High-Field, High-Current Superconductors

J. K. Hulm and B. T. Matthias

Superconductors are electrical conductors in which electrical resistance vanishes and ohmic dissipation ceases below a critical temperature (T_c), which is typically a few degrees above absolute zero. This article is concerned with a special class of superconductors which have the unusual property of retaining their zero resistance state while simultaneously passing a high electrical current density ($\sim 10^6$ amperes per square centimeter) and being subjected to a high magnetic field (up to 50 teslas). In the jargon of this subject, these materials are known as high J_c, type II materials.

The coming availability of steady fields as high as 50 T has profound implications for both science and technology. Many new and exciting experiments will be possible in this frontier region (*1*). High-field superconducting magnet technology is already affecting other research fields—for example, biochemistry (nuclear magnetic resonance in high fields) and fundamental particle physics (new high-field accelerators with 100 percent duty cycles). The new technology is also being applied to large electrical generators, magnetic fusion reactors, and magnetohydrodynamic power systems.

Summary. This article deals with superconducting materials which have zero electrical resistance while carrying high electrical current densities (around 10^6 amperes per square centimeter) in high magnetic fields (up to 50 teslas). The technological importance of these materials is due to their use in the windings of loss-free electromagnets which generate high magnetic fields. Such magnets are the foundation for superconducting electrotechnology, a rapidly growing field whose applications include advanced electrical machines and fusion reactors. The article focuses primarily on the materials aspects of this new techology. A brief overview is given of the physical principles which underlie this special type of superconducting behavior, and some of the important basic parameters are examined. The technology required to adapt the materials to electromagnets is also discussed. A few concluding remarks concern future possibilities for materials that can be used in generating very high magnetic fields.

Why are high J_c, type II materials important? Quite simply, it is because they permit a major advance in electrotechnology. Present-day electric power technology is built around the copper-iron electromagnet, which dates back to the work of Volta, Oersted, and Faraday in the early years of the 19th century. Since the magnetic induction of iron saturates at about 20,000 gauss ($\equiv$ 2 T, where T is the tesla), this magnetic field level constitutes the practical upper limit for conventional power technology (Fig. 1). However, by using high J_c, type II superconductors to construct magnet windings, the 2-T barrier can be surpassed in a dramatic fashion. Superconducting magnets have already attained 18 T. It appears to be feasible to reach at least 50 T with known materials. Although most of these devices are still in the early development stage, the era of superconducting electrotechnology seems to be dawning.

In view of the materials emphasis of this article, it is not possible to describe the wide range of superconducting electrical equipment which is now under development. Fortunately, the electromagnet constitutes a common element for most of these devices. We will therefore focus our discussion on superconducting magnet materials. We begin with an overview of the scientific principles underlying high J_c, type II superconducting behavior. This is followed by a description of the type of material necessary for magnet conductors and the various technologies required for conductor fabrication. Finally, we treat some of the more promising development areas and the prospects for achieving much higher magnetic fields.

General Principles

Superconductivity was discovered by Kamerlingh Onnes in 1911 (*2*), but high J_c, type II materials did not emerge clearly until 50 years later. A brief outline of the intervening events may help to clarify the differences between various types of superconducting material.

Onnes (*2*) observed the vanishing of resistance in pure metals at a critical temperature characteristic of each material—for example, mercury at 4.2 K, lead at 7.2 K, and so on. He later discovered that at a temperature well below T_c, the application of a magnetic field of a few hundred gauss would entirely quench superconductivity and restore the full normal state resistance. In pure metals, this quenching phenomenon occurred quite suddenly at a well-defined critical magnetic field (H_c). Such behavior is now classified as type I superconductivity.

In the 1920's it was discovered that metallic alloys did not exhibit the sharp magnetic quenching characteristic of pure metals. In particular, de Haas and Voogd (*3*) found that lead-bismuth alloys consisted of a mixture of superconducting and normal material at fields from a few hundred gauss up to 20,000 gauss. The effect was regarded as a metallurgical artifact caused by failure to achieve homogeneous samples; since these alloys also quenched into the normal state at low current densities ($\sim 10^2$ A/cm²), no technological interest developed.

Theoretical work (*4, 5*) in the Soviet Union after World War II led to an alternative explanation for the broad "mixed state" transition of alloys. It was proposed that for alloy materials, the surface energy between the superconducting and normal regions could be negative, which would encourage the formation of a mixture of superconducting and normal regions over a wide range of fields. This condition was characterized as superconductivity of the second kind, now more commonly labeled type II behavior.

During this same period, experimental work on transition metal compounds in the United States led to the discovery of

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the occurrence of high critical temperatures in the A15 crystal structure, in particular V_3Si (*6*) (T_c = 17 K) and Nb_3Sn (*7*) (T_c = 18 K). In 1961, Nb_3Sn (*8*) was found to be not only unquenchable at 88 kilogauss but also capable of simultaneously carrying a supercurrent density in excess of 10^5 A/cm^2.

The discovery of the remarkable properties of Nb_3Sn stimulated a great deal of work on type II superconducting behavior, from which the following picture has emerged. High magnetic field superconductivity occurs for those high T_c superconducting materials which are characterized by a relatively short coherence length in the superconducting state. The coherence length, ξ, is a measure of the maximum spatial rate of change of the superconducting order parameter. It is closely related to the size of the ground state wave functions in the superconductor. Coherence lengths for typical high-field materials are of the order of 100 angstroms or less, whereas considerably larger values are typical of pure metal superconductors such as In, Pb, or Sn.

