Stability Evaluation of Nb_3Sn Superconductive Tape in a Helium Gas Environment

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Abstract

The stability behavior of Nb_3Sn superconductive tape is studied in a variable temperature cryostat where the helium gas pressure is varied between about 20 and 1.000 torr and the temperature between 4.2 and 20 ^oK.
The $I_c(H)$ short sample characteristic is measured at different gas pressures and temperatures.
Magnetization measurements are also made for stacks of discs punched from Nb_3Sn tape. The temperature of the sample is observed during the whole magnetization cycle, particularly during and after the occurence of flux jumps. The influence of the time variation of H and T on the magnetic stability of the sample is observed.
Small samples inductively wound in the form of pancakes are also measured with a preset value of transport current and superposed magnetic field.
The measurements for the above three types of samples are repeated in liquid helium and the results are compared with those obtained in helium gas.
The results, besides being of general interest, are particularly applied to the construction of the two levitated rings (60 and 120 cm in diameter) for the superconductive quadrupole being built at Garching.

Contents

1. Introduction

An ideal toroidal magnetic configuration for studying the stability and confinement of plasmas in fusion research is achieved by means of one or more current carrying rings which are magnetically supported.

The absence of electrical and other connections to the rings is essential. Only superconducting rings can be considered if experimental times of some length are required. The operating time is given by the warmup rate of the thermally and electrically disconnected rings and by the difference between the initial temperature after cooldown (usually $4,2^{\circ}$ K) and the transition temperature T_c of the superconductor. A superconductor with a high transition temperature, such as Nb_3Sn ($T_c \cong 18^{\circ}$ K), has an obvious advantage over NbTi ($T_c \cong 10^{\circ}$ K). Only the Levitron experiment at Culham uses NbTi, the others (Levitron at L.R.L., Livermore, Spherator at Princeton P.P.L.) use Nb_3Sn (Ref.1, 2, 3).

At the present time, however, experience with Nb_3Sn coils at temperatures above $4,2^{\circ}$ K is scarce and the purpose of this paper is to study the behavior of diffusion processed Nb_3Sn tape up to T_c. This work is part of the preliminaries to building a levitated multipole, "Wendelstein 6" (W6), at Garching (with the following data: two rings 60 and 120 cm in diameter with 400 and 200 kA, respectively) (Ref. 4).

The following measurements were therefore performed in helium gas and in liquid helium:

a) Critical values of field, current, and temperature (HIT) of short samples.

b) Magnetization of stacks of discs punched from Nb_3Sn tape with varying field and temperature.

c) Investigations of the stability of a small coil, also with varying field and temperature, and with and without transport current, particular attention being paid to radial (transverse to the ribbon) fields up to 30 kOe and to currents up to 100 A (these being, respectively, the maximum field and operating current of the two superconducting rings of the W6 Quadrupole).

2. Cryostat and temperature measurements

A variable temperature cryostat was constructed for the above measurements. The inlets for the current leads to the samples are situated at the top of the cryostat gas chamber, which is cylindrical, 26 mm in diameter, and 208 mm long; the samples are located at the bottom of the chamber (to minimize heat conduction through the current leads). The temperature of the copper chamber can be adjusted by a heater embedded in the chamber bottom and kept constant or varied linearly (range 4.2 - 18 ^{o}K, dT/dt = 1.4 - 14 ^{o}K/min) by a control circuit. Care was taken (design and final checks) to ensure that the temperature in the gas chamber is homogeneous. The chamber is placed in the bore (diameter 50 mm, length 240 mm) of a superconducting coil (I_{max} = 600 A, H_{max} = 55 kOe) which produces a homogeneous field around the sample. The field H can also be controlled automatically between +50 kOe and -50 kOe with an approximately linear time dependence (dH/dt = 4 - 50 kOe/min).

For all temperature measurements gold-iron to chromel thermocouples (Heraeus) were used (reference temperature = 4.2 ^{o}K). The thermocouples are conveniently small for soldering to the samples. The sensitivity ($\approx 14\ \mu V/{}^{\circ}K$) and linearity of such thermocouples as given by the manufacturer were checked with a calibrated germanium resistor.

As verified by a few spot checks, variation of the gas pressure from 20 to 1,000 torr does not influence the results on the samples, as is expected since the thermal conductivity of the gas is practically independent of the pressure in this pressure range.

