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RECENT SUPERCONDUCTIVITY TESTS AND STUDIES

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ABSTRACT

The results of recent tests with Nb_3Sn and Nb-Zr alloy wires show that the superconducting critical-current properties of both materials are very promising in tests made with short samples.

At present, Nb-Zr alloys have higher critical current densities than Nb_3Sn in magnetic fields below 60 kgauss. Nb_3Sn will go beyond 60 kgauss and has remained superconducting as high as 180 kgauss. Pulsed dc tests on short wires of Nb-25 a/o Zr at frequencies from 1 to 1,000 pps give the same critical currents as the dc tests.

Tests with small coils have not progressed beyond the 15-kgauss range. A coil wound with Nb-25 a/o Zr alloy wire reached 7.8 k gauss—a factor of 2 1/2 below the design point—but remained superconducting at the 7.8 kgauss plateau in external fields up to 70 kgauss. A coil of Nb_3Sn wire performed as predicted at 90 amp and 8 kgauss.

The effort now is to find out why short lengths of superconducting wire have better critical-current properties than coiled long lengths.

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INTRODUCTION

In early 1960, superconductivity was not considered seriously by many people for laboratory magnets. Most of the research in applied superconductivity was in the development of superconducting vacuum-evaporated thin films for computer use and for miniaturising electronic equipment. The superconductivity work was directed toward making things smaller, and very little effort was expended toward making more powerful magnets. The practical use for superconducting magnets seemed far away. At this time, to name only a few, Autler at Lincoln Laboratories was working with iron-cored niobium-wire magnets,[1] and Bozorth et al. at the Bell Telephone Laboratories were examining the magnetic properties of Nb_3Sn.[2] In August 1960, several papers on superconductivity were presented at the Cryogenic Engineering Conference.[3]

We began some superconductivity studies in mid-1960 on a part-time basis. The goal of this work was improvement of the resistive properties of superconducting metals, or a solution to the difficult problem of winding thin-film magnets.

In February of this year Kunzler and his associates at the Bell Laboratory announced that the intermetallic compound Nb_3Sn remained superconducting in magnetic fields as large as the 88 kgauss, and with current densities exceeding 100,000 amp/cm^2.[4] The implications of these experimental results to the advance of high-energy nuclear instrumentation were enormous. It became possible to construct large superconducting magnets which consumed almost neglible power

and produced fields in the neighborhood of 100 kgauss. Field strengths previously attainable only at great expense and in magnets of small size were now within reality.

It was known that certain intermetallic compounds, notably Nb_3Sn, had very high critical fields and transition temperatures, but these materials were extremely brittle and unsuitable for forming. The people at Bell Laboratories approached this as a packaging problem. They loaded a niobium tube with powdered tin and niobium, then swaged and drew the packed niobium tube to fine wire and sintered it at $\approx 1000^\circ C$.

In April 1961, Arp and Kropschot[5] at the Bureau of Standards (NBS) in Boulder and Betterson et al. of ORNL observed superconductivity in Nb_3Sn in pulsed magnetic fields.[6]

The 0.50-mm—diam NBS wire was oriented parallel to the applied magnetic field, which reached a peak value of 185 kgauss in 7 msec. NBS reported currents from 23 amp (10^5 amp/cm^2, based on core diameter) at 135 kgauss and $4^\circ K$ to 5 amp at 180 kgauss and $1.6^\circ K$.

ORNL oriented their 0.38-mm—diam wire sample both parallel and transverse to the applied magnetic field, which reached a peak value of 120 kgauss in 20 to 150 μsec. ORNL reported currents from 250 amp, in zero external field, to 45 amp at 125 kgauss in their best longitudinal sample. In the transverse sample the wire carried 2 amp at 90 kgauss. The temperature was $4.2^\circ K$ in both cases.

At the APS spring meeting in April 1961 in Washington, a niobium alloy with 33 a/o zirconium was reported to be superconducting, again by Kunzler of the Bell Laboratories.[7] The advantage of this wire was that it did not require sintering, and therefore could be used again. In the present state of the art, sintered Nb_3Sn wire can be wound only once, because flexing it appears to damage

the brittle core. Kunzler's tests showed that the Nb-33 a/o Zr alloy had a critical temperature of 16.5°K and an observed current density of 10^4 amp/cm^2 at 80 kgauss at 1.5°K. The wire required 97% cold working to achieve this current density. In the "as melted" condition, the current density was only 500 amp/cm^2.

In May 1961, T. G. Berlincourt, R. R. Hake, and D. H. Leslie of Atomics International announced that the current density had been increased another order of magnitude to 10^5 amp/cm^2 in a Nb-25 a/o Zr alloy.[8] The applied field was perpendicular to the sample in a field of 29 kgauss at 4.2°K. The sample was a strip 0.069 mm×0.38 mm rolled from wire, to increase the amount of cold work.

