# Superconductivity in High Magnetic Fields at High Current Densities

J. E. KUNZLER

*Bell Telephone Laboratories, Incorporated, Murray Hill, New Jersey*

## I. INTRODUCTION

ATTEMPTS to use superconductors for the windings of solenoid magnets were made soon after superconductivity was discovered by Onnes[1] in 1911. The reason for the interest in the possible use of superconductors for windings of solenoid magnets is that power is dissipated if the windings are made of an ordinary conductor—that is, as current flows through a conductor, electrical energy is converted to heat due to the resistance of the metallic path. If the volume of the field within the magnet is large, or if it is operated at high field strengths, these losses represent major practical problems.

Thermodynamic considerations of the production of magnetic fields show that no power is required to sustain a magnetic field once it is established. This fact is also evident from the existence of permanent magnets. This situation has been vividly described by Kolm[2] who pointed out that "sustaining magnetic fields is probably the only major type of operation that we perform with absolutely zero efficiency." Since one of the properties of a superconductor is that it has zero resistance, it has been apparent for some time that if one were to use a superconducting material that remains superconducting in magnetic fields at least as large as those at which the magnet is intended to operate, the power problem would vanish. However superconductivity and high magnetic fields are in general incompatible—that is, resistance is restored to a superconductor by a magnetic field of sufficient intensity. The superconductors that were known at the time Onnes and his co-workers initially attempted to construct solenoid magnets consisted only of some of the so-called "soft" superconductors. These materials, such as lead, tin, and mercury, are usually mechanically soft and characteristically have low critical fields—that is, the superconducting state is destroyed by a small magnetic field, a field of a few hundred gauss.

In 1930 de Haas and Voogd reported[3] studies using Pb-Bi alloys, which are so-called "hard" superconductors, and reported critical fields as large as about 20 kgauss. They recognized the possibility of superconducting magnets when they stated that, "If a solenoid were made of the saturated solid solution of bismuth in lead, we should be able to generate magnetic fields of 14 000 gauss at the boiling point of helium without development of heat and at 2°K, even fields of 19 000 gauss." However they apparently did not construct a magnet and presumably their measurements were made at low current densities. Shoenberg[4] has considered the possibility of superconducting magnets, taking into account the observations of de Haas and Voogd and has concluded that magnets of even a few kgauss were not feasible because of the small amount of material that remains superconducting at these field strengths. Mendelssohn[5] arrived at a similar conclusion but by a somewhat different path. Fortunately it turns out that many of the "hard" superconductors can sustain very high current densities in high magnetic fields even though only a small fraction of the material remains superconducting. In fact it has recently been found[6] that superconducting Pb-Bi alloys can sustain moderately large current densities (e.g., 3000 amp/cm$^2$ at 15 kgauss and 1.5°K). It is surprising that the reasonably high current carrying capacity of Pb-Bi alloys was not observed earlier. It appears that no attempt was made to make the measurements in an externally applied magnetic field of many kilogauss, although Keesom[7] reported measurements for fields of less than a few hundred gauss. It is quite conceivable that if such measurements had been made, and the information successfully disseminated at the time of the early Pb-Bi studies, our state of technological development today might be quite different, possibly to an extent that is hard to envision.

Some substantial progress in magnet construction was achieved when Yntema[8] reported an electromagnet using niobium for the windings and operating at about 7 kgauss. His results were confirmed by unpublished investigations of Hulm.[9] However, the first detailed description of solenoid operation at fields above 1 kgauss was reported by Autler.[10] He described the operation of a niobium wound solenoid at a field of 4.3

[1] H. K. Onnes, Commun. Phys. Lab. Univ. Leiden, **120b** (1911); **122b** (1911); **133d** (1913); **139f** (1914).
[2] Henry H. Kolm (private communication).
[3] W. J. deHaas and J. Voogd, Commun. Phys. Lab. Univ. Leiden, **208b** (1930); **214b** (1931). Superconductivity of Mo-Ti in fields as large as 30 kgauss at very low current densities (34 amp/cm$^2$) has been reported by R. R. Hake, D. H. Leslie, and T. G. Berlincourt, Bull. Am. Phys. Soc. **4**, 362 (1959).
[4] D. Shoenberg, *Superconductivity* (Cambridge University Press, Cambridge, England, 1952), 2nd ed., p. 40.
[5] K. Mendelssohn, *Low Temperature Physics, Four Lectures* (Academic Press, Inc., New York, 1952), p. 125.
[6] F. S. L. Hsu, P. R. White, E. Buehler, and J. E. Kunzler (to be published).
[7] W. H. Keesom, Commun. Phys. Lab. Univ. Leiden, **234f** (1935); Physica, **2**, 35 (1935).
[8] G. B. Yntema, Phys. Rev. **98**, 1197 (1955).
[9] J. K. Hulm (private communication).
[10] S. H. Autler, Rev. Sci. Instr. **31**, 369 (1960); Bull. Am. Phys. Soc. **6**, 64 (1960).

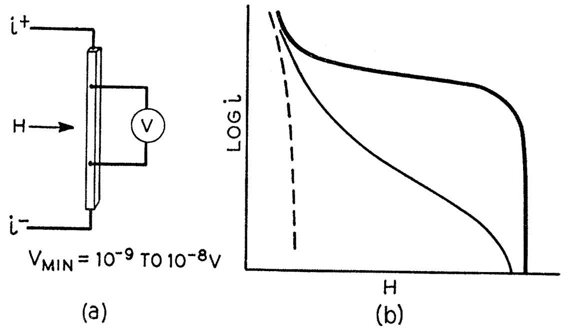


FIG. 1. Schematic representation of the experimental arrangement (Fig. 1a) and an idealized representation of typical results (Fig. 1b). In Fig. 1a the cryostat is omitted and the magnetic field is shown normal to the current direction. The presence of a voltage is detected with a sensitive dc amplifier having a sensitivity of $10^{-9}$ to $10^{-8}$ v depending on the experimental arrangement. The curves of Fig. 1b represent the boundaries between the absence of a detectable voltage (superconducting) and the presence of the smallest observable voltage (nonsuperconducting). The heavy curve represents typical behavior of a "hard" superconductor saturated with strain by extreme mechanical deformation (hard working), the light curve represents the behavior of a partially worked alloy and the dashed curve illustrates the effect of annealing.

kgauss and a temperature of 4.2°K. More recently he has produced fields of about 10 kgauss.

