activity was observed after a flux jump, which was always registered by the magnetic probe. It is probable that the absence of magnetic signature observed in many heat jumps was not due to poor sensitivity of our probe, but it really indicated that no flux rearrangement took place as concluded from the still present thermal activity. Work is under way to further clarify this point.

The results of this study are summarized in Table II. They covered the temperature range from 10°K to 1.9°K. In each column the number of flux jumps appear together with the observed type of activity. For simplicity no distinction was made between the two types of C activity which only appeared in a few cases always above 5°K. Type A, on the other hand, was observed almost in all runs; we should point out that in many cases it consisted only of a thermal oscillation without flux or temperature jumps. This observation was made at temperatures above 4.2°K. At temperatures below 4.2°K a transition from thermal oscillation to thermal spikes was observed in some samples. This is listed in the table as AB and AD activity.

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10. S.M. Wasim, C.G. Grenier, and N.H. Zebouni, Phys. Letters 19, 165 (1965).

11. N.H. Zebouni, A. Venkataram, G.N. Rao, C.G. Grenier, and J.M. Reynolds, Phys. Rev. Letters 13, 606 (1964).

12. L.J. Neuringer and Y. Shapira, Phys. Rev. 148, 231 (1966).

13. P.G. deGennes and J. Matricon, Rev. Mod. Phys. 36, 45 (1964).

Sample GE 22CY030 again presented an interesting example of activity change from $5.5^{o}K$ down to $1.9^{o}K$. It started with Type A that gradually was transformed into Type D. The other samples did not go through such clear evolution.

Outside of presenting the results of this experiment, we are not in a position to offer a consistent physical picture to account for these observations.

Thanks are due to Mr. Howard Hart and Mr. Vincent Patrizi for their help in taking data and construction of parts of the equipment used in this work.

ISOTHERMAL

COMPOSITION OF MATERIAL	LEGEND P.F. = Power Failure		4.2° JUMPS UP	4.2° JUMPS DOWN	2.5° JUMPS UP	2.5° JUMPS DOWN	1.9° JUMPS UP	1.9° JUMPS DOWN
S. S. + CU + Nb_3Sn + CU + S. S.	G.E. 65A900000	SLOW	0	0	0	0	0	0
		P.F.	0	0	0	1	0	0
CU + Nb_3Sn + CU	G.E. 22CY030	SLOW	0	4	0	8	0	0
		P.F.					0	1
Ag + Nb_3Sn + Ag	R.C.A. 60304	SLOW	2	5	2	9	0	0
		P.F.						
CU + Nb_3Sn + S. S.	G.E. 65A900001	SLOW	7	16	0	1	0	0
		P.F.						
CU + Nb_3Sn + CU	R.C.A. 60299	SLOW	14	20	45	14	24	12
		P.F.						

ADIABATIC

LEGEND: P.F. = Power Failure T.A. = Thermal Activity		10° JUMPS UP	10° JUMPS DOWN	7° JUMPS UP	7° JUMPS DOWN	5.5° JUMPS UP	5.5° JUMPS DOWN	5.0° JUMPS UP	5.0° JUMPS DOWN	4.2° JUMPS UP	4.2° JUMPS DOWN	3.5° JUMPS UP	3.5° JUMPS DOWN	2.5° JUMPS UP	2.5° JUMPS DOWN	1.9° JUMPS UP	1.9° JUMPS DOWN
G.E. 65A900000	SLOW	0	0	0	0	0	0	-	-	0	2	0	2	1	1	1	1
	P.F.	0	0	3	2	-	3										
	T.A.		0		C	A	C		-	A	AB	A	B	AB	AB	AB	AB
G.E. 22CY030	SLOW	0	0	0	1	0	1	0	2	2	5	3	5	4	5	4	3
	P.F.	0	2														
	T.A.	0	0		0		A	A	A	A	A	A	AD	AD	AD	D	D
R.C.A. 60304	SLOW	0	0	0	0	0	0	0	0	3	6	4	10	8	9	8	7
	P.F.	-	0	-	8												
	T.A.		0		C		0		0	A	A	AB	AB	AB	AB	AB	AB
G.E. 65A900001	SLOW	0	0	1	1	-	-	0	1	2	2	3	2	3	2	3	3
	P.F.																
	T.A.		0	A	A		-		A	AB	AB	AD	AD	AD	AD	AD	AD
R.C.A. 60299	SLOW	0	0	0	0	3	2	-	-	4	2	4	2	3	2	2	1
	P.F.	0	0	-	4												
	T.A.		0		C		B		-	AD	AD	D	D	AD	AD	AD	AD

