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Superconductivity: Large-Scale Applications

Bonanza or bagatelle? Research in this decade should provide the answer.

R. A. Hein

The existence of a class of metallic conductors which when cooled to very low temperatures lose all their electrical resistance has been known for over 60 years. We denote this class of materials as superconduetors. In the 1960's a host of proposals were made to apply these superconductors to technologies where the I^2R, or Joule heating, of normal metallic conductors imposes a limit (I = current; R = resistance). In the late 1960's and early 1970's such efforts became substantial in the development of rotating electrical machinery, huge high-magnetic-field solenoids, transmission lines, and levitated vehicles.

The annual expenditure in the United States for research and development in applied superconductivity has been steadily increasing, and this fiscal year it is estimated to be about $26 million (*1*). This article is an overview of areas involving large-scale applications of superconductivity for which the 1970's are a decade of critical decision.

General Background

Cryogenics and low-temperature physics have their origin in the 19th-century quest to liquefy the so-called permanent gases (*2*). Cailletet and Pictet, working independently of each other, gave birth to low-temperature research in 1877 when they succeeded in liquefying oxygen, whose normal boiling point (NBP) is 90°K (Fig. 1). Dewar liquefied hydrogen (NBP = 20°K) in 1898, and Kamerlingh-Onnes liquefied helium, the last of the permanent gases (NBP = 4.2°K), in 1908.

Once having obtained these low temperatures, "cryogenists" turned their attentions to the properties of matter at low temperatures. In this regard Kamerlingh-Onnes' laboratory at Leiden had a definite advantage, because until 1925 it was the only place where liquid helium could be produced.

Dewar's work with platinum at liquid-hydrogen temperatures suggested that Nernst's theoretical predictions regarding the temperature dependence of the electrical resistivity of metals were in error. Kamerlingh-Onnes extended such measurements down to liquid-helium temperatures, and included gold and mercury. Although both platinum and gold exhibited a measurable, temperature-independent resistivity at helium temperatures, mercury gave a completely unexpected result. In a series of papers Kamerlingh-Onnes reported data which led him to conclude that when mercury is cooled below a characteristic temperature of 4.2°K it enters a new state of matter in which its electrical resistance is zero (*3*). He called this state the superconducting state and denoted the characteristic temperature as the transition temperature T_0. Workers at Leiden quickly established the fact that other metals also became superconducting; for example, they found that tin and lead were superconductors with T_0 values of 3.7°K and 7.2°K. From 1925 to 1946 the number of laboratories capable of producing liquid helium still numbered only five or six. However, in 1946 there appeared a commercial version of a helium liquefier designed and built by S. C. Collins of Massachusetts Institute of Technology. By 1950 many laboratories could liquefy helium, and superconductivity was no longer the exclusive property of the cryogenists.

Although the number of known superconducting elements, alloys, and compounds exceeded several hundred and transition temperatures as high as 17°K were known, the keynote speaker at the 1952 Low Temperature Physics Conference at Schenectady, New York, is reported to have said that low-temperature physics represented an ivory tower field of research, a field which would never become commercially practical (*4*). To that speaker it was inconceivable that anyone might cool a large-scale commercial system to liquid-helium temperatures in competition with a room-temperature system. However, in the late 1960's cryogenics blossomed into a multibillion-dollar business; superconductivity ceased to be a scientific curiosity and became a broad base for innovative engineering in many areas (*5*).

Cryogenics blossomed because the aerospace and atomic-age systems requirements led to the development of advanced liquefiers and cryogenic systems capable of producing, storing, and transferring huge quantities of cryogens. The status of superconductivity changed because the need of high-energy physicists for high-intensity magnets led to the commercial development of high-current, high-field superconducting materials in the form of useful wires and tapes. As a result of these advances, it could be said as we entered the 1970's that superconductivity offered a solution to some of the pressing technological needs of our society. Here I refer

The author is head of the Cryogenic and Superconductivity Branch, Solid State Division, Naval Research Laboratory, Washington, D.C. 20375.

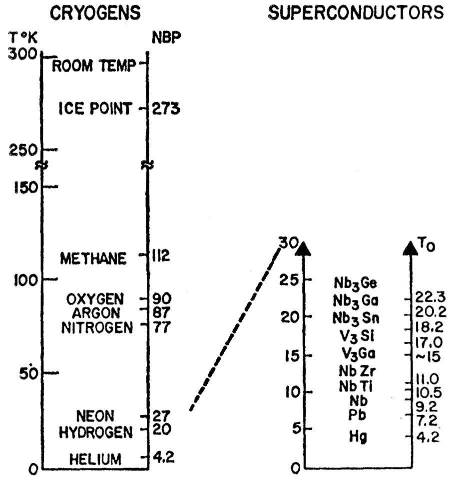

Fig. 1. Temperature ranges available with liquid cryogens and of interest for superconductivity.

to the generation, storage, and transmission of huge blocks of electrical power, and to the need for a high-speed ground transportation system. Superconductivity also offers more compact and powerful electric drives for naval propulsion systems.

Superconducting Solenoids

The oldest and most advanced superconducting technology is that of magnets, and it forms the base for all but one large-scale application (the exception is power transmission).

Kamerlingh-Onnes realized the technological importance of his discovery in connection with the fabrication of solenoids capable of generating intense magnetic fields with no I^2R losses. He did not succeed in his attempts to build such a solenoid, because while the current through his wires was being increased, the normal resistance suddenly appeared. The current which, at a particular temperature, causes R to first reappear is called the critical current $I_c(T)$. He also found that when the lead or tin wires were wound into a solenoid, $I_c(T)$ decreased by almost an order of magnitude. These results did not cause Kamerlingh-Onnes to abandon his dream of high-intensity solenoids, for he said (*6*): "If therefore the potential phenomena which frustrated this in the experiment with the coils may be ascribed to 'bad places' in the wire, and if we may therefore be confident that they can be removed, and if moreover the magnetic field of the coil itself does not produce any disturbance then this miniature coil may be the prototype of magnetic coils without iron, by which in future much stronger magnetic fields may be realized than are at present reached by the use of the strongest electromagnet." It has taken 50 years to realize Kamerlingh-Onnes' dream and, ironically, it has been made possible by the presence of metallurgically "bad" places (such as dislocations) in the conductor.

Kamerlingh-Onnes' work with solenoids led him to investigate the effects of an external magnetic field on the superconducting state. He found that at a temperature T, less than T_0, the condition $R = 0$ holds only for external magnetic fields less than a certain critical field $H_c(T)$. He found that the temperature dependence was approximately parabolic: $H_c(T) = H_0[1 - (T/T_c)^2]$. In 1916 F. B. Silsbee pointed out that $I_c(T)$ is a result of the existence of $H_c(T)$. The Silsbee rule is that $I_c(T)$ is the value of current at which the self-field of the current equals $H_c(T)$ on the surface of the conductor.

By 1933, 17 pure elements and over 53 alloys and compounds were known to be superconducting, with NbN having the highest T_0 (10.1°K). The electrical and magnetic properties of alloys and compounds were known to be quite different from those of the pure elements, so much in fact that (*6*) "at first sight one is inclined to think of two different types of superconducting state." Thirty years of increasingly active research were to pass before the work of Kunzler *et al.* (*7*) at Bell Telephone Laboratories (BTL) showed that two types of superconductors do indeed exist.

The discovery of Kunzler *et al.* was that Nb_3Sn could carry a direct current density of 10^5 amperes per square centimeter in a field of 8.8 teslas (88 kilogauss) without showing any I^2R loss. Such "high-field" superconductors, which can support large lossless transport currents in the presence of large magnetic fields (Fig. 2), belong to a class of materials known as type II superconductors. They are characterized by possessing high values for the critical magnetic field at which the normal state first appears. This field is denoted as H_{c2} and is called the upper critical field (Table 1). In contrast to type II materials (usually alloys or compounds) one has type I superconductors (pure elements) for which a field of a few hundred gauss will suffice to restore the normal state. Type II superconductors are the basis for the high-field superconducting solenoid technology, which originated in 1963 when the BTL group built a 7.0-tesla solenoid with Nb_3Sn as the conductor. Thereafter, design engineers looked on type II superconductors to supply high magnetic fields at low power for high-energy physics, magnetohydrodynamic generators, and nuclear fusion reactors. Magnet systems for high-energy physics have been the dominant development, involving annual expenditures in the United States of about $7 million (*1*). Major efforts in Germany, France, the United Kingdom, and Japan have also been in effect for years.