A number of materials have been studied at Bell Telephone Laboratories. Three of these materials that have provided considerable information concerning the behavior of hard superconductors and are of interest in connection with high magnetic fields are reviewed here. The materials and the more significant observations are as follows. (1) The critical current $I_c$, as a function of applied magnetic field $H$, has been measured for molybdenum-rhenium alloys. A magnet has been constructed and its operating characteristics were found to be consistent with the measurements. (2) The characteristics of $Nb_3Sn$ and $Nb_3Sn$ "wires" have been studied at helium and hydrogen temperatures in fields as large as 88 kgauss. The critical field of $Nb_3Sn$ filaments at 0°K exceeds 200 kgauss. (3) Superconducting niobium-zirconium alloys have been found to have useful current densities at fields as large as 80–100 kguass, (for example $>10{,}000$ amp/cm² at 80 kgauss and 1.5°K).

Superconductors are often classified as being "hard" or "soft." This classification apparently originated because it appeared that there was a close association with their mechanical properties. However a description that we find more useful relates to the behavior in a magnetic field. Although a "soft" superconductor is generally mechanically soft, it need not be. However it characteristically has a low critical field, a critical field not exceeding a few kgauss. The magnetic field can penetrate a "soft" superconductor to a depth corresponding to the penetration depth λ. The current is carried in this surface layer and for wires the current carrying capacity is proportional to the diameter $d$ of the wire. When the superconductivity of the soft superconductor is destroyed by a magnetic field, it is destroyed more or less abruptly. The "hard" superconductors are generally chemically and/or physically inhomogeneous. Such materials are generally mechanically hard since hard substances often can sustain a large degree of physical inhomogeneity. After a magnetic field destroys the superconductivity of a substantial fraction of a "hard" superconductor, it is found that a small portion of the material remains superconducting to much higher fields. In these fields it is believed that the small remaining amount of superconductivity exists in thin filaments having a diameter smaller than λ. The number of such filaments is proportional to the cross sectional area of the wire and thus the current carrying capacity of such a wire is proportional to $d^2$. With one exception to be discussed later, the maximum current carrying capacity of the "hard" superconductors described here is found to vary approximately as the cross sectional area.

## II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is indicated schematically in Fig. 1(a). The samples are short, approximately $\frac{7}{8}$-in. long rods or wires of the superconductor being investigated. The thickness of the samples varies from a few hundredths of a mm to over 1 mm depending on the investigation. Current leads are attached to the ends of the samples. Potential leads are attached well

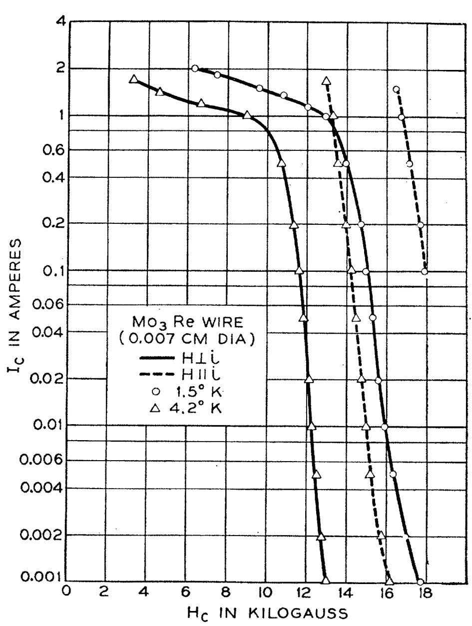


FIG. 2. Experimental observed curves (magnetic field vs critical current) of the 0.007-cm diam. $Mo_3Re$ wire used for the solenoid in Fig. 3. The knees in the curves with $H\perp I$ at both 1.5° and 4.2°K are typical of behavior observed in several materials. Data for each curve were taken by starting with the smallest value of current and repeating the initial point after the pertinent series was complete. This was done to ascertain that no annealing had occurred when the sample was driven into the normal state at high current density.

away from the ends of the sample and the potential drop is measured with a sensitive dc amplifier. In measurements that were made in the apparatus at fields as high as 18 kgauss, the smallest voltage that could be detected was $10^{-9}$ v. In the measurements extending to fields as large as 88 kgauss, the smallest detectable voltage was $10^{-8}$ v. The magnetic field was usually applied transverse to the sample as is shown in the figure. The high field measurements were made in a copper solenoid magnet capable of a maximum field of 88 kgauss. More details concerning this magnet are given in Sec. VI.

