Part I—NON-SUPERCONDUCTING ELECTROMAGNETS

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(presented by C. E. Taylor)

I. POWER CONSIDERATIONS

The cryogenic electromagnet is based on the enormous reduction in electrical resistance which occurs when pure metals are cooled to a few degrees Kelvin; the limiting resistivity is determined only by metal purity and crystalline orderliness. Several metals have exhibited a several thousand-fold reduction in resistance when immersed in liquid helium; however, a corresponding several thousand-fold reduction in total power consumption is impossible because a refrigerator, which consumes many times the resistive power of the electromagnet, must be used to keep the magnet cold. For example, a refrigerator with an efficiency of 30 percent that of a reversible refrigerator, operating between a coil at 10°K and room temperature, will require about 100 times the coil power itself. We can write $P_{total} = G_R P_{mag}$ where P_{mag} = ohmic heating in the magnet and

$$G_R = 1 + \frac{1}{\eta_R}\frac{(T_H - T_c)}{T_c} \tag{1}$$

where η_R is refrigerator efficiency compared to a reversible refrigerator, T_H = ambient temperature and T_c = cold temperature. Clearly, no power saving will result unless the resistance reduction of the conductor is greater than G_R.

Another very important factor is that all metallic conductors exhibit increased electrical resistivity when immersed in a magnetic field. This magneto-resistance effect is usually negligible for most practical applications at room temperatures, but it can become the predominant resistance effect for pure metals at low temperatures. The resistivity of metals can, in general, be represented by three additive components as follows:

$$\rho = \rho_i + \rho_T + \rho_B$$

where ρ_i is dependent on purity, ρ_T is the classical lattice resistivity which is a function of temperature, and ρ_B is the magneto-resistance. It has been observed, in many classical magneto-resistance measurements, that ρ_B depends on ρ_i and ρ_T in addition to magnetic field; therefore, higher purity metals should have lower magneto-resistance. However, based on recent measurements, the influence of purity on magneto-resistance, for very high purity Al and Na, is not clear.

The choice of conductor metal is not easy since one must balance factors of magneto-resistance, ease of purification, and cost. On the basis of available data, it appears that two ultra-pure metals, aluminum and sodium, should be far superior to all others. They both exhibit a low magneto-resistance which approaches a limiting value as magnetic field is increased. They can be purified to a high degree at moderate cost, aluminum by electrolytic refining and sodium by vacuum distillation. They are relatively abundant. Indium also has a low magneto-resistance which saturates at modest fields;[1] however, it is extremely expensive in comparison with aluminum and sodium. Copper suffers from a high magneto-resistance as does tin.[1] Some measured values of magneto-resistance are given in Fig. 1 in which $(R_B - R_{B=0})/R_{B=0}$, the fractional resistance increase when field B is applied, is plotted against the factor $BR_\theta/R_{B=0}$ where R_θ is the resistance at the Debye temperature and $R_{B=0}$ is the zero-field resistance at the temperature at which the measurement was made.

Using these magneto-resistance data, average resistivities can be calculated for a given temperature, purity, and magnetic field. The required refrigerator power is calculated from Eq. (1) and can be compared with the power

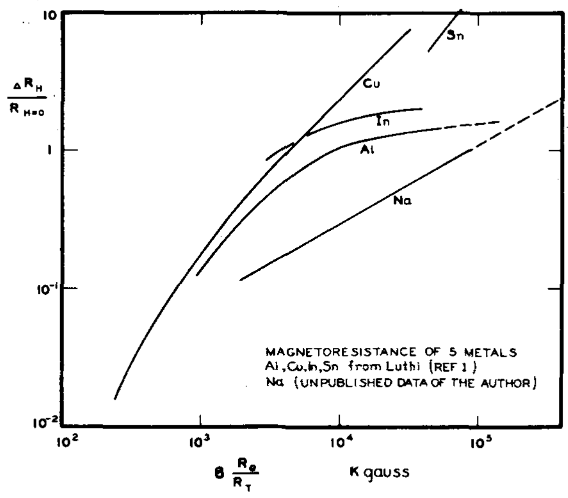

Fig. 1 Magneto-resistance of aluminum, copper, indium, tin and sodium.

required by a conventional water-cooled copper coil of the same size and same field. There will be an optimum operating temperature at which the required power is minimum. Typical curves of power saving versus temperature have been published.[2,3]

In Table 1 the power required for a water-cooled copper solenoid divided by the total power (including refrigeration) required by equivalent Na and Al solenoids is given. This table is based on solenoid proportions (independent of size) which give minimum total power. The temperatures shown are optimum for the various magnetic fields. A refrigerator efficiency of 0.3 is assumed. These figures show, for example, that power savings of the order of a factor of eight are possible for 100 kgauss solenoids and somewhat more saving at lower fields. The reliability of these power-saving estimates should be qualified by the following comments:

(a) The magneto-resistance data for aluminum were obtained using pulsed-field techniques with small wires.[1] Some constant-field measurements, also on very tiny samples, indicate that there may exist values of magneto-resistance about 40 percent higher than that used in the estimate.[4]

(b) An aluminum impurity resistance corresponding to the best available electrolytic material is used. Higher purity, zone-refined Al can be produced in small ingots; however, the handling of this material, without contamination, may present serious problems.

(c) The sodium estimates are believed to be reliable and are based on the authors' measurements on large samples. The magneto-resistance measurements are extrapolated from 18 kgauss, but this extrapolation is believed to represent a conservative upper limit.