Another important parameter is the penetration depth, λ, or the thickness of a surface layer carrying electric currents which prevent penetration of the magnetic field into the interior of the superconductor. For a high-field material, λ is significantly greater than the coherence length, which gives rise to the negative interface energy between superconducting and normal regions mentioned earlier. A direct result is that at a lower critical field, H_{c1}, it becomes energetically favorable for the material to enter the mixed state, exhibiting the magnetization curve shown in Fig. 2.

Below H_{c1}, the material is a pure superconductor in the "Meissner state," in which, except for the penetration depth, the magnetic field is excluded from the interior of the material. Above H_{c1}, individual quantized flux bundles, each with a magnitude of 2×10^{-7} G-cm^2, penetrate the interior of the material. Each fluxoid is surrounded by a cylindrical supercurrent vortex, which is associated with the decay of magnetic field from the center of the fluxoid to its boundary. With increasing field, more and more fluxoids enter the material, forming a periodic array or lattice. At very high fields, the fluxoids become quite closely packed (*B* in Fig. 2) so that there is hardly any decay of field in the region between fluxoids. Thus, the material is almost completely penetrated by the field; the diamagnetic magnetization approaches zero, and at H_{c2} the supercurrent vortex structure collapses. The field H_{c2} is proportional to $1/\xi^2$ and can become very large as the coherence length drops below 100 Å. Values of H_{c2} as high as 60 T have been reported (*9*).

Materials which satisfy the type II condition, $\lambda/\xi < 1/2$, fall into two classes, intrinsic and impurity-dominated (*10*). A useful approximate criterion for intrinsic type II behavior is that T_c exceeds 8 K. In principle, any superconductor can be converted to impurity-dominated type II behavior if, by the addition of impurities or other "defects," the normal state resistivity can be raised to a sufficiently high value.

It should be realized that high-field superconductors are a subgroup of type II superconductors in which H_{c2} happens to be particularly high. The origin of a high H_{c2} value may be intrinsic, impurity-dominated, or include both effects acting in unison.

In addition to high T_c and H_{c2} values, other properties are essential for a good high-field magnet conductor. A carefully annealed homogeneous single crystal of high H_{c2} material is not useful as a magnet material, primarily because the fluxoid structure of such a material is only weakly tied to the crystal lattice. If a current is passed through such a material in the mixed state and a small threshold current density J_c (< 1 A/cm^2) is exceeded, the Lorentz force $\mathbf{J} \times \mathbf{B}$ between the current and the fluxoids causes the latter to move through the lattice. Such flux flow produces observable resistance and power loss, which is believed to be connected with the motion of the fluxoid cores (*11*).

Fluxoid motion cannot be prevented above J_c, but J_c itself can be greatly increased through the deliberate introduction of imperfections into the crystal lattice. Dislocations, precipitates, and grain boundaries all play a role in enhancing J_c by "pinning" fluxoids to the atomic lattice (*12*). Figure 3 shows typical values of J_c at various fields for the two most widely used magnet materials.

That the levels of J_c indicated by Fig. 3 are reasonable for magnet performance can be seen as follows. The internal field of a long solenoid is approximately fJt, where J is the conductor current density, t is the winding thickness, and f is the packing ratio, which allows for insulation, cooling, mechanical support, and other non-current-carrying features of the winding. Experience dictates maximum f values around 0.1, so that for J_c = 10^5 A/cm^2, it is possible to reach 10 T with a solenoid of thickness 10 cm. Somewhat thicker windings can be endured at this field level, but costs and cryogenic requirements rapidly become

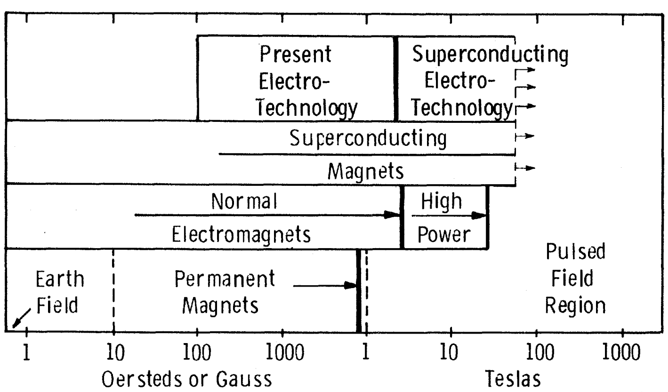

Fig. 1. Comparison of normal and superconducting electrotechnology.

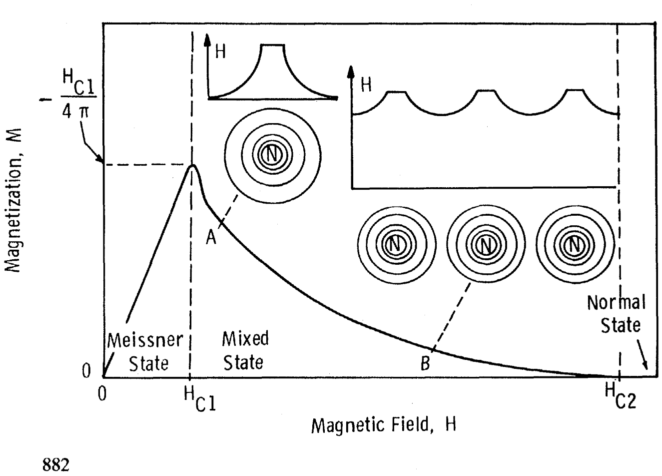

Fig. 2. Magnetization versus field for low J_c, type II superconductor.

objectionable if t is increased above 1 meter.