Measurements were made by selecting a fixed value of magnetic field and slowly increasing the current until a detectable voltage could be observed. A series of such points as a function of magnetic field define a boundary between regions where a continuous superconductive path exists (superconducting) from those where a trace of resistance is observed (nonsuperconducting), as is illustrated in Fig. 1(b). Alternatively, measurements are taken by keeping the current fixed and gradually increasing the magnetic field until a detectable voltage is observed. In general, measurements by these two methods were found to agree with each other. It is convenient to represent the data by plotting the maximum current carrying capacity (critical current) against the externally applied magnetic field as shown in Fig. 1(b). The heavy curve illustrates characteristic behavior observed for "hard" superconductors. A maximum of hard working (extreme mechanical deformation) is usually required to produce the sharp knee in ductile materials. The lighter curve illustrates typical behavior for a partially worked sample. The limiting magnetic field is approximately the same in both cases. The dashed curve represents the behavior of an alloy that is relatively strain free and also consists of one phase. It has been demonstrated experimentally that the annealing of a hard worked alloy, initially having characteristics corresponding to the heavy curve, will result in characteristics approaching those of the dashed curve. However if the dashed curve were continued to sufficiently low values for the current, it would contain a region in which the values of $H$ increased more rapidly, and eventually it would approach the same limiting value of magnetic field as the solid curve.

### III. MOLYBDENUM-RHENIUM ALLOYS

Molybdenum and rhenium form a ductile solid solution over a reasonable range of composition. Superconductivity in this system was first reported by Hulm.[11] The properties of a typical sample of Mo-Re and the description of a solenoid constructed from the material have been described earlier.[12] The $I_c$ vs $H$ characteristics for wires of molybdenum-rhenium were determined.

[11] J. K. Hulm, Phys. Rev. **98**, 1539 (1955).

[12] J. E. Kunzler, E. Buehler, F. S. L. Hsu, B. T. Matthias, and C. Wahl, J. Appl. Phys. **32**, 325 (1961).

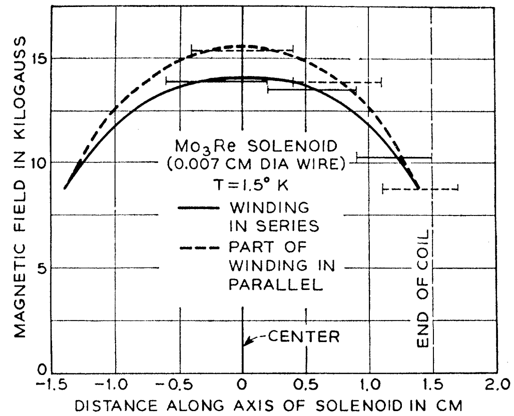


FIG. 3. Magnetic field as a function of position along the axis of the superconducting $Mo_3Re$ solenoid with the windings connected in series and with sections of windings connected in parallel. Average values of the magnetic field over the intervals indicated were measured using probes centered along the axis of the solenoid core. The parallel winding arrangement yields a higher field, as is shown by the dashed curve.

From these characteristics and the simple physics of a solenoid, one would expect to be able to predict the properties of a solenoid magnet constructed from wire having the same characteristics. Such a magnet was constructed and operated at fields exceeding 15 kgauss as was predicted. Although agreement between the measurements and the operating characteristics is expected, it is reassuring to have an experimental verification.

The characteristics of an alloy corresponding to the approximate composition $Mo_3Re$ are shown in Fig. 2. The sample consisted of a short length of hard-worked (drawn from 0.12 cm diam without annealing) wire having a diameter of 0.007 cm. In addition to the characteristics with the magnetic field transverse to the sample at 4.2° and 1.5°K, characteristics are also shown with the magnetic field longitudinal to the sample. These latter measurements are interesting but not essential to the present discussion. The knee in the curves represents the optimum conditions for obtaining the maximum field from a magnet designed to use a minimum of material. From the curve at 1.5°K it is expected that with a current of one amp and a sufficient number of turns to generate the desired field, a magnetic field of 13 kgauss could be produced in a magnet. If it were desired to increase the field to 15 kgauss, the curve suggests that a current of about 0.1 amp is the maximum permissible. Thus the number of windings and hence their thickness would need to be ten times greater than for the previous case. Likewise, to increase the field to 16 kgauss would require a layer 100 times thicker, since the maximum current would be 0.01 amp (this does not include additional material that probably would be required for the necessary additional length of the solenoid).

The small solenoid constructed by using 0.007 cm diam wire is a little less than 2 cm in diameter and approximately 3 cm long. It has 30 000 turns of windings

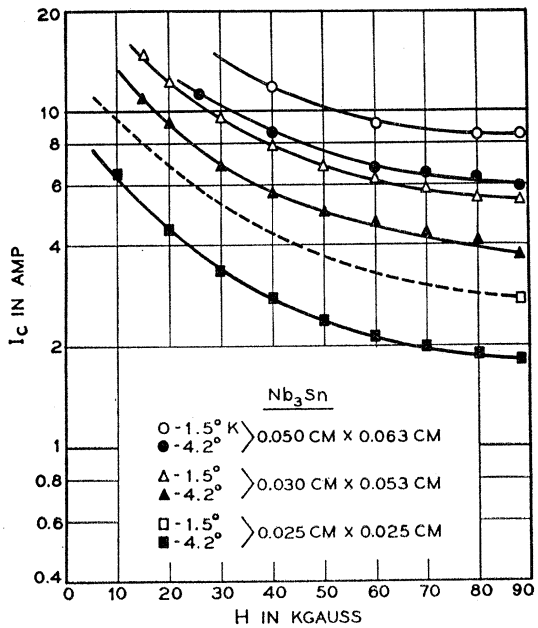


FIG. 4. Critical current vs applied magnetic field for three sample sizes of bulk $Nb_3Sn$ at 1.5°K and 4.2°K. The magnetic field was perpendicular to the current direction. Each experimental point represents the maximum current at the value of magnetic field indicated, for which no voltage drop along the sample was observed, the smallest detectable voltage being a few hundredths of one microvolt.

divided into 100 layers. The core of the solenoid is about 3 mm in diameter and allows the insertion of a small magnetoresistance probe,[13] which makes use of the magnetoresistance of copper, for measuring the magnetic field strength. The insulation between windings in each layer was a metal, gold in this case. The resistance of an ordinary metal compared to that of a superconductor is essentially infinite. Thus once the magnetic field is established, nonsuperconducting metals provide satisfactory insulation. However their shunting resistance must be considered when changes in the magnetic field strength are involved.

