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SUPERCONDUCTING MAGNETS

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ONE of the characteristic features of present-day science is the very rapid adoption of the results of the investigation of new phenomena (within five years of their discovery) in everyday practice.[1] Not five, but a little over fifty years have already passed since the discovery of the phenomenon of superconductivity,[2] and although the extensive use of superconducting solenoids in laboratory practice has already begun and the discovery of superconductivity in strong magnetic fields can be nominally referred to 1961 (generally speaking, it is more correct to refer it to 1930[4]), one must nevertheless concede that the adoption of various devices based on the use of this surprising phenomenon was somewhat delayed.

We recall that the possibility of employing superconductors in the windings of a solenoid intended for the production of strong magnetic fields was already foreseen by Kamerlingh Onnes[5] soon after the observation of superconductivity. However, he soon established[6] that under the action of a current (magnetic field) the surprising property discovered by him disappears. The smallness of the "critical" fields for known materials, i.e., the magnetic fields in which the superconductor becomes an ordinary "normal" metal, made it impossible for a long time to employ superconductors for the production of magnets. Only at the beginning of the Sixties was it observed that certain compounds and alloys[3,7,8] remain superconducting in sufficiently strong fields on the order of a hundred kilo-oersteds and, no less significantly, for very strong currents. (The superconducting Pb-Bi alloys discovered in 1930[4] with a critical field of the order of 20 kOe were not used at that time because the critical currents of the samples investigated at the time turned out to be negligibly small.[9]) The rapid growth of the new "superconducting" technology, and the development of experimental and theoretical investigations in the field of superconductivity in strong fields due to these discoveries, in particular to the work of Kunzler, Buehler, et al.,[3] is well known. However, it must be said that the unpleasant, from our point of view, property of superconductors transforming into the usual "normal" metal under the influence of temperature or current, or by their own magnetic field, the basic "product" for the described sphere of application of superconductors, delayed to some extent the progress of this new technology even during the past five years; at any rate, this property has in many respects determined the specifications of the majority of technical problems which had to be solved in the construction of superconducting solenoids and which we shall consider in part in this article. (The presence of similar unpleasant properties in superconductors is apparently not essential; at least, the possibility of the existence of linear superconductors[10] which "come about" solely through ponderomotive forces—the action of fields of hundreds of kilo-oersteds, has been theoretically predicted.)

1. TRANSITION OF SUPERCONDUCTING COILS INTO THE "NORMAL" STATE

The author always finds it difficult not to put the accepted term "normal" in quotes, because after all it is the superconducting state which is the normal state of a superconducting solenoid. Let us then consider what takes place when a portion of the winding of a superconducting solenoid goes over for any reason into the "normal," state, i.e., the state in which it possesses an electrical resistance. (The electrical resistance of the superconductors of greatest interest to us in the normal state should on principle be rather high[11]—it is precisely the decrease in the free path of the electrons which leads in the final analysis to the increase of the critical fields of such superconductors.) The energy dissipated in the normal zone heats, by thermal conduction, also the adjoining superconducting portions above the critical temperature; the normal zone grows until the entire stored magnetic energy of the solenoid is expended. The maximum temperature at the center of this zone depends on the decay time of the current in the solenoid, the average heat conduction and the heat capacity of the windings, and the total energy, and can amount even in the case of small solenoids to hundreds of degrees; this makes possible the destruction of the insulation and irreversible changes (annealing) in the superconducting material, which have a negative effect on the critical parameters of the solenoid. When the total energy in the solenoid is on the order of hundreds of joules[12] a complete destruction of portions of the wire is also possible. Overvoltages appearing between turns with nonuniformly distributed resistance also constitute a considerable danger. Breakdown of the insulation, short-circuiting of part of the turns, or arcing in the windings can lead to the destruction of portions of the wire.

The natural means of combating these dangers which come down as a whole to a decrease of the average resistance of the material of the windings and to an increase in their heat conduction came to be used soon after construction of the first solenoids; the simplest and most efficient method of achieving this is by covering the superconducting wire with a thin (30–40 μ) layer of copper. The effective resistance of the windings decreases thus by a factor of some hundreds; this also increases automatically the characteristic times of the process, which in turn facilitates the distribution of the magnetic energy over a large volume. We note that the use of copper cladding facilitates considerably the technical realization of special measures for the electrical shielding of the solenoid, to a description of which we shall return again (Sec. 5).

It is no less important to note that the use of cladding made it possible also to decrease somewhat the unpleasant effect called "degradation" which consists in an appreciable (unpredictable) decrease of the critical currents of the wire in solenoids compared to values which could be expected from the results of experiments with short lengths of the same wire. Thus the introduction of thin copper cladding was of great assistance in the solution of various technical difficulties standing in the way of the production of sufficiently large and efficient solenoids; more exactly, these difficulties have been pushed back to some new limits, to new scales of dimensions and energies of the magnetic systems. Much time and the work of numerous investigators were required before Kantrovitz and Stekly[13] succeeded in 1965 to take the next step towards even larger, so far still poorly perceivable scales of superconducting systems, a step which can in its significance and stimulating interaction be ranked along with the previously mentioned discoveries of 1961.[3,7,8] The method proposed by these authors practically removed the danger of the dissipation of magnetic energy in the windings and simplified thereby the entire problem of shielding the solenoid; it made it possible in general to get rid of degradation and to predict the parameters of the solenoid accurately. At that, this method which led to such qualitative improvements consisted in essence in a further decrease of the effective electrical resistance of the windings and in an increase of their thermal conductivity; this was achieved in particular by covering the superconducting wire with a considerably thicker layer of the same copper.

Before one delves deeper into the details of the problems we touched upon, one must answer the question which could have been raised at the beginning of this section: *how can a length of the normal phase appear in the winding of a "superconducting" solenoid?*

2. FLUX JUMPS AND THE DEGRADATION PHENOMENON

It may seem that in a winding made of superconductor, i.e., of material with no resistance, the normal phase can appear only as a result of an external (thermal, electromagnetic, or mechanical) interaction, or when the current and its own magnetic field increase to supercritical values characteristic for the given material. But even the latter phrase contains a certain uncertainty—the material of the windings may not be quite uniform and the critical parameters may depend on a number of conditions under which they are determined. Good agreement between the critical currents of solenoids with the results of preliminary measurements carried out on short lengths of the same wire was observed only in the first experiments with a small solenoid of Mo-Re alloy.[7] On the other hand, in all subsequent work with new, more promising materials (Nb-Zr, Nb-Ti, Nb_3Sn) and with larger solenoids a considerable, in a typical case *a three- or fivefold and* partly an even sharper, decrease in the typical currents of the solenoids ("degradation") was systematically observed compared to the values characteristic of small samples of these materials. We *note that it was possible* to show by a number of methods[14,15] that the phenomenon of nonuniformity of a material appearing inevitably in large amounts of material is nevertheless not a dominating effect.

What can be the reasons for the degradation? How do the conditions of the wire in a winding generally differ from those under which measurements of the critical currents of a short length of the same wire are made? One quite natural difference lies in the poorer heat dissipation than under conditions of free immersion in liquid helium. Electromagnetic influence of neighboring turns on each other (the "proximity" effect) also can not be excluded. Finally, it turned out[16] that it is also very important that in testing *short samples* usually one of the measured parameters (more often than not the magnetic field) is kept constant, whereas in the solenoid changes of the current and of the magnetic field occur simultaneously. Indeed, if measurements with proportionally increasing field and current are carried out on short lengths of wire, then it is possible to reproduce a considerable part of the degradation effect[16] even in the case of small samples. (A similar procedure is thus very useful in investigations of new materials, the comparison of different batches of wire, etc.)

At least the first peculiarity pointed out by us—the difference in heat dissipation—indicates rather clearly the possibility of some dissipative processes in the superconductor. How sharp is the dividing line between the superconducting and normal state? Precisely what dissipative processes are possible in a superconductor?

The superconducting materials used in producing solenoids are type-II superconductors, whose distinctive feature when compared with type-I superconductors is the absence in them of the Meissner effect. Beginning from some relatively small value H_{c1}, the magnetic field tends to penetrate into the bulk of the material,[17] the *flux lines grouping themselves inside into more or less* regular (depending on the uniformity of the material) structures of vortex formations called Abrikosov vortices, fluxoids, etc. At the centers of these vortex formations the magnetic field is close to the external field, and the material is "almost" a normal metal. A simplified assumption can be made that the effective radius of the normal cores of the vortices increases with the magnetic field until at some value H_{c2} the entire medium (except for thin layers near the surface[18]) becomes completely normal. If the vortex lattice starts to move under the action of the Lorentz force due to the external (or induced) currents then, because of the resultant emf, the currents penetrate partly into these "almost" normal regions[19] in the centers of the vortices where the essentially usual release of Joule heat occurs. Other, apparently less powerful dissipative processes are also possible, such as for example those connected with the radiation of ultrasound waves[20] produced by varying elastic stresses in the material. These stresses appear in the interaction of the vortices with the "palisade" of various defects of the crystal structure through which they must pass.