It might appear at first sight that much higher values of J_c would be beneficial in enabling thinner solenoids to generate the same field strength. Unfortunately, some difficulties arise in magnets as J_c is increased. To illustrate this, we consider a typical magnetization curve for a high J_c, type II material, as shown in Fig. 4.

Characteristic of the behavior of high J_c material is the occurrence of an additional hysteretic component of magnetization which is approximately equal to $\pm J_c r$, where r is the sample radius. The sign is plus for increasing field and minus for decreasing field. The extra magnetization is due to the fact that for a high J_c material, the magnetic field induces large-scale circulating currents in the bulk of the mixed state, which oppose the change of field. These induced currents rise to the critical value J_c; with further increase of magnetic field, dissipative flux flow occurs, the shielding currents collapse, and the magnetization moves toward the equilibrium type II value.

A type II material carrying a current of density J_c is said to be in the critical state (*13*). Unfortunately, this is a rather unstable state, primarily because any attempt to change H will cause dissipative flux motion and consequent heating. The rising temperature further depresses J_c locally, which causes more flux flow and more heating. This feedback mechanism can cause spontaneous collapse of the critical state magnetization (*14*), as illustrated by the oscillations in Fig. 4. The magnetization collapses suddenly and then gradually builds back up again as H changes. This phenomenon is known as flux jumping.

Most early high-field magnets experienced premature normalization difficulties (*15*). At an excitation current well below J_c, the self-field of the magnet induced flux jumps in the winding, releasing heat locally and causing a short length of conductor to enter the normal state. This normal zone then propagated through the entire winding, fed by the stored energy of the magnet.

Since the critical state magnetization term is proportional to the radius of the superconducting specimen, the energy released per unit volume by collapse of this type of magnetization within a magnet is also dependent on the radius of the superconducting wire. The flux jump problem can therefore be ameliorated by reducing the size of the superconductor (*16*). Magnet conductors are now constructed from fine filamentary superconductors, separated from each other by normal metal, which serves to decelerate the transition to the normal state. The filament diameter is usually less than 50 micrometers.

Summarizing the discussion up to this point, there are three primary requirements which a high-field superconducting magnet conductor must satisfy. First, the material should exhibit relatively high T_c and H_{c2} values, at least exceeding 8 K and 10 T, respectively. Second, it must be susceptible to a method of preparation which results in a high concentration of defects, without appreciable reduction of T_c or H_{c2}. Third, but no less important, the preparation technique must parallel the superconductor with a pure metal stabilizer such as copper; fine subdivision of the superconductor is also desirable.

In addition to these primary requirements, there are other magnet design parameters which affect the conductor design. For example, the winding must withstand large mechanical stresses due to $\mathbf{J} \times \mathbf{B}$ forces. Thus, if possible, the conductor itself should be strong and its superconducting properties should not be appreciably degraded by stress. It may be necessary to use other high-strength materials as bracing or packing elements in the winding, at the expense of lower f. These may also be in conflict with the basic need to expose the conductor to maximum cooling by liquid helium. It is no exaggeration to say that good magnet design requires the best skills and cooperation of mechanical, electrical, and heat transfer engineers, combined with special demands on materials engineering for the conductor itself.

We will now turn our attention to materials which either satisfy the three primary conductor requirements or promise even more attractive properties in the future.

High T_c

All of the presently known high T_c superconductors were discovered exclusively by experimental investigation of the occurrence of superconductivity throughout the periodic system (Fig. 5). Niobium, at the center of the transition

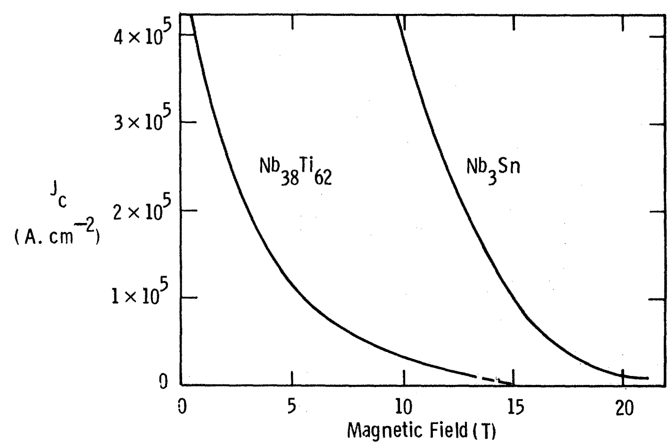

Fig. 3. Critical current density as a function of field, $Nb_{38}Ti_{62}$ and Nb_3Sn.

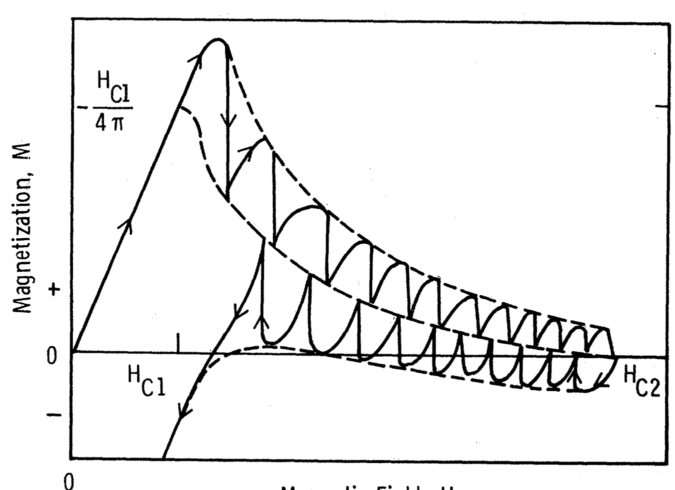

Fig. 4. Magnetization versus field for a high J_c type II superconductor.

metal group, exhibits the highest T_c value for an element, 9.25 K. It should be noted that many elements become superconducting at ultrahigh pressures, usually by the formation of new phases. Most of these are not stable at atmospheric pressure and thus at present have little technological value.