From consideration of the physics involved, it is expected that the current carrying capacity of a wire in a solenoid would be the same as the current carrying capacity of a wire in an external field of the same magnitude. That is, a piece of wire does not care whether the field it "sees" comes from current carried by itself and neighboring windings or from an externally applied transverse magnetic field. The small solenoid was designed to operate at approximately one amp. Thus it was expected to produce a maximum field of approximately 13 kgauss when all of the windings were in series. Figure 3 shows the results of magnetoresistance field-probe measurements in the solenoid while operating at the maximum field consistent with having the windings superconducting (i.e., $V<10^{-9}$ v across the entire windings). The magnetic field strength is plotted against the position along the axis of the solenoid. The heavy bars represent averages of the field over the length of the probe and the curves are drawn taking into account symmetry and the averages represented by the bars. The solid curves show that the maximum field is approximately 14 kgauss whereas the expected field was about 13 kgauss. This difference is probably due to differences in the characteristics along the length of the wire. The sample used for the measurements of Fig. 2 was taken from approximately the 40th layer whereas, the maximum field is determined by the characteristics of the wire next to the core.

With all of the windings connected in series, it is only those near the center that are carrying the maximum permissible current. If the layers of windings are arranged so that each is independently supplied with current, and the amount of current were decreased through the inner layers of windings and increased through the outer layers, a net gain in the maximum field is expected. This effect has been demonstrated experimentally by dividing the coil into three sections. These sections could be driven independently; however, it is also possible to operate them in parallel. This arrangement makes current distribution self-adjusting since if the maximum current carrying capacity (critical current) of one section is exceeded slightly, a small resistance will result and the current will be automatically shunted to the other sections. However, care must be taken to include a small amount of resistance in each section. Otherwise problems associated with an infinite time constant (finite inductance and zero resistance) can be encountered. The dashed curve (Fig. 3) shows the results obtained with the parallel arrangement. The maximum field exceeds 15 kgauss.

The most important conclusions to be drawn from the molybdenum-rhenium results is that one can construct a magnet based on the characteristics determined from measurements on short samples of the material. The engineering and fabrication problems are of course a separate consideration.

### IV. $Nb_3Sn$ INTERMETALLIC COMPOUND

$Nb_3Sn$ is a brittle intermetallic compound. Its discovery and its high transition temperature near 18°K was reported by Matthias and co-workers.[14] Investigations of current carrying capacity in high magnetic fields have been made using two types of materials. One type consisted of samples of bulk $Nb_3Sn$. It was found that this material remained superconducting at 88 kgauss at a current density high enough to be of interest for magnets (~3000 amp/cm²). However the material is brittle and not usable in this form. The second type of material is $Nb_3Sn$ cores in niobium clad "wire" which were prepared in a successful attempt to circumvent brittleness problems of bulk $Nb_3Sn$. It was found that the "wire" was also superconducting at 88

[13] F. S. L. Hsu and J. E. Kunzler (to be published).

[14] B. T. Matthias, T. H. Geballe, S. Geller, and E. Corenzwit, Phys. Rev. 95, 1435 (1954).

kgauss and in addition it could sustain a much higher maximum current density, about a factor of 50 higher. In the better samples it was found that at 88 kgauss and 4.2°K current densities as large as 150 000 amp/cm$^2$ could be sustained with the material remaining superconducting. Preliminary data concerning bulk $Nb_3Sn$ and $Nb_3Sn$ "wire" has been reported.[15]

It was also found that the "wire" form of this material had interesting characteristics at liquid hydrogen temperatures. For example at 60 kgauss and 14.2°K current densities as large as 6000 amp/cm$^2$ could be sustained. From these data it has been possible to learn something of the filamentary nature of $Nb_3Sn$ in high fields. It has also been possible to extrapolate the critical field data to helium temperatures by using the hydrogen temperature results, and it is found that the critical field of the filaments (or of filamentary $Nb_3Sn$) is in excess of 200 kgauss.

### A. Bulk Samples

Samples of bulk $Nb_3Sn$ were made by cutting small rectangular rods from an ingot of $Nb_3Sn$. The ingot was prepared by fusing a stoichiometric mixture of Nb and Sn at approximately 2400°C and carefully cooling it. The results of critical current versus the applied magnetic field measurements on samples having three different cross sectional areas are shown in Fig. 4. Measurements were made on each sample at 1.5°K (open symbols) and 4.2°K (solid symbols). These data show three interesting features. First, at 88 kgauss there is no sign of the characteristic knee followed by a very rapid decrease in critical current with increasing field. From these data it is apparent that the maximum magnetic field for which superconductivity exists in $Nb_3Sn$ is much higher, probably well over 100 kgauss. Second, the curves of the figure show that the maximum current carrying capacity (i.e., critical current) at 1.5°K is some 50% higher than the critical current at 4.2°K. This point is referred to later. And finally, the critical current of the sample does not vary as the cross sectional area, as has been observed for the other samples of "hard" superconductors, nor does it vary as the diameter of the sample which is typical of "soft" superconductors, but rather the current varies in a manner roughly halfway between. This suggests that a substantial fraction of the current is being carried by the bulk of the material and also a substantial fraction is being carried by a surface layer. It is not believed that the surface layer is a layer corresponding to the penetration depth. Rather it is believed that this surface layer is a much thicker layer of material strained during the cutting of the sample. It is probable that this layer contains many more filaments and thus a higher current-carrying capacity than bulk material. Such higher-current carrying capacities are possible as can be seen from the data described in connection with the "wires."