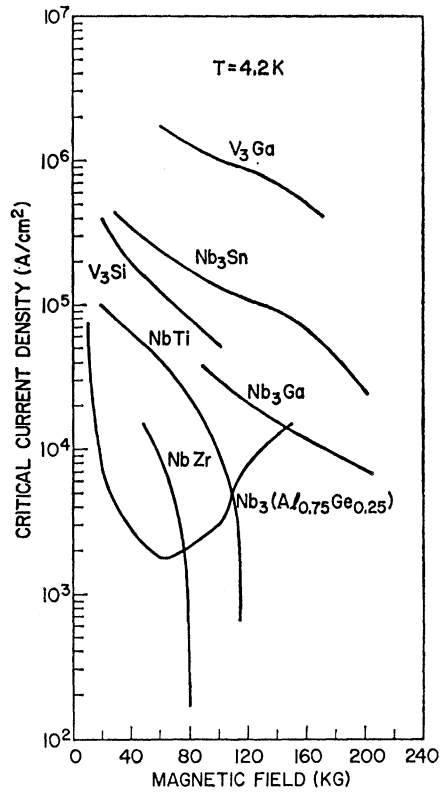

Fig. 2. Critical current density J_c as a function of applied magnetic field for selected supreconductors. Curves are based on data available in the literature.

High-Energy Physics

The interest of high-energy physicists in superconducting magnets is understandable when one considers the magnet technology (*8, 9*) connected with a high-energy synchrotron. A typical installation can involve as many as a thousand magnets in the beam handling and detection systems. Since the scientifically most interesting lifetime of an accelerator of a particular energy is about 10 years, there is a constant effort to find ways to raise the energy and to reduce the capital and operating costs of such accelerators.

If the new high-energy accelerators under construction or operating at the European Organization for Nuclear Research (CERN), Geneva, and at the National Accelerator Laboratory (NAL), Batavia, Illinois, used superconducting magnets, their energy would be increased threefold. [At present the 400-Gev (400 × 10^9 electron volts) synchrotron at NAL is the world's most powerful.] Conversely the 2-kilometer ring diameter at CERN could be reduced by a factor of 4 or 5 if the electromagnets of the ring were replaced by 60-kilogauss superconducting magnets.

Why has this not been done? As usual, advances do not come easily. It was not long before a new word became prominent in the world of superconducting physics, namely, "degradation" (*3, 8, 10*). When metallurgists developed techniques to produce sufficient quantities of type II superconductors such as NbTi, NbZr, and Nb_3Sn to wind a solenoid, it was found that the solenoid would become resistive (normal) for currents of only one-quarter to one-half of that required to drive a "short sample" specimen into the normal state; that is, when the wire was wound into a coil, its superconducting properties were degraded (*11*). Work between 1962 and 1967 showed that this was because closed-current loops are formed within the superconductor as the current in a solenoid (and hence *H*) is increased. Such loops can spontaneously collapse (causing flux jumps) and give rise to a pulse of thermal energy (*3, 8, 10*). If this heat is not quickly carried away, it will increase the temperature and drive the material normal. Intense research solved this problem, so that today "cryogenically stabilized" Nb_3Sn and NbTi conductors and "intrinsically stable" NbTi conductors (Fig. 3, A and B) are commercially available. The former are provided with a backing of a normal conductor such as copper or aluminum, and the latter are prepared in the form of fine filaments (10 to 50 micrometers in diameter) and embedded in a normal conducting matrix for mechanical strength.

These advances have led to the development of reliable laboratory-scale research magnets with fields up to 15 teslas and magnets for fusion research with stored energies of several megajoules. However, even with the tremendous improvements in materials, the problem of maintaining precise field configurations during thermal cycling, the adverse effects of radiation from

Table 1. Superconducting parameters of some useful superconductors. These parameters are sensitive to the preparation of materials. The listed figures are nominal values. Critical fields are given for 4.2°K; 1 tesla = 10,000 gauss.

Material	T_0 (°K)	H_{c1} (tesla)	H_{c2} (tesla)
Nb	9.2	0.13	0.25
NbTi	9.5–10.5	0.04–0.06	~9.0–12
$Nb_{25}Zr$	10.9	0.04	7.0
V_3Ga	14.8	*	19.6
Nb_3Sn	18.2	~0.02	22.5
Nb_3Al	18.8	~0.02	24.0
Nb_3Ga	20.3	*	32.0
Nb_3Ge	22.3	*	*

* No value found.

the beam, and the required pulsed operation (0.5 hertz) have caused management to decide to build the new accelerators at CERN and NAL with conventional electromagnets (*11*). However, magnet development continues, and the progress in the 1970's will affect the next generation of accelerators.

A spin-off of this materials research is the development of d-c solenoids of large volume and high intensity for bubble chamber magnets. One of the first large-scale applications of superconductivity was the magnet system for the 12-foot (3.7-meter) hydrogen bubble chamber developed for the high-energy physics program at Argonne National Laboratory; the system was operational in 1970 (*12*). Argonne's success has led to the construction of even larger and more energetic magnet systems (Table 2). Within the last several months, NAL has successfully operated its 30,000-liter hydrogen bubble chamber, which utilizes a superconducting magnet with a 4.3-m bore (*13*). The design current of 5 kiloamperes produces a central field of 3.0 teslas, corresponding to a stored energy of 396 megajoules. However, this magnet system, even with its huge stored energy, must take second place to the system just put into operation at CERN. The Big European Bubble Chamber (BEBC) magnet at CERN is the most energetic one in existence today (Fig. 4).

The BEBC superconducting magnet is designed for use with a 33,500-liter hydrogen bubble chamber. The magnet was originally scheduled to go into operation in 1972, but it was on 25 February 1973 that current was first passed through it (*14*). After a 9-day cool-down and with 20,000 liters of liquid helium in the cryostats, a current of 5 kiloamperes was passed through the coils; this produced a central field of 3.1 teslas, corresponding to a stored energy of about 550 megajoules. The complete bubble chamber was operated at its fully rated current of 5.7 kiloamperes on 18 November 1973 and is presently being used to obtain data (*15*).

The 1.8-tesla magnet of the Argonne bubble chamber could have been of a conventional design, since the required field strengths did not rule out conventional magnets; however, the annual operating cost of the superconducting system is about $500,000 less than that of a conventional system, whereas the capital investment costs are about the same.

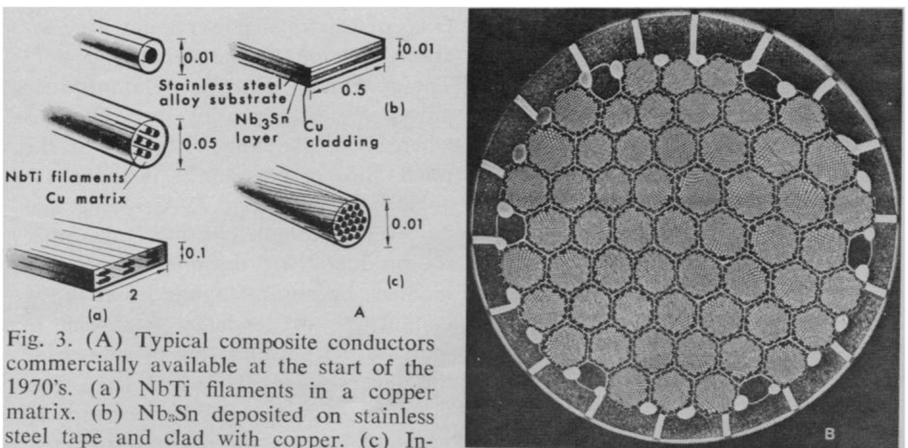

Fig. 3. (A) Typical composite conductors commercially available at the start of the 1970's. (a) NbTi filaments in a copper matrix. (b) Nb_3Sn deposited on stainless steel tape and clad with copper. (c) Intrinsically stable conductor consisting of an array of fine filaments of NbTi in a copper matrix. The conductor is twisted to reduce a-c losses. Measurements are in inches. [From D. Fishlock (*48*)] (B) Composite showing the current state of the art for a-c or pulsed magnet operation. This composite, manufactured by the Imperial Metals Industry, consists of fine NbTi filaments (light gray) sheathed in copper (dark gray) and the copper-nickel barrier (light gray). There are 241 filaments per cell, and the conductor consists of 55 such cells. The NbTi filaments are 5.4 μm and the wire is 1 mm in diameter. [From R. A. Popley *et al.* (*49*)]

Table 2. Some characteristics of large magnet facilities; I.D., inner diameter; L., length.