Nb_3Sn wires from 0.38-mm to 1.52-mm diam, and niobium-zirconium wire of 0.25-mm and 0.51-mm diam and 25 and 33 a/o zirconium have been tested at Berkeley.[9] Critical current measurements of 0.25 mm Nb-25 a/o Zr wire have been made with half-wave sinusoidal currents at frequencies of 1, 10, 100, and 1000 pps. We found no significant effect of the pulsed current on the properties of the wire. Several small superconducting solenoids have also been tested.

This brief review does not include all the people, laboratories, or companies now working on applied superconductivity. To our knowledge there are 17 laboratories or universities, and 19 manufacturing companies that are engaged in the development of superconducting coils or wire. Many other alloys and compounds, binary and tertiary, have been tried, but we would need no others for the present if we could learn to apply those that already exist.

Tests with Superconducting Wires

The applied field and critical current density characteristics of some Nb_3Sn[10] and Nb-25 a/o Zr[9] Zr alloy wires observed in tests at the Lawrence Radiation Laboratory are shown in Fig. 1. These two superconductors are the best available at this time and can be considered for most laboratory magnets. The current density is based on the total wire diameter with insulation (see Table I). Double glass insulation is assumed for the Nb_3Sn wires, and a heavy coating of synthetic resin is assumed for the Nb-Zr wires. Coil-winding space factors are not included.

The sample is placed in liquid helium, and an external magnet is used to give the desired applied field. The current is applied to the wire sample from an external dc power supply. When the critical current is reached, a resistive potential suddenly appears across the sample.

All of the data shown in Fig. 1 were taken with the wire submerged in a helium bath at 4.2°K in a magnetic field applied transverse to the current in the wire test sample. The critical field of the Nb-Zr alloys improved when the bath was cooled to about 2°K, shifting about 12 kgauss to the right.

Two sizes of Nb-Zr alloy wire were used to determine the effect of cold working. The 0.020-in.-diam wire (0.51 mm) was cold worked in excess of 99.0%, and the 0.010-in.-diam wire in excess of 99.8%. Figure 1 shows that on the basis of this small amount of data there is not a significant difference between the 0.010- and the 0.020-in.-diam wire. The difference between the two 0.020-in.-diam samples is greater.

There are many variables of the wire that can effect the results; for example, the cold working, chemical composition, homogeneity, purity, details of the manufacturing process, and the joining of the test wire to the sample holder.

The junction of the superconductor to the sample holder must be made carefully. The experimental results of the wire tests can be affected greatly by the Joule heating at the junction. A poor junction will heat excessively and may quench the superconductor. At high magnetic fields, motion of the sample must be prevented to avoid eddy-current heating. Heat transfer characteristics, above and below the λ point of liquid helium, and the specific heat capacity of the terminal junction are also important.

The Nb_3Sn data were obtained earlier and had the additional variables of core-to-sheath ratio, core composition, and sintering procedure. The Nb_3Sn wires were all sintered at 970°C for 16 hr in an out-gassed, evacuated, and sealed-off quartz tube.

The slopes of the curves in Fig. 1 show that the Nb-Zr alloys are suited for magnets of less than 70 kgauss. The Nb_3Sn compound, on the other hand, has lower over-all current densities, but it is necessary for high-field magnets up to possibly 150 kgauss.

Tests with Small Solenoids

Three small superconducting coils were tested. Two were wound with Nb_3Sn wire, and one with Nb-25 a/o Zr wire. The first coil tested was made of about 7 ft of 0.025-in.-diam Nb_3Sn wire. The coil was wound on a 1/8-in.-diam stainless steel spool, ≈ 1/4-in. wide, and had 75 turns. This wire was made at Lawrence Radiation Laboratory and was sintered, after the coil was wound, at 970°C for 16 hr in a quartz tube evacuated to less than 10^{-5} mm Hg and sealed before firing. No electrical insulation was used between turns. The wire was made from a 1/4-in.-o.d. x 1/16-in.-i.d. x ≈ 2-in.-long niobium sheath, packed in air with a weight mixture of 2.35 parts Nb to 1 part Sn powder of smaller than 325 mesh. The end was plugged with a Nb plug and the rod swaged into 0.025-in.-diam wire.

The Nb sheath is a superconductor at low field and therefore, to start the coil, the superconductivity of the sheath must be quenched without quenching the Nb_3Sn core. The sheath was quenched with an external field of ≈ 8 kgauss. At this field the Nb sheath becomes an electrical insulator relative to the superconducting Nb_3Sn core. The current was then applied to the coil from a dc external source in the usual manner.

The coil did not make a magnetic field on the first attempt. We had discovered previously, on another sample, that Sn leaked out of the wire core during the vacuum sintering operation and coated the outer surface of the coil windings. It is possible that the Sn peaked directly out of the sides of the wire, because in this state of the art the core does not always stay in the center of the wire during the swaging process. (A cross section of the wire often looks somewhat like a spiral nebula, as shown in Fig. 2.) The Sn may have combined on the outside

of the Nb sheath during sintering and formed the Nb_3Sn compound, which would cause a high-field superconducting short circuit.