In the case when the number of such defects (such as boundaries and subboundaries of crystallites, finely dispersed precipitations of various phases, dislocation aggregates, etc[21,22]) is sufficiently large, the vortex lattice *is rigidly pinned to the inhomogeneities and no* dissipation occurs as long as the external currents (i.e., the Lorentz force) are not sufficiently large. There is, however, a finite probability that the vortices jump over the obstacle because of thermal excitation resulting in the observation of a peculiar phenomenon—the "creeping" of the magnetic flux.[23]

A similar jumping of the vortices, occurring on account of thermal excitation or when the external current increases sufficiently, and the accompanying dissipative phenomena can in principle lead to an avalanche-like process of transition of appreciable volumes of the superconducting material to the completely normal state. The annihilation of two fluxoids[24] with oppositely oriented moments which can occur, for example, when the external field direction is changed is considered to be very efficient in this respect. The energy released in the course of the annihilation is apparently sufficient to heat a small volume of material above the critical temperature.

The probability of the development of an avalanche-like process of transition into the normal state is determined by a relation involving the total magnetic energy stored in the nonequilibrium magnetization of an inhomogeneous material, the rate of dissipation of external currents in the region of the jump, the difference between the free energies for the normal and superconducting states, the heat conduction of the medium, etc. A sufficiently complete quantitative theory which could allow one to predict in which instances a superconductor is stable against "flux jumps" has so far not been developed. Let us note the following points. The probability of destructive "jumps" decreases with increasing temperature and in the range of sufficiently high fields[20]; the degradation is therefore more strongly exhibited at sufficiently low temperatures (say, below $T_c/2$) and intermediate fields (10—15 kOe for Nb-Zr alloys).

The degradation apparently decreases in substances which exhibit strongly the so-called "paramagnetic limitation"[25] of the upper critical field H_{c2}. In such substances the dimension of the normal cores of the vortices, i.e., of regions in which the fundamental dissipative processes occur, is determined in fields not too close to H_{c2} not by the magnitude of this field but by the considerably larger magnitude which would have been observed in the absence of paramagnetic effects.[19] It is probable that a similar mechanism leads to a decrease in the degradation in the group of Nb-Zr alloys for large zirconium contents.[26]

Being unable to consider further in any detail either these interesting effects or the phenomena related to the nature of the interaction of the vortices with various structural defects,[21,22,27] the anisotropy of this interaction, etc, we return to a study of the conditions that determine the critical currents of a superconductor located within the winding of a solenoid. The further increase in the number of factors entering into the picture naturally renders our description more and more qualitative. It is easy, for example, to imagine that a simultaneous increase of the field and current in the winding as a whole favors a decrease of the critical currents, since the changing magnetization must be accompanied by dissipation. However, we are still far from being able to predict this effect quantitatively from any readily determined parameters of the superconductor. The same is unfortunately also true of the possibility of taking into account the heat conduction of the substances filling the windings, the damping of the electromagnetic interaction of neighboring turns when flux jumping occurs[28] with the aid of copper cladding, etc. The effect of cyclic magnetization and the heating of turns on the critical current, appearing graphically in the form of "conditioning," i.e., a change of the critical current in successive measurements, appears also quite natural and likely; it is rather difficult, however, to produce a clear picture of the effect, all the more because of the nonsystematic nature of the "conditioning" in a number of alloys.[29]

A series of fine effects causing degradation is due to the diamagnetism of the coil winding as a whole.[29] As is well known, in a solenoid of finite dimensions the magnetic field almost vanishes in a certain region of the winding. Because of the nonlinear field dependence of the magnetization of type-II superconductors, in a superconducting solenoid this region is displaced when the current changes, and the direction of the effective field acting on the turns near this region can completely change. For further removed turns the effective field can turn somewhat with changing current. A change in the direction of the magnetic field may, as we have already noted, cause an "annihilation" instability which will most probably affect those portions of the wire located in the region of "low" fields.

Effects connected with the reorientation of the field allow one to explain again quite qualitatively the dependence of the degree of degradation on the shape of the solenoid, the order of connecting the sections, the change of polarity of the current, etc.

The problem of the effect of the dimensions of the magnetic system on the critical currents was in its time quite acute,[30] all the more because a decrease in the critical currents, inversely proportional to the coil dimensions, was predicted on the basis of certain simplified similarity criteria.[31] It would nevertheless appear that the mechanisms causing degradation cannot depend so strongly on the dimensions; thus, the conditions of heat exchange and electromagnetic screening in a coil containing ten layers can in essence hardly differ from the conditions in a large solenoid. The effects connected with changes of the current and of the magnitude and direction of the field are determined by the geometric characteristics of the solenoid, but there should again be no major dependence on the dimensions themselves (for instance, on the radius of curvature of the wire). Indeed, we note that the problem of enhanced degradation with increasing solenoid dimensions has now to a considerable extent lost its timeliness. At present, methods developed to stabilize currents in a superconducting solenoid, permit one to exclude degradation entirely, i.e., they make it possible to realize the maximum critical currents attainable for a given substance. On the other hand, the utilization of stabilized windings in sufficiently large systems is, except for a small number of conceivable exceptions, an indispensable condition for their normal operation.

3. THERMAL STABILITY OF WINDINGS IN SUPERCONDUCTING COILS

The subsequent fate of the "normal" portions which appear with flux jumps (or mechanical displacements, random heating, etc) may turn out variously. If there is

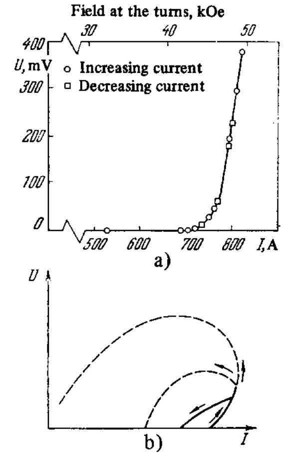


FIG. 1. a) Increasing resistance of a fully stabilized coil on increasing the current above the critical value. [57] b) Possible types of transitions for small stability margins. [47] The dashed lines depict nominally the direction of the uncontrollable transitions.

no copper cladding, or if its thickness is sufficiently small the situation is that already described in Sec. 1. The general features of the theory of the thermal propagation of the normal phase in single wires[32,33,34] and solenoids[35] has been worked out in such a way that in the simplest cases it is possible to estimate the characteristic times of the transition process, the magnitudes of the electrical voltages within the winding, the dimension of the affected region, and the temperature developing at the center of these regions.

It turns out that when the thickness of the copper cladding is increased and the heat dissipation to the outside medium is sufficient, the rate of propagation of the normal phase decreases, and can finally vanish.[31] For a sufficient amount of normal metal the normal region will not increase for arbitrary currents up to the maximum critical value. At the same time, the portion of the normal phase which appeared for some arbitrary reason may "collapse" and the current may pass completely into the superconductor, so that the evolution of heat will generally cease. On increasing the current above the maximum critical value, the resistance of the superconducting material begins to increase and part of the current passes over into the normal metal. The temperature of the conductor increases; however, so long as it does not exceed the critical temperature a part of the current nevertheless continues to flow in the superconductor[36] whose resistance remains sufficiently small. On decreasing the total current a fully reversible (Fig. 1a) passage of the current into the superconductor is possible, the resistance disappearing at the same value of the current at which it appears.

The possibility of a reversible transition above the critical current means, along with other appreciable advantages, also complete prevention of degradation, i.e., the possibility of stable operation of the superconductor at maximum attainable currents.