Location and facility	Coils I.D. (m)	Coils L. (m)	Current (amp)	Central field (tesla)	Stored energy (megajoule)	Status
Brookhaven National Laboratory, 2-1-m bubble chamber	2.1	0.9	4000	2.0	40	Operational, 1969
Argonne National Laboratory, 3.7-m bubble chamber	4.8	3.0	2200	1.8	80	Operational, 1970
Rutherford High Energy Labotory, 1.5-m bubble chamber	1.9	2.3	7500	7.0	340	Uncertain
Brookhaven National Laboratory, 4.3-m bubble chamber	4.9	1.8	8500	3.0	725	Uncertain
National Accelerator Laboratory, 3.9-m bubble chamber	4.3	0.9	5000	3.0	396	Operational, November 1973
CERN, 3.7-m bubble chamber	4.7		5700	3.5	800	Operational, August 1973

The long-term successful operation of these huge superconducting systems will do much to overcome reservations about superconducting systems and will open the way to the development of superconducting energy storage systems.

Electric Power Transmission

Since the advent of public electrical supply in the latter half of the 19th century, the demand for electrical power has steadily increased (*16*). To meet this demand, the utilities have increased the maximum size of their in-service generators from 100 million volt-amperes in the 1930's to 1500 Mva in 1970. Because of increased generator capabilities and demands, transmission line ratings have increased from a few million volt-amperes in 1930 to 2 Gva in 1970.

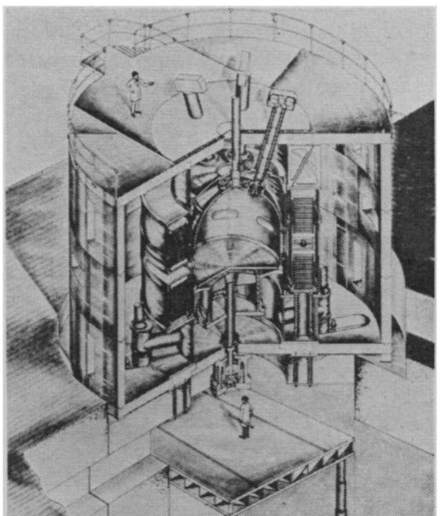

Fig. 4. Artist's concept of the Big European Bubble Chamber at CERN showing the relative size and position of the superconducting windings. The cryogenic system is somewhat larger than that at the National Accelerator Laboratory, which requires 5150 liters of liquid helium and has a boil-off rate of 50 liters per hour. [From G. Bogner (*14*); copyright IPC Business Press, England]

It has been predicted that the present U.S. generating capacity of 340 Gva will have to increase to 1300 Gva by 1990 (*16*). Individual plant capacities as large as 11 Gva are envisioned. The problems associated with the economical generation and distribution of large blocks of electrical power are regarded by many power engineers as the challenge of the 1980's. Thus, it is no surprise that many of these engineers are looking toward superconductivity as a means for better power generation, storage, and transmission.

Setting aside the question of how this increase of 1000 Gva in generating capacity will be obtained, it is evident that higher-rated transmission lines will have to be installed. How are we going to transmit large blocks (1 to 10 Gva) of electrical power from the generating station to the demand center? The maximum amount of transmitter power P_m is given by $P_m = IV \cos\varphi$, where V is the line voltage, I is the rated line current, and φ is the phase angle between V and I. Assuming that $\cos\varphi$ is a constant, one must maximize the product IV in the most economical manner. Because of ohmic losses in the conductor, the tendency has been to increase the power rating by increasing the line voltage. This had lead to a doubling of in-service voltage every 10 years to the present maximum of 675 kv. The use of still higher voltages will necessitate tall (45 m) and expensive towers.

The anticipated increase in the number and ratings of new lines to meet the increased demands of the 1980's and 1990's has led to public and private objections to the use of overhead lines. Economic factors, however, favor overhead lines, which is why 90 percent of the present U.S. power transmission is by overhead lines. Since the utilities may have to install underground cables, they are exploring ways to make them economically attractive (*17*).

The history of the development of higher-rated underground cables reveals a steady increase in line voltages from 33 to 400 kv (*18*). The present limitation on cables is predominantly the inability of the surrounding soil to conduct away not only the I^2R heating in the conductor but also the heating produced (assuming a-c transmission) in the dielectric supports, which is proportional to V^2 and thus becomes significant at the higher voltages. The dielectric properties of the solid insulator limit operational cable temperatures to not more than 80°C. This limitation has led to what Hollingsworth (*18*) has called the "most radical" concept yet to be considered: cryogenic cable using the properties of superconductors.

The advantage of a superconducting transmission line is that since $R = 0$, one can maximize the product IV by increasing I several orders of magnitude over that in copper or aluminum cables. This not only does away with I^2R losses in the conductor in the d-c case but also reduces the losses by several orders of magnitude in the a-c case. A superconductor will not carry a lossless a-c current. For a-c transport currents the power loss is given by $Q =$

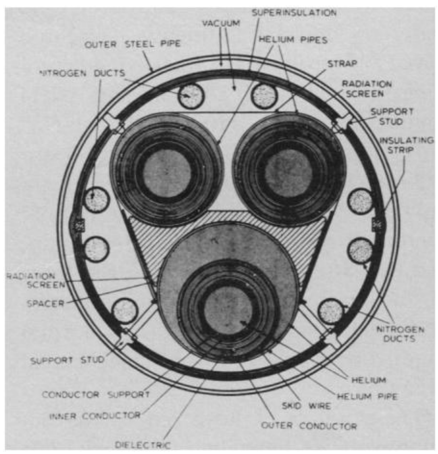

Fig. 5. Cross section of a semiflexible superconducting a-c cable. The outer diameter of this system is 4.7 cm, and it is rated at 275 kv. This design is representative of those being developed by several laboratories. Each of the three phase conductors is a coaxial flexible conductor of the type shown in Fig. 6. [J. A. Baylis (*20*); courtesy of the Royal Society of London]

$fAE_{c1}(H_p/H_{c1})^x$, where f is the frequency, A is the surface area, E_{c1} is a constant, H_p is the peak a-c field at the surface, and H_{c1} is the lower critical magnetic field (Table 1). The exponent x has the value 3 for $H_p < H_{c1}$ and the value 4 for $H_p > H_{c1}$. This equation tells us that for a-c operation one wants a small E_{c1} and a large H_{c1} for a particular H_p. Since these cables will probably not require high voltages, the dielectric losses will also be decreased. Both of these factors will make it possible to transmit power at the gigawatt level without reaching the thermal limit of the cable. There are other advantages, such as greater critical lengths for a-c cables, smaller size, and large power density (increased by a factor of 6), which are discussed in the literature (*19*). The main drawback of superconducting cables is that they require new technologies for the elaborate thermal insulation and refrigeration needed at the low operational temperature. Detailed studies [see the bibliographies in (*16*) and (*19*)] indicate that such cables will be economically competitive in long circuits with power ratings of 2 Gw or more. Although such cables will probably not be needed until 1990, some rather serious decisions will have to be made in this decade if they are to be operating by that time.

The major problem (*20–22*) is to design a superconducting cable which, with its cryogenic envelopes and cooling systems, will be economically competitive with the SF_6-cooled cables or with high-pressure, oil-filled cables. Figure 5 shows a three-phase, a-c cable design. The coaxial conductors for the three phases are contained within a common envelope at room temperature. The phase cables are of the newly developed flexible coaxial type shown in Fig. 6. The actual conductors are aluminum-backed niobium strips or niobium-plated aluminum wires. The inner conductor, say of Nb/Al strip, is laid on the nonconducting helical former with the Nb facing outward, and the outer conductor is laid on polyethylene-tape dielectric with the Nb facing inward. Skid wires are used to hold the dielectric in place. A cable such as this is flexible and accommodates thermal contraction. Each phase cable is cooled by liquid helium, which flows through the "pipe" in which the cable is situated. The upper two smaller pipes (Fig. 5) are the helium inlet lines, and the larger lower pipe is the helium return line. This design is for a 275-kv a-c line with a 4-Gw capacity and an overall outer diameter of 4.7 cm.