The coil was etched in a solution of $2H_2SO_4 + 2HNO_3 + HF$, and then produced its rated field of 7.7 kgauss at 90 amp (see Fig. 3). The wire critical-current curve is plotted from the test data in Fig. 1. The wire used in this coil is the same as that used in the critical-current test. The coil-characteristic curve ($B_0 = 70\ i$) is the straight line starting from zero. The coil data were obtained by measurement. The magnetic field was measured with a 1/16-in.—diam search coil that was pulled through the field. The coil went normal at 7.7 kgauss. However, the coil was in an external field of 9.5 kgauss, and therefore the Nb_3Sn was in a resultant field of 12.2 kgauss, made up of its own field of 7.7 kgauss at right angles to the external field of 9.5 kgauss. The resultant field curve for the coil is the dashed line; it intersects the wire critical curve near the test point. The wire in this coil performed the same as it did in short samples.

The second coil was also made of Nb_3Sn with 265 ft of 0.015—diam wire; its performance is shown in Fig. 3b. This coil operated at 23 amp and reached a field of 12 kgauss; the resultant field on the wire was 15 kgauss. The design point was 20 kgauss at 38 amp. The coil does not have electrical insulation and the rise time of the magnet is about three hours.

Although in principle the Nb_3Sn coils can be potted in a normal metal, our future test coils will be insulated with SiO_2, to obtain a higher starting voltage so that the coil can be turned on in a reasonable time.

The third coil tested was made of 80 ft of 0.010-in. —diam Nb-25 a/o Zr wire. The wire is electrically insulated with a 0.003—thick epoxy coating. The design point of this coil was 20 kgauss at 78 amp, as shown on Fig. 3c. On the first run the coil reached only 17 amp and produced a field of 4.4 kgauss. An external field from 0 to 70 kgauss was applied to the coil. The coil consistently went normal at about 17 amp, for all fields, up to approximately 70 kgauss; above 70 kgauss the critical current of the wire diminished rapidly to zero, as expected. The coil performance was disappointing in that the critical currents expected from measurements of short samples was higher by a factor of about 2 1/2.

This result did indicate, however, that the wire is a superconductor up to 70 kgauss.

The dimensions and coil characteristics of these three coils are shown in Table II. A photograph of the coils and a wire test sample is shown in Fig. 4.

Coil Design

The operating point of a coil is at the intersection of the coil-characteristic line and the wire critical-current curve, as shown in Fig. 3. The coil-characteristic line can be calculated, but a safety factor dependent upon a degree of ignorance must be applied to the wire critical-current curve.

The coil can be designed so that it has axial stacks of coils. Thus each coil section can be separately tested and selected for optimum location in the coil assembly. The coil sections may be replaced if either the coils develop faults or a better wire becomes available.

A coil section can be further subdivided so that each subsection can be operated near the critical current. In this manner, maximum use can be made of the wire.[11] Thick coils, especially, will show a gain. Long thin coil

assemblies may require only a single pair of leads for each coil section but each section may operate at a different current. However, multiple leads may be desired for coils made of Nb_3Sn wire that cannot be used again once it has been sintered.

Present coils are driven by an external current source that allows the current to be controlled. As long as the wire size and currents are small, the heat leak into the dewar is not a problem.

Persistent currents may be desirable for some uses. These coils can be started with an external current supply connected directly to the coil. A superconducting switch, which is simply a superconducting wire, is connected across the coil terminals, and can be held in the normal state by local heating or by a magnetic field. When the desirable current is reached, the heat or field is removed and the wire switch is allowed to go superconducting. The persistant current will circulate in the coil, and the external current source can then be removed.

The electromagnetic pressure in a magnetic field is proportional to the square of the magnetic field, as expressed by $P = B^2/1.735$, where P is in $lb/in.^2$ and B is in kgauss. The solenoid may be envisioned as a pressure vessel with a wall of thickness $t = (B^2R)/(1.735S)$, where t is in inches, coil radius R is in inches, and the tensile stress, S, is in lb/in^2. For example, a magnetic field of 100 kgauss will have an internal pressure of about 6000 lb/in^2. A solenoid designed with an average tensile stress of 50,000 lb/in^2 in the coil and spool will have a wall thickness equal to 1/10 the coil radius. However, the stresses in the wire, spool, and potting compound will all be different because each material has a different area and modulus of elasticity. Tension tests made at Boulder with Nb_3Sn wire showed that the wire was still superconducting as the tension stress approached the ultimate.[12] When the limit of these designs is reached, so-called force-free coils can be considered.[13]