Increasing the amount of normal metal in the conductor and assuring good heat dissipation from all windings of the coil is indeed the basis of the method of thermal stabilization of solenoids proposed by Kantrovitz and Stekly.[13] The conditions essential for the stabilization of windings were formulated in their first paper[13] as follows: "The amount of normal material and the amount of cooling surface exposed to the helium be such that with all the current flowing in the normal material the superconductor temperature be below its critical temperature in the presence of the magnetic field (but at zero current in the superconductor)." In the case of a single "one-dimensional" conductor this condition can be written in the form

$$\alpha = \frac{\rho_n I_c^2}{hPA\,(T_c - T_0)} \leqslant 1, \tag{1}$$

where ρ_n is the resistivity of a normal metal, I_c is the critical current of the superconductor, A is the cross section, P is the perimeter of the entire conductor, T_c is the critical temperature of the superconductor for zero current (for a given field), and T_0 is the temperature of the external medium. The quantity h is the heat dissipated into the external medium from unit area of the surface for a temperature difference of one degree. This assertion was subsequently proved in this form in the work of Stekly and Zar.[37] One should, however, point out the assumptions which one must make in deriving this condition even for a one-dimensional model. First, it is assumed that the heat dissipation is proportional to the temperature difference of the conductor and the helium; in other words, that the magnitude of h is constant. Secondly, it is assumed that there is ideal electrical contact between the superconductor and the normal metal. The assumptions of a uniform temperature distribution over the cross section of the metal (including also the superconductor) and of the linear dependence of the critical current on the temperature are less important. However, as was noted in[38], the nonfulfillment of the first two conditions can change appreciably the conditions essential for assuring thermal stability. As is well known, the dependence of the heat dissipation on the temperature difference in boiling is appreciably nonlinear due to the transition from bubble to film boiling. In superfluid helium the heat exchange is also nonlinear. A consistent account or sufficiently complete experimental investigation of the influence of all these effects on the thermal stability has so far not been carried out, although a series of related problems is being studied.[39,40,41]

On going over from a linear "one-dimensional" conductor to the case of a real three-dimensional winding the problem of stability becomes more complicated. A simple analysis for the case of a constant average heat conduction has been carried out by Stekly.[42] The problem of the propagation of heat in a heterogeneous structure, whose irregular channels can be stopped up by bubbles, etc, is in itself sufficiently complex; this refers all the more to the problem of the thermal stability of a winding with a variable resistance. Some investigations of the nature of the heat exchange in such systems are being carried out,[43] however so far no sufficiently complete data are available. For practical calculations it is recommended[44] that one assume values of the heat dissipation coefficient which are low by a good margin—up to 0.1 W/cm². Of course, the problem of stability is not solved by choosing a large margin, because in a number of constructions intended, for example, for space investigations[45] there may appear very strict requirements on their weight, overall dimensions, and efficiency. In such cases the problem may be complicated by the fact that the stability in this essentially nonlinear problem should be determined with respect to finite perturbations; there are, however, so far no reliable data about the parameters of the basic internal source of perturbations—the flux jumps. In certain cases there may appear powerful external sources of perturbations, such as, for example, the field action of the currents in the plasma channel of a magnetohydrodynamic generator, the action of mechanical vibrations, etc.

It may seem that because of a certain lack of clarity in the problem of the thermal stability of windings, a discussion of the problem of the optimization of the solenoid construction by varying some parameters over the cross section is somewhat premature. However, the parameter α of (1) changes rapidly with the magnetic field (both I_c and T_c, as well as the resistivity ρ_n depend on the field), and even the simplest assumptions may lead to considerable economies in the overall quantity of superconductor, a decrease in the overall dimensions and weight of the construction, in the total cost, etc. The optimization can be attained either by supplying various sections of the winding with different currents or by changing the parameters of the conductor (the number of superconducting wires or the amount of normal metal). In this regard a technique of producing a conductor which permits such variations is preferable.

In order to calculate the stability under such conditions, it is useful to know the maximum value of the current for which there is no propagation of the normal phase even for $\alpha > 1$. We cite an expression, valid under the same assumptions as (1), for the current I_0 for which the rate of propagation of the normal phase vanishes[38]:

$$I_0 = I_c\left(\sqrt{1/4\alpha^2 + 2/\alpha} - 1/2\alpha\right). \qquad (2)$$

In practice one can assume that $I_0 = I_c/\sqrt{\alpha}$. The current I_0 changes rather weakly with magnetic field (Fig. 2). If it is therefore required that the safe limit in the region where $\alpha > 1$ is not exceeded, then the superconductor will be strongly "underloaded" with current. It is hence clear that if the fundamental purpose is economy in the total quantity of superconducting material, the winding should be calculated in such a way that nowhere should the value of α differ very much from unity. In attempting to ensure a maximum current density in the winding (i.e., a decrease in the dimensions), it turns out that it is more convenient to have incomplete stabilization[46] ($\alpha > 1$) for which the superconductor operates stably only for currents below the critical value. In order to exclude the possibility of transition to the region of unstable currents, one can in this case calculate the solenoid in such a way that the current should reach its critical value everywhere in the region with $\alpha < 1$ (for example, in the region of maximum field).

On increasing the current above the critical value for $\alpha < 1$ there will appear, as we have already noted, a finite resistance which will increase with the current (Fig. 1a). The rate of increase depends both on the local value of α and also on the rate of increase of the size of the normal region with the current; this rate is determined in particular by the geometry of the solenoid. The dependence of the total resistance of the solenoid on the current was calculated by Stekly and Zar.[37] However these data are obtained under the same assumptions which were assumed in deriving the principal stability condition (1). In addition, no account was taken of the finite heat conduction transverse to the turns of the winding. Naturally, the patterns of transitions actually possible will be incomparably more varied than the diagram calculated by these means (Fig. 1b). For example, the stability condition may break down because of the gradual clogging of the channels through which the liquid flows by bubbles; the transition of the solenoid will then be jump-like. It is possible that this will not be accompanied by a complete decay of the current, the latter merely decreasing to some value; this will again be followed by a disappearance of the solenoid resistance so that only some fraction of the total magnetic energy of the solenoid will turn into heat. Finally, such intermediate situations are also possible[47] in which the resistance varies smoothly but there will be no complete reversibility, so that zero resistance will only be "re-established" for a current somewhat below the critical current.

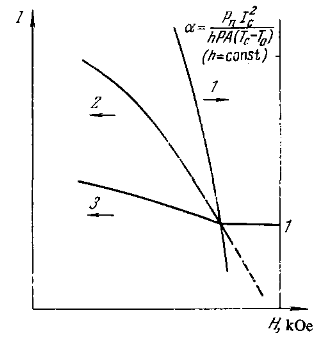


FIG. 2. The nature of the change of the stability parameter α (curve 1) with the magnetic field. Curve 2—critical current for short samples, 3—the current I_0 for which the propagation of the normal regions becomes possible.

The total amount of energy dissipated in such "incomplete" transitions to the normal state is in particular determined by the rapidity with which the appearance of resistance in the winding can be registered and how quickly the current can be decreased to a safe limit. Clearly, for efficient operation of the solenoid, fully reversible transitions, when even the release of considerable power in the course of sensible time intervals is admissible, are preferable. However, the necessity of insuring sufficiently small values of α for obtaining smooth transitions is in fact always connected with a considerable increase in the dimensions and weight of the entire construction.

The total stabilization of solenoids with small working bores may even require an increase in the consumption of superconductor because the gain due to the exclusion of degradation can be fully compensated by an increase in the external dimensions of the solenoid. It is useful to emphasize that such a situation is only established by specific relations between the current densities in the superconductors, the resistance of the normal metals in the magnetic field, the heat transfer in the liquid helium, etc, i.e., it is generally speaking random. For example, it is easy to imagine that on increasing the coefficient of heat transfer to the outside medium by a factor of some tens or for a similar decrease of the resistance of the normal cladding, the establishment of a stable regime will generally not only give rise to no increase in the weight of the solenoid, but will on the contrary lead to an appreciable cutting down of the weight on account of the increase in the current density in the superconductor, i.e., on account of the exclusion of degradation which can be appreciable in an unstable solenoid.

Thus the tendency towards further decreasing the resistance of the cladding and towards improvement of the heat exchange is fully justified. Besides, we should stipulate at this point that with increasing dimensions of superconducting systems and field ranges the foremost problem will be to ensure the mechanical strength of the winding. At the same time the current density calculated for the entire cross section of the winding must decrease steadily because of the introduction of the "reinforcing" elements; in the final analysis this will render the resistance of the shunting cladding a completely noncritical parameter. The maintenance of more effective heat exchange will only be expedient from the point of view of decreasing the total amount of helium used in a given system.

The possibilities of decreasing the resistance are, as is well known, connected with the use of metals (with closed Fermi surfaces) whose resistance in a magnetic field does not increase without limit. So far only aluminum is of practical interest; the use of aluminum even with a resistance equal to that of copper will result in considerable economy in the weight of the system. The difficulties with the technical mastery of aluminized conductors may be related to the contact resistance of the oxide layer of the aluminum, as well as to the increase of resistance of the pure metal under the action of mechanical stresses.

Better methods of heat extraction from solenoids are also being sought; thus, studies have been carried out of heat exchange in a stream of compressed helium,[41] schemes have been investigated[46] in which use is made of heat-conducting bridges which dissipate the heat of transition processes, etc. Worthy of notice is also the problem of the utilization of the amazing properties of superfluid helium which is, as is well known, also a superheatconducting medium. Although the admissible thermal flow is in this instance limited to a quantity of the order of 1 W/cm^2, above which a vapor film appears between the solid surface and the liquid, the possibility of maintaining more effective heat transfer[41] cannot be excluded. In any case, the prospects of extensive technical utilization of this other "superphenomenon" (whose adoption in practice is in this case also appreciably belated) for cooling magnetic systems or superconducting resonators[48] cannot but be exciting and tempting.