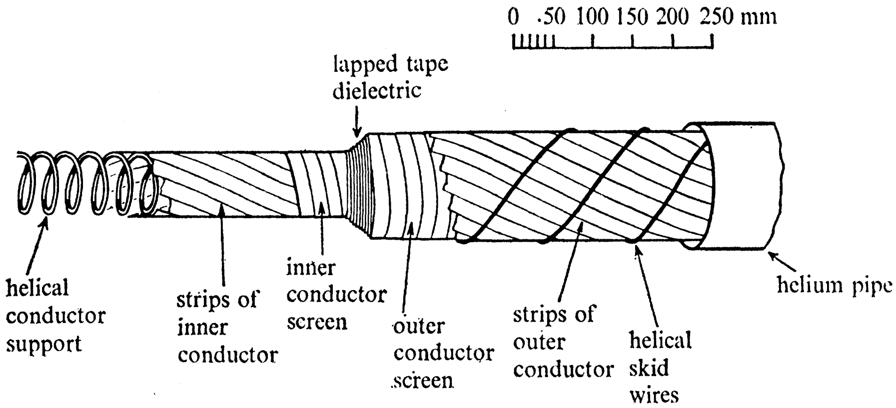

Fig. 6. Flexible conductor of the type being developed at several laboratories. Liquid helium flows through the center and around the outside of the conductor. In a coaxial arrangement the superconductor must be on the outside of the inner conductor and the inside of the outer conductor. To date, such cables have been made with Nb/Al tapes and Nb/Al wires. [J. A. Baylis (*20*); courtesy of the Royal Society of London]

Designs of this type differ from rigid-cable designs that were in vogue in the United States and Europe at the start of the 1970's. The emphasis now seems to be on development of semiflexible and flexible cables (Table 3). Whereas rigid cables would most likely be fabricated in lengths not exceeding 20 m, semiflexible cables can be fabricated in lengths up to 500 m and transported to the site on large drums. The cable would then be pulled into a rigid cryogenic enclosure. Flexible conductors made with Nb/Al have been developed in Europe, and similar conductors made with Nb_3Sn are under development in the United States and Europe.

The complexity of cryogenic operation is a penalty one must pay for using superconductors, and the economics and reliability of refrigeration systems are of major concern. Refrigeration is cheaper when the units are larger and hence farther apart. Optimum spacing varies between 5 and 30 km for differ-

Table 3. Superconducting power cable programs.

Location and facility	Type	Conductor
Austria		
Institute for Low Temperature Research, Graz	Flexible; a-c	Nb; Pb
Canada		
Hydro Quebec Research Institute, Varennes	Various	Study
France		
Centre de Recherches de la CGE and Air Liquide France, Grenoble	Semiflexible; d-c Semiflexible; a-c	NbTi/Al Nb/Al
Japan		
Furukawa Electric Company, Tokyo	Rigid; a-c, d-c	NbTi/Nb/Cu; Nb/Cu
United Kingdom		
Central Electricity Research Laboratory, Leatherhead, Surrey	Rigid; a-c, d-c Semiflexible; a-c, d-c	NbTi/Nb/Cu; NbZr/Nb/Cu Nb/Al; Nb/Cu
United States		
Union Carbide, Linde Division	Rigid; a-c	Nb/Cu
Brookhaven National Laboratory	Flexible; a-c	Nb/Al; Nb_3Sn/Al
Los Alamos Scientific Laboratory	Not known; d-c	Nb_3Sn/Al; other type II
Stanford University	Semiflexible; a-c	Nb_3Sn/Al; other type II
West Germany		
Siemens Company, Erlangen	Rigid and semiflexible; a-c, d-c	Nb/Al; Nb_3Sn/Al
Allgemeine Elektrizitäts Gesellschaft, Kabelmetal, Linde, Frankfurt	Flexible; d-c	Nb_3Sn/Al
Soviet Union		
G. M. Krzhizhanovsky Power Engineering Institute, Moscow	Rigid; a-c	Nb; Nb_3Sn

ent cable ratings and designs. Because of the cost of refrigeration, a design criterion for operation at 5°K is that the total losses in the composite should be less than 0.1 μw per square meter of surface area. For operation at 10°K improved refrigeration performance increases this design limit to 0.3 $\mu w/m^2$.

Detailed measurements of the a-c losses in superconductors such as Nb, NbTi, NbZr, and Nb_3Sn indicate that Nb is the best choice in the a-c case for operation at 5°K. However, recent improvements in the metallurgy of the type II conductors indicate that the choice is not definite (*20*). The higher allowed loss figure for operation at 10°K makes Nb_3Sn a candidate as well. Regardless of the choice, the conductor will be a composite formed by using copper or aluminum to serve as a backing for a thin layer (10 to 50 μm) of superconductor.

In addition to providing mechanical support, the normal metal backing helps to meet the fault-current requirements of transmission cables. (In a-c systems the fault-current requirement is that the cable withstand momentary overloads of up to 15 times the rated line current and be operational immediately afterward.) Such a current will drive the superconductor into the normal state, in which its electrical conductivity is considerably less than that of copper or aluminum. The resultant I^2R would be disastrous, so there must be an alternate path for the current during the time the superconductor is in its normal state. For Nb_3Sn, with its large critical current density J_c, a simple two-component composite will suffice, whereas in the case of Nb some workers prefer a three-component composite such as Nb/Nb-Ti/Cu or Nb/NbZr/Cu. However, such composites are more expensive to manufacture. With regard to the fault currents, one must also consider that since the superconducting cable is a high-current low-voltage cable, fault currents 15 times the rated current may not be compatible with the overall transmission system, so auxiliary equipment may be required to keep the fault currents down to four to seven times the rated current. In the case of d-c cables, terminal conversion equipment limits fault currents to twice the rated current; thus, the fault-current problem is not as severe as in the a-c case. Sufficient metal to cryostatically stabilize the conductor should be capable of handling the fault current, and thus d-c cable designs are deemed adequate and suitable Nb/Cu and Nb/Al conductors exist. Unfortunately, most transmission cables are a-c, although d-c transmission is becoming more acceptable to the utilities.

The initial work on cables centered about conductor development, but with the successful fabrication of composite conductors attention is now being focused on suitable dielectric materials and cryogenic engineering, and I will not discuss these problems here.

Totally flexible lines are also under development (Table 3), and in at least one case the program is quite advanced. At the Institute for Low Temperature Research at Graz, Austria, P. A. Klaudy has developed a totally flexible cable. This cable can be fabricated in lengths up to 200 m, transported to the site on a drum, and simply unwound into a trench. A 50-m-long test section existed when I visited Graz in 1970, and plans are now under way to install a 100-kv experimental link several hundred meters long in parallel with an existing overhead line. The project at Graz should be operational in 1975 or 1976 and may be the first industrial use of a superconducting line.

With the exception of the Union Carbide program (*22*) most of the U.S. projects are relatively new (*17*). Apparently Union Carbide is staying with its rigid Nb tube construction, whereas the programs at Brookhaven and Stanford are based on flexible Nb_3Sn cables. The plans of the Brookhaven group call for installation of a 700-m outdoor test cable in 1976.

Although 1975 and 1976 will see the start of field tests at Graz and Brookhaven, the planned cables seem to be a bit short for a real test of the economics and reliability of refrigeration systems. The major problem with refrigeration and thermal insulation is reliability. All the evidence so far suggests that reliability can be built into such systems, but manufacturers are reluctant to invest the required development funds for a market that is still uncertain. The economic feasibility and reliability of superconducting lines will have to be proved in this decade if they are to play a significant role in the 1980's.