After investigation in gaseous helium, the samples were measured in liquid helium simply by admitting liquid helium into the gas chamber without removing the sample from its holder.

3. Critical (HIT) surface measurements and results

To allow work with conveniently low values of the current (< 100 A, owing to current lead and power supply limitation) the short samples for the (HIT) measurements were reduced from the original 5 mm wide ribbon (GE diffusion processed ribbon, see Fig. 1a) by carefully milling them down to 0.50 mm. Ten samples were made at one time by stacking them in a holder which was then milled along with the ribbons. No edge damage due to the machining could be observed in micrographs of the narrowed part of the sample. The sample was mounted and monitored (voltage and temperature) as shown in Fig. 1a.

Figure 2 shows $I_c(T)_{H = const}$ curves for two differently rated samples. The values measured in liquid helium are about 20 % less than those given by the manufacturer.

The horizontal line to the left of each point in Fig. 2 indicates the temperature increase of the sample relative to the preset temperature of the gas environment. This is due to ohmic heating at the contacts between the sample and current leads.

The results are quite close to the ones obtained by Aron and Ahlgren on vapor-deposited Nb_3Sn, and a detailed comparison analysis is made by Haller and Belanger (Ref.5, 6). It is of particular interest for the project under consideration to note that a current of 100 A at a field H = 30 kOe can still be carried by the ribbon at temperatures up to 13 ^oK.

4. Magnetization measurements and results

Magnetization measurements were made on samples (Fig. 1b) formed by a stack of about 150 discs, 5 mm in diameter, punched from the same tape that was used for the sample 26 in Fig. 2. The insulation varnish was not removed in this process. The stack was pressed together in a holder. The magnetization was measured by integrating the difference voltage of two identical 5,000 turn coils, one of which contains the holder with the specimen. The integrated signal is recorded on a two-channel plotter vs the external field, the other channel recording the specimen temperature (see example Fig. 3). Another two-channel recorder plots the two quantities vs time.

The magnetization curve of the specimen in gaseous helium at 4.2 ^oK shows flux jumps recurring regularly after a field interval of ΔH_{fj}. Each jump releases energy, which raises the temperature of the sample above the critical temperature. Afterwards the temperature drops again to 4.2 ^oK with a time constant of about 5 sec. Contact with liquid helium makes the sample stable, as seen from the corresponding magnetization curve; the full penetration field of $H_p \cong 28$ kOe is reached without flux jumps (irrespective of dH/dt in the range used here) followed by a creep curve.

The quantity which best characterizes the stability behaviour is ΔH_{fj}, whose dependence on H, dH/dt, and especially T will be discussed in the following.

The dependence of ΔH_{fj} on H is only slight. It drops linearly with increasing field, but not more than about 30 % (at 45 kOe). In the following only ΔH_{fjI}, i.e. the initial (largest) ΔH_{fj} is considered.

The variation of dH/dt shows a tendency for ΔH_{fjI} to increase somewhat with decreasing dH/dt. Our values of dH/dt of 4 kOe/min were not low enough to show the drastic increase which has been reported (Ref. 7, 8), and which is theoretically expected when thermal and magnetic diffusivity are comparable (Ref. 9). Furthermore, the increase could only be observed near 4.2 ^oK and disappeared at higher temperatures.

At higher values of dH/dt, a different effect influences ΔH_{fjI}, viz. the warming up of the sample by the penetrating flux. For dH/dt = 40; 16; 4 kOe/min one observes ΔH_{fjI} = 11.3; 12.3; 13 kOe and corresponding temperatures, just before the jump, of T = 5.3; 4.5; 4.35 ^oK. This is in gas at 4.2 ^oK. Furthermore, at 40 kOe/min the sample stays at 9 ^oK after the first flux jump, while at 16 kOe/min it returns to a temperature below 4.5 ^oK, and similarly at 4 kOe/min below 4.35 ^oK. The following measurements were therefore all made at 4 kOe/min; the temperature given is the temperature of the sample measured before the jump.

The dependence of ΔH_{fjI} on T is illustrated in Fig. 4. ΔH_{fjI} does not decrease much before the temperature reaches 12 ^oK, after which it drops noticeably. Beyond about 15 ^oK no flux jump takes place and the field creeps.