4. THE PROPERTIES OF WIDELY EMPLOYED SUPERCONDUCTING MATERIALS

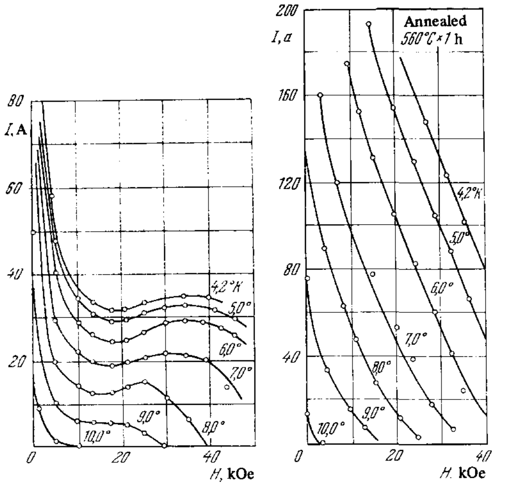
Superconducting materials suitable for the construction of solenoids can be divided into two groups—a group of deformable alloys (Nb-Zr, Nb-Ti, ternary compositions) and a group of intermetallic compounds (Nb_3Sn, V_3Ga, etc). The differences in the physical properties of these materials determine to a large extent the form in which they are used in the preparation of conductors. We shall also consider separately certain methods of preparation of stabilized conductors.

The most important characteristic of a given conductor is the critical current whose magnitude depends on the external magnetic field and the temperature. Usually one cites the dependence of the critical currents on the magnetic field at 4.2°K. The $I_c(H)$ dependence is as a rule measured on small samples in constant external fields; often only the maximum value of the critical currents are cited which can be realized, for example, in fully stabilized conductors. In a number of cases one can attain in stabilized conductors even higher critical currents, because degradation is not fully excluded even in small samples. The critical current which can be obtained in a solenoid prepared with a nonstabilized conductor does not exceed the current in short samples and it is always difficult to predict it in advance. Here one must basically depend on the total experience accumulated in working with a given conductor. A measurement procedure[16] with a simultaneous increase of the current of the sample and of the field of the external magnet with 3–6 values of the proportionality constant may be very useful for such estimates. One can attempt to imitate in some way the effect of the reorientation of the field[49] on the critical currents in the region of low fields. One should, of course, also measure the critical currents in constant external fields, and it is desirable to obtain for each value of the field several points from successive measurements. The sharp difference between the results obtained by means of these different methods, the presence of an appreciable effect of "conditioning," i.e., an increase of the critical currents in successive measurements, the presence of a clearly exhibited "minimum" effect (a decrease of the critical currents in the intermediate range of fields of 10--20 kOe and an increase of the critical currents with increasing field) should always make our prediction worse. In the opposite case one might hope that the critical current of a solenoid will be close to the minimum current determined by means of all the different methods of measurement.

A. Deformable Alloys. Most widely employed in the production of solenoids are various ductile alloys based on niobium; basically this is due to the relative simplicity of the methods for preparing wires of these alloys, although a series of special measures must be taken on account of the high chemical activity and the special mechanical properties of the alloys. Round wire 0.25 mm in diameter is usually used. Further decrease of the diameter increases the current density and helps to remove effects connected with magnetization, i.e., degradation[29]; however, thinner wire is almost never produced. This is explained by the increasing difficulties of preparing and winding such wire.

An interesting property of the deformable alloys is the strong dependence of the critical currents on the degree of deformation, as well as the anisotropy of the critical currents determined by the orientation of the external field with respect to the slip planes appearing in the material as a result of cold deformation. For example, in rolled samples the critical current has a maximum when the external field is oriented parallel to the plane of rolling.[50,51] At the same time, the current density in a ribbon is larger than in a wire with comparable deformation, since in a wire because of the very nature of the deformation the distribution of current over the cross section cannot in general be uniform. However, the gain from the use of ribbons in small unstabilized solenoids will hardly compensate for certain inconveniences connected with their use.

Another interesting feature of a number of alloys is



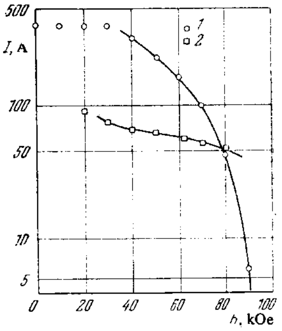
FIGS. 3 and 4. Dependence of the critical currents of Nb + 25% Zr wire on the magnetic field and temperature. [44] On the left—cold-deformed, on the right—heat treated samples.

the possibility of increasing the critical currents by means of special heat treatment. An increase in the critical currents after annealing at 500—800°C was first observed[52] in Nb-Zr alloys. This phenomenon is connected with certain phase transitions. Similar transitions occur also in a series of other alloys for which a corresponding heat treatment is also possible.[53,54] The initial attempts to make use of this phenomenon to increase the critical currents in unstabilized solenoids were unsuccessful because of the accompanying increase in the degradation; subsequently, however, it turned out to be possible to find suitable regimes of heat treatment, for example for Nb-Zr alloys with increased zirconium content,[26] which had a number of advantages compared with the widely used Nb + 25% alloy. At present heat treatment is also used in the case of certain other alloys which can also be employed in unstabilized solenoids, for example in the case of the Nb + 22% Ti alloy produced by the firm Atomics International[54,44] or in the case of the ternary BT-65 alloy produced in the USSR.[56] Thermally treated Nb + 25% Zr wire has also been employed in the largest stabilized solenoids.[13,57] The effect of annealing this alloy at 560°C on the critical current is shown on Figs. 3 and 4.

There is a tendency to increase the operating currents and the cross sections of the superconducting elements[41] in large stabilized systems. Flat configurations whose perimeter is larger than that of a round conductor of the same cross section are preferable from the point of view of the heat exchange with the surrounding casing. The use of heat treatment for increasing the current density in such conductors is very convenient. The anisotropy of the critical currents decreases strongly under heat treatment,[51] behaving as if on annealing an almost isotropic term were added to the anisotropic distribution of the critical currents.[50] Instances of the use of flat conductors so far are few; some examples can be found in the excellent reviews of Laverick[41] and Chester.[29]

The critical temperature of the alloy Nb + 25% Zr is approximately 11°K[8], and H_{c2} is close to 70 kOe. Nb-Zr alloys with high Zr content[58] have higher critical fields (up to 90 kOe); however, the critical currents of the cold-deformed samples of these are unacceptably low, and their use is therefore only possible after suitable heat treatment.

FIG. 5. Critical currents of HI-120 (Nb-Ti) alloys (Westinghouse, USA) (curve 2) and of the alloy Nb + 40% Zr + 10% Ti (Hitachi, Japan) [59] (curve 1).



Even higher critical fields—up to 140 kOe—are observed in the case of the group of Nb-Ti alloys and for alloys of "ternary" composition (Nb-Zr-Ti). The critical currents of the HI-120 (Nb-Ti) alloy produced by the American firm Westinghouse and the Nb + 40% Zr + 10% Ti of the Japanese firm Hitachi[59] are shown in Fig. 5. The critical temperatures of alloys with titanium are on the whole lower than in the case of the Nb + 25% Zr alloy and can amount to 8°K. Because of the higher values of H_{c2}, the various alloys with titanium will in the future replace the widely employed Nb + 25% Zr alloy, although all of them are in danger of being displaced by the promising materials based on the compound Nb$_3$Sn which has critical fields higher by almost a factor of two.

As we have noted, the data presented in Figs. 3—5 correspond to the maximum critical currents of short samples. The critical currents of wires of various materials employed in unstabilized solenoids can vary strongly even from batch to batch. One should consider a typical average value with which one can compare the parameters of various materials to be 20—25 amperes for a wire with a diameter of 0.25 mm; this corresponds to a current density of (4--5) × 10^{-4} A/cm^2. Such currents are usually realized in solenoids with fields up to 50 kOe for the Nb + 25% Zr alloy, and up to 80--90 kOe for Nb-Ti alloys. In fields close to H_{c2} the degradation has almost no effect, and the critical currents in solenoids usually coincide with the values cited for short samples.

B. Conductors Based on the Intermetallic Compound Nb$_3$Sn. Nb$_3$Sn is so far the only substance of this class which has found practical application. Between 1954 and 1967[86] this material[60] "held the record" with regard to the maximum critical temperature (18.05°K). It has recently been noted[61] that the values of the critical fields of Nb$_3$Sn are also no worse than those of all other known materials including V$_3$Ga for which the initial cheerful estimates[62] apparently turned out to be too high (Fig. 6). In addition, no industrial methods of preparing practically useful conductors have so far been worked out for other compounds.