Studies of superconducting compounds were started before World War II by Meissner, Justi, and their co-workers (*17, 18*) who examined the carbides and nitrides of the transition metals. They managed to find several compounds with T_c above 10 K and in one case, NbN, just over 15 K.

In 1950 we began an effort to determine the critical conditions for the occurrence of superconductivity and, in particular, high T_c values. Our experiments led to the formulation of a rather clear-cut criterion. For high T_c among materials based primarily on the transition metals, the average electron concentration per atom, *e/a*, is the primary parameter. The definition of *e/a* is very simple. Counting all electrons outside a filled shell will give *e/a* for a single element, whereas for compounds the arithmetic average has to be taken. There are certain critical values of *e/a* which favor high T_c—for example, 4.7 and 6.4. The rule is valid for elements, their mutual solid solutions, and compounds formed between them (*19*). This *e/a* criterion is in general valid only for phases containing one or two elements.

Our experiments led to the discovery of superconductivity in the A15 structure (*6*), which has since yielded four distinct compounds with T_c above 18 K, as listed in Table 1. High T_c values are also exhibited by certain pseudobinary A15's (*20*).

The clear superiority of A15 compounds over all other contenders, at least as far as high T_c is concerned, has focused great attention on this structure. A test of the *e/a* rule for the known superconducting A15's is illustrated in Fig. 6, where the peaks mentioned above are apparent. The curves of Fig. 6 are essentially boundaries to the data. It seems that *e/a* values of 4.7 and 6.4 favor, but, because of various side effects, do not ensure high T_c values.

Most of the A15 superconductors with T_c values below about 19 K (Table 1) can be prepared by direct melting of the constituents. The materials with higher critical temperatures all require special techniques of synthesis. For example, T_c for the unique compound Nb_3Ge was brought up to 23 K by sputtering a thin film of the material onto a heated substrate (*21*). In the case of Nb_3Ga, quenching is necessary to achieve high T_c (*22*). These various compounds are also susceptible to depression of T_c by disorder or by deviations from stoichiometry, which does not ease the problems of conductor fabrication.

Table 1. Superconducting binary and pseudobinary compounds having the A15 crystal structure.

Compound	T_c (K)	$H_{c2}(0)$ (T)	$-(dH_{c2}/dT)$, $T = T_c$ (K^{-1})
Nb_3Sn	18.0	29.6	2.4
Nb_3Al	18.7	32.7	2.5
Nb_3Ga	20.2	34.1	2.4
Nb_3Ge	23.2	37.1	2.4
$Nb_3Al_{0.7}Ge_{0.3}$	20.7	44.5	3.1
$Nb_3Al_{0.5}Ga_{0.5}$	19.0	31.6	2.4
V_3Si	17.0	34.0	2.9
V_3Ga	14.8	34.9	3.4

Future increases in T_c would appear to depend heavily on further advances within the A15 structure. The *e/a* correlation suggests that other intermetallic compositions might exhibit high T_c values if only they could by synthesized in the A15 structure. A good example is Nb_3Si, which does not form an A15 phase with conventional preparation (*23*). By explosive compression to megabar pressures, superconductivity has recently been reported in Nb_3Si between 18 and 19 K (*24*). Novel methods of preparation such as this may yield metastable forms of higher T_c material in binary or pseudobinary systems and are certainly to be encouraged.

High H_{c2}

Upper critical field data for several important high-field superconductors are plotted against temperature in Fig. 7. Both $Nb_{38}Ti_{62}$ and Nb_3Sn have been available in filamentary composite form for some time and are widely used. The other materials in Fig. 7 have not yet been developed as filamentary conductors, and consequently the highest field generated by a superconducting magnet to date is about 18 T. In the face of the unexploited materials potential shown in Fig. 7, to advocate further advances in H_{c2} may seem to be gilding the lily. Nevertheless, the prospect of a megagauss material is extremely exciting and is by no means ruled out by present knowledge.

We have already noted the subdivision of type II materials into two classes, the pure or intrinsic type and the impurity-dominated type. From Gorkov's work (*10*), it is found that H_{c2} (0) (that is, H_{c2} at $T = 0$) for intrinsic materials is proportional to $(\gamma T_c)^2$, where γT is the linear term in the normal state heat capacity at low temperatures. Similarly, $H_{c2}(0)$ for impurity-dominated material is proportional to $\rho_n \gamma T_c$, where ρ_n is the electrical resistivity in the normal state. With some approximations, the intrinsic and impurity regions can be separated by plotting $H_{c2}(0)$ against γT_c, as in Fig. 8.