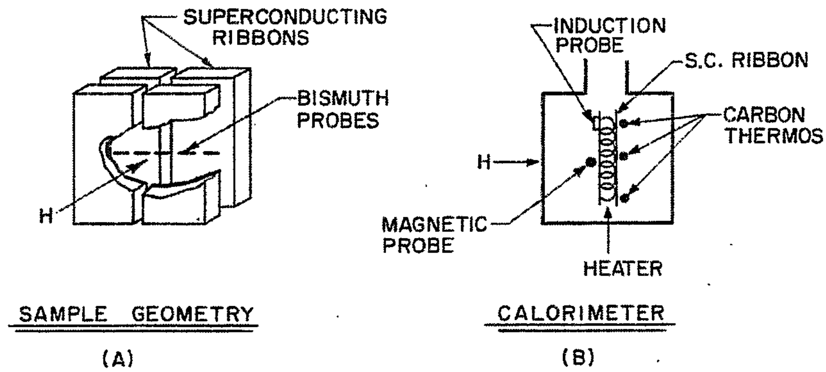

Fig. 1. (A): Split plate arrangement. For clarity the separation between strips and their thickness have been exaggerated. Five magnetoresistance microprobes measured the magnetic induction in the gap.
(B): Schematic view of the calorimeter and samples.

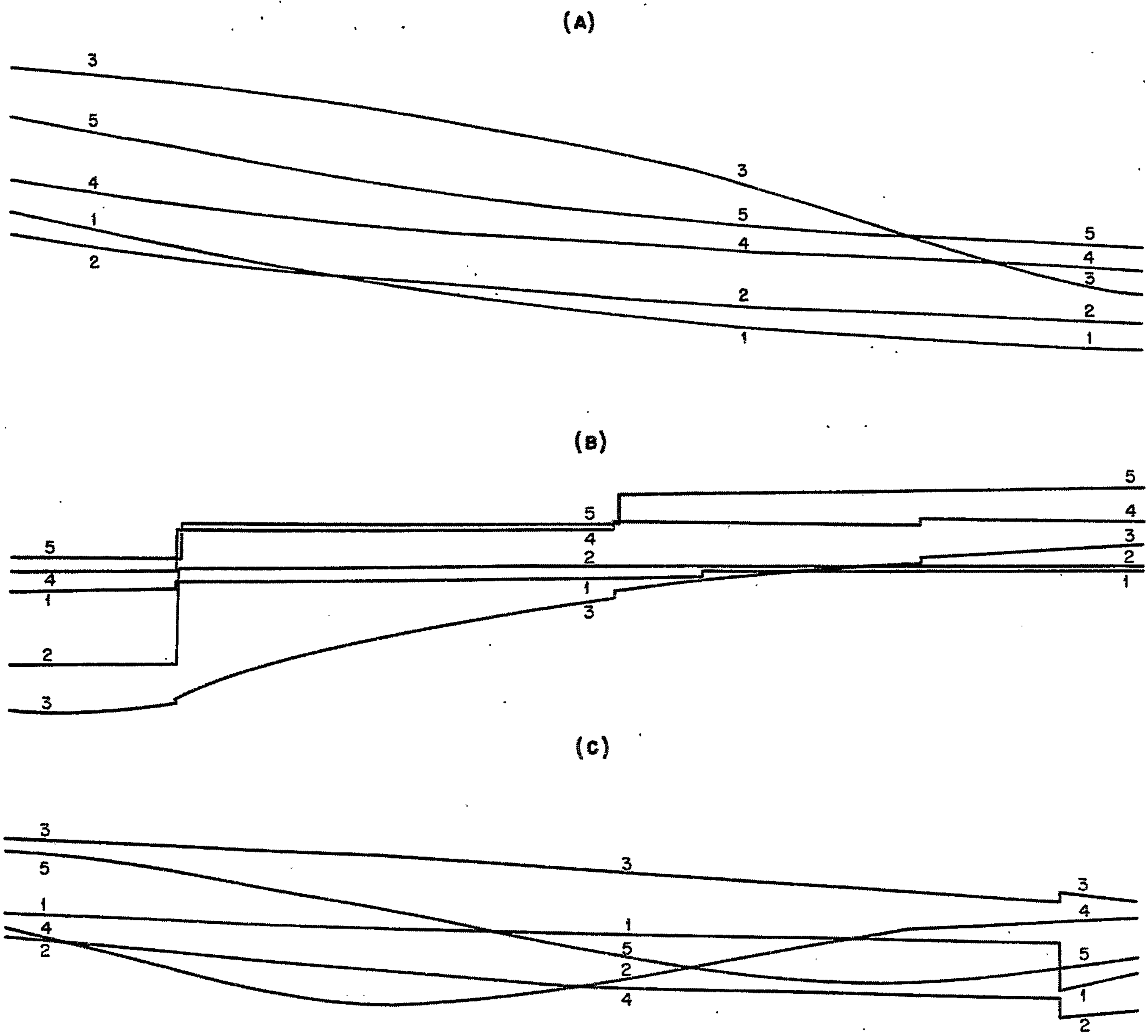

Fig. 2. Observations made on sample GE 22CY030.