The question of safety is really the question of what happens to the stored energy when a coil goes "normal" due to, say, loss of refrigeration. The solution, as with conventional magnets, is to dissipate the energy in a way that does not destroy the coil. This implies converting the stored energy to heating of an internally located shorted turn. The shorted turn might be the metal spool that the coil is wound on and, in some designs, also the dewar vessels or other components enclosing the magnetic field. If this technique can be used, the temperature rise in a coil of 100-kgauss could easily be less than 200°C, or an absolute final temperature of -100°C. The rate of helium evolution will be limited by film-boiling coefficients to less than 10 w/cm^2, so this factor may be accommodated by adequate venting. If the coil thickness is determined by $t = (B^2R)/(1.735\ S)$, and all of the energy stored in the magnetic field is converted to specific heat in the coil assembly; then the temperature rise, ΔT°K, is constant for all fields and radii, and depends only upon the specific heat, c_p, and the density, w, of the material and upon the design tension stress, S in the solenoid coil assembly (i.e., $\Delta T = S/2wc_p$). The only power required to operate a superconducting magnet is that required to keep the superconductor cold. When an external current supply is used, power is not dissipated in the superconducting coil, but there is a heat loss in the leads between the current supply and the coil.

The refrigeration loss is the thermal-radiation and conduction losses between, say, liquid-helium temperature, 4.2K°, and ambient temperature. Heat can be removed at one or more intermediate temperatures chosen so that minimum refrigeration power is used.[14] Thermal-radiation shields are usually operated at liquid-nitrogen temperature in small systems. The thermal-radiation heat flux for some insulations is listed in Table III.[15,16]

Heat is lost by conduction through the coil support; the current leads; refrigerant, vacuum, and pressure-relief piping; and the connections to liquid-level and temperature indicators.

The refrigerator capacity is sometimes determined by the amount of time desired to cool the coil to the operating temperature. The refrigerator may have a high cool-down load and a low operating load. The coil assembly, if very heavy, may require a large refrigerator to remove the specific heat within a reasonable time. However, the dewar that surrounds the coil assembly may be very efficient and have a very small heat leak. The refrigerator would then operate at a very low load, once the solenoid was cold and the magnet field turned on.

The dewar surrounding the coil, the vacuum-insulation system, and the refrigeration system can be made to fit a wide range of coil designs because the coils will not vary much in thickness.

A 50-kgauss superconducting magnet, made with Nb-Zr alloy wire, and having a 32-in.-diam clear opening and a coil height of 46" would have the following characteristics when superconducting wires can perform in long lengths as they do in short lengths.[9]

Design Summary

Inner radius of coil	18 in.
Coil thickness	0.67 in.
Total coil height	56 in.
Conductor height	40 in.
Ampere-turns	8.6×10^6
Current, constant for all turns	154 amp
Wire diam with resin insulation	0.022 in.
Current density	50,000 amp/cm^2
Turns	56,000
Weight of wire	718 lb
Weight of coil assembly at 10,000 psi stress	4430 lb
Magnetic field	50 kgauss
Conduction heat loss, 4 to 77°K, 2 in.^{2} area, 10 in. long, stn stl	5w
Radiation heat loss, 10^5mm Hg vacuum 4 to 77 $^\circ$K, 100 ft^2	2.5w
Total heat loss at 4.2°K	7.5w
Refrigeration capacity at 4.2°K	50w
Heat capacity of coil assembly, 4 to 77°K	37w-hr
Time to cool coil, 77 to 4°K with 50w	45 min
Liquid-helium coil bath	250 liters
Time to liquify 250 liters	13 hr
Nitrogen use by magnet and refrigerator	25 liters/hr

Cost Summary

Summary showing the potential difference in cost.

	Conventional iron-copper magnet	Superconducting magnet
Coil	$ 250,000	250,000[a]
Core	100,000	
Refrigeration, 50w at 4.2°K		150,000
Power Supply, 7 mw	700,000	
Initial Cost	$1,050,000	$400,000
Power Cost[b] for 5 years	850,000	
Initial Cost plus 5 years power cost	$1,900,000	$ 400,000

[a]Nb-Zr alloy wire preliminary price of 350 per lb

[b]2000 hr/yr, power cost 0.01 kw/hr

Conclusion

Two superconducting materials perform very well in tests with wires 6 cm long. Preliminary results of pulsed-dc tests on short wires of Nb-25 a/o Zr at frequencies from 1 to 1000 pps give the same critical currents as the dc tests. In the three small coils with wire lengths from 7 to 265 feet, the results were scattered. One coil reached the critical current expected; another was low by a factor of about 2 1/2.

More coil tests must be made to determine the effect of wire length on critical current. Long time reliability must also be studied. The basic behavior of superconductivity in metals and the effects of composition, homogeneity, impurities, and strain are not yet well understood.

Wire of Nb_3Sn or Nb-Zr alloy is commercially available, but the wire is still in the developmental state and can not be purchased with "copper wire" dependability. Purchasers can not specify the wire completely, and manufacturers can not guarantee the superconducting properties of the wire. The only reliable acceptance test so far is to try it.