The bottom curve of Fig. 8 denotes the intrinsic type II case, which seems to be well represented by pure Nb_3Sn (*25*). Each dashed curve in Fig. 8, labeled according to a specific level of normal resistivity in microhm-centimeters, represents the sum of the intrinsic and impurity components for that level of resistivity. The numbers in parentheses are the actual normal resistivities for the materials. A higher resistivity sample of Nb_3Sn is compared with the pure material. The increase in H_{c2} caused by impurities is small because of the downward shift of γT_c. It is well known that $Nb_{38}Ti_{62}$ is impurity-dominated, and $PbMo_6S_8$ is probably of the same type. Thus, the record high H_{c2} value of this Chevrel phase compound is primarily due to its unusually high electrical resistivity (*26*), which overcomes the handicap of a T_c value somewhat below that of the A15 compounds.

The model on which Fig. 8 is based ignores other possible difficulties in the search for higher critical fields. The most famous of these is the paramagnetic limit (*27, 28*), which suggests that type II behavior will not be energetically favored above a field, H_p, such that the magnetization energy associated with the spins of conduction electrons in the normal state exceeds the superconducting condensation energy. Experience has shown that there is, indeed, an appreciable paramagnetic lowering of $H_{c2}(0)$ in superconductors formed from elements in the first long period, such as Ti and V. However, the effect is less noticeable in materials formed predominantly from elements in the second and third long periods, such as Nb and Mo. This is usually attributed to the effect of spin-orbit scattering, which causes spin depairing in the superconducting ground state and thus tends to equalize the spin magnetization energy terms between the superconducting and normal states. Spin-orbit scattering is known to increase with increasing atomic mass, which is consistent with the experimental data mentioned above.

As Fig. 8 indicates, there is considerable scope for further advances in $H_{c2}(0)$, provided ways can be found to increase T_c, γ, or ρ_n. The normal resistivity offers perhaps the easiest line of attack on this problem.

High J_c Composites

Shortly after it was realized that conductors for magnets could be stabilized against flux jumping by means of fine filamentary construction, successful conductors of this type were produced from the Nb-Ti alloy system. This material is extremely ductile, which greatly facilitates the manufacturing process.

To produce this type of conductor, rods of Nb-Ti alloy are inserted into holes drilled in a large pure copper billet. The billet is then hot-extruded down to a size suitable for wiredrawing, which usually involves a reduction of about 50 to 1. Cold drawing is then carried out, with perhaps a few intermediate anneals, until the Nb-Ti filaments reach the desired size, usually less than 50 μm. The process ends with a long anneal at 375°C, which causes a second phase precipitation accompanied by a rearrangement of the dislocation cell structure. This results in a substantial increase of J_c, to levels around those shown in Fig. 3.

A monolithic, multifilamentary Nb-Ti conductor is shown in Fig. 9 (top conductor). This material contains about 1000 superconductor filaments 50 μm in diameter which have been exposed by etching away the copper matrix. The current-carrying capacity of this small conductor at 4.2 K and 5 T is about 10,000 A, which is comparable with the capacity of the larger bar of plain copper (bottom conductor in Fig. 9) at room temperature and 2 T in the field coil of a large generator.

Conductors based on Nb-Ti are generally excellent for applications up to about 8 T, but the T_c and H_{c2} performance of these alloys (Figs. 3 and 7) is quite limited. Regrettably, we know of no other ductile alloy systems which exhibit appreciably better critical superconducting parameters at present. The Nb-Ti lies close to the 4.7 *e/a* peak (*29*) and has a ρ_n of about 60 μohm-cm (*30*). There are ductile alloys near the 6.4 *e/a* peak, such as Mo-Re, but here the normal resistivity is much lower and gives rise to a disappointingly low H_{c2}. There seems to be a basic conflict between ductility and high T_c or H_{c2}.

To build magnets for fields appreciably above 8 T, intermetallic compounds must be used. Intermetallic superconductors cannot be drawn directly into wire, because of their extreme brit-

