THE PROLONGED ADOLESCENCE OF SUPERCONDUCTIVITY

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Abstract

The application of superconductivity to purposes affecting everyday life has been retarded by our pursuing only the development of materials while ignoring the problems associated with their practical use. The most important potential applications are in medicine, metallurgy, mining, pollution abatement, power generation and transportation.

Introduction

Magnet technology is distinguished by a breakthrough comparable to the invention of the wheel. Traditional electromagnets represent man's only device operating at zero efficiency, an ironical situation if you consider that a magnet should not really require any power at all! Sixty years ago superconductivity eliminated the irony and provided us with frictionless magnets, just as the wheel provided us with frictionless transportation. The analogy may have more than superficial significance, as we shall see.

You would expect a profession with such a breakthrough to its credit to be riding high and the parking lot outside to be teeming with chauffeurs waiting beside shiny limousines. Instead, we are no better off than our less successful colleagues in science and technology. In fact, we are doing worse! Nobody outside this room has shown much interest in our breakthrough, and management is questioning the wisdom of continued investment in material technology when the only market in sight consists of a dozen impoverished physics laboratories whose interest rarely extends beyond some free samples. The program of this conference, like the three which preceded it, reflects this situation: all of the papers, with one single exception, are concerned with research magnets or the materials to make them. *Sixty years after the discovery of superconductivity, there still has not been one single practical application, nor for that matter one single new application.* Superconductivity has been used to do a few things in the laboratory more cheaply, but it still has not been used to do anything that could not be done without it, nor anything which affects everyday life. *Superconductivity still has not come of age.*

A very similar situation undoubtedly prevailed after the invention of the wheel. Before its potential value was recognized, there was very little incentive to overcome the formidable technological obstacles to its practical application. Nevertheless, those obstacles were ultimately overcome and the wheel enjoyed a period of widespread use, which may be coming to an end.

I feel that superconductivity will share the destiny of the wheel. The technological obstacles to its practical application are really no more formidable than those of the wheel, and will seem just as trivial in retrospect. In fact, they already do! What obstacles remain are more psychological than technological, and reflect the fact that man's thinking has not become significantly more flexible than it was at the time the wheel was invented. Man's lifespan, however, has become significantly longer in comparison to the rate of change, and this is really the root of all our political, ecological, economical, social, moral and technological problems.

History

Instead of the customary review of our triumphant progress in superconductivity, I would like to point out how slow our progress will seem to a more intelligent civilization, both from the purely intellectual as well as the purely practical viewpoint.

Not long after the discovery of superconductivity in mercury in 1911, for instance, attempts to measure the decay constant of supercurrents should have made it obvious that they represent a flagrant violation of Maxwell's radiation law: *zero resistance doesn't explain why circulating electrons don't radiate energy!* As early as 1912, Bohr invented quantum mechanics in order to cope with the identical violation committed by the electron which orbits the proton in a hydrogen atom without radiating energy. In the twenties the laws of quantum mechanics were firmly established and universally taught, yet the calamity of superconductivity was not related to them for another decade until the mid-thirties, when Fritz London first pointed out that superconductivity (and superfluidity) must represent macroscopic manifestations of quantum effects. This announcement should have galvanized a generation of physicists who, by then, had a thorough education in quantum mechanics. However, the concepts had obviously not as yet been assimilated intellectually, because London's revelation was generally ignored for another decade or two, although several individuals did in fact pursue his insight. It was only in the late fifties and early sixties that the next generation of physicists made the conceptual breakthrough. It was then that flux quantization and the Josephson effects were discovered and that the first good theory emerged, the BCS theory. This theory does explain superconductivity from first principles; however, ten years after its formulation it still fails to relate it to atomic or molecular structure. This statement may be an uncharitable oversimplification; but it is a fact that researchers looking for new superconducting materials are still forced to rely on the methods of seventheenth century alchemy.