[15] J. E. Kunzler, E. Buehler, F. S. L. Hsu, and J. H. Wernick, Phys. Rev. Letters **6**, 89 (1961).

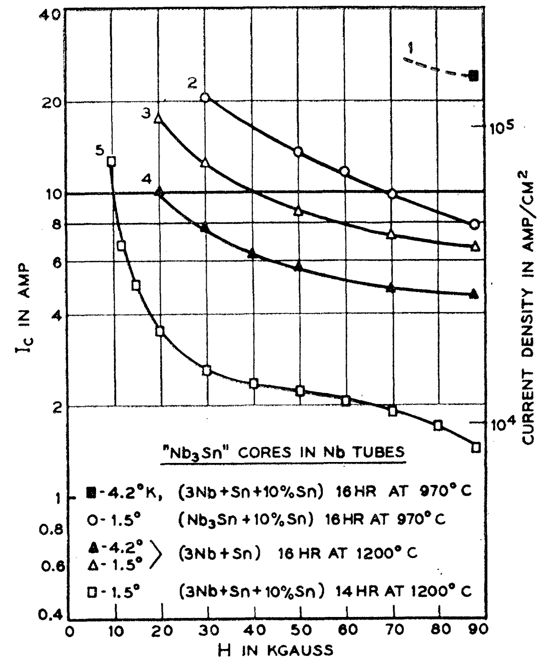


FIG. 5. Critical current vs applied magnetic field for Nb-clad cores of "$Nb_3Sn$." The outside diameter of the cores was about 0.015 cm and the outside diameter of the Nb jackets was about 0.038 cm. "+10% Sn" in the table legend means 10% more Sn by weight than is required to form $Nb_3Sn$, assuming no reaction with the Nb tube. The magnetic field was perpendicular to the current direction. Each experimental point represents the maximum current, at the value of magnetic field indicated, for which no voltage drop along the sample was observed, the smallest detectable voltage being a few hundredths of one microvolt.

The average critical current density of the rods of bulk $Nb_3Sn$ is approximately 3000 amp/cm$^2$ at 4.2°K and 88 kgauss.

### B. $Nb_3Sn$ "Wire" Samples

$Nb_3Sn$ "wire" samples were prepared by taking a niobium rod approximately $\frac{1}{4}$ in. in diameter and drilling a $\frac{1}{8}$-in. hole through it. One end of the tube was plugged and the tube then filled with an intimate mixture of elemental niobium powder and elemental tin powder. This material was firmly packed into the tube and the remaining end sealed closed. The rod was then swaged and drawn (mechanically reduced) into "wire." In a typical final dimension, the outer diameter of the wire was 0.38 cm and the outer diameter of the core was 0.015 cm. In this form the niobium and tin powder are still in elemental form and the wire is ductile. Under such conditions, the "wire" can be wound in a solenoid, firmly anchored into place, and reacted to form a $Nb_3Sn$ core in the "wire." Thus the $Nb_3Sn$ core need not be mechanically or physically disturbed after it has been produced. Since not enough material has been available to form a coil that is capable of producing sizable fields, short samples of the wire were tested in the manner similar to that used for the molybdenum-rhenium and the bulk $Nb_3Sn$ samples.

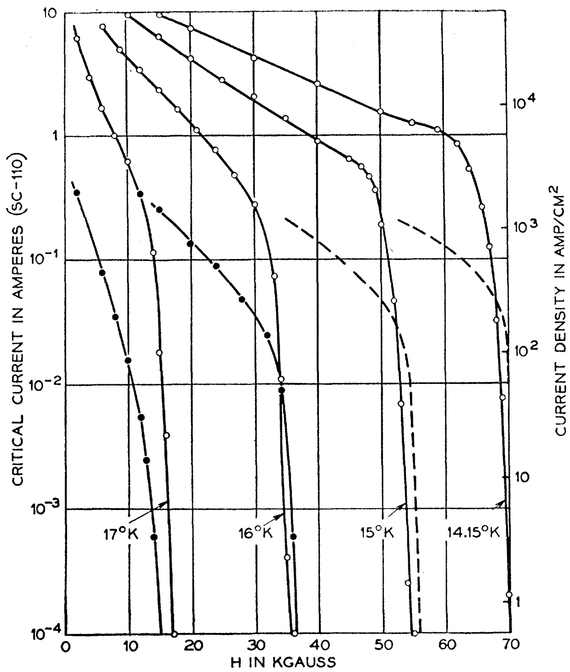


FIG. 6. Critical current vs applied magnetic field of $Nb_3Sn$ and $Nb_3Sn$ "wire" at liquid hydrogen temperatures. It is significant that although the current densities for the two types of samples differ by nearly a factor of 1000, the limiting magnetic field is essentially the same for both cases. The critical current density for superconducting $Nb_3Sn$ "wire" in liquid hydrogen at 14.2°K and in a magnetic field of 60 kgauss is about 6000 amp/cm². ○ = SC-110. $Nb_3Sn$ core in Nb wire. 0.03-cm = diam wire; 0.015-cm-diam core. ●-SC-78. Bulk $Nb_3Sn$, current density×100.

Typical examples of results for a number of compositions prepared under various conditions and fired at various temperatures and times are summarized in Fig. 5. One of the better samples is represented by "curve 1" which contains a single point. Only one point is included because the apparatus used for these experiments was not designed to carry the currents required. In the superconducting state at 88 kgauss and 4.2°K this material will sustain a current density of 150 000 amp/cm². Figure 5 also shows that the maximum current carrying capacity increases some 50% from 4.2° to 1.5°K. Therefore the sample corresponding to "curve 1" is expected to have a critical current density greater than 200 000 amp/cm² at 1.5°K. A number of samples have been prepared with characteristics similar to that of the "curve 1." A few are better, but many are somewhat poorer and have maximum current carrying capacities within a factor of 2 of "curve 1."