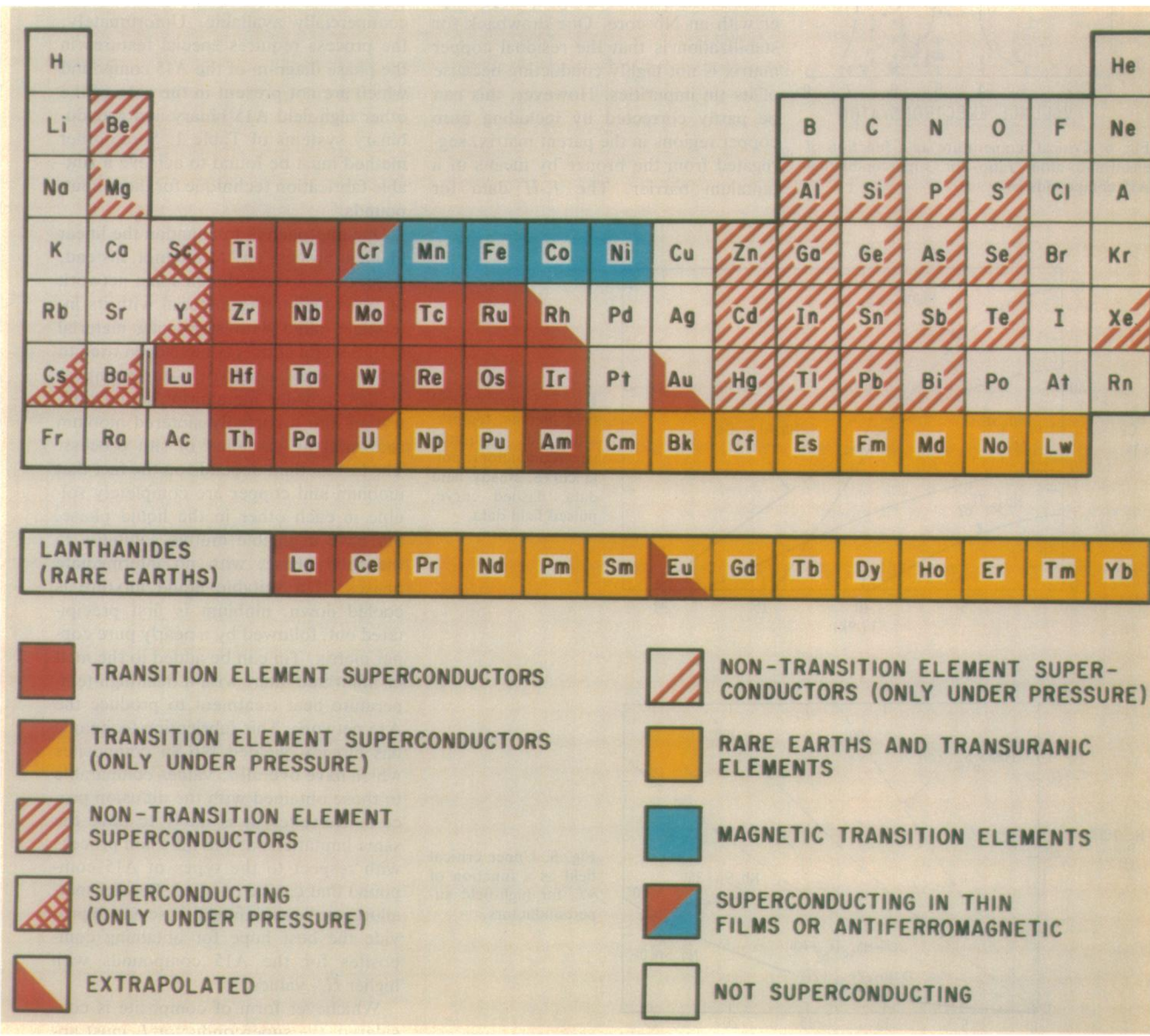

Fig. 5. The periodic system of superconductors.

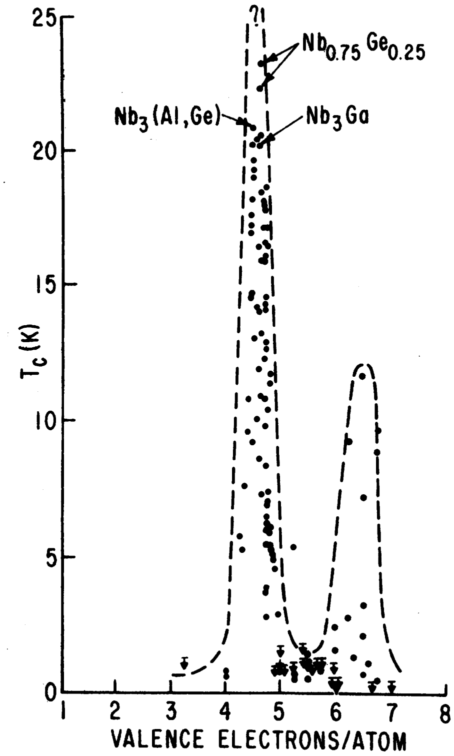

Fig. 6. Critical temperature as a function of electron-to-atom ratio for superconducting A15 compounds (36).

tleness. Thus early efforts to produce conductors were focused on Nb_3Sn tapes produced either by directly reacting Nb with molten Sn or by depositing both components at high temperatures from metal halide vapors (chemical vapor deposition). Such tapes are useful for small working volume, high-field magnets; in larger systems the superconductor needs to be subdivided for stability.

Useful subdivided composites of V_3Ga and Nb_3Sn were first achieved by an ingenious diffusion process (31, 32). In this technique, fine filaments of Nb metal are embedded within a bronze (Cu-Sn) matrix, in a manner analogous to that already described for Nb-Ti filaments in copper. After drawing is completed, a high-temperature heat treatment causes tin to migrate out of the bronze into the niobium filament, forming an Nb_3Sn layer with an Nb core. One drawback for stabilization is that the residual copper matrix is not highly conducting because of its tin impurities. However, this can be partly corrected by including pure copper regions in the parent matrix, segregated from the bronze by means of a tantalum barrier. The J_c-H data for

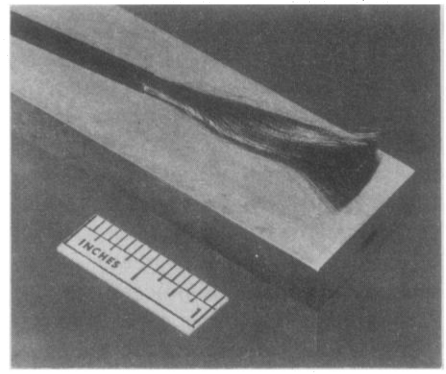

Fig. 9. Multifilamentary Nb-Ti composite conductor; beneath it is a copper bar.

Nb_3Sn in Fig. 3 were obtained for a diffusion-reacted composite of this type.

Multifilamentary composite conductors of both Nb_3Sn and V_3Ga are now commercially available. Unfortunately, the process requires special features in the phase diagram of the A15 compound which are not present in the case of the other high-field A15 binary and pseudobinary systems of Table 1. Some other method must be found to achieve a suitable fabrication technique for these compounds.