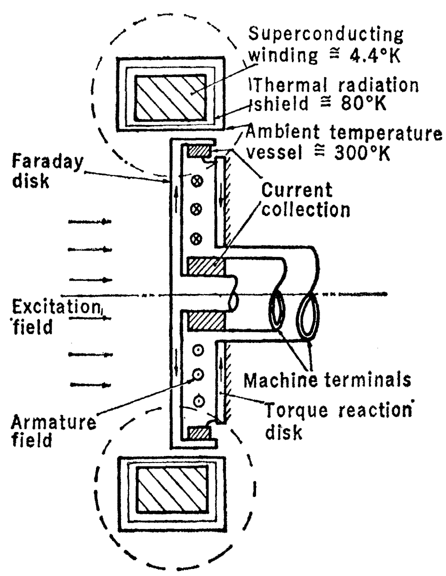

Fig. 7. Schematic representation of a homopolar machine (Faraday disk or Barlow wheel). The voltage generated by rotating the disk in the presence of a useful magnetic flux Φ is $V = \Phi N/60$. Superconducting windings yield values of Φ that are three to five times the value obtained with a conventional winding. [A. D. Appleton (*29*); courtesy of the Royal Society of London]

Rotating Electrical Machinery

Let us now turn to the problem of generating the electrical power that will be needed to meet the demand of the 1980's. The first efforts, in the 1960's, to incorporate superconducting windings in rotating electrical equipment were directed toward military applications, in which weight and size were the dominant concerns. These programs established the feasibility of using superconductors in field windings and the need to shield the superconductor from any a-c magnetic field. Interest waned, however, and it was a spin-off of superconducting magnet technology—namely, the commercial availability of stabilized NbTi conductors—that caused the recent push to develop large d-c and a-c rotating machinery with superconducting field windings (*23–27*).

In March 1970 the International Research and Development Company (IRD) of the United Kingdom demonstrated that their 3250-horsepower (2.4-Mw) homopolar motor with a superconducting NbTi field winding could operate at full load in an industrial environment (*26*). A homopolar machine is simply a Faraday-disk machine (Fig. 7) in which the armature (thin circular disk) rotates inside an axial magnetic field. This generates a voltage between the outer and inner rims of the disk, causing a current to flow as shown in Fig. 7. Such machines operate at low voltages and high currents. The voltage is given by $V = \Phi N/60$, where V is in volts, Φ is the useful magnetic flux in webers, and N is the speed in revolutions per minute. Useful flux is the flux which cuts the disk between the inner and outer brushes. Superconducting windings yield values of Φ that are three to five times greater than those obtained with conventional windings, which is why they are used. The power (kilowatts) developed by a machine such as the one shown in Fig. 7 is $P = 10^4 q\Phi DN$, where D is the diameter of the outer slip ring (meters) and q is the current collected per meter of slip ring (amperes per meter).

There was some question about the effect of the armature reaction forces on the superconducting field winding, so IRD built a small (35-kw) model and on the basis of its performance built the 2.4-Mw machine. To obtain this rating with reasonable values of armature current, one must increase V. Therefore, one either connects a number of disks in series on the same shaft or segments a single disk (radial cuts). The segmented-disk approach was the one IRD decided on; they used 40 segments, and the machine voltage at 200 rev/min was 440 volts. The field winding of the larger motor contains 50 tons of NbTi wire, and at 750 amperes it generated a central field of 3.5 teslas.

Figure 8 shows the two motors built by IRD. The larger machine was used to drive a huge water pump at the Fawley Power Station (*27*), in a test designed to show that superconducting motors are here. Unfortunately, the test was only a qualified success. The superconducting properties presented no difficulties, but the overall cryogenic system was unreliable because of a faulty compressor. Therefore, the Central Electricity Generating Board could not accept the motor, which has since been removed.

Although industrial applications of high-rated homopolar machines have been discussed, their development has been pushed only for marine propulsion systems (*28*). The U.K. Ministry of Defense (MOD) has funded the development by IRD of a d-c superconducting generator and motor suitable for use as a propulsion system for high-speed naval vessels. The reluctance of MOD to use liquid-metal collection systems has highlighted a major engineering problem, namely, the development of a solid brush compatible with a high current density. The absence of iron in these machines also introduces a

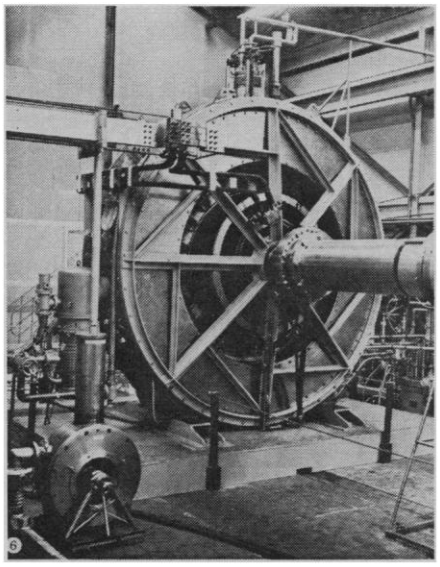

Fig. 8. Two motors with superconductive field windings built by the International Research and Development Company. The demonstration model (lower left) was operated in 1966 and the full-sized (2.4-Mw) machine was operated in 1970. [Courtesy of the International Research and Development Company Ltd., Newcastle-upon-Tyne, England]

problem of confining the magnetic field to the immediate vicinity of the machine. There are also questions about increasing the voltage rating, the best arrangement of the slip rings, and so forth. Since these and similar problems do not involve superconductivity, they are not discussed here.

Present efforts in behalf of the MOD involve the use of multifilament NbTi conductors. The early Niomax conductor (NbTi/Cu) manufactured by Imperial Metals Industry (IMI) raised doubts about how rapidly the magnetic field of the coils could be changed without quenching the superconducting state. However, the magnet development programs for pulsed magnets have led to a three-component conductor: NbTi filaments surrounded by a copper-nickel alloy in a copper matrix (Fig. 3). This conductor can meet the required rate of field changes anticipated for propulsion systems.

Another innovation is the use of vacuum impregnation to pot the superconducting windings in an epoxy resin —another spin-off of the pulsed magnet and high-energy physics programs. The superconducting windings of IRD's newest generator and motor are potted. The generator has been built, the motor winding is nearing completion, and sea trials are planned in early 1975 (*29*).

The U.S. Navy has launched a major effort to develop a superconducting motor-generator set for ship propulsion systems. Work at the Naval Ship Research and Development Center, Annapolis, Maryland, has led to a novel design known as the shaped-field drum machine (*30*). The superconducting windings are stationary but situated inside concentric drum conductors located on the rotor, and an iron shield shapes the field. Apparently the U.S. Navy is not against the use of liquid-metal brushes. A small prototype motor has been produced and it is believed that a d-c system should be pursued rather than an a-c system. Study contracts for designs have been let to Garret Aerospace and General Electric for a 30,000-horsepower (~ 22-Mw) motor generator set.

For a-c machinery the market is in the area of central power stations. An easy readable account of the basic considerations for a-c machines in general and superconducting ones in particular has been written by Mole *et al.* (*25*).

The synchronous machine has three principal windings: an a-c armature (stator) winding, a d-c field winding, and a damper (shield) winding interposed between the first two windings. For operation there must be relative motion between armature and field windings. Current-collection problems for large blocks of power rule out rotating the armature winding, so one is left with two basic choices: rotate the field winding outside the stationary armature (stator), or rotate the field winding inside the armature winding. Conventional design considerations rule in favor of rotating the field winding inside the stator, and this is also the case with superconducting windings. The Edison Electric Institute (EEI) in 1967 funded a project at MIT to develop a 45-kva machine. The MIT design (*27*) called for rotating the superconducting winding as well as its cryostat inside a normal conducting armature (stator). By June 1969 the MIT machine was successfully demonstrated. This success has lead to worldwide activity in developing still higher rated machines. Because of the commercial competition in this area, it is not possible to give a complete list of the companies engaged in development programs. Interested readers are referred to the literature (*31, 32*). At MIT, work was begun on a machine with a capacity of 2 to 3 Mw, and in 1970 Westinghouse started work on a 5-Mw machine (Fig. 9, a and b).

Problems associated with a rotating cryogenic system present challenges to the cryogenic and structural engineers. The armature conductors (stator) are no longer shielded by iron and see the full value of the machine's magnetic field, and eddy currents have to be taken into account in designing them. The MIT and Westinghouse groups have come up with designs *(24, 25)* which they feel will meet all demands.

Apparently cost trade-offs have ruled in favor of a multifilament $Nb_{48}Ti/Cu$ composite rather than the three-component conductor being employed by IRD. A conductor used at MIT consists of 24 transposed filaments, each 0.01 inch in diameter, embedded in a rectangular copper matrix with overall dimensions of 0.125 by 0.050 inch. The copper-to-superconductor ratio is 2.6/1, and the winding consists of 668 turns. The winding is potted by the liberal use of fiberglass and epoxy and contains numerous cooling passages. The overall field winding will have a current density of 1.25×10^8 amp/m^2 (root mean square). For a winding current of 800 amperes (50 percent of the rated capacity of the conductor) it will produce a field of about 2.5 teslas. This machine is rated at 3 Mw if an iron shield is used and 2 Mw if an aluminum shield is used. (The iron shield increases the weight of the machine by almost a factor of 2.) This machine is scheduled for testing this year.