Progress was equally slow on the practical front. During the first fifty years nobody believed that superconductors would ever withstand enough field or current to be of practical interest. Only two incidental applications were explored in the fifties: radiation detection and information storage. Then in 1960 came the first practical breakthrough when John Kunzler succeeded in making niobium-tin wire. A frenzy of research soon led to other practical materials, none of which have as yet been applied in the real sense of the word. The reason is not that they are too expensive, as has been naively suggested, but that none of the organizations which invested so enthusiastically in materials paid the least attention to the technological problems associated with their practical use. It is little wonder that only a dozen physicists beat a path to their door! To any other potential customer, superconducting magnets remained a hopelessly impractical laboratory curiosity at an embryonic stage of development.

Now, twelve years after Kunzler, things have changed, although through no effort by the superconducting community. Trucks, ocean-going cryogenic tankers, airplanes and space vehicles carry liquefied gases around the Earth and other planets of the solar system, and I have even seen a horse-drawn dewar carry liquid methane to a remote indian reservation (if you enjoy anachronisms). Despite this fact, superconductivity still has not come of age, and its adolescence gives every indication of continuing indefinitely unless we ourselves take an active part in overcoming the remaining obstacles to its application, both the technological and the psychological ones.

State of the Art

There is an abundance of practical superconducting materials. The most prominent *technological* obstacle to their application is the lack of a practical system to provide large superconducting magnets with stable refrigeration. The practice of immersing large magnets in a pot of boiling helium is like building rubber-powered airliners: an unwarranted extrapolation of table-top technique. It is difficult to understand why the practice continues, six years after we demonstrated the effectiveness and stability of a forced circulation system using supercritical helium. Mario Morpurgo at CERN has applied this technique to three magnets, the most recent being the Omega bubble chamber magnet, one of the largest in the world. It is surely a sign of stagnation that nobody has taken note of this development.

There are also formidable psychological obstacles to the application of superconductivity. What we need more than anything else to overcome these is the kind of tour-de-force accomplished by Lindbergh when he flew the Atlantic. There was really no technological innovation involved in the feat, and yet no amount of wind tunnel testing or economic analysis could have done as much to make the world believe in the possibility of commercial trans-atlantic air travel. Several people around the world, myself included, have been trying for some time to pull a Lindbergh in superconductivity, but for some reason it has not as yet come to pass. Perhaps we lack Lindbergh's flair for drama. Or perhaps our technological society has lost the elan which surrounded early aviation. Maybe the spirit of St. Louis is dead or living elsewhere.

Practical Applications

I want to discuss briefly, or at least enumerate, some of the applications of magnet technology made possible by superconductivity which should be represented on the program of this conference. The most important, from the viewpoint of potential market, are undoubtedly the power industry, transportation and magnetic separation. I shall leave these for last, and begin with several lesser applications which may, however, be closer to realization.

In Medicine, superconductivity makes possible magnetic fields of sufficient size, intensity and gradient to guide magnet-tipped catheters through blood vessels of the brain to places not accessible by conventional surgery. Intravascular magnetic navigation, as this new technique is called, has already been demonstrated at the Massachusetts General Hospital in four actual operations in which aneurisms, or blood vessel failures, were successfully blocked. Conventional electromagnets adequate to perform this operation would require many times the power available to even the largest hospital. It appears that society cannot as yet afford the investment required to develop this application.

Superconductivity also offers fields of sufficient size, intensity, homogeneity and constancy to perform nuclear magnetic resonance measurements on an entire patient. According to recent observations, this might provide the first positive means for diagnosing the presence of cancer tissue, on the basis of its characteristic resonance spectrum. So far, there has not yet been a facility available to explore this possibility in small animals.

Electron microscopy provides an application already being pursued commercially both here and in Japan: superconducting beam focussing magnets offer the intensity, gradient and stability to make possible the resolution required to see the structure of genetic material. They will also permit microscopy at higher energies where less tissue damage occurs.

Metallurgy is overdue for a rather spectacular application. For about ten years, pulsed magnetic fields have been used to perform certain metal forming operations, including swaging, blanking, deep-drawing and others. It may be a comfort to know that the airplane which brought you here almost certainly had its control cables swaged to their connectors magnetically. Induced eddy currents turn out to do this more reliably than mechanical dies. In a continuous background field such as can be provided by superconducting magnets, this technique can be applied to many new operations, including high speed production and the compound forming of large honeycomb panels which would be crushed by conventional forming presses. Beer cans and engine nacelles might be made that way.