Although the data of Fig. 5 suggest that using reaction temperatures below 1000°C should result in marked improvement of properties and that the behavior of a stoichiometric mixture of niobium and tin fired at 1000°C should have better properties than "curve 1," this does not appear to be the case. However additional data show that a stoichiometric mixture and a mixture containing 10% by weight of the tin in excess, appear to have similar properties when fired at approximately 1000°C.

Although the average current density of $Nb_3Sn$ "wire" cores at 4.2°K is as high as approximately 150 000 amp/cm², the current density of the filaments is probably much higher. It is known from susceptibility measurements of Bozorth and co-workers[16] that less than a few percent of the $Nb_3Sn$ remains superconducting (in the sense that the magnetic field is completely excluded) at fields exceeding 70 kgauss. If it is assumed that the volume of material occupied by the filaments is small, then the average current density in the filaments must be many millions of amp/cm².

### C. Nature of the $Nb_3Sn$ Filaments

Measurements of $I_c$ vs $H$ of $Nb_3Sn$ "wires" and $Nb_3Sn$ bulk samples have been made at liquid hydrogen temperatures. These measurements not only further illustrate the unusual properties of $Nb_3Sn$ but also provide information concerning the filamentary nature of $Nb_3Sn$. A preliminary report was recently given elsewhere.[17] Results of data taken in the liquid hydrogen range are contained in Fig. 6. The curves having open symbols represent measurements using $Nb_3Sn$ "wires." The critical temperature determined by resistance measurements at zero field and the limit of zero current is 17.8°K. $I_c$ vs $H$ measurements are shown on the figure for temperatures of 17°K, 16°K, 15°K, and 14.15°K. At these temperatures the magnetic field available is high enough to destroy the superconductivity at low current densities and the knee characteristic of "hard" superconductors is apparent. Also the characteristics of the upper curves are high enough in current density to be useful. Thus, in a field of 60 kgauss at 14.15°K, a current of 1 amp can be carried in the superconducting state. This amounts to a current density of approximately 6000 amps/cm² for the $Nb_3Sn$ core of the "wire." The lower set of curves (the ones with solid symbols and dashed lines) are measurements on bulk $Nb_3Sn$ samples. In order to plot them on this figure, they are displaced upward by two decades; that is, the difference between corresponding curves of the bulk material and of the wires is about a factor of 1000. However, the limiting magnetic field, the field in the region where the current carrying capacity is rapidly dropping toward zero, is approximately the same for the two materials.

This result appears to be quite significant and can be explained by assuming that the filaments have a characteristic critical field, independent of their mechanical history, and that the difference between the curves is in the number of filaments. It is, therefore, convenient to define this limiting field as the critical field of $Nb_3Sn$ filaments or of filamentary $Nb_3Sn$. The effect of in-

[16] R. M. Bozorth, H. J. Williams, and D. D. Davis, Phys. Rev. Letters **5**, 148 (1960).
[17] J. E. Kunzler, F. S. L. Hsu, and E. Buehler, Bull. Am. Phys. Soc. **6**, 123 (1961) (post-deadline paper F16).

creasing the number of filaments in the $Nb_3Sn$ wires is to raise the position of the curve but not to change the critical field. Thus the "wires" may contain something of the order of a 1000 times more filaments than bulk $Nb_3Sn$. This interpretation supports the suggestion of Hauser[18] and of Shaw and Mapother[19] that the filaments are associated with dislocations. Hauser[18] has calculated the variation of critical field with the diameter of a thin rod in a transverse magnetic field. He finds that when the diameter, $d$, is comparable with, or less than, the penetration depth, $\lambda$, that the critical field increases as $2\lambda/d$. His calculations along with high critical field of filamentary $Nb_3Sn$ suggest that the diameter of the filaments is small, less than the penetration depth and probably considerably less than 100 A. Under these conditions the critical field can easily be 10–100 times the critical field of the ideal bulk materials (in a state where it is free of strains, dislocations, and is exhibiting soft superconducting properties). Also, the rapid decrease of current at fields just exceeding those of the knee, when considered in the light of Hauser's calculation, suggests the distribution of filament diameters must be narrow. The association of the filaments with dislocations seems to fit the experimental facts better than any other model that has occurred to us.

### D. Critical Field of $Nb_3Sn$ Filaments at 0°K

From the measurements at liquid hydrogen temperatures, it is also possible to make an estimate of the critical field of $Nb_3Sn$ filaments. This has been reported previously[17] and the data are summarized in Fig. 7. The critical field of $Nb_3Sn$ filaments or of filamentary $Nb_3Sn$ is plotted against temperature. The points represent measurements of the limiting magnetic field in the region where the critical current-carrying capacity is decreasing very rapidly with the field and corresponds to a current density of 1 amp/cm$^2$. The points are best fitted by a straight line. A linear extrapolation of this line gives the value of 340 kgauss at 0°K which probably represents an upper limit of the critical field. The dashed curve represents a parabola and probably represents a lower limit of the critical field and is approximately 200 kgauss.