The largest a-c superconducting machine is the Westinghouse one (Fig. 9), which is rated at 5 Mva and is capable of being upgraded to 15 Mva. The superconducting winding is a two-pole coil wound with a NbTi/Cu filamentary conductor, which is of the intrinsically stable class of superconductors. The winding and associated Dewar rotate inside a normal-state stator. The completed machine was first tested near the end of 1972. Full-load tests have not been conducted, for lack of a suitable test bed, but the tests that have been made show the technical feasibility of this design. However, the economics of such a generator have yet to be established. Superconducting generators are expected to be 99.6 percent efficient, or about 0.3 to 1.0 percent more efficient than conventional machines. If long-term reliability can be established, this would represent an annual saving of several hundred million dollars. In a discussion of huge generators at central power stations it was pointed out that one day of additional downtime per year would eliminate any potential savings *(33)*.

I gather that worldwide interest in superconducting machines is engendered not so much by their improved efficiency as by their savings in weight and size compared with conventional machines. For example, a second development program at Westinghouse calls for a 5-Mva, 400-hertz generator to be delivered to the U.S. Air Force. The apparent rationale here is that of saving weight. A conventional oil-cooled generator has a specific mass of 0.6 to 10 pounds per thousand volt-amperes in the small ratings and a potential 0.5 pound/kva for a 5000-kva machine (1 pound $\sim$ 0.4 kg). Superconducting windings yield, with refrigerator included, 0.3 pound/kva. Higher ratings yield even lower specific mass values.

By the end of the 1970's the period of the testing and evaluation should be drawing to a close. It seems now that the only thing that might stall commercial utilization of superconducting generators would be failure to develop an economically acceptable, reliable refrigeration system to be integrated with the machines. However, as often happens, improved conventional machines might appear and nullify the advantages of the cryogenic machines.

Energy Storage and Transfer

The commercial production of stabilized type II superconductors and the successes of the large bubble chamber magnets have led to renewed interest in inductive energy-storage coils. Boom *et al.* *(34)* state that the total U.S. generating capacity of the electric utilities in megawatt-hours is approximately twice the actual megawatt-hours produced. That is, the in-service generators required to meet peak demands are used only 50 percent of the time. One way to meet increased demands is to level out the demand curve, and this is presently done by pumped hydrostorage. When demand is low the excess power is used to operate pumps to store water in high-lying reservoirs, and this stored energy is used when demand is high.

The use of superconducting solenoids to directly store electrical energy has been proposed for some time. The 1970's have seen the initiation of study programs at the University of Wisconsin and the Los Alamos Scientific Laboratory *(34, 35)*. In these studies, storage systems with capacities of 10,000 megawatt-hours (3.6×10^{13} joules) are discussed. The physical dimensions of such systems are so large that one is inclined to scoff at the idea until he thinks of the remark made in 1952 that low-temperature physics would

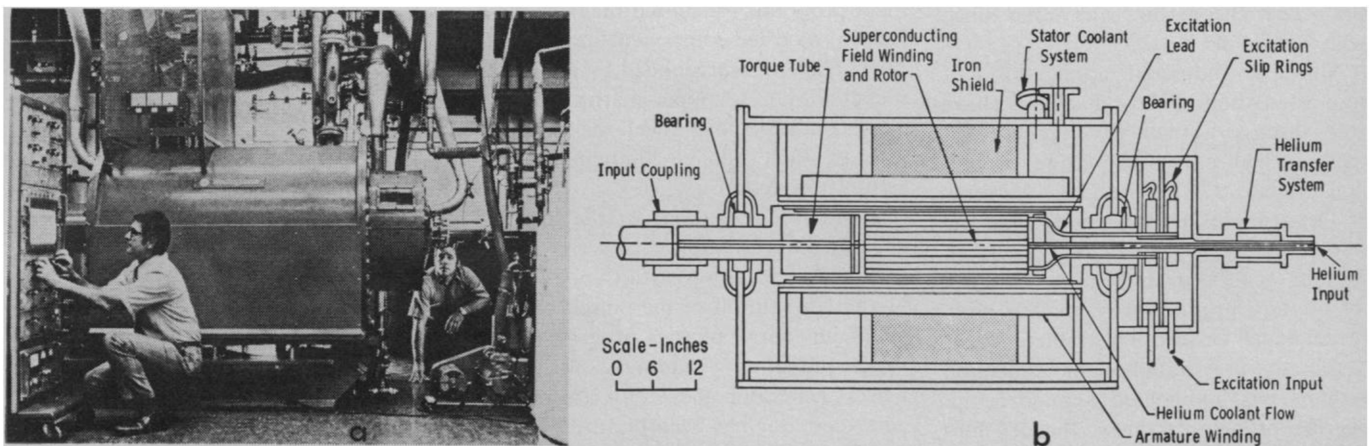

Fig. 9. (a) Westinghouse 5-Mw generator with NbTi/Cu superconducting field windings. It was operational in 1972 but has not operated under full load. (b) Cross section of the Westinghouse 5-Mw superconducting generator. [Courtesy of Westinghouse Research Laboratories, Pittsburgh, Pennsylvania]

never become commercially practical (*4*). For example, a single-layer solenoid proposed by Boom *et al.* (*34*) is 103.8 m in radius and 105 m long. It would be wound with a NbTi/Al composite which would contain internal cooling channels for the superfluid helium. The operating temperature would be 1.8°K, and the central field of the solenoid would be 3.1 teslas. A major problem with such coils is finding ways to handle the enormous forces involved.

Such a structure would be buried in bedrock; a circular trench 10 m wide, 100 m deep, and 100 m in radius would be dug, and the coil would be wound in situ. This football field–size superconducting magnet assembly would require cryogenic components much larger than any previously constructed. That they could be constructed seems likely in view of the successful development of the cryogenic systems for bubble chambers and the 1.8°K refrigerator for the superconducting linear accelerator at Stanford.

An energy storage and transfer system has been proposed by Smith (*36*) for the operation of a synchrotron with superconducting magnets in a 0.5-hertz pulsed mode (*8*). This scheme (see Fig. 10) involves the use of two mutually perpendicular coils, one of which forms part of the primary circuit of the superconducting transformer while the other is part of the energy storage circuit. A third superconducting coil (field coil) is rotatable and is connected to an external power supply. I interpret the operation scheme to be as follows. During the initial charging operations the field coil is positioned so as to induce a maximum persistent current I_p in the primary circuit and none in the storage coil. A 90° rotation causes I_p to decrease to zero while inducing a current in the storage coil circuit. An additional 90° rotation induces a current $-I_p$ in the primary while causing the storage current to return to zero. The change in I_p with time accompanying this 180° rotation produces an induced electromotive force in the secondaries which powers the synchrotron magnets. Such energy transfer is practically lossless and makes it possible to operate a synchrotron with minimum net power requirements. Figure 10 indicates the physical size needed for a 1000-Gev synchrotron. The largest coil would be typically 3 to 4 m in radius, and would be capable of transferring 10^9 joules. To my knowledge, none of these energy storage or transfer schemes are yet under active development.

Superconducting Magnets for Superfast Trains

The need for high-speed ground transportation can be argued from the point of view of the environmentalist or the conservationist, but the commercial thinking can be summarized simply as: speed brings more revenue (*37*). This quest for yet higher speeds has led to active commercial competition between Japan, Germany, the United States, the United Kingdom, and other countries (*38*). Superconductivity comes in once one agrees that conventional wheel track systems will never be viable for speeds in excess of 300 km/hour and that top speeds of 550 km/hour are preferable (*39*).

The first assumption seems well founded. The world's fastest commercial train has been in operation for 10 years between Tokyo and Okayama, a distance of 676 km. Apparently the problem of track maintenance has forced a reduction in the top speed from 240 to 210 km/hour. Even if this problem did not exist or could be alleviated, as suggested by work on an advanced passenger train project in the United Kingdom (*37*), the failure of adhesive wheel and track drive systems at high speeds restricts the speeds with such a drive to 300 km/hour or less. These limitations have refocused attention on concepts first expounded at the start of this century: the use of magnetic forces for the suspension (levitation) and guidance systems and the use of a linear induction motor to supply the drive.