One approach is to abandon the linear filament process and to attempt, instead, to produce a three-dimensional network of superconducting material with its interstices filled with stabilizing material (33). Several concepts have been tried to produce such a network—for example, straight powder metallurgy, liquid infiltration into a partially sintered niobium rod, and the so-called in situ process. The last method depends on the fact that niobium and copper are completely soluble in each other in the liquid phase, but have negligible mutual solubility in the solid phase, with no intermediate phases. If a suitable liquid mixture is cooled down, niobium is first precipitated out, followed by a nearly pure copper matrix. Tin can be added to the melt or infiltrated later, with a final high-temperature heat treatment to produce the A15 network. This fabrication technique has already yielded Nb_3Sn composites which have overall J_c values comparable to those obtained with the diffusion process. However, it is likely to have the same limitations as the diffusion process with respect to the types of A15 compound that can be handled. Powder metallurgy or liquid infiltration seems to provide the best hope for obtaining composites for the A15 compounds with higher H_{c2} values.

Whichever form of composite is considered, the superconductor J_c must approach 10^5 A/cm² for practical magnet

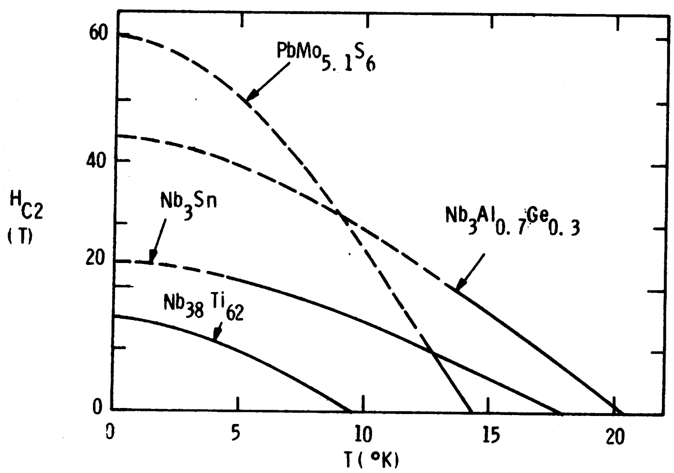

Fig. 7. Upper critical field versus temperature for high-field superconductors; solid curve, steady field data; dashed curve, pulsed field data.

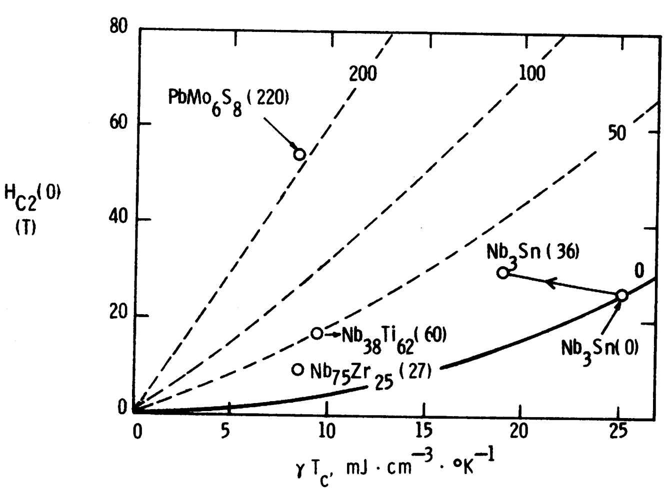

Fig. 8. Upper critical field as a function of γT_c for high-field superconductors.

construction. Nb-Ti alloys achieve this level by a combination of cold work and heat treatment; the fluxoids are pinned by dislocation clusters. For A15 compounds, the fluxoids are probably pinned by grain boundaries; it is fortunate that most of the processing techniques discussed above can be manipulated to yield small grain sizes and adequate J_c levels. It is not clear that this natural dispensation will extend to other materials of interest for use at very high fields; indeed, preliminary work on the Chevrel phases (*34*) has yielded poor J_c levels so far.

At present, the majority of superconducting magnets in use or under development utilize some form of Nb-Ti multifilamentary composite. A15 tapes are utilized in a few high-field research magnets. A very large magnet, using an Nb_3Sn filamentary composite, is currently being developed by Westinghouse and Airco for Oak Ridge National Laboratory. This magnet is part of an experimental prototype system for a future tokamak fusion test reactor. It will offer a severe test of the viability of A15 composites.

Future Possibilities

Major efforts are now in progress to build large magnets in the range 5 to 12 T for application to fusion systems, high-energy particle accelerators, magnetohydrodynamic power ducts, electrical generators, and other large electrical power devices. By large, we mean a working volume of at least 1 cubic meter or a stored energy in excess of 1 megajoule, or both. Considerably less effort—indeed, hardly any at all—is being devoted to pushing into the unexplored zone above about 18 T. It must be admitted that much of the magnet technology which is being developed for the lower-field range will be extremely useful above 18 T. Unfortunately, this will not in itself be sufficient to open up the frontier.

Specific development work is needed on superconducting composite conductors suitable for use above 18 T. There are several promising candidates for this purpose, including the A15 compounds Nb_3Ge and $Nb_3Al_{0.7}Ge_{0.3}$ and Chevrel phase compounds such as $PbMo_{5.1}S_6$. The requirements include fluxoid pinning strength sufficient to yield J_c values above 10^5 A/cm^2, pure metal cladding or bonding to the conductor, and, if possible, fine subdivision of the superconductor. This program seems to present an exciting challenge to materials scientists and engineers.