In view of the changing temperature in the W6 rings, it is of interest to investigate the stability of the magnetization when the temperature is changing.

First the following procedure is considered: at a constant temperature the field is raised to $0 < H < \Delta H_{fjI}$. If the temperature is then raised (at constant field) the magnetization decreases gradually and either continues to decrease smoothly to zero (at the critical temperature $T_c(H)$) or else comes to a quench when the magnetization has fallen to a value of 60 to 40 % of the initial value. Whether or not a quench takes place depends solely on the value of the constant field and not on the starting temperature of the procedure. The value of this field is about 8 kOe (it is about 10 % higher when the lowest dT/dt is applied). One enters 8 kOe as a boundary in Fig. 4 above which, on increasing the temperature at constant field, a quench is observed roughly in the region where one reaches the ΔH_{fjI} curve. Below this boundary the sample is stable, and creeps to zero, roughly along the ΔH_{fjI} curve.

A different procedure consists in lowering the temperature at a constant field $0 < H < \Delta H_{fjI}$. After reaching a lower temperature T the field is raised at a constant T. One then observes that the ΔH_{fjI} curve can be crossed, and the quench (flux jump) occurs at a much higher field. The improvement in stability is the better, the higher the temperature at which H is established. The stability is improved in this procedure mainly because the magnetization established by the field H is smaller at higher T (owing to the smaller critical current density J_c). The quench occurs, although at higher fields, nevertheless at approximately the same magnetization as for the ΔH_{fjI} curve.

Finally, a third procedure is investigated, starting from T_c (or lower T) and increasing H and lowering T simultaneously. If in this procedure the ΔH_{fjI} curve is not crossed, the quench may be at a very high field (e.g. 33 kOe at T = 11 ^{o}K, after starting from T_c or even $T > T_c$). Otherwise a quench occurs roughly at the intersection with the ΔH_{fjI} curve (see the three cases given in Fig. 4).

The series of magnetization tests suggest that the most convenient way of energizing the W6 rings is to do so as close to T_c as possible, which would consist (see Fig. 5) in presetting at $T > T_c$ the magnetic field given by a system of external coils forming part of the W 6 field configuration and then in energizing the W 6 rings while cooling them down, taking care to reach the nominal values of field (30 kOe) and current (100 A) by moving along on the surface (HIT) and then further cooling down to 4.2 ^{o}K. This procedure should ensure best stability and also a minimum of field diamagnetism in the ring windings (and therefore minimum field distortion). This is also in agreement with the general stability criteria (Ref. 10, 11, 12) inasmuch as the described procedure applies the criterion of keeping the current density J_c of the superconductor low both by increasing its temperature and by presetting a magnetic field on it.

5. Coil measurements and results

A double-pancake sample coil (2 x 30 turns) was made as indicated in Fig. 1c using one length of the same material used for the short sample 58, but without reinforcing stainless steel. A persistent switch was formed as indicated in Fig. 1c . A Hall probe (Fig. 1c), sensitive only to the self-field of the sample coil, monitors its transport current I. The sample coil was tested with its axis perpendicular to the 50 kOe coil field. This geometry reflects more closely the operating conditions of the W6 rings, where a radial field up to 30 kOe is present in part of the winding.

Figure 5 comprises a series of tests performed on the sample coil with the aim of investigating its stability behavior in helium gas under conditions (persistent mode operation, gradual increase of temperature) which allow extrapolation of the results to the behavior of the W6 coils.

The (I-H) curve obtained by presetting the current before increasing the field is always lower than I_c (H-I) obtained by presetting the field and then increasing the current. Both transitions are unstable, i.e. they represent a coil degradation compared with the short sample I_c shown. Simultaneous increase of I and H gives values somewhere between the two curves (Ref. 13, 14). In helium gas the critical values given by the solid lines (Fig.5) are even lower; these should be taken as a basis of comparison when considering results at higher temperatures. The occurrence of flux jumps during the raising of H is evidenced particularly in helium gas by signals from a thermocouple located at the sample coil (Fig. 1c). The signals are of the same nature as those reported in Fig.3 (the heat transfer time constant between sample and helium gas is about 20 sec.).