The distinguishing physical characteristic of the intermetallic compounds of the type Nb$_3$Sn, justifying our separate treatment of these, is their exceptional brittleness which makes it impossible to obtain wires from them by using the usual devices. This difficulty

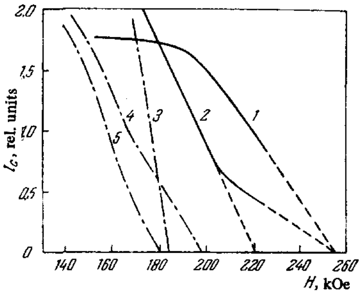


FIG. 6. Critical currents of some samples of the compounds Nb_3Sn, and V_3Ga. [61] 1–Nb_3Sn, "multistrand" samples, 950°C X 20 hours; 2–the same, 800°C X 20 hrs; 3–V_3Ga, surface layer, 1200°C X 10 hours; 4–V_3Ga, Kunzler's "wire", 1485°C X 2 hours; 5–the same, 1440°C X 2 hours.

was cleverly overcome in the initial work of Kunzler, Buehler, Hsu, and Wernick[31] who prepared small samples of "wire" from a niobium tube with a Nb_3Sn core and later also a trial solenoid[63] for obtaining a field of 70 kOe. The solenoid was wound using a tube containing powdered tin and niobium, and was then heated to about 1000°C. The production of large quantities of such wire and of sufficiently large solenoids is rather difficult. An obvious shortcoming of this technique is the fact that it is impossible to employ or reconstruct the device when a section of wire is damaged. At present the French firm Sodern produces a similar type of wire and small laboratory solenoids for fields of the order of 100 kOe.

Other methods of obtaining Nb_3Sn conductors[64-66] were subsequently also developed. In the production of the well-known material "Cryostrand"[67] of the American firm General Electric, a layer of Nb_3Sn is formed by diffusion of tin from the surface into a niobium wire. At the time, record fields were obtained with this wire; at present, however, its production has ceased with the development of a more promising flexible ribbon conductor.[68] In fact, although the production of the wire is relatively uncomplicated, the construction of solenoids and their utilization are very difficult, because it is impossible to rewind damaged coils.[67]

Flexible conductors which do not have this shortcoming are now produced by a number of methods. A common feature of these is that the Nb_3Sn layer is formed on a thin ribbon (on the order of 10 μ) in which deformations due to bending do not exceed admissible limits.

In one of the methods which we shall illustrate with an example[66] of the technique of the French firm CSF the Nb_3Sn layer is also produced by diffusion of tin into a 12-micron niobium foil. The foil is pulled through a tin bath kept at 1000°C at a rate of 12 m/h (Fig. 7). The entire setup is enclosed in a jacket evacuated to 10^{-6} mm Hg; this is essential in order to exclude contamination of the niobium substrate which would otherwise become too brittle.

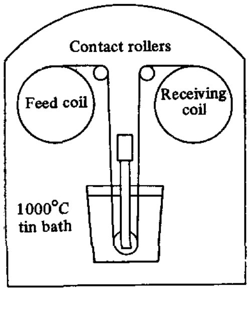


FIG. 7. Schematic arrangement of the device for producing flexible ribbon clad with Nb_3Sn. [66]

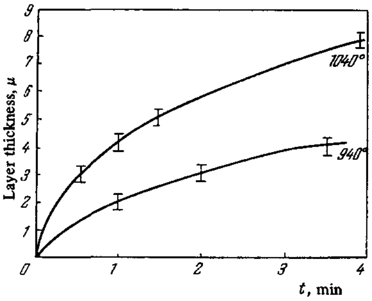


FIG. 8. Dependence of the thickness of the Nb_3Sn layer on the duration of the treatment and on the temperature. [66]

The dependence of the thickness of the Nb_3Sn layer on the time the ribbon is submerged in the tin at two different temperatures is shown on Fig. 8. For a layer thickness of the order of 3 μ the critical current in a field of 100 kOe amounts approximately to 100 A per centimeter of ribbon (Fig. 9). The critical current depends to some extent on the orientation of the plane of the ribbon with respect to the direction of the magnetic field. It is interesting that no such anisotropy is observed in similar type of American material made by General Electric.[68] The difference is possibly connected[44] with the dimensions of the Nb_3Sn crystallites in these samples. The production of Nb_3Sn conductors by this technique appears, as we have convinced ourselves, rather straightforward. A more complex technique is that of RCA, although the parameters of the resulting material are somewhat higher. In this technique a thin ribbon made of a special alloy is covered by a layer of the compound formed in the decomposition of gaseous tin and niobium chlorides. The reaction occurs in a corrosive medium at a temperature of the order of 1000°C. This imposes definite limitations on the choice of the substrate material which must retain after the treatment suitable mechanical properties.

The well-known shortcoming of the two methods of obtaining flat Nb_3Sn conductors which we have described is the low efficiency in their production. The review[44] reported the development of a method of cathode sputtering of the compound Nb_3Sn which would make possible a considerably higher rate of coating.

The RCA ribbon was, in particular, used to build the solenoid[69] in which a field of 140 kOe was obtained at 4.2°K, and a field of 170 kOe when the temperature was lowered. Any further increase of fields of superconducting solenoids is difficult because of the decrease in the critical currents near the field H_{C2} which in the case of Nb_3Sn is apparently close to 240 kOe.[61] The value of

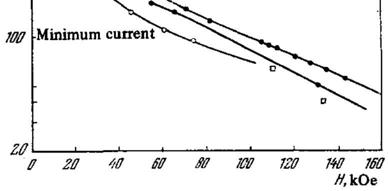


FIG. 9. Critical currents of various samples of 12.5-mm wide ribbon made by CFS (France). [66]

H_{c2} is determined to some extent by the technique by which the samples were obtained. Thus, for instance, in specially prepared "multi-strand" samples consisting of a large number of very fine niobium wires covered with Nb_3Sn the value of H_{c2} exceeds 240 kOe (Fig. 6).

C. Stabilized Conductors. One of the first forms of partly stabilized conductors were various cables consisting of a number of twisted superconducting copper wires connected with each other by a suitable metal. By increasing the number of copper strands, one can in principle attain fulfillment of the condition $\alpha < 1$ for arbitrary critical currents. However, at the same time, a considerable portion of the cross section will be occupied by the connecting metal (indium is frequently used) which contributes relatively little to the decrease in the resistance of the cable. The ratio of the parameter to the cross section in the case of a round conductor is less favorable than in the case of a flat strip; in addition, a flat configuration is apparently somewhat more convenient for producing a stable and regular winding in large coils. Cables have the advantages of simplicity and high efficiency in their production in which diverse standard equipment can be used. The expensive indium can be successfully replaced by various compound low-melting solders with suitable mechanical properties in the entire temperature range. The high electrical resistivity of such alloys causes no difficulties, because the basic running (or "longitudinal") resistance is determined only by the copper conductors. On the other hand, the contact ("transverse") resistance in the thin layers of solder is relatively small. Numerous other variants of producing stabilized conductors of cables and single wires soldered to a common copper or aluminum strip, soldered together in a flat configuration, etc, are possible.

Perhaps the first completely stabilized conductor which has also been employed in the largest operating magnet described by Stekly[57] was a copper ribbon with longitudinal grooves into which superconducting wires plated with electrolytic copper were placed. The wire was then pressed into the ribbon; this could result in breaks, but in view of the complete thermal stability of the ribbon no propagation of the normal phase from the breaks was observed. However, for very large numbers of breaks the finite resistance appearing at each point can result in unjustifiably large losses.

By using suitable equipment, the process of producing such a ribbon can be made very efficient. High efficiency is apparently also attained by simultaneously extruding or drawing a bundle of wires or ribbons[29] in an aluminum[70] or even copper[71] sheath. In these processes one can obtain a conductor of rectangular or box-like cross section (for the passage of helium in systems with forced cooling).

The problem of stabilizing flat flexible conductors based on Nb_3Sn is solved rather simply because, unlike in the case of superconducting alloys based on niobium, the compound Nb_3Sn can be readily plated with soft solders. The stabilizing copper ribbon can be soldered directly to the Nb_3Sn layer on both sides of the ribbon. The possibility of bending the ribbon is at the same time retained to some extent because the deformation in the central portion of the cross section will remain small.