(A): Smooth flux penetration for positive dH/dt. In all traces the vertical scale represents the magnetic induction between the plates. The external magnetic field H(t) was measured in the horizontal scale. In A and C it increased from right to left, whereas it decreased in traces B.

(B): Flux jumps observed for negative dH/dt. These traces were obtained after (A) above.

(C): Smooth penetration is observed again after reversal of the external field. Partial cancellation of the positive magnetization, remaining from the cycle (A)(B) above, occurred through the flux jump seen at the beginning of the record.

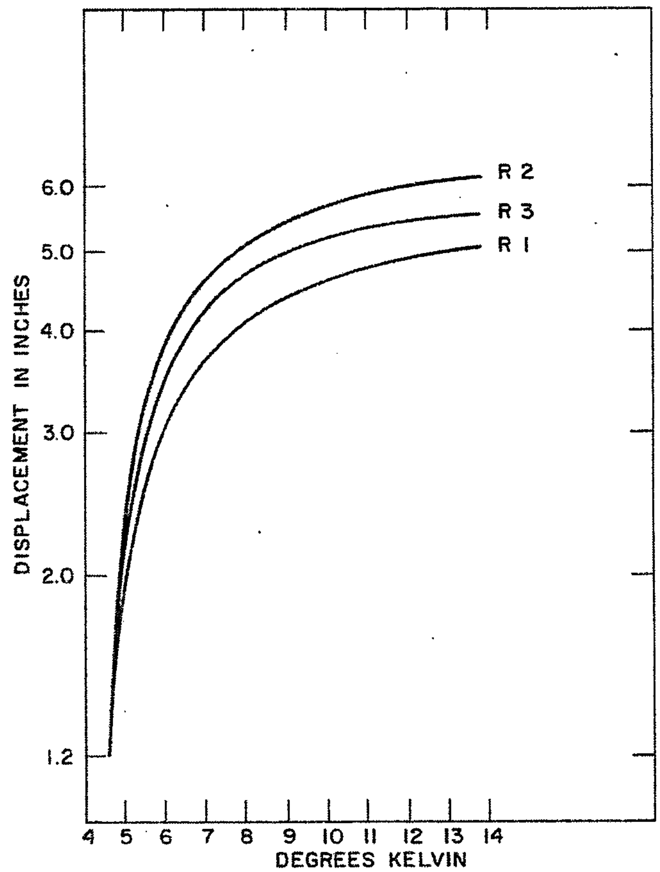

Fig. 3. Typical calibration curves for the temperature range between 4.2^oK to 14^oK.

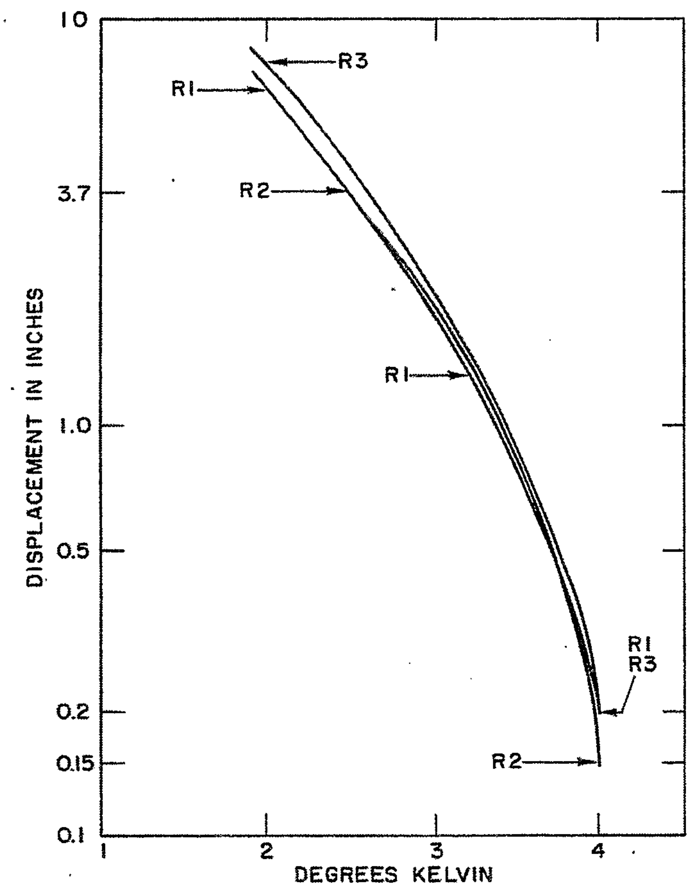

Fig. 4. Calibration curves below $4.2^{o}K$. The apparent discrepancy in the slope resulted from the definition of the zero displacement point.