The remaining set of curves shown in Fig. 5 was obtained by presetting at 4.2 ^{o}K a field (H = 0;14 ; 20; 35; 50 kOe) then energizing the coil with current (I = 100; 300 A) and establishing the persistent mode, and finally by increasing the temperature (dT/dt = 3 ^{o}K/min) up to T_c.

While one might expect that the current I drops along the critical $(HIT)_c$ surface of the short sample, the quantity $(dI/dT)_{H = const}$ is different from zero already at low temperature values. In actual fact, the energy stored in the sample coil $(E = LI^2/2)$ is gradually dissipated owing to the flux penetration associated with the temperature increase. These losses were calculated for the coil sample at H = O (Ref. 15). The results, plotted in Fig. 5 for I = 1OO and 3OO A by a dot-dash line agree well with the experimental curves.

As a conclusive result it is noted that no flux jumps occur and I decreases smoothly with increasing temperature at preset (HI) and vanishes at T_c (stable nature transition). Unstable transitions do occur when the temperature increase is stopped (e.g. at 1O ^oK) and the field H is increased, i.e. (I-H) procedure (not shown in Fig. 5).

6. Conclusions

The experimental results, besides determining physical properties ($I_c(H,T)$;$\Delta H_{fjI}(T)$; $T_c(H)$; etc.) of the Nb_3Sn tape, allow the following conclusion for the W6 rings:

1. The $(HIT)_c$ measurements allow precise design determination of the upper limits of temperature, current, and field.

2. Magnetization and coil measurements show stability of the material under the influence of temperature drift dT/dt. This is particularly true of the W6 rings since the current involved is low (1OO A) and the temperature drift is small.

3. It is convenient to energize the W6 rings at high temperatures and along the critical $(HIT)_c$ surface.

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9. Figure captions

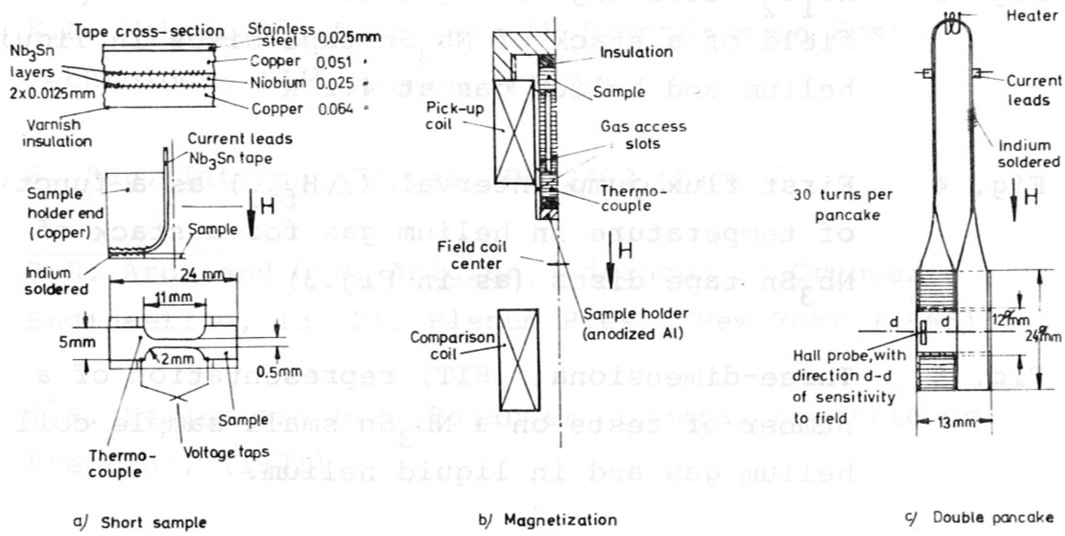
Fig. 1 Samples and measuring arrangements

Fig. 2 Critical current vs temperature with different magnetic fields as a parameter for diffusion processed Nb_3Sn tape

Fig. 3 XY_1Y_2 recording of magnetization and temperature vs field of a stack of Nb_3Sn tape discs in liquid helium and helium gas at 4.2^oK

Fig. 4 First flux jump interval (ΔH_{fjI}) as a function of temperature in helium gas for a stack of Nb_3Sn tape discs (as in Fig.3)

Fig. 5 Three-dimensional (HIT) representation of a number of tests on a Nb_3Sn small sample coil in helium gas and in liquid helium.