The present price of superconducting wire ranges from 100 to 400 $/lb, or about two to eight times the cost of Nb. Niobium is about as plentiful in nature as nickel.

Superconducting magnets are not here yet, but if they are fundamentally feasible they may develop faster than bubble chambers. The first small chambers were operated in 1954, two years after the discovery by Glaser in 1952. The 72-inch bubble chamber was first operated in 1959, almost 7 years after the discovery.

The cryogenic aspects of superconducting magnets are routine engineering problems. Metallurgical research has been accelerated during the past ten years, and Nb alloys are available in large quantities. There is a general interest by industry. The effort now is to find out why short lengths of superconducting wire have better critical-curve properties than coiled long lengths.

FOOTNOTES AND REFERENCES

*Work done under the auspices of the U.S. Atomic Energy Commission.

1. S.H. Autler, Superconducting Electromagnets, Rev. Sci. Instr. 31, 369, (1960); also see: P.A. Moldauer, Theory of Average Nuclear Reaction Cross Sections, Bull. Am. Phys. Soc. 6, 66 (1961).

2. R.M. Bozorth, A.J. Williams, and D.D. Davis, Critical Field for Superconductivity in Niobium Tin, Phys. Rev. Letters 5, 148, (1960).

3. K.D. Timmerhaus, Advances in Cryogenic Engineering, in Proceedings of the 1960 Cryogenic Engineering Conference, Boulder, Colorado, Aug. 1960.

4. J.E. Kunzler, E. Buehler, F.S. Hsu, and J.H. Wernick, Superconductivity in Nb_3Sn at High Current Density in a Magnetic Field of 88 kgauss, Phys. Rev. Letters 6, 89 (1961).

5. V.D. Arp, R.H. Kropschot, J.H. Wilson, W.F. Love, and R. Phelan, Superconductivity of Nb Sn in Pulsed Fields of 185 Kilogauss, Phys. Rev. Letters 6, 452 (1961).

6. J.O. Betterton, R.W. Boom, G.D. Kneip, and R.E. Worsham, Superconductivity of Nb_3Sn in a Pulsed Magnetic Field, Phys. Rev. Letters 6, 532 (1961).

7. J.E. Kunzler, Bull. Am. Phys. Soc. 6, 298 (1961).

8. T.G. Berlincourt, R.R. Hake, and D.H. Leslie, Superconducting at High Magnetic Fields and Current Densities in Some Nb-Zr Alloys, Phys. Rev. Letters 6, 671 (1961).

9. P.R. Aron, and H.C. Hitchcock, Superconductivity of Nb-25 a/o Zr Alloy in High dc Magnetic Fields, Lawrence Radiation Laboratory Report UCRL-9790 (submitted to Phys. Rev. Letters).

10. P. R. Aron, and H. C. Hitchcock, (University of California, Berkeley), unpublished data.

11. R. W. Boom, and R. S. Livingston, Superconducting Solenoids, preprint of a conference paper for Wescon Conference to be held in San Francisco in August 1961.

12. R. H. Kropschot, (National Bureau of Standards, Boulder, Colorado) private communication.

13. D. R. Wells, R. G. Mills, A. Bahr, and R. L. Peskin, The Design of Reduced Force Coil Systems, Tech. Memo No. 111, August 30, 1960, Princeton University.

14. C. Trepp, Power Consumption for Cryogenic Insulations. Lawrence Radiation Laboratory Report UCID-1321, Feb. 22, 1961 (unpublished).

15. D. G. Chelton, and D. B. Mann, Cryogenic Data Book, National Bureau of Standards Cryogenic Engineering Laboratory, Boulder, Colorado, May 15, 1956.

16. K. D. Timmerhaus, Advances in Cryogenic Engineering, in Proceedings of the 1959 Cryogenic Engineering Conference, University of California, Berkeley, California, Sept. 1959.

FIGURE CAPTIONS

Fig. 1. Critical current density versus applied magnetic field. Nb-25 a/o Zr alloy has high current densities below 70 kgauss, but Nb_3Sn will reach fields above 100 kgauss.

Fig. 2. Photomicrograph of early Nb_3Sn-cored wire in Nb sheath (0.025-in—diam wire made at Lawrence Radiation Laboratory and used in coil tests plotted in Fig. 3a). The Sn appears to have been entirely converted to Nb_3Sn. Some nonconverted Nb-powder particles are visible in the core.

Fig. 3. Coil performance of three superconducting coils. The coil characteristic line is the measured gauss/amp property of the coil. The resultant field curve of the wire is the resultant field of the external Nb quenching field and the field of the coil. The test operating points are shown. The design operating point of the Nb_3Sn coils is the intersection of the resultant field and the wire critical-current curve. The Nb-25 a/o Zr coils do not have an external quenching field.