Although the critical field of "soft" superconductors is usually a parabolic function of temperature, it appears that the "hard" superconductors behave differently. For example, it is found that the behavior of the limiting magnetic field of molybdenum-rhenium (critical field of Mo-Re filaments), as a function of temperature, is almost linear to temperatures of 1.5°K. However, the third law of thermodynamics requires that the curve become flat at absolute zero. Similar trends have been observed in Nb-Zr and other hard superconductors. Furthermore, as was pointed out in connection with

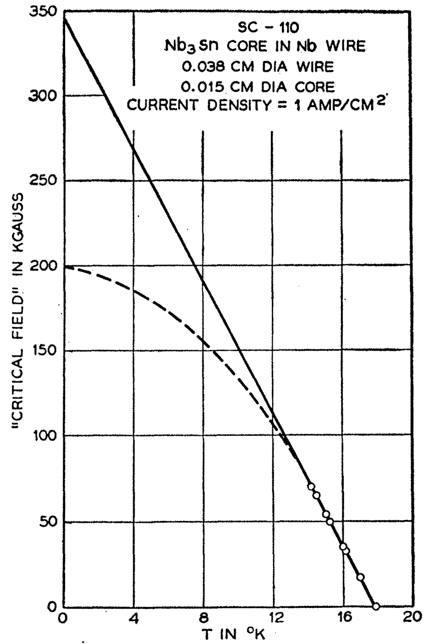


FIG. 7. Critical field of $Nb_3Sn$ filaments. The solid curve probably represents an upper limit and the dashed curve a lower limit. The critical field of filaments of "hard" superconductors appears to show more nearly a behavior represented by the solid curve (linear extrapolation) than the dashed curve except that the slope must also be zero at 0°K.

Figs. 4 and 5, the current carrying capacity increases over 50% in cooling $Nb_3Sn$ from 4.2° to 1.5°K. If the curves were flat or near flat in this region, this behavior would not be observed. Therefore it seems quite probably that the critical field of $Nb_3Sn$ filaments at 0°K is somewhere between 250–300 kgauss. Even after this value has been reduced by approximately 15% (the difference between the limiting magnetic field and the field at the knee), it appears that the magnetic field at useful current densities is in excess of 200 kgauss. This conclusion is supported by recent pulse field measurements.[20–22] In one set of these measurements,[20] it was found that in superconducting $Nb_3Sn$ wire at a field of 180 kgauss, a current density of approximately 25 000 amp/cm$^2$ was attained. Furthermore the knee had not yet been reached. Assuming that the engineering and fabrication problems can be solved in a satisfactory manner, it appears that $Nb_3Sn$ will be useful for magnets of at least 200 kgauss.

## V. NIOBIUM-ZIRCONIUM ALLOYS

Niobium and zirconium form a complete range of solid solutions at elevated temperatures. This alloy system as well as niobium-titanium and vanadium-

[18] J. J. Hauser and E. Buehler (to be published); J. J. Hauser and E. Helfand (to be published).

[19] R. Shaw and D. E. Mapother, Phys. Rev. **118,** 1474 (1960).

[20] H. R. Hart, I. S. Jacobs, P. E. Lawrence, and C. L. Colbe, Bull. Am. Phys. Soc. **6,** (1961) (post-deadline paper).

[21] V. D. Arp, R. H. Kropschat, J. H. Wilson, W. F. Love, and R. Phelan, Phys. Rev. Letters **6,** 452 (1961).

[22] J. O. Betterton, Jr., R. W. Brom, G. D. Kneip, R. E. Worsham, and C. E. Roos, Phys. Rev. Letters **6,** 532 (1961).

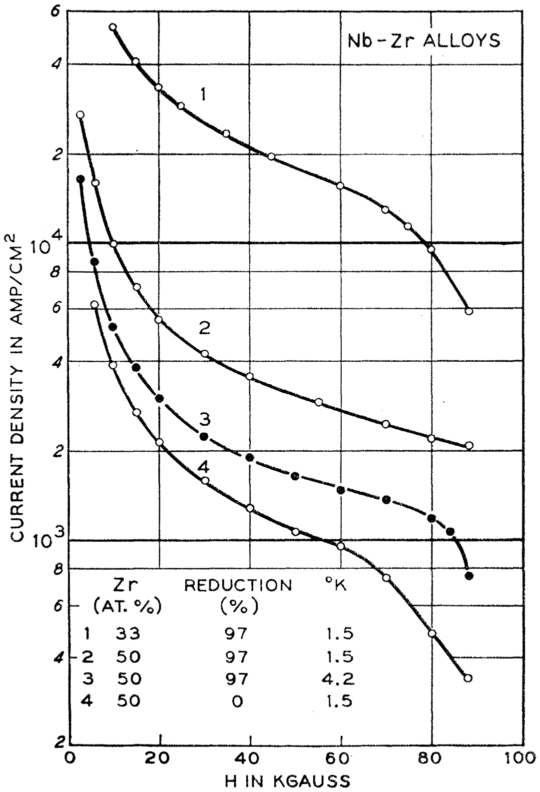


FIG. 8. Critical current density vs applied magnetic field for some Nb-Zr alloys. From the data in this figure and data not shown, it is found that the critical field of filamentary Nb-Zr reaches a maximum at a composition between 65 and 75% Zr while the critical current density reaches a maximum at a composition between 25 and 35% Zr.

titanium were suggested by Matthias as being promising materials for magnets. The latter materials have critical fields comparable with niobium-zirconium. However, the current carrying capacity or critical current is a factor of 5 to 10 smaller. Since the niobium-zirconium alloys appear to be the most promising, the other alloys are not discussed further in this review, but are discussed along with more details concerning Nb-Zr alloys elsewhere.[23]

Nb-Zr alloys have characteristics that are useful for magnets with fields in the 80 to 100 kgauss range. The alloys used in this investigation were prepared by arc melting small buttons of a number of compositions. Samples were prepared by cutting rectangular rods from the buttons or alternatively by rolling the button into a sheet and then cutting rectangular rods from the sheet. Results of a number of typical samples are shown in Fig. 8. When the data shown in the figure are considered along with data not included, it is found that an interesting trend exists. The critical field of filamentary Nb-Zr increases with increasing zirconium concentration, reaches a maximum between 65 and 75 atm % zirconium, and then drops quite rapidly. However the maximum current carrying capacity increases with decreasing zirconium content, reaches a maximum at about 25 to 35% zirconium and, falls rapidly at lower concentrations. A sample having 33% Zr and reduced 97% by cold rolling has a critical current density of 10 000 amp/cm$^2$ at 1.5°K and 80 kgauss (curve 1, Fig. 8).