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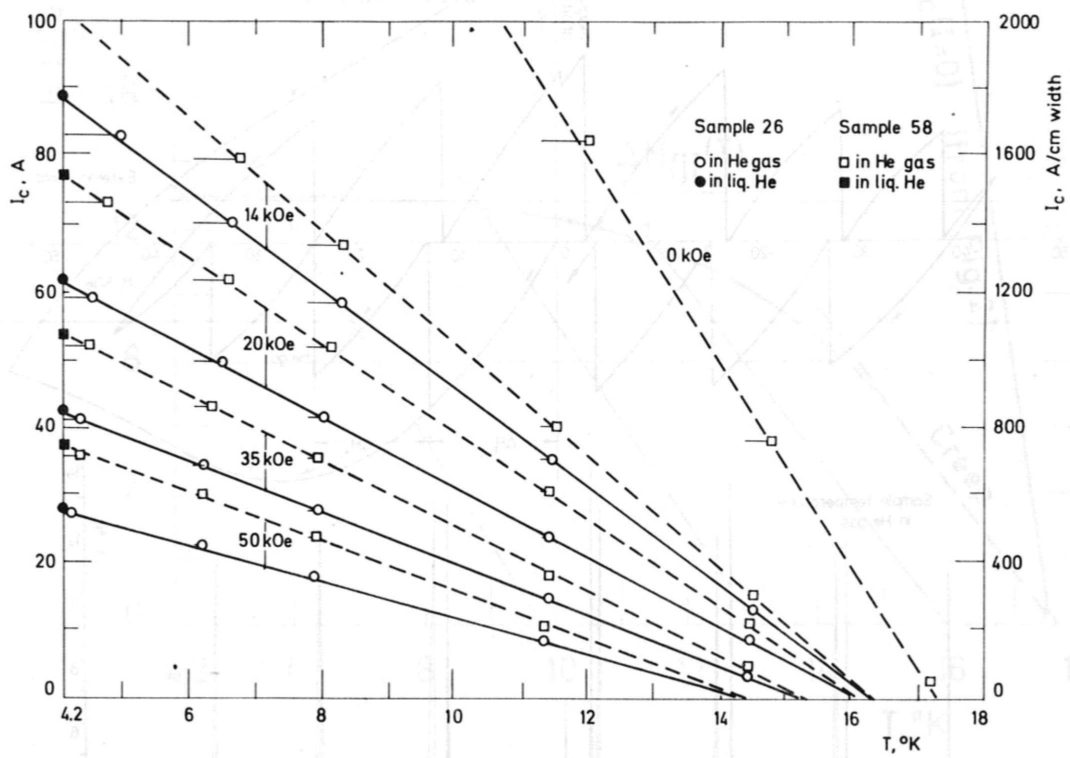