The required ratio of the quantities of superconductor and normal metal can be found from formula (1), if it is desired to attain the maximum current; in the opposite case the admissible current is determined from formula (2). However, the magnitude of the effective coefficient of heat removal h, which enters in these formulas, is to some extent undetermined, and its choice is determined by the conflicting requirements as to the weight of the system, convenience and safety in operating it, etc. If one substitutes in formula (1) the parameters of Stekly's[53] strip with a value $h \sim 1\ \mathrm{W/cm^2}$ deg corresponding to bubble boiling, then the value of α will amount to ~0.025, so that here one has almost a triple stability margin, even in the case of film boiling. (One should, however, take into account that when using such a strip in flat coils only about one tenth of the perimeter is used in cooling with helium. A single conductor with such a perimeter can only be stable for bubble boiling.)

Formulas (1) and (2) only allow one to find the ratio of the quantities of superconductor and normal metal. On the other hand, their absolute quantities are chosen from a series of additional considerations. Convenience in the preparation and winding, the presence of suitable supply sources, the extent of the helium loss on introducing into the Dewar currents of a given magnitude, the time necessary for "loading" the solenoid with a given source, etc, are all factors which play a considerable role in this choice.

5. SUPERCONDUCTING SYSTEMS

The various types of superconducting magnets can be divided into the following three categories:

1) small unstabilized solenoids intended principally for laboratory investigations,
2) unstabilized large systems,
3) completely stabilized large systems

The expediency of preparing small solenoids with unstabilized windings is due to the possibility of obtaining large current densities and a corresponding decrease of the dimensions of the solenoid. The characteristic current density referred to the entire cross section of the winding is usually close to $(2-4) \times 10^4\ \mathrm{A/cm^2}$ (in solenoids of Nb-Zr alloys up to 50–60 kOe, in alloys with titanium up to 70–80 kOe, and up to 100 kOe with the compound Nb_3Sn). To illustrate this, we note that to obtain a field of 50 kOe with a current density of $3 \times 10^4\ \mathrm{A/cm^2}$ the thickness of the winding of not too short a solenoid need be only 2 cm. For a typical universal laboratory solenoid the total amount of intrinsically superconducting material amounts to 1 kg; the weight of the finished solenoid is 1.5–2 kg. Only a few liters of liquid helium are required to cool the solenoid from liquid nitrogen temperature.

A considerable number of experiments, for example in solid state physics, are carried out in a magnetic field close to liquid helium temperatures. In such instances it is usually rather easy to place all the necessary equipment and samples in a solenoid bore 25 mm in diameter. If measurements are also to be carried out at other temperatures, special Dewars are used in which the working volume is screened from the low-temperature region. One such metallic cryostat[72] which was used in measurements of the Mössbauer effect[73] had an open longitudinal bore 14 mm in diameter; the diameter of the inner screen in the liquid helium was only 25 mm. If the inner region is extended to 25 mm, the diameter of the solenoid bore can in such systems amount to 38–45 mm.[74] Small Dewars with "radial" access where the field of the solenoid is oriented perpendicular to the direction of the channel have also been described.[75]

The rate of evaporation of liquid helium from small cryostats is quite negligible even when currents of tens of amperes are supplied to the solenoid, so that the duration of an experiment is mostly determined by the patience of the experimenter. However, if one attempts every time to attain a high longitudinal field, one can exceed the critical current several times because the magnitude of the critical current varies from case to case. The usual "average" laboratory solenoid stores several kilojoules of energy which are converted in each transition into heat; this can be accompanied by the loss of one or two liters of liquid helium. In order to continue working, one may in such instances have to replenish the helium supply after three or four transitions.

One can also cite examples in which a transition of the solenoid to the normal state is caused by the action of the object under investigation. Thus, during measurements of critical currents of small trial coils a sharp jump of the field during the transition of the coil and heating of the coil may also result in the transition of the entire solenoid into the normal state, especially when the measurements are carried out close to the maximum field. Finally, in order to obtain the maximum field when the solenoid exhibits an appreciable "conditioning" effect, one must deliberately increase the current several times until the superconductivity is "destroyed."

For the sake of economy of liquid helium, one can in these instances use various systems which allow one to "extract" the energy of the solenoid and dissipate it outside the cryostat. The most efficient system[76] (Fig. 10) provides for rapid shutting off of the low-resistance supply, so that the solenoid remains connected only to the external resistance (capacitor) R_0. The decay time of the current in the system is then mainly determined by the value of R_0 and only to a small extent by the increasing resistance of the windings. The value of R_0 depends on the permissible voltage on the terminals of the winding and the necessary efficiency of the device. The fraction of the total energy dissipated in the solenoid can be estimated in accordance with the simple formula

$$\frac{E}{E_0} = \left(\frac{\tau}{\tau_0}\right)^2,$$

where $\tau \approx L/R_0$ and τ_0 is the characteristic time of decay of the current in the solenoid without external load. For small solenoids wound with single-strand wire with a thin copper coating τ_0 can be 150–300 milliseconds. In order to obtain 90-percent efficiency with a solenoid of 10 H, a 200-ohm contact resistance is required; the maximum voltage on the coil terminals is in this case about 5 kV. Thus the requirements of insulation between the layers for a solenoid operating with such a system are somewhat large.

In some measurements, when it is essential to keep the field constant with high accuracy, it is best to connect a solenoid in a short circuit. It is then impossible to use a system with an external relay. However, instead of a mechanical relay one makes use of a "superconducting" relay[77] which consists of a section of superconducting wire of suitable length, and which is transformed to the normal state by means of pulsed heating by a device registering the instant at which the transition begins (Fig. 10). The use of various systems to "extract" the energy with small laboratory solenoids is a relatively simple matter and can be recommended in all instances when it is expedient to cut down the use of liquid helium.

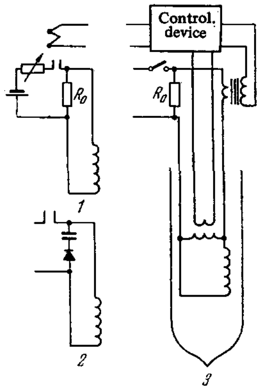


FIG. 10. Schematic diagrams of devices for electrical shielding of solenoids: 1—dissipation of energy by an external resistance; 2—transfer of the energy into a capacitor; 3—scheme with a superconducting relay.

Solenoids wound with wire made of ductile alloys calculated for the production of 50–70 kOe fields are already quite widespread. They are comparatively universal, so that they can be used to carry out the most diverse investigations. Solenoids intended for higher fields, especially exceeding 100 kOe, are thus far still unique laboratory installations. For the most part they are prepared of conductors with Nb_3Sn, although a 100-kOe solenoid in whose inner portion a Nb-Ti alloy has been employed has also been reported.[78] In some instances comparatively small Nb_3Sn solenoids placed inside a conventional water-cooled solenoid make it possible to increase the field of this solenoid and thereby extend the possibilities of the investigations.[46] (We note that[46] investigates the possibility of an appreciable increase of the attainable stationary fields when using a conventional solenoid within a superconducting one that produces fields of the order of 100 kOe.)

Let us cite the parameters of one of the largest laboratory solenoids[69] in which a field of 140 kOe was obtained at 4.2°K[44] and according to some information a field of 170 kOe at a lower temperature.

The solenoid is wound with RCA ribbon covered with the compound Nb_3Sn. The ribbon is 2.3 mm wide. The solenoid dimensions are: a 25 mm bore, an outer diameter of ~120 mm, and a length of ~90 mm. The average current density in the cross section must apparently be no less than 4.0×10^4 A/cm^2, i.e., it is exceptionally high.

Similar current densities—of the order of 3×10^4 A/cm^2—are obtained in fields close to 100 kOe and with ribbons where the Nb_3Sn layer is obtained in a diffusion reaction.[66,68] Wider ribbons (6.35 and 12.6 mm) are usually employed. Such ribbons are wound in flat pancakes which are combined in such a way that the directions of winding in neighboring pancakes are opposed. The external terminals of two neighboring pancakes are soldered together outside the winding. The inner terminals must be joined through intermediate rings which are located in region of maximum field. Such contacts turn out to be rather efficient, although they do have a small resistance.

So far there is still little experience in the use of conductors based on Nb_3Sn. Degradation is of course also observed in this instance, especially in the region of low fields[79]; however, in view of the considerably larger current density in high fields, this phenomenon does not usually appear to be as annoying as in the case of alloys.

If one disregards the uncertainty connected with the lack of knowledge of the critical current which will be obtained with a given material, then the calculation of small coils reduces to finding the optimum dimensions determined by the desired field homogeneity, the amount of available material, etc, and is very simple for ordinary solenoids. Various magnets with radial access,[75] quadrupole lenses,[44,80] and toroids,[45] can also be readily calculated by the generally known methods. However an extremely accurate calculation of fields of various configurations is complicated by the fact that the effect of the diamagnetism of a superconducting winding cannot, generally speaking, be allowed for sufficiently accurately because it is determined by a number of unknown or variable parameters. The residual moment of windings can be considerably stronger in the case of the compound Nb_3Sn than in the case of alloys.