Magnetic levitation suspension systems can use either an attractive or a repulsive magnetic force. In the attractive system electromagnets on board the vehicle are extended under a ferromagnetic "track"; the repulsive systems now under development use on-board superconducting magnets and a normally conducting "track."

An excellent account of the serious contest for the final choice of the attractive or the repulsive system is given by Hanlon (*40*). The main concerns of the proponents of the attractive system are its inherent instability, which necessitates servo controls for the electromagnets, and the small gaps (10 to 20 mm) required between the magnet and the ferromagnetic rail. The latter requirement places severe constraints on track smoothness. Proponents of the repulsive suspension emphasize that the magnetic fields attainable with superconducting solenoids are of sufficient strength that the gap between the magnets and the track can be 15 to 30 cm. Thus, track smoothness is no problem. A repulsive interaction is also inherently stable, and sophisticated controls are not required. The only major uncertainty concerns the long-time reliability of the associated cryogenic systems. Attractive systems being developed by Messerschmitt-Bölkow-Blohm and Krauss-Maffei in Germany are in a

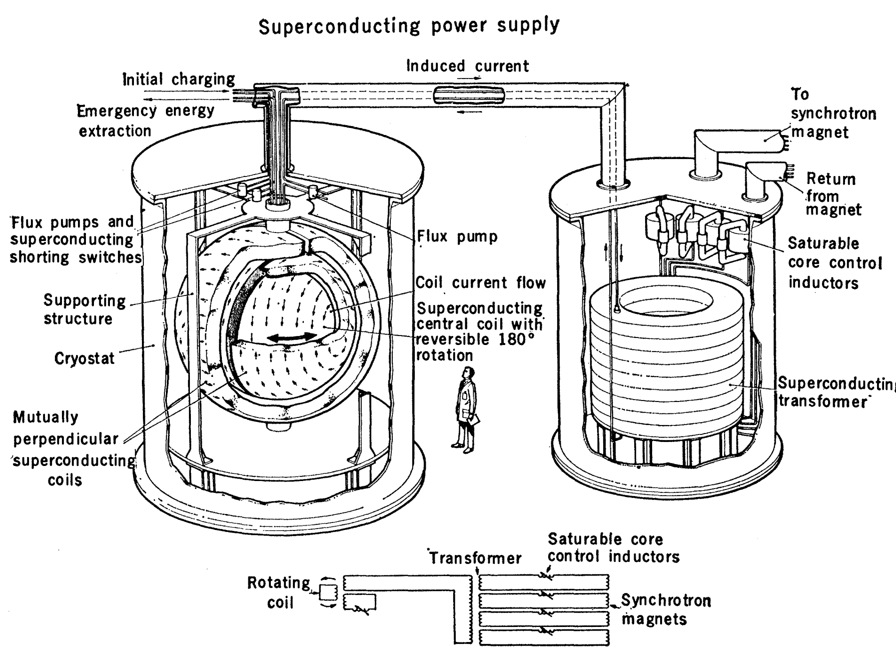

Fig. 10. Artist's concept of a proposed energy storage and transfer system described in the text. [Courtesy of Rutherford High Energy Laboratory, Chilton Didcot, Berkshire, England]

more advanced stage than are the repulsive cryogenic systems (*41*). However, the latter appear to be closing the gap.

The most advanced program for developing a repulsive superconducting system is sponsored by the Japanese National Railway (JNR), with the project of AEG-BBC-Siemens (see below) coming in a close second. The superconducting systems under development are based on the repulsive interaction between a moving magnet and eddy currents induced in a nearby stationary conductor. The train concept involves a track made up of discrete closed loops of conductor or a continuous sheet of conductor over which a magnet or system of magnets in constrained to move. When the relative velocity is high enough (over 50 km/hour) the repulsive interaction gives rise to a lift force F_L of sufficient strength to levitate the magnet and the structure (vehicle) which supports the magnet system. The lift force is a function of the relative speed, and detailed calculations have been made for various magnet and track configurations (*42*). The same eddy currents that produce F_L also dissipate energy in the normally conducting tracks in the form of I^2R heating. This dissipation gives rise to a drag force F_D, which reaches its maximum value at low speeds and then falls off as $V^{-1/2}$. Laboratory tests with rotating magnets and conductors have shown the essential correctness of theoretical predictions of F_L and F_D and the technical feasibility of using such a scheme for magnetic levitation of passenger-carrying vehicles.

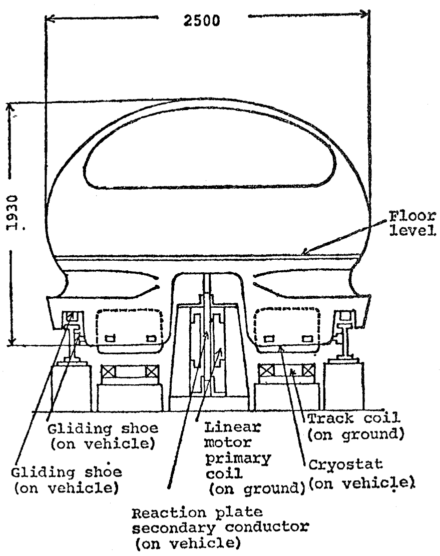

Fig. 11. Schematic of the 3.8-ton test vehicle built by the Japanese National Railway. The dimensions are given in millimeters and the location of the onboard superconducting magnets, track loops, and linear induction motor is shown. [K. Oshima and Y. Kyotani (*39*); copyright IPC Business Press, Surrey, England]

Encouraged by such laboratory results, JNR constructed a 2-ton vehicle powered by a linear induction motor and operated on a small test track made up of discrete loops of aluminum conductors. This vehicle attained a speed of 50 km/hour at a levitation height of 9 cm over a prescribed distance of 100 m. This test, conducted in July 1972, is said to be the first public demonstration of a full-sized vehicle with superconducting magnets to provide the levitation.

A second demonstration model has also been built and tested (Fig. 11). This four-passenger vehicle is 7 m long, 2.5 m wide, weighs 3500 kg (3.85 tons), and uses four superconducting coils, each with a rating of 250 kiloampere-turns. Each onboard helium cryostat contains two rectangular coils (1.55 by 0.3 m) and has a capacity of 200 liters of liquid helium. The overall weight of the cryostat assembly is 1000 kg. Operation of this vehicle was part of the centenary celebration of JNR.

With a linear induction motor for propulsion and the superconducting solenoids operating in the persistent mode, a speed of 60 km/hour and a levitation height of 6.0 cm was attained. These tests were performed on a 240-m track consisting of two rows of 355 rectangular aluminum coils (0.48 by 0.33 m). Data obtained with this test vehicle extrapolate to a levitation height of 7.0 cm for a speed of 500 km/hour and yield a ratio of F_L/F_D of approximately 80.

The JNR plans to operate another test vehicle on a 7-km track at speeds up to 500 km/hour in 1975. Final designs for the "train" are due by 1977, and the in-service target date is 1985.

Other countries are not as far along as Japan, but the German effort has made significant strides in the last 2 years. AEG-Telefunken; Brown, Boverei, and Cie; and Siemens have a cooperative effort under way to build and test a magnetically levitated vehicle employing superconducting solenoids. Substantial financial support (50 percent) is being given by the German ministries of Research and Technology and of Transportation. The present status of the AEG-BBC-Siemens project is that a 20-ton passenger-carrying vehicle is nearing completion, as is a circular test track 280 m in diameter at Siemens in Erlangen. I have no details about the track or vehicle other than that onboard superconducting solenoids will be employed, but an artist's conception (Fig. 12) of the proposed train suggest a null-flux type of magnetic suspension with a continuous-sheet track in place of the loop track design of JNR. It is planned to test the vehicle at speeds up to 200 km/hour on the Erlangen test track and

Table 4. Maglev (magnetic levitation) projects.