Fig. 4. Small superconducting coils and wire test fixture.
Left to right: Nb_3Sn coil made of 7 ft of 0.025-in—diam wire (reached 12 kgauss at 23 amp). Nb_3Sn coil made of 265 ft of 0.015-in. —diam wire (reached 12 kgauss at 23 amp). Nb-25 a/o Zr coil made of 80 ft of 0.010-in. —diam wire (reached 9 kgauss at 30 amp without an external field). The coil was superconducting at 4.4 kgauss at 17 amp in external fields up to 70 kgauss. Wire test fixture 6-cm long supported in Micarta and soldered to copper blocks.

Table I. Wire insulation thickness assumed in Fig. 1.

	Wire diam (in.)	Wire diam with insulation (in.)
Nb_3Sn double-glass insulated	0.015	0.021
	0.021	0.030
	0.025	0.034
	0.060	0.069
Nb-Zr synthetic resin	0.010	0.012
	0.020	0.023

Table II. Coil characteristics.

Wire manufacturer →	LRL	Kawecki	Wah Chang
Type of wire	Nb_3Sn	Nb_3Sn	Nb-Zr
Wire diam, in.	0.025	0.015	0.010
Wire length, ft	7	265	80
Wire weight, lb	0.012	0.174	0.059
Coil i. d., in.	0.125	0.375	0.375
Coil o. d., in.	0.55	1.625	1.00
Coil width, in.	0.265	0.365	0.375
Number of turns	75	1014	430
Insulation	None	None	Epoxy 0.003-in. wall
Calculated B=Ki	94i	520i	300i
Measured B=Ki	70i	520i	260i
Coil max current, amp	90	23	30
Coil max field, kgauss	7.7	12	7.8
External quench field, kgauss	9.5	9	0 to 66
Wire resultant field, kgauss	12.2	15	4.4 to 70.4
Rise time	≈ 15 sec	≈ 3 hr	≈ 0

Table III. Insulation heat flux.

Insulation type	Temperature range (°K)	Heat flux (w/ft^2)
Vacuum 10^{-5} mm Hg	300 to 77	1.250
Vacuum,[a] 10^{-5} mm Hg	77 to 4	0.025
Vacuum,[a] 10^{-6} mm Hg	77 to 4	0.007
Multiple shield, 1/2 in. thick	300 to 4	0.070
Multiple shield, 1-1/2 in. thick	300 to 4	0.025

[a]Inside-to-outside area ratio = 0.9

Emissivity = 0.05

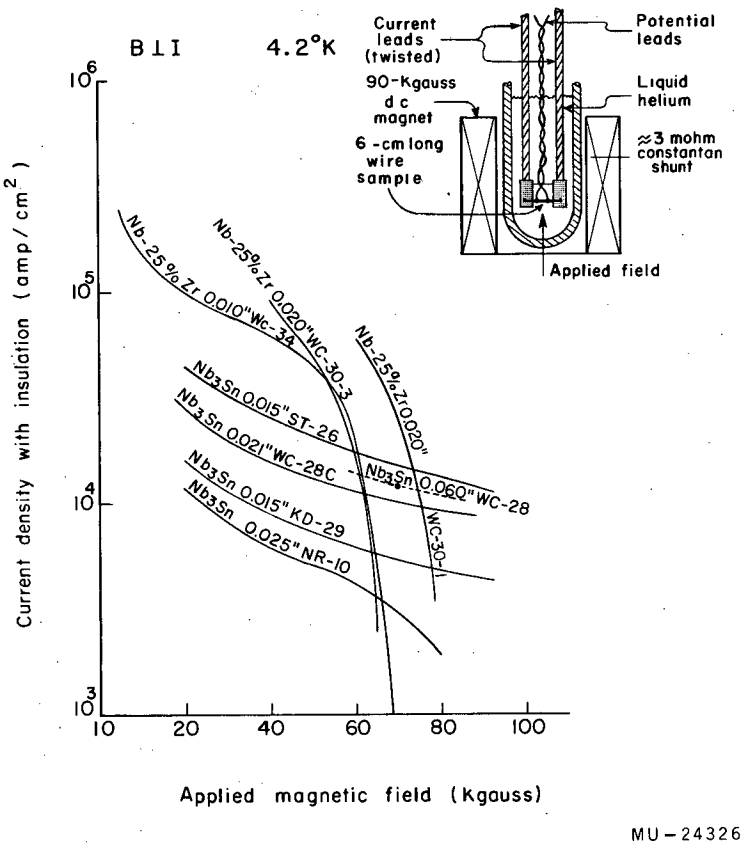

Fig. 1. Critical current density versus applied magnetic field. Nb-25 a/o Zr alloy has high current densities below 70 kgauss, but Nb_3Sn will reach fields above 100 kgauss.