TABLE 1

Material	Solenoid field kgauss	Optimum temperature (°K)	Power saving ratio
Al	0	16	25
	20	17	12
	50	17	10
	100	17	9
Na	0	6	17
	20	8	10
	50	8	9
	100	10	7

Aluminum would seem preferable because it is stronger and less chemically active than sodium; however, it is not at all clear whether this particular advantage is the determining factor. There are indications that aluminum is very sensitive to cold-work and careful annealing is required before use. Radiation damage may be more serious for aluminum and it remains to be seen whether repeated straining during coil operation, due to magnetic forces, will cause significant increase in resistance. Sodium must, of course, be protected from the air by coating or encapsulation; however, it is extremely insensitive to cold-work and is producible at high purity at a very low cost.

II. EXPERIMENTAL WORK

A. Copper Coils

Small, pulsed coils have been used in liquid-helium experiments for many years. Several magnets have also been operated in liquid nitrogen; however, few steady-current experiments have been made at lower temperatures. Lacquer[8] and colleagues, at Los Alamos Scientific Laboratory, have constructed a number of small liquid-hydrogen cooled coils. These were made by winding a high-purity copper strip, 5 inches wide by 0.019 inch thick, in a spiral manner using thin spacers for creating axial coolant passages. (Ref. 8 also lists some of the earlier pulsed experiments). A 2.5-inch diameter, 62-kgauss coil was built which operated continuously until the liquid hydrogen was exhausted. The purpose of this development was to achieve high fields in small volumes using a small, easily regulated power supply and to overcome the heat transfer limit of ordinary copper coils.

Borouik, et al,[9] experimented with small wire-wound liquid-hydrogen cooled copper solenoids of about 1-inch inside diameter; these developed 43 kgauss.

These two experiments were successful and revealed no unusual behavior. Large-scale use of this technique with copper coils, however, requires an excessive amount of continuous refrigeration.

B. Aluminum Coils

An aluminum coil, of 3-inch inside diameter by 11-inch outside diameter, and 16 inches long, that was designed to produce 100 kgauss, has been constructed at the Cryogenic Engineering Laboratory of the National Bureau of Standards at Boulder, Colo., and is nearly ready for test. This coil is made up of 16 identical "pancake" sections, each spirally wound from 0.004-inch thick by 1-inch wide high-purity aluminum wire, purchased commercially. Liquid hydrogen is to be pumped radially outward through channels machined into the flat faces of each section.

C. Sodium Coils

The use of sodium as a conductor material is being investigated by the authors. A solenoid, of 8-inch inside diameter, has been constructed to test the feasibility of designing larger solenoids. Several hundred pounds of high-purity sodium have been distilled at the Laboratory, at Livermore, from commercial sodium. The coil structure shown in Fig. 2 is 8 inches in inside diameter, 16 inches outside diameter, and 12 inches long. The sodium is cast in ⅝-inch square, stainless-steel tubing (0.010-inch wall thickness), which is wound in 4 cylindrical layers, with 49 turns per layer. Helium-gas coolant will pass axially through the cooling grooves which are seen in Fig. 2. A cooling system to test this coil, which can remove 5 kw at 7°K for 1 minute, is nearing completion. Helium gas at 10 atm will be available for 1-minute periods.

III. OTHER PROBLEMS

A substantial overall power reduction is clearly possible; however, the following problems must also be considered in addition to conductor resistance.

A. Insulation

Modern insulations, now being commercially applied to cryogenic liquid containers, can limit heat leakage to the order of 0.05 w/m^2 of surface using 2-inch insulation.[5] For ordinary applications, this heat leakage is completely negligible compared to ohmic heating in the conductors.

B. Heat Leak in Leads

Heat leak along the leads, and heat produced within the leads, can be limited to about 0.04 w/amp for completely uncooled leads and to less than 0.01 w/amp for liquid-nitrogen-cooled leads.[6,7] For example, two 10,000-amp leads, if properly sized, will allow less than 200 watts of heat leakage from 300°K to 10°K. For most cases this is small compared to total magnet power, and can be decreased further by using more turns of smaller conductor.

C. Mechanical Support

Mechanical support is a more serious problem. Sodium must be completely supported by structural material, both externally and internally, to resist shearing stresses. In high-purity form aluminum is also a weak material.

Fig. 2 Mold for coil of 8-inch inside diameter; sodium has not yet been cast in place.

Practical structures have been designed to resist the magnetic forces and strength is not considered a fundamental limit, at least for the moderate fields discussed here.

D. Heat Transfer from Coil to Coolant

The obvious application for cryogenic magnets is for fields in large volumes (say 1 m^3 or larger) since, for such cases, power consumption becomes an important consideration. In a large cryogenic coil with small power density, heat transfer by gas cooling is practical. Helium gas serves both as a coil coolant and as a refrigerator working fluid.

E. Capital Costs as Compared to Conventional Coils

Cost estimates indicate that, for a large solenoid-type cryogenic magnet, the capital costs, including refrigerator, are about the same as the capital costs of a conventional copper coil of the same size, including the dc power supply. Power cost is much less for cryogenic magnets (see Table 1).

IV. CONCLUSIONS

It must be emphasized that this technique is probably of little use for fields in small volumes or for pulsed fields; it may or may not be of interest for the main field of a modern synchrotron. More interesting applications may be in auxiliary equipment such as bubble chambers, or large solenoidal spectrometers.[10] One must be aware that this technique is still very much in the development stage; however, the development involves straightforward engineering and no fundamental problems seem to stand in the way.

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