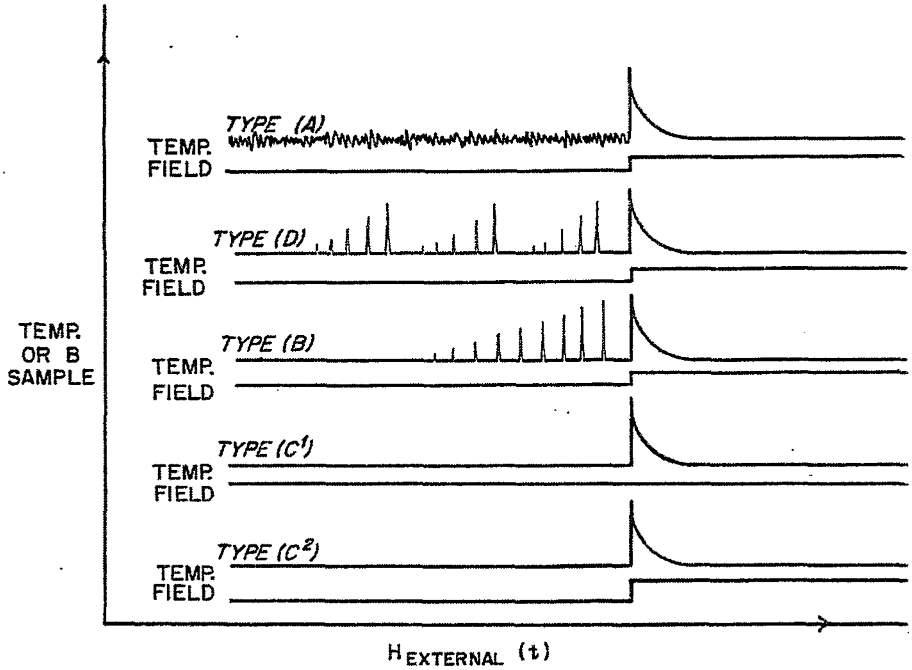

Fig. 5. Different types of thermal activity observed under semiadiabatic conditions.

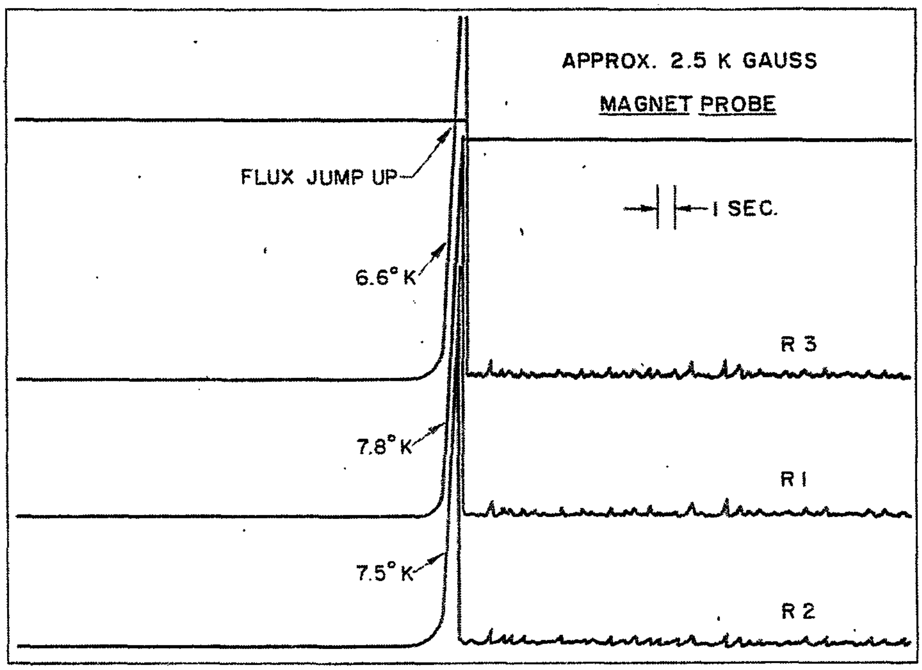

Fig. 6. A copy of an actual record showing Type A activity.