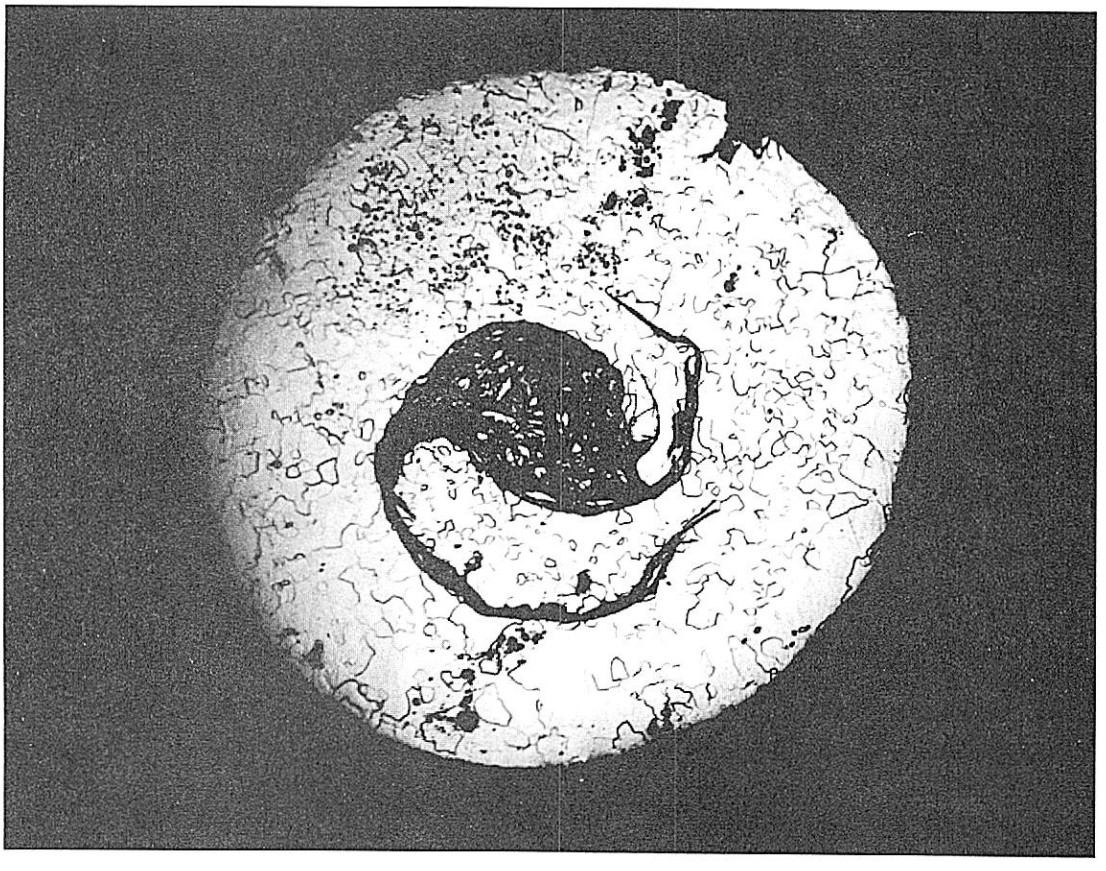

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Fig. 2. Photomicrograph of early Nb_3Sn-cored wire in Nb sheath (0.025-in—diam wire made at Lawrence Radiation Laboratory and used in coil tests plotted in Fig. 3a). The Sn appears to have been entirely converted to Nb_3Sn. Some nonconverted Nb-powder particles are visible in the core.