Location and facility	Suspension	Status
Canada		
Queens University Institute for Guided Land Transport	Attractive	Purchase Krauss-Maffei system
Japan		
Japanese National Railroad laboratories and several industrial laboratories	Repulsive	Operated a 2-ton vehicle in 1972: world's first superconducting system
United States		
Stanford Research Institute	Repulsive	Levitated 0.4-ton vehicle in 1972; four superconducting magnets
Ford Motors Research Laboratories	Repulsive	
General Motors Research Laboratories	Repulsive	Superconducting magnets built for wheel tests
Massachusetts Institute of Technology	Repulsive	
United Kingdom		
University of Warwick	Attractive	Test vehicle under construction
University of Sussex	Repulsive	
West Germany		
Krauss-Maffei	Attractive	
Messerschmitt-Bölkow-Blohm	Attractive	Operated world's first full-scale experimental vehicle (6 tons), May 1971; high-speed test scheduled for 1973 (8-ton vehicle)
AEG-BBC-Siemens	Repulsive	Test vehicle and track nearing completion (October 1973)

then (in 1975) at speeds up to 500 km/hour on the 70-km national facility test track currently being constructed near Augsburg, Germany. This national testing facility, costing some $28 million, will be used for the various types of high-speed ground transportation systems. The German government plans to spend approximately $125 million by 1976 on the design, development, and testing of prototype systems (*43*).

Efforts in the United States are on a smaller scale, with work at the Stanford Research Institutes on a Department of Transportation contract being the most advanced in that a powerless vehicle weighing some 225 kg has been successfully levitated by using superconducting magnets. Work in the United Kingdom has just been initiated by grants from the Wolfson Foundation (Table 4).

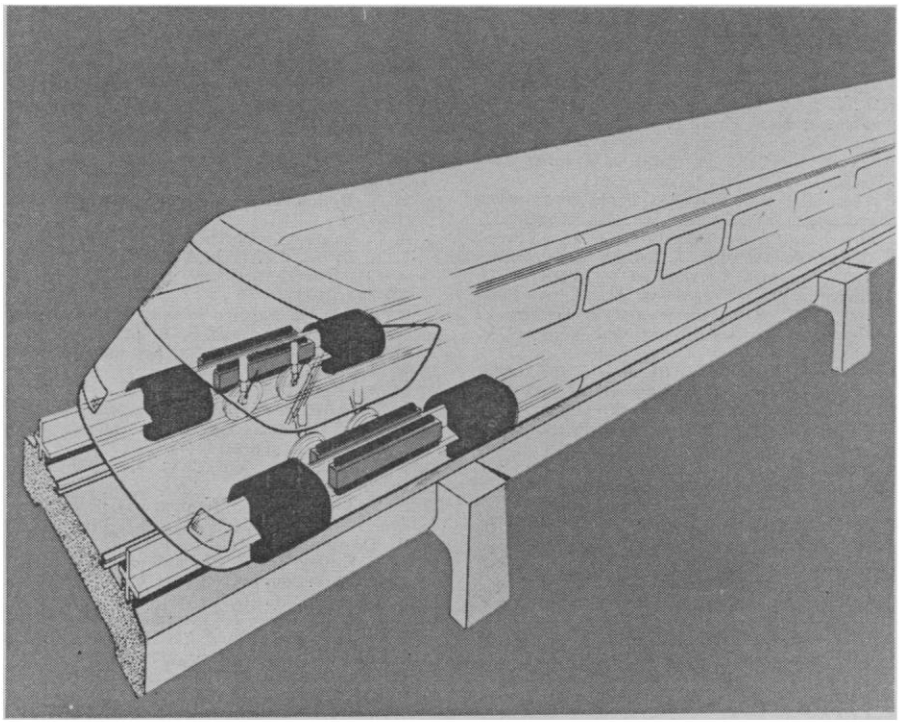

Fig. 12. Artist's concept of the AEG-BBC-Siemens superconducting train, showing the location of the superconducting coils for levitation and guidance as well as the coils for the linear induction motor. Note the use of a continuous track. [Courtesy of Siemens Research Laboratories, Erlangen, Germany]

Summary and Commentary

The 1960's saw the realization of Kamerlingh-Onnes' dream of high-intensity magnetic fields generated with low-powered superconducting solenoids. The late 1950's and early 1960's also saw the operation of huge cryogenic plants capable of producing and storing quantities of liquid oxygen, hydrogen, and helium undreamed of by the early low-temperature physicists and cryogenists.

Materials development in the 1960's has placed superconductors with high current densities (10^5 amp/cm^2) at the disposal of electrical engineers, who have exploited them in the development of large high-intensity solenoids for high-energy physics and d-c machines. The 1970's have seen research and development efforts on superconducting suspension and guidance systems for magnetic levitation, superconducting cables for underground transmission of electrical power, and rotating superconducting machinery.

At a recent symposium one speaker (*44*) entitled his talk "Superconducting devices—bagatelle or bonanza?" The 1970's should answer this question for us.

The most serious problem faced by the entrepreneurs of superconductivity, by and large, is the huge amount of high-risk capital required for the envisioned research and development. For example, Frankel (*45*) stated that the capital investment for a single complete power-generating system is so great that the chances of risk capital being available (and justified) for trying out a really revolutionary innovation on a full scale are becoming progressively smaller. I view the current level of effort by manufacturers of heavy electrical equipment as merely keeping a foot in the door and not letting the competitors get too far ahead. The leading manufacturers have orders on hand that will take 8 to 10 years to fill, so their wait-and-see attitude and reluctance to invest large amounts of capital in an unproved market are understandable.

A recent study (*31*) by the Science Research Council of the United Kingdom concluded that "although the time scale for the development of superconducting alternators is necessarily long, and the justifications for such machines at present uncertain, their potential is sufficiently great to warrant research being undertaken directed towards this objective." They recommended an effort on a modest scale at universities. This conservative approach is in keeping with the thinking prevalent in the United Kingdom at the end of the 1960's. Norris (*46*) was less than enthusiastic about superconducting cables, and Wilkinson (*47*) was pessimistic about the role of superconductors in any a-c application.

Large-scale and small-scale applications of superconductivity have been proposed for the past 12 years. Progress has been slow, and naturally some disenchantment has set in. Realization of superconducting components for big accelerators has been so slow that new accelerators are being built with conventional magnet systems. The need for additional high-speed ground transportation is so pressing that the Japanese National Railway will probably install a new high-speed conventional line rather than wait for superconducting magnetic levitation systems to be developed.

I believe that this slow progress is due to an initial oversell of superconductivity and the fragmented approach by various funding agencies to research and development.

Except in the case of naval ship propulsion systems, economics is the most important factor in determining the future of superconducting technologies. I do not believe that small independent efforts at university, industrial, and government laboratories are the most expedient way to prove economic feasibility. Full-sized installations with full-sized refrigerator plants are needed for a meaningful assessment of economic feasibility and long-time reliability. Now is the time to settle the question of bonanza or bagatelle if superconductivity is to be part of the energy picture in the 1980's.

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Physical-Chemical Basis of Lipid Deposition in Atherosclerosis

The physical state of the lipids helps to explain lipid deposition and lesion reversal in atherosclerosis.

Donald M. Small and G. Graham Shipley

Atherosclerosis, the major cause of death in the United States, is characterized by focal fatty thickening in the inner aspects of large arterial vessels supplying blood to the heart, brain, and other vital organs. These lesions obstruct the lumen of the vessel and result in ischemia of the tissue supplied by the vessel. Prolonged or sudden ischemia may result in a clinical heart attack or stroke from which the patient may or may not recover.

For more than a century, scientists have associated the atherosclerotic lesions with the accumulation of lipids, specifically cholesterol and its esters, in the inner layers (intima) of large arteries. Many investigators have studied the metabolism and transport of cholesterol and have shown, for example, that increased cholesterol in the blood is related to an increased prevalence of coronary artery disease and heart attack (*1*). Much of the recent work in the field of atherosclerosis has been centered either on the characterization and metabolism of the specific serum lipoproteins which transport cholesterol and its esters (*2*) or on the histology, chemical composition, biochemistry, and metabolism of the cells and chemical components of arterial walls (*3*). Little attention has been paid to the physical state of cholesterol and its biologically important esters, and no effort has been made to relate this physical state to that of lipids in the normal or diseased human arterial wall (*4*).

The fact that large quantities of certain lipids (especially cholesterol, cholesterol esters, or phospholipids) accumulate in atherosclerotic lesions and, furthermore, that the rate of exchange of cholesterol between atherosclerotic

Dr. Small is professor of medicine and chief of the biophysics section and Dr. Shipley is assistant research professor of medicine, both in the Department of Medicine, Boston University School of Medicine, Boston, Massachusetts 02118.