Behind the conductor development program lies the more fundamental question of improving the basic superconducting parameters, particularly T_c and H_{c2}. We have indicated some of the possible directions of attack in this area. The possibility of forming new compounds in the transition metal region of the periodic system is by no means exhausted, particularly in view of the growing spectrum of new techniques of synthesis which have appeared in recent years. In particular, the field of true ternary compounds is in its infancy, not yet a decade old, but is already very promising.

In the case of T_c, past progress has depended entirely on experimental exploration for new materials. Theory has had very little to contribute, mainly offering explanations after the event rather than predictions beforehand. We see no reason for a change in this situation.

As regards H_{c2}, early experimental studies of low H_{c2} alloys (*35*) provided the basis for Abrikosov's remarkable theory of type II behavior. However, the discovery of high-field, high-current superconductors was made independently of theory and came about primarily from materials exploration. The Abrikosov-Gorkov theory has certainly provided excellent guidelines for further work in this area.

We have noted that high-field, high-current superconductors have opened up a new regime of electric power technology (Fig. 1). This regime will be further advanced if better materials can be found. In our view, there is a reasonably good prospect for a 30 K superconductor and a 1-megagauss superconductor in the future, either separately or perhaps together in the same material. It would seem to be of value to both science and technology to pursue these goals.

References and Notes

1. *High Magnetic Field, Research and Facilities* (National Academy of Sciences, Washington, D.C., 1979); see also *Phys. Today* **32**, 21 (September 1979).
2. H. Kamerlingh Onnes, *Leiden Commun. No. 119B* (1911); *ibid., No. 120B*; *ibid., No. 122B*.
3. W. J. de Haas and J. Voogd, *ibid., No. 199C* (1929); *ibid., No. 214B* (1931).
4. V. L. Ginzburg and L. D. Landau, *Zh. Eksp. Teor. Fiz.* **20**, 1064 (1950).
5. A. A. Abrikosov, *Sov. Phys. JETP* **5**, 1174 (1957).
6. G. Hardy and J. K. Hulm, *Phys. Rev.* **87**, 884 (1953).
7. B. T. Matthias, T. H. Geballe, S. Geller, E. Corenzwit, *ibid.* **95**, 1435 (1954).
8. J. E. Kunzler, E. Beuhler, F. S. L. Hsu, J. H. Wernick, *Phys. Rev. Lett.* **6**, 89 (1961).
9. S. Foner, E. J. McNiff, E. J. Alexander, *Phys. Lett. A* **49**, 269 (1974).
10. L. P. Gorkov, *Sov. Phys. JETP* **9**, 1364 (1960).
11. Y. B. Kim, C. F. Hempstead, A. R. Strnad, *Phys. Rev.* **129**, 528 (1963).
12. P. W. Anderson, *Phys. Rev. Lett.* **9**, 309 (1962).
13. C. P. Bean, *ibid.* **8**, 250 (1962).
14. S. L. Wipf and M. S. Lubell, *Phys. Lett.* **16**, 103 (1965).
15. J. K. Hulm, B. S. Chandrasekhar, H. Riemersma, *Adv. Cryog. Eng.* **8**, 17 (1963).
16. C. Laverick, *Proc. Int. Symp. Magnet. Technol. Stanford* (1965), p. 560.
17. W. Meissner and H. Franz, *Z. Phys.* **65**, 30 (1930).
18. G. Aschermann, E. Friederich, E. Justi, J. Kramer, *Phys. Z.* **42**, 349 (1941).
19. B. T. Matthias, *Phys. Rev.* **97**, 74 (1955).
20. _____, T. H. Geballe, L. D. Longinotti, E. Corenzwit, G. W. Hull, R. H. Willens, J. P. Maita, *Science* **156**, 645 (1967).
21. J. R. Gavaler, *Appl. Phys. Lett.* **23**, 480 (1973).
22. G. W. Webb, L. T. Vieland, R. E. Miller, A. Wicklund, *Solid State Commun.* **9**, 1769 (1971).
23. D. Dew-Hughes and L. T. Luhman, in *Treatise on Materials Science and Technology* (Academic Press, New York, 1979), vol. 14, p. 437.
24. V. M. Pan *et al.*, *JETP Lett.* **21**, 228 (1975).
25. T. P. Orlando, E. J. McNiff, S. Foner, M. R. Beasley, *Phys. Rev. B* **19**, 4545 (1979).
26. Ø. Fischer, *Appl. Phys.* **16**, 1 (1978).
27. A. M. Clogston, *Phys. Rev. Lett.* **9**, 266 (1962).
28. B. S. Chandrasekhar, *Appl. Phys. Lett.* **1**, 7 (1962).
29. J. K. Hulm and R. D. Blaugher, *Phys. Rev.* **123**, 1569 (1961).
30. T. G. Berlincourt and R. R. Hake, *ibid.* **131**, 140 (1963).
31. K. Tachikawa and T. Tanaka, *Jpn. J. Appl. Phys.* **6**, 782 (1967).
32. A. R. Kaufmann and J. J. Pickett, *J. Appl. Phys.* **42**, 58 (1971).
33. R. Roberge, *J. Magn. Magn. Mater.* **11**, 182 (1979).
34. D. Dew-Hughes and L. T. Luhman, in *Treatise on Materials Science and Technology* (Academic Press, New York, 1979), vol. 14, pp. 435–436.
35. L. W. Schubnikow, W. I. Chotkewitsch, J. D. Schepelew, J. N. Rjabinin, *Phys. Z. Sowjetunion* **10**, 165 (1936).
36. B. W. Roberts, *Natl. Bur. Stand. U.S. Tech. Note 825* (Suppl.) (1974), p. 7.

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