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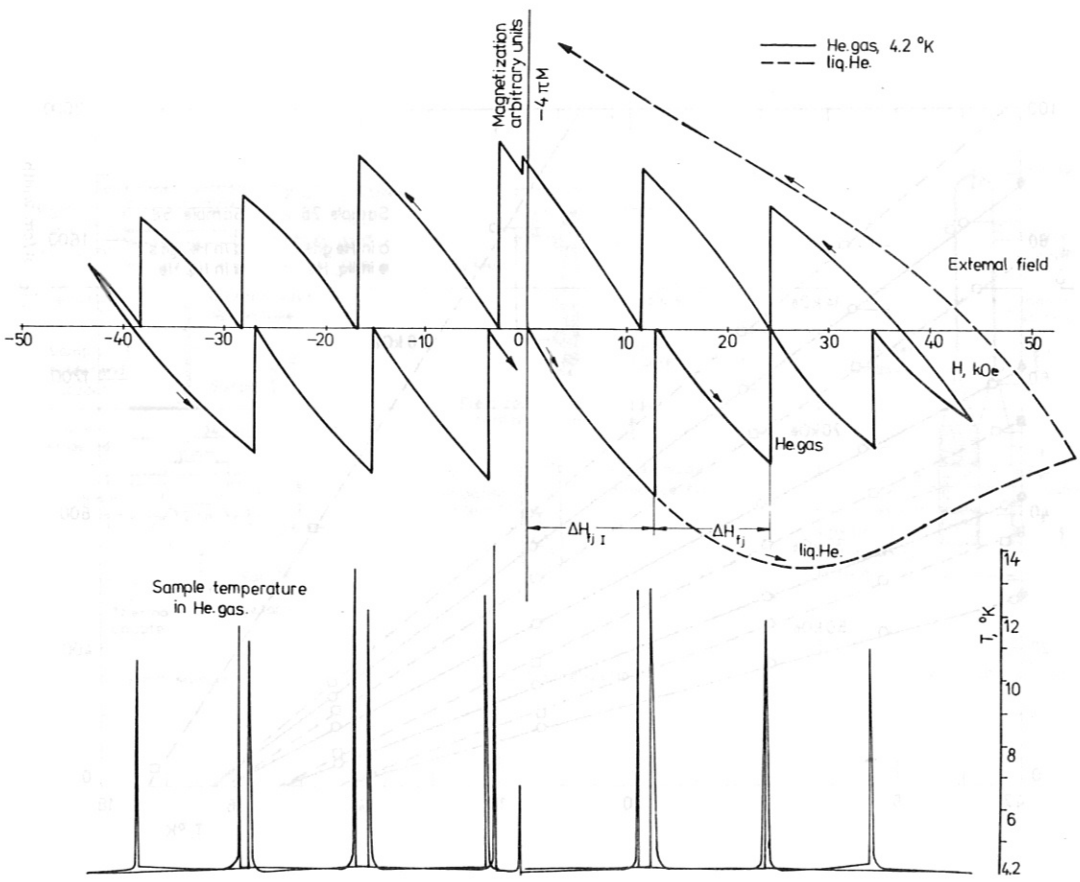

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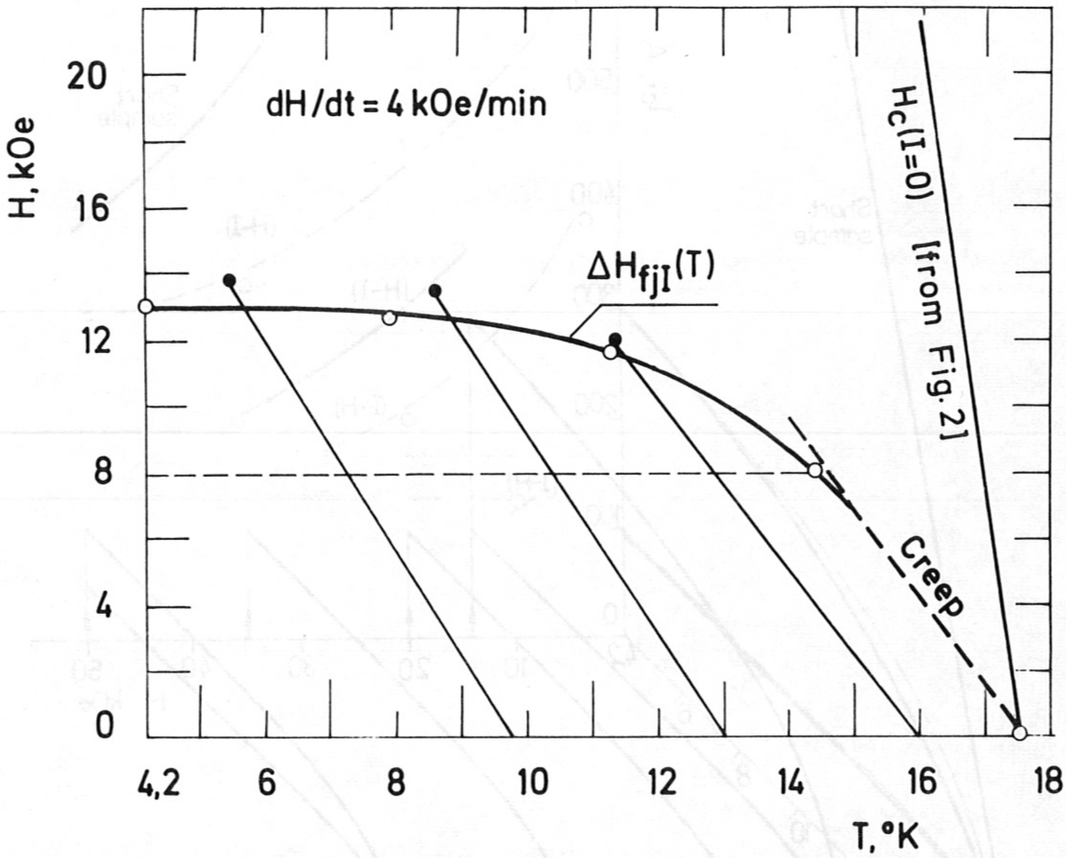