Magnetic separation has been practiced in the mining industry for several decades. It relies on a force which is proportional to three quantities: the magnetization induced in the particles being separated, the size of the particles, and the gradient of the applied field. The practitioners of this art are not really aware of this circumstance, nor of innovations in magnet technology. Magnetic separation has therefore been limited to a few primitive applications, such as the separation of iron ore of relatively large particle size, or the removal of tramp iron from processed food.

Only three common elements are ferromagnetic, whereas a very large number of materials, most oxides included, are paramagnetic. Paramagnetic materials are not normally considered magnetic because it takes more than an ordinary magnet to magnetize them appreciably; but on the other hand, they don't saturate magnetically: their magnetization continues to increase linearly with applied field. We have found that with some sophisticated magnet technology, even without superconducting magnets, it is economically possible to magnetize very many common paramagnetic materials sufficiently to permit their separation from a less magnetic mixture. If an effort is made to provide high field gradients, the method is even applicable to particles down to colloidal size.

High intensity separators, as they have come to be called, are already being used in one area of the mining industry: they purify kaolin used for paper coating by removing colloidal impurities which are about 10,000 times less magnetic than iron. Spectacular though this performance may be, its implications have not as yet been appreciated, at least not by the mining industry. In the battle of entropy, which after all is the battle of life, we have only very limited means for manipulating small particles on a large scale: filtration, flotation and electrostatic separation. When a mineral is too finely divided for any of these methods, it is unrecoverable for all practical purposes. When water is polluted by suspended solids, it is worse than useless. Magnetic separation now provides us with a more widely applicable method for the large-scale manipulation of small particles, even down to colloidal size.

Let me cite several examples we are now pursuing on a laboratory scale, in cooperation with Magnetic Engineering Associates, the Cambridge firm which built the first high intensity separators used in the kaolin industry. It turns out, for example, that coliform bacteria along with many dissolved and suspended nutrients, can be removed from water by seeding it with a colloidal iron oxide and passing it through a high intensity separator at flow rates about 100 times higher than rates associated with filtration. This makes it possible to entertain realistic dreams about decontaminating natural bodies of water (perhaps even Lake Erie), or at least decontaminating the sewage and industrial waste we cannot now afford to treat. It has also been possible to remove much of the sulfur and fly-ash components from pulverized coal, under conditions which suggest the possibility of an economically feasible large-scale process. Most finely divided metal oxides which are now being discarded on tailing piles are sufficiently paramagnetic to be recovered by high intensity separation. One of the most promising applications involves iron ore. For about a century, the U.S. iron industry has depended heavily on a very low grade iron ore found in the Mesabi Range, called taconite. It is finely ground, beneficiated by means of huge magnetic drum separators (probably the largest application of magnet technology in the world), and then fed into blast furnaces in the form of compressed pellets. Reserves of magnetic taconite, however, are running out, exposing vast quantities of a more highly oxidized mineral which is called "semi-taconite" or "non-magnetic taconite". Semi-taconite cannot be beneficiated by any economically feasible method so far discovered and is being dumped in large quantities with detrimental results on various bodies of water. We have shown on a laboratory scale that semi-taconite can be beneficiated by high intensity separation. The first continuous separator to perform this process, built by MEA, is now undergoing laboratory tests. It uses conventional magnets, and so will the first generation of machines to operate in the field. Sooner or later, however, somebody will have to stage a Lindbergh stunt and install a superconducting magnet in a Mesabi Range mine. The mining people still view the suggestion with more amusement than interest.

A very pertinent lesson which has emerged from our work is that to apply magnet technology to mining and sewage treatment, magnet technologists will have to become directly involved in the problems of mining and sewage treatment. Hard as this may be, it is easier than teaching magnet technology to miners and sanitary engineers. The lesson applies to other areas as well.