A careful calculation of the homogeneity of the field is required, for example, in the case of solenoids intended for NMR investigations[74] when it is essential to obtain a field homogeneous over the volume of the sample with an accuracy up to 10^{-8} of the basic value. In this case the solenoids must be made sufficiently long so that the diamagnetic contribution to the total field is small (for an infinitely long solenoid this contribution vanishes). In addition, in a solenoid with a rectangular winding cross section and a regularly distributed diamagnetic moment the field homogeneity should be higher than in windings with zero susceptibility. Of course, the windings of solenoids for NMR are in fact usually not simply rectangular in shape, but include several cavities or additional windings serving to correct the homogeneity of the basic field; however, the appropriate small corrections can apparently be estimated. The situation is worse with regard to the regular distribution of the diamagnetic moment which can actually change at random during flux jumps, transitions to the normal state, etc. Nevertheless, the successful utilization of superconducting solenoids in NMR studies attests to the fact that these difficulties can be overcome.

Let us consider as an example the Varian solenoid (USA),[74] with the aid of which one can carry out measurements of proton resonance up to 200 MHz (47 kOe) with a resolution of 1 Hz. The solenoid is 35.7 cm long, has an external diameter of 12.7 cm, and an inner bore diameter of 4.25 cm. The diameter of the bore in the region at room temperature where one can place the sample, the coils, etc, is 26 mm. The solenoid weighs 13.2 kg. The solenoid is a "sixth-order" coil; this means that the basic compensating rings at the sides of the windings are calculated in such a way that the second and fourth-order terms in the series expressing the dependence of the field on the distance from the center vanish. It is assumed that within a sphere with a diameter of 2 cm the field inhomogeneity should not exceed 10^{-6}. Various unaccounted for variations related to deviations from an ideal winding can be compensated by means of additional small windings. Finally, radial variations of the field can be effectively excluded by rapid rotation of the sample about its axis with a small air turbine, the nuclear spins having only time to react to the average field.

NMR solenoids for higher fields are at present also being constructed. Thus, the development of a solenoid with a maximum field of 84 kOe and a 30-mm bore has been reported.[81] The solenoid consists of two independent sections, the outer section being wound with a seven-strand cable of Nb-Zr alloy, and the inner section—with single-strand Nb-Ti wire. The outer section is 39.4 cm long, and the outer diameter is 18.5 cm. The inhomogeneity of the field does not exceed 10^{-5} in a sphere of 15-mm diameter.

Solenoids with even larger homogeneity wound entirely with cable conductors are being developed.[82]

The NMR solenoids are perhaps the largest research solenoids. This is due in the final analysis to the necessity of obtaining a high field homogeneity. The penetration into this field of cable conductors, which are probably less suitable from the point of view of insuring field homogeneity, is a reflection of the general tendency to replace in larger systems single-strand conductors by multi-strand cables. The dimensions of the solenoids which we have considered correspond to the intermediate range between these two variants of windings. The largest magnet wound with single-strand wire[45] constructed still before the cable era was a toroid 1.5 m in diameter and containing 6000 turns.

What constitutes the advantages of cable conductors for larger unstabilized systems? The most obvious advantage which appears at the head of commercial advertisements of overseas firms is the considerable facilitation and speeding up of the process of winding coils with cables, which is of course from the practical point of view of considerable significance. The resulting current density in the cross section of the winding turns out, as a rule, to be lower[44] than in the case where single-strand wire is employed (see p. 795). The small increase of the critical current (calculated for a single wire) which is sometimes observed in cables with high content of copper wires and which is connected with a partial increase of the stability against flux jumps because of the improvement of the heat extraction from the wire does not usually compensate for the accompanying decrease in the filling factor.

Some averaging of the parameters of the individual wires in the bundle and the possible "compensating" effect of the wires upon each other as a whole apparently facilitate the regularization of the critical currents of cable conductors in coils. Nevertheless, a reliable prediction of the magnitude of the critical current of a solenoid is, as in the case of single-strand conductors, only possible on the basis of the entire working experience with the given specific type of conductor.

The most important advantages of multistrand conductors can be recognized if one investigates the safety problem of large solenoids. Let us consider how the magnitudes of the electrical overvoltages and the overheating change with increasing energy of the magnetic system, assuming that no additional protective system is employed. An additional protective system may, of course, be used for higher efficiency, helium economy, etc; it is, however, desirable that the solenoid should not be damaged, even when such a system fails.

For the case of wire with no copper cladding the appropriate estimates can be made comparatively readily[12]; here the value of the inductance is of the order of one henry, which is on the whole confirmed by the sad experience of numerous experimenters.[67,83] Analogous estimates for copper-clad wire are somewhat more difficult to carry out. The determining factor here is the dependence of the rate of propagation of the normal phase on the thickness of the cladding. For small thicknesses the rate of propagation along the wire increases[84] and then begins to decrease, in spite of the fact that for simple "one-dimensional" models[32] the rate should decrease monotonically. The rate with which the boundary of the normal region moves in directions perpendicular to the direction of the windings is determined by such variable and poorly defined technical parameters as the type and thickness of the insulation, the strain of the windings, etc. Further complications are due to the fact that the resistance of the normal zones depends not only on their dimensions, as in the previous case, but also on the temperature of these zones.

By using data obtained in testing various large coils, such estimates can be refined, although a complete account of all the parameters of importance in our case is not always possible. The most useful data are those concerning the decay time of the current in the solenoids. For one of the largest coils wound with single-strand copper wire[78] with an inductance of 180 H and a total energy of 20 kJ the decay time was only 225 millisec. If the increase of the resistance of the wire during heating is appreciable, as in the case of unclad wire, then the decay time τ_0 increases only as $L^{1/4}$; the corresponding specific losses in the windings also increase as $L^{1/4}$.[35] In order to estimate τ_0 and the heat released in the case of copper wire one should, generally speaking, take into account the increase of the resistance of copper with temperature. For rough estimates of the excess heat one can assume[29] that because of the accompanying increase of the specific heat the maximum temperature of overheating in this case also increases as $L^{1/4}$.

According to the calculations of the authors of[78], the maximum heating of their coil did not exceed 60°K. Heating up to 300–400°C when failure of the insulating materials is already possible (this corresponds to a specific density of heat release of the order of 1000 J/cm^3[12]) can be considered admissible. It is seen that for a coil with copper-clad wire the heating should not exceed the dangerous limit up to very high energies.

The coil of[78] went over several times into the normal state without any noticeable damage. In tests of the toroidal coil which we have mentioned,[45] certain irreversible phenomena were apparently observed after transitions at a total energy of the order of 30 kJ; these could most probably be connected with electrical breakdown. Unfortunately, the decay time of the current in this coil was not reported.

The described coils[78,45] are, apparently, the largest of those which were and will generally be produced with single-strand conductors; this is due to complications in the process of winding and mainly to an increase of the overvoltages in such systems. We note that the total overvoltage on the normalized sections in the solenoid of[78] should be of the order of 10 kV. The overvoltages[35] increase as $L^{3/4}$ for unclad wire and somewhat more rapidly for copper-clad wire. Thus the increase of overvoltages is the principal danger in larger coils.

On going over from the wire to a cable with equal ratios of the quantities of copper and superconductor, the transition time should change slightly on account of the change in the heat conduction across the turns of the winding. Therefore the total voltage on the normal sections will decrease almost in proportion to the thickness of the cable (the number of strands), although the overheating and strains calculated per turn will also vary slightly.

Increasing the number of copper conductors in the cable delays the transition times and decreases accordingly even further the danger of electrical breakdown. Since this is usually accompanied by a decrease in the average current density, the specific losses also decrease. However, the use of ever increasing amounts of normal metal in an unstabilized conductor cannot always be acknowledged as rational. From the point of view of safety it would be much more convenient to employ a smaller amount of copper in the form of a short-circuited winding, since in this case the energy of the solenoid would be uniformly distributed over the entire volume of the coils. Such a winding can generally speaking also be used to "extract" the energy from a solenoid.[76,77]

By increasing the content of normal metal in the conductor the parameters will approach closer and closer those of a stabilized system. The average current density in the first large stabilized coils[57] was close to 3000 A/cm^2.[29] It is proposed that shortly the attainment of a density of the order of 9000 A/cm^2 will be entirely possible.[41]

This value is already close to the characteristic values of the current densities for large unstabilized systems[44] which will of course in turn be perfected with an attendant increase in the degree of reliability of their parameters. A difference of a factor of 2–4 in the current density for these variants may mean in the case of small coils a considerably larger difference in weight and dimensions, and be the determining factor in considering the advantages of this or that variant. For a sufficiently large system the weight is simply inversely proportional to the current density, so that this difference is smoothed out somewhat. For coils of such dimensions R that the value of the maximum mechanical stresses, which for a simple geometry will be of the order of HRj, approaches or exceeds the elastic limit of the conductors themselves, this difference becomes in general unimportant, since the weight will only be determined by various structural elements serving to relax the mechanical stresses. The following description of a series of the largest systems in existence or being developed at present will serve as an illustration of these considerations and will assist in a better presentation of the relative role of all the factors in systems of various scales.