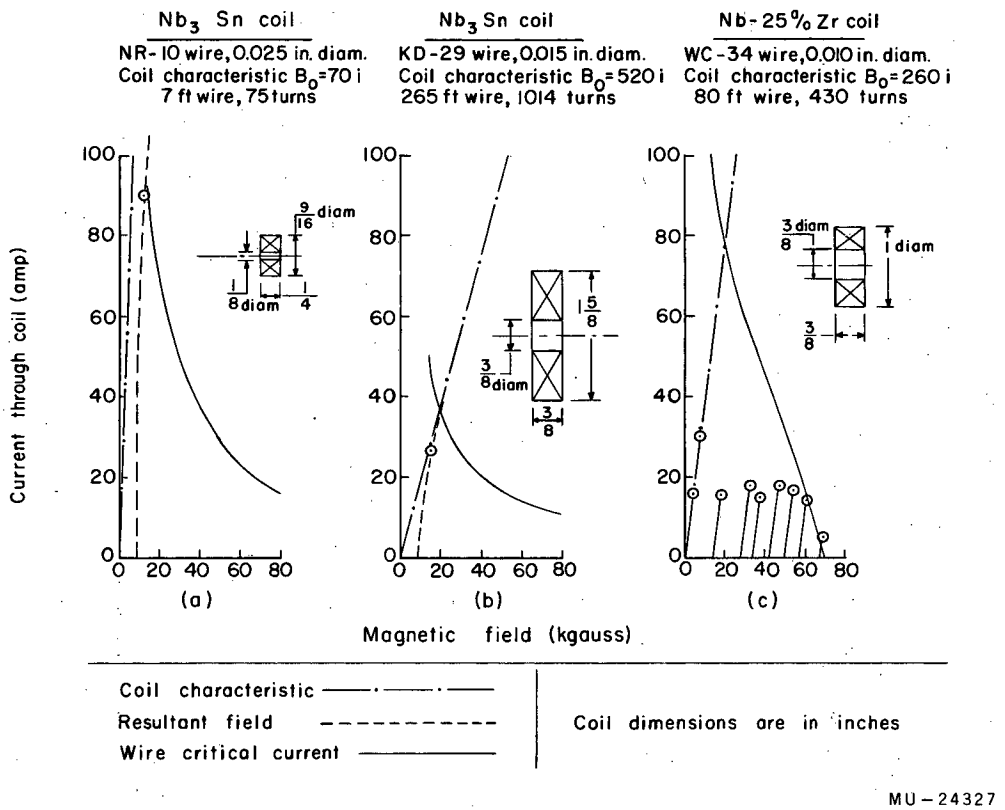

Fig. 3. Coil performance of three superconducting coils. The coil characteristic line is the measured gauss/amp property of the coil. The resultant field curve of the wire is the resultant field of the external Nb quenching field and the field of the coil. The test operating points are shown. The design operating point of the Nb_3Sn coils is the intersection of the resultant field and the wire critical-current curve. The Nb-25 a/o Zr coils do not have an external quenching field.

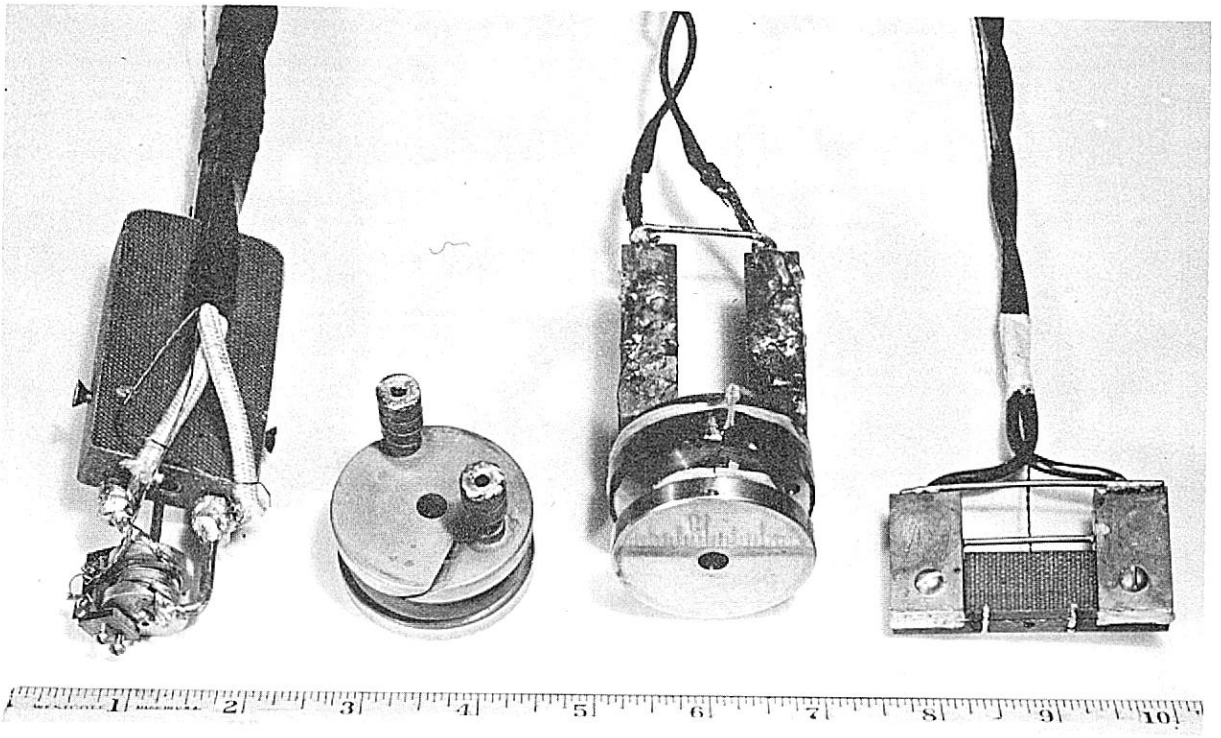

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Fig. 4. Small superconducting coils and wire test fixture. Left to right: Nb_3Sn coil made of 7 ft of 0.025-in.—diam wire (reached 12 kgauss at 23 amp). Nb_3Sn coil made of 265 ft of 0.015-in. —diam wire (reached 12 kgauss at 23 amp). Nb-25 a/o Zr coil made of 80 ft of 0.010-in. — diam wire (reached 9 kgauss at 30 amp without an external field). The coil was superconducting at 4.4 kgauss at 17 amp in external fields up to 70 kgauss. Wire test fixture 6-cm long supported in Micarta and soldered to copper blocks.

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