The power industry offers the most massive potential application of superconductivity, part of it long-range and part more immediate. The long-range applications include magneto-hydrodynamic (MHD) power generation, and controlled thermo-nuclear fusion. MHD may be regarded as the first advance in combustion technology since Prometheus gave us fire, based on recognition of the fact that combustion is in reality a plasma process involving charge transfer, even though it has always been treated as if it were purely chemical. It is possible to extract electrical energy directly by performing combustion in a magnetic field, and superconductivity makes the required field economically possible. Fusion, the energy source of the stars, would solve our energy crisis forever without generating radioactive waste products. In stars, the hot plasma particles are confined by gravitational force. On earth, magnetic fields can be made to do so by forcing the charged particles to move only along magnetic field lines. Only superconductivity will make fields of the required intensity economically feasible. Both MHD and fusion are still in the realm of research, although MHD is much closer to realization.

Superconductivity also has more immediate applications, which can be summed up in two sentences:

Superconducting motors and generators are about one tenth the size of equivalent normal machines.

Superconducting power transmission lines can be made to carry ten times more power over ten times longer distances than the largest economically feasible conventional transmission line.

Superconductivity therefore offers a ten-fold decrease in capital cost, the dominant cost of power. It also offers the possibility of generating power in larger units (present machines having reached the mechanical limit of size), and at locations chosen to minimize environmental damage. This means that we can continue to waste stationary power at our present rate of increase beyond the foreseeable future, and assures even the more underprivileged parts of the world of a high standard of living, at least if standard of living is indeed measured by per-capita energy consumption (not very long ago it was customary to measure it by per-capita soap consumption).

There are basically two types of superconducting machines: alternators, which depart from traditional machine design by having rotating superconducting field windings on the inside, and a stationary normal armature on the outside. Of course the stationary armature will eventually be superconducting if the machine is designed to connect to a superconducting power line. Woodson, Smith and Thullen at MIT, who pioneered this technique and built a 45 kW generator, find that the rotating liquid helium seal turns out to be a problem easily solved once its inevitability has been accepted. The important fact, however, is that it did constitute an insurmountable psychological obstacle to many people for many years.

DC machines, the second type, are logically of the homopolar type, also called "acyclic"; this machine was invented by Faraday and is also known as the Faraday Disk motor, although modern versions may use cylindrical instead of disk rotors. Appleton of the International Research and Development Company in Newcastle built the first practical machine having superconducting field windings and a normal rotor, the so-called Fawley Motor, with a rating of 3,250 hp. Finniston of IRD and the Ministry of Technology deserves at least equal credit for promoting the project several years ago; it is unquestionably the nearest thing to a Lindbergh stunt so far, and has most certainly made a profound impact on the credibility gap.

As a result of these shoestring efforts, superconducting machinery is now being taken seriously in many quarters, but nowhere as seriously as in our most sophisticated industry, the war industry. Superconducting propulsion motors one tenth the size of conventional ones make turbo-electric systems feasible for even the smallest naval vessels and hydrofoils, and give larger ships a decisive competitive advantage in mission effectiveness. Marine engines are being vigorously developed in all the advanced countries and may well turn out to be the first practical application of superconductivity.

Transportation applications offers one of the most surprising applications, which is why I have left it for last. Superconductivity may ultimately replace the wheel, thereby giving prophetic significance to my analogy. Unfortunately transportation also provides a very sad example of damage which has already been done by the prolonged adolescence of superconductivity.

Wheeled trains become impractical above 130 or 150 mph due to the inevitable imperfection of rails, a circumstance verified by the Japanese in their operation of the New Tokaida Line. Since air traffic is reaching saturation on many routes, there is need for a fundamental innovation.

On the basis of elaborate studies done in the mid-sixties, our Department of Transportation decided about four years ago to follow the French lead in developing tracked air cushion vehicles. Two German industrial teams, Krauss-Maffei and Messerschmitt-Bölkow-Blohm, started at about the same time to develop magnetic levitation systems based on the attraction of conventional electromagnets riding below a steel rail, an inherently unstable system which is stabilized by feed-back control. Both of these approaches now turn out to be dead ends for a variety of reasons, but primarily due to the fact that they operate at such small clearance gaps as to provide very little advantage over the wheel. They will simply not go much faster than wheels and cost a great deal more. It appears that the DOT decision to back tracked air cushions, or TACV, as it is called, is somewhat analogous to a decision in 1920 to back airships and ignore aeroplanes, which were then in their adolescence.

Superconductivity plays the role of the aeroplane in this analogy. As early as 1966, Powell and Danby, two magnet technologists here at Brookhaven, pointed out the advantages of repulsive levitation systems made possible by superconductivity. Several other studies followed, but all of them were too academic to be taken seriously. The mistake of ignoring superconductivity has now become obvious. A third German team including Siemens, AEG and **Brown-Boveri is** actively developing superconducting levitation, and the Japanese are well along in a multi-million dollar program involving Hitachi, Toshiba and Mitsubishi, scheduled to have several miles of superconducting system operating at high speed by 1976. Our own Department of Transportation, on the other hand, has only just now recognized that superconducting levitation systems are technically feasible, and still has not given evidence of believing that superconductivity might indeed represent the winning approach to providing *both* lift and propulsion for high speed ground transportation. If superconductivity does indeed prove the winner, as the Japanese have concluded, then we are forfeiting world leadership in one of the prime technological markets of the next several decades, a market which is vital to our entire aerospace and electronics industry.

The irony of this situation is that we possess unquestioned competence in magnet technology, superconductivity, cryogenic engineering, power conditioning, vehicle dynamics, aerodynamics, control technology, systems engineering, and all the other areas involved. For lack of leadership, however, we have failed to mount the broad interdisciplinary effort required, the sort of effort which is customarily lavished on weapons systems.

Richard Thornton and I started to take a serious look at the overall problem about two years ago, and have developed what to us appears to represent the ultimate contribution of superconductivity: *guided electromagnetic flight.* As the term suggests, the motion of a magnet above a non-magnetic, conducting surface is in many ways the electromagnetic analog of aerodynamic flight: lift is produced at the expense of drag, and the lift force is sufficiently resilient so that the vehicle's trajectory is essentially governed by its inertia. Contrary to aerodynamic flight, however, electromagnetic flight can be guided because the electromagnetic lift forces increase drastically as the magnet approaches the conducting surface. Superconductivity makes possible the large and intense magnetic dipoles required for flight at a reasonable "altitude". These same dipoles also provide a means for propelling the vehicle efficiently by means of a relatively weak travelling magnetic field generated by normal conductors in the guideway. The *magneplane*, as we have called this system, is illustrated below:

A cylindrical vehicle equipped with superconducting coils is suspended resiliently by eddy current repulsion one foot above a cylindrical, trough-shaped aluminum guideway surrounding the lower third of the vehicle's circumference. The vehicle is free to roll so as to assume the correct bank angle in curves. It is propelled by a travelling magnetic field generated by current loops which form an integral part of the guideway. This field is synchronized by wayside control units on the basis of information transmitted from the vehicle; it reacts against the vehicle coils to provide synchronous acceleration, deceleration or cruise, and also generates vertical and lateral forces to apply active damping to oscillations in the heave, sway, pitch, yaw and roll modes. Lift-to-drag ratio is about 20 at 250 mph, propulsion efficiency is about 80%, and guideway loading is about 2 lb/in^2. Due to the uniform distribution of vehicle weight and the large suspension clearance, guideway alignment and rigidity are not critical. This makes possible a reasonably priced active guideway. It weighs about as much as conventional rails (100 lb/ft), requires no additional support structure, and can be laminated continuously from rolls of aluminum and fiberglass, suitably folded and interleaved. The vehicle is carried on retractable wheels until it reaches about 40 mph; it can be operated in the open up to 300 mph, and in a partially evacuated tunnel beyond jet aircraft speeds.

The magneplane project was initiated by MIT, Avco and Raytheon, and was described in detail at the 1972 Applied Superconductivity Conference in Annapolis last May. Current NSF support will permit the completion of an operating 1/25 scale model in several months. It will hopefully generate the level of support required for a half-scale and ultimately a full scale system. Sooner or later magneplanes will be the standard mode of travel; whether they are made in Japan, Germany or the USA remains to be seen.

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