It is expected that the current carrying capacity of niobium-zirconium alloys can be increased to values much higher than those represented by Fig. 8, as conditions are optimized with respect to composition and hard working. On the basis of experience with other materials, it is expected that drawing the Nb-Zr alloys into wire will increase the maximum current carrying capacity several fold over that of the rolled samples. It seems likely that several compositions will be useful in the construction of a single magnet. For the outer windings, where the maximum field is not a limitation, it may be desirable to use the highest current carrying materials. However, for the inner windings where the maximum magnetic field is required, it would be desirable to use a composition capable of the higher fields at the expense of some of the current carrying capacity of some other composition.

The niobium-zirconium alloys are ductile and are much easier to fabricate than $Nb_3Sn$ "wire." Also the engineering design and construction of magnets with the alloy will be considerably simpler than with the $Nb_3Sn$ "wire." Thus it is likely that most magnets in the range up to 80–100 kgauss will be constructed of Nb-Zr. A magnet constructed of material having the characteristics of curve 1 in Fig. 8 and operated at 1.5°K, would require an approximately 3-in. thick layer of windings to produce 80 kgauss. However, $Nb_3Sn$ will complement the Nb-Zr alloys and should be useful for magnets of fields of at least 200 kgauss, providing the engineering problems can be solved in a practical manner.

Although the range of transition temperatures of Nb-Zr alloys are comparable to those of Mo-Re alloys, the highest critical fields of Nb-Zr alloys are about five times higher than the comparable values for Mo-Re alloys. This fact demonstrates, that in addition to the chemistry of the material, physical and structural properties (such as those that affect the filament diameter) are important. Matthias[24] has discussed some of the relevant factors pertaining to transition temperatures. These results emphasize the need for greater theoretical understanding and hopefully may help stimulate some additional theoretical thinking along these lines.

## VI. APPLICATIONS OF SUPERCONDUCTORS TO MAGNETS

The availability of superconducting magnets operating at high fields will have a number of practical conse-

[23] J. E. Kunzler, Bull. Am. Phys. Soc. **6,** 298 (1961); J. E. Kunzler, B. T. Matthias, E. Buehler, and F. S. L. Hsu (to be published).

[24] B. T. Matthias, Revs. Modern Phys. **34,** 499 (1961).

quences. It will allow the consideration of new communication devices which utilize high magnetic fields. Such devices have not seriously been considered in the past because of the impracticality of the high magnetic fields that are necessary. Such magnets are also of interest for power generation in conventional apparatus as well as for the magnetic containment of thermonuclear plasmas should these devices become practical. Currently it appears that a majority of the applications which require large magnetic fields will be able to benefit from superconducting magnets. One of the most immediate applications is likely to be for laboratory magnets. Magnets such as the 88-kgauss magnets used in the majority of the work reported here probably can be replaced by superconducting magnets, and thus make magnets more readily available to every research laboratory.

It is interesting to compare the 88-kgauss copper solenoid magnet used in many of these measurements with a comparable superconducting magnet. The 88-kgauss magnet has working space approximately 5 cm in diameter, 10 cm long, and requires about 1.5 megawatts of power to produce a magnetic field of 88 kgauss. Since all of this power is converted to heat, a cooling system handling 1000 gal per min of water is required. The cooling towers, power switching gear, motor-generator set, etc. require the equivalent of several large rooms of space and the total cost is several hundred thousand dollars.

The cryostat housing a superconducting solenoid magnet that is expected to provide the same amount of working space and that will operate at comparable fields, is visualized as being about $\frac{1}{2}$ m in diameter and approximately 1 m high. It is expected to weigh a few hundred pounds and will be powered from a current supply capable of supplying an essentially zero load. The cryostat will be portable and will require 2 or 3 liters of liquid helium (retail cost about \$10/liter) per day for refrigeration. After the initial problems are solved, it is estimated that the cost of such superconducting magnets would be a few tens of thousands of dollars each.

The possibility of using superconductors for the production of high magnetic fields and for related purposes such as power transmission and magnetic shielding, has made it possible to consider such problems in a new and often in a completely different perspective. The materials currently under consideration and most of the thinking about their applications are but a few months old. As more is learned about the behavior of superconductors in high magnetic fields, it can be expected that many more progressive steps will follow.

## ACKNOWLEDGMENTS

In addition to the many collaborators whose contributions are partially acknowledged in the text or by reference, the writer is indebted to a number of others, including T. H. Geballe, R. Kompfner, J. H. Scaff, and M. Tanenbaum for their stimulating suggestions and for encouragement.

*Note added in proof*: Since this review was written, Berlincourt, Hake, and Leslie[25] have reported results on superconducting Nb-Zr alloys at fields up to 30 kgauss. By introducing a maximum of mechanical work, they achieved current densities exceeding 100 000 amp/cm$^2$ at 30 kgauss in Nb–25% Zr. Kunzler, Matthias, Buehler, and Hsu[23] have found that the maximum field at which superconductivity persists in Nb–25% Zr (in the limit of zero current) at 1.5°K is between 80 and 90 kgauss while the maximum field at which useful current densities can be achieved appears to be about 60 to 70 kgauss.

[25] T. G. Berlincourt, R. R. Hake, and D. H. Leslie, Phys. Rev. Letters **6**, 671 (1961).