One of the largest operating coils which is also one of the first systems with cable conductors was tested[44] at the Argonne National Laboratory (USA) in October 1964. The coil was intended for work with a helium bubble chamber. The bore diameter was 178 mm and the outer diameter was 610 mm. The coil consisted of four independent sections (one inside the other) wound with twisted indium-impregnated cables of various types with a varying content of copper wires. Wire made of Nb-Zr alloys was employed in the outer sections, and wire made of Nb-Ti—in the inner sections.

The maximum critical currents calculated per single wire were within the limits of 20—30 A for the various sections. The current density calculated for the entire cross section of the winding was in various sections between 4500 and 9100 A/cm^2. Thus in this case, too, there is appreciable degradation and the introduction of additional copper into the cable leads on the whole only to a decrease in the current density. However, this system was safe in operation and underwent a considerable number of transitions without damage. The maximum field of this coil was 67 kOe, and the maximum energy of 600 kJ corresponds to the heat of evaporation of 220 liters of liquid helium.

An unstabilized system with even more "energy capacity" and a maximum field of 150 kOe, in which a field of 135 kOe has recently been obtained,[87] is being developed.[85] This coil will constitute a system with "magnetic probes" and will be used to investigate controlled thermonuclear reactions. The field at the center of the system will be about half the field in the probes, i.e., it will amount to 75 kOe. The bore diameter in the central portion will be 50 cm, and in the probes it will be 15 cm. The total energy of the system will be about 2 MJ. RCA ribbon with Nb_3Sn will be used to produce the coil. The magnetic field pressure at 150 kOe already exceeds 900 atm. In view of the fact that the dimensions of the system are such that the diameter of the bore in the region of the probe is approximately equal to the thickness of the winding, the average stresses in the windings should also be of the order of several kg/mm^2. Although this quantity is so far not unduly large, extensive sectionalization with radial and coaxial partitions has been provided for in the construction in order to prevent accumulation of stresses in lower layers and in order to add stability to the ribbon winding against lateral stresses. The average current density turns out in this case to be close to 1000 A/cm^2. Although, as we have seen, in smaller coils with Nb_3Sn current densities are attained which are higher even by a factor of four.

The necessity of reinforcing the winding can also appear at more moderate fields, even in systems of comparable dimensions, for such configurations of the fields when the mechanical stresses cannot be held in check by the turns themselves.

This situation can be illustrated by using as an example the largest of the systems operating at present[57] and developed at the Avco-Everett laboratory (USA) (Fig. 11). This magnetic system is a model of an MHD generator coil. The magnetic field must in this case be directed perpendicular to the axis of the generator channel and must be homogeneous over a considerable length of the channel. The bore diameter of the coil into which one could insert a channel with a system of heat screens was 30.5 cm (the setting up of a channel in this model was not planned). The windings themselves were inserted into a cylinder 85 cm in diameter; however, the outer dimension of the entire construction including the reinforcing collars was 137 cm. The entire system weighed a little more than 7 tons, of which more than 4 tons were accounted for by the framework. Without entering into a discussion concerning the optimum nature of the structural calculation of the first experimental model, we note that the magnitude of the stresses tending to break apart the halves of the windings for a system 3 m long must amount to thousands of tons.

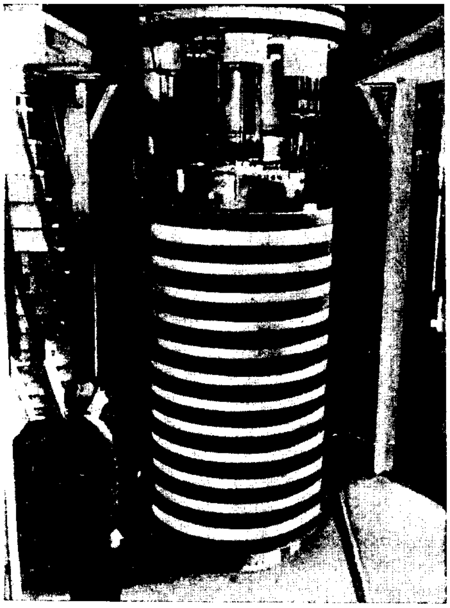


FIG. 11. Magnetic system of the firm Avco-Everett (USA).

Fully stabilized copper ribbon with a cross section of 1.0 × 12.5 mm with nine wires of Nb + 25% Zr alloy 0.25 mm in diameter rolled into the ribbon was used in the windings. The total length of ribbon exceeded 20 km and it weighed about 2.5 tons, the superconductor weighing only 80 kg. Such an increase in the weight of the conductor due to requirements of thermal stability is in this model rather unimportant against the background of an increase of the weight of the entire system connected with the mechanical strength of the windings.

The maximum current in the coils for which no increase in the resistance was noted amounted to 740 A, or 82 A per single strand, which was in good agreement with the data obtained previously in experiments with separate conductors and smaller coils. The maximum field in the region of the windings was 43 kOe, and at the center of the system it amounted to 37.7 kOe. Since the stability margin was rather appreciable, it turned out to be possible to increase the field up to 40 kOe. At that value the rate of evaporation of helium reached 200 l/hour; however, the transition was fully reversible (Fig. 1a). For a total inductance of the system of 15 h and a mechanical generator voltage of 12 V, the time necessary for such an excursion into the supercritical region and for recovery could not be less than 2—3 minutes; the minimum losses of helium during this time amounted to 10 l. The evaporation rate of the helium from the Dewar when the coil was switched off was

12 l/hour, whereas for the maximum current it was ~30 l/hour. It should be noted that the system included several separate sections with independent terminals, so that the current flowed through a total of ten leads. As is seen, the problem of supplying large coils with currents of several kiloamperes does not cause great technical difficulties. The total amount of liquid helium contained in the Dewar during tests of the system was about 2.5 m^3. However, only 1.5 m^3 were required to cool the coils from liquid nitrogen temperature. The maximum magnetic energy of the coil amounted approximately to 4 MJ which corresponds to the heat of evaporation of 1.5 m^3 of the liquid.

The example which we have considered and with whose analysis we shall conclude the description of a series of specific designs makes it possible to demonstrate rather graphically the considerable advantages of stabilized systems: safety and operating reliability, the possibility of accurate calculation and prediction of the parameters, and the full utilization of the possibilities of superconducting materials. This example shows that the various technical difficulties in the construction of large superconducting magnets can be overcome. Of course, the problem of safety has not been completely solved even for stabilized coils, even if merely because one must always consider the possibility of the appearance of various emergency situations (for instance, in the case of sudden failure of the vacuum in the Dewar). Emergency measures may include, for example, rapid blowing out of the liquid helium from the Dewar[44] (this would lead to a uniform distribution of all the energy stored in the winding), the dissipation of the energy by an external load, etc. The technical problems connected with the realization of these measures will become rapidly more complicated with increasing dimensions. The problem of the mechanical strength of the windings will become more and more complicated.

One could cite a number of examples which would allow one to present the stages of further increases in the scale of magnetic systems. The largest operating system is characterized by an energy of ~4 MJ. A project for a bubble-chamber magnet with a gap 4.2 m in diameter[44] is being worked on at present. The total energy of this system will apparently be of the order of 80 MJ. Industrial MHD power generators may in the future require systems with a volume of tens of cubic meters and a total energy of the order of 10^{10} J.[29] However, even this is so far not the largest number mentioned in this connection. The possibility has been considered[44] of constructing a superconducting energy storage device for 10^{12} J which would serve to smooth the daily fluctuations of the requirements in power systems (10^{12} J corresponds to the 15-second output of all power stations of the USSR at their mean annual output). So far it is of course not easy to conjecture on how far the corresponding engineering problems become more complex when the scales of the tasks increase by a factor of tens of thousands or a million. However, even the very posing of such problems adds confidence that they will be solved, and it is possible that we shall witness such an impressive increase of scales during a period of the order of five years, a period which has become the characteristic time[1] for measuring the rates of technical progress. After all, a similar increase of scales—by a factor of a million—from the first miniature coils with an energy of some joules has already in fact occurred, although now on looking back this increase does not appear to be so impressive. But try to imagine yourself in the position of the gentleman wearing the helmet on Fig. 11 five years ago!

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