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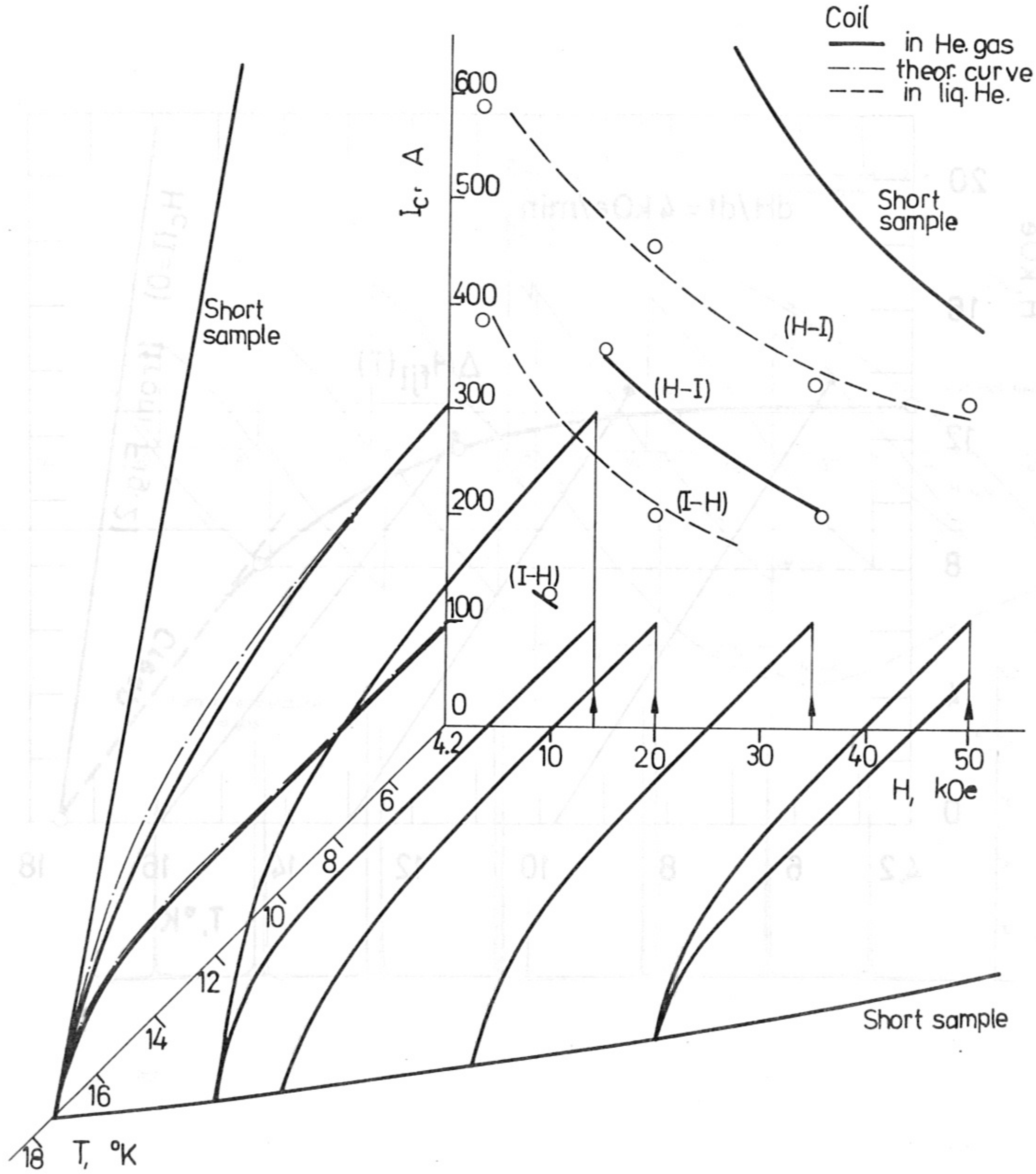

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