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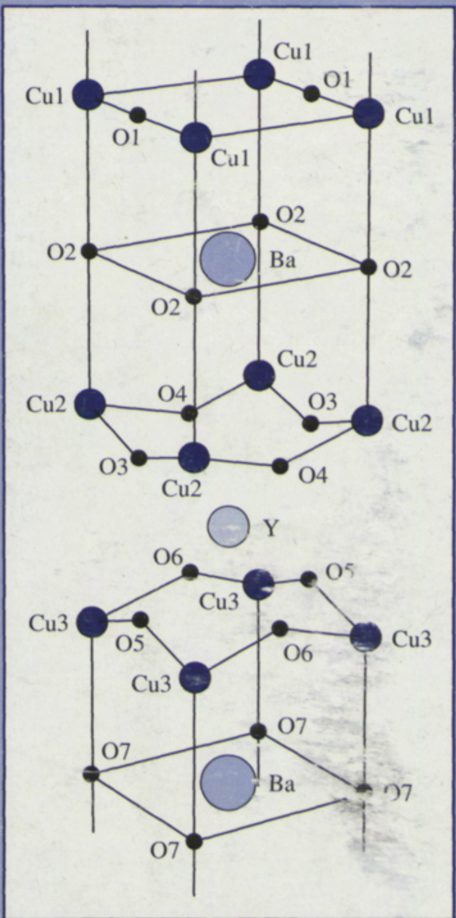

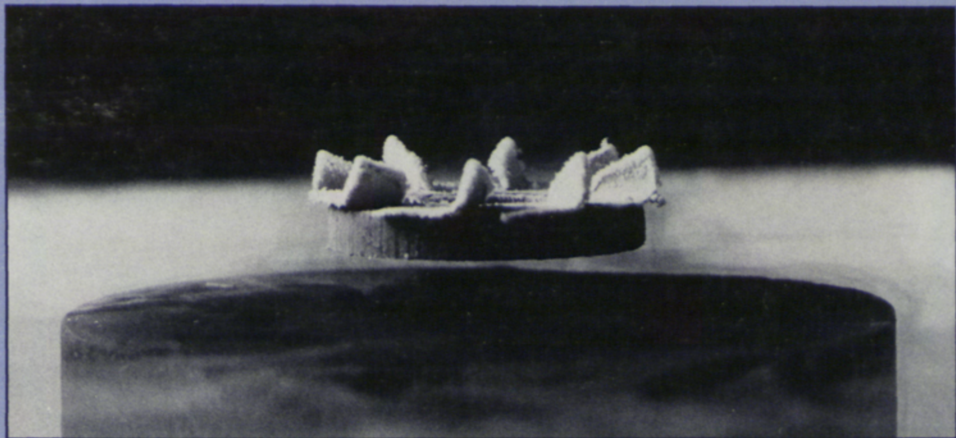

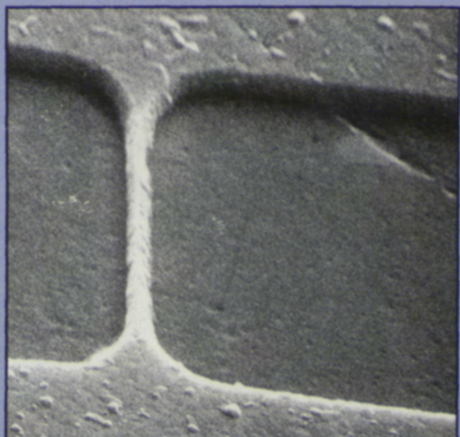

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WINTER 1990

THE PROMISE
OF
SUPERCONDUCTIVITY

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Opposite: What are they looking at? A floating magnet. The scene is in a freshman chemistry laboratory, where students in a class taught by Professor Francis DiSalvo, Jr., are carrying out an experiment in magnetic levitation. The week before, the students had synthesized a "high-temperature" superconducting material (a yttrium–barium–copper oxide ceramic) and this week they are measuring its properties, which include the repulsion of magnetic fields and hence the ability to cause levitation (see the article by Francis C. Moon). A photo on the outside cover is a close-up of a levitating magnet.

Cover illustrations: The crystal structure of the high-temperature superconductor $YBa_2Cu_3O_7$ is at left (see also page 7). The photograph at top right shows a permanent rare-earth magnet being levitated by a superconductive ceramic at liquid-nitrogen temperature (see page 13). The superconductor has been cooled by pouring liquid nitrogen over it; vaporized nitrogen can be seen above the magnet. The photograph at center is a scanning electron microscope image of a thin-film superconductor microbridge (see page 11).

Buhrman

Moon

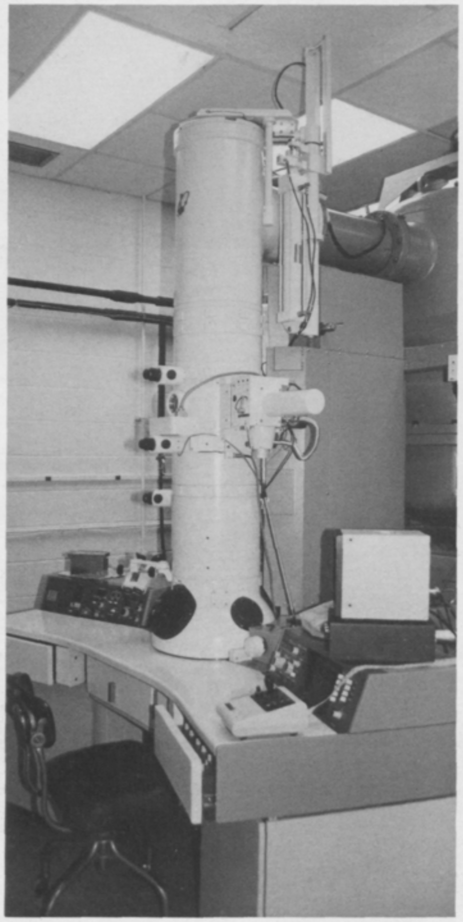
Raj

Padamsee

Krusius

Compton

BUILDING ON A SOLID BASE: CORNELL RESEARCH IN SUPERCONDUCTIVITY



The discovery in 1987 of a high-temperature superconductor—one that exhibits superconductivity at temperatures considerably above absolute zero—resulted in a flurry of activity in the scientific community, but it didn't necessitate new research programs at Cornell. Research on low-temperature superconductivity was already well established, and the new discovery was simply welcomed as a promising development that augmented the ongoing efforts. Programs in areas such as electron microscopy, ion-beam technology, and thin-film techniques easily accommodated study of the new superconducting materials. This situation is reflected in the articles that appear here.

Also evident in these articles is a notable characteristic of research at Cornell: frequent use of an interdisciplinary approach. The overall program in superconductivity involves people in six disciplines—chemistry, physics, applied and engineering physics, materials science and engineering, mechanical and aerospace engineering, and nuclear studies—often in cooperative work.

The development of interdisciplinary facilities at Cornell is key to the success of cooperative programs such as these. Research in superconductivity is carried out not only in the laboratories of individual faculty and staff members, but in special centers on campus: the National Nanofabrication Facility, the Materials Science Center, the Laboratory of Nuclear Studies, the Laboratory of Atomic and Solid State Physics, and the Center for Theory and Simulation in Science and Engineering (a national supercomputing facility). Also important are cooperative programs that draw on facilities and expertise at both university and industrial laboratories.

A primary aim of the programs in superconductivity, as for all Cornell research in science and technology, is to improve the basic understanding of underlying physical and chemical processes. But possible applications are often major considerations as well. Included in the articles printed are descriptions of practical devices or techniques that are close to commercial use. Several patents have already been issued.

The following brief summaries of research programs headed by faculty members in a number of departments provide an overview of the current activity in superconductivity at Cornell.

■ **Robert Buhrman**, professor and director of the School of Applied and Engineering Physics, has been working in the field of superconductivity since he did his doctoral research at Cornell in the early 1970s. His current research interests include thin-film superconductors, discussed in his article in this issue, and superconducting devices.

Buhrman's work receives support from the Office of Naval Research, which has been funding a program on low-temperature, and now high-temperature, superconductivity since 1977. Also, the Air Force has supported research on Josephson junctions for use in sensors and oscillators. Currently, the Defense Advanced Research Projects Agency (DARPA) funds a project on the physics and electronic-device applications of the new high-temperature (high-T_c) superconductors that is directed by Buhrman and three faculty colleagues—John Silcox, James W. Mayer, and Albert Sievers. Also, Buhrman is principal investigator for a project on ion-implantation techniques for preparing high-T_c superconductors that is sponsored by the New York State Institute on Superconductivity; coinvestigators are research associates **David Lilienfeld** of the National Nanofabrication Facility, and **Peter Børgesen** in materials science and engineering.

■ **John Silcox**, the David E. Burr Professor of Engineering, and his research group in applied and engineering physics are studying the atomic structure of high-T_c $YBa_2Cu_3O_{7-x}$ materials (grown by Buhrman's group) at resolutions in the range of atomic dimensions. Grain boundaries, grain size, defects, second phases, and the substrate/film interaction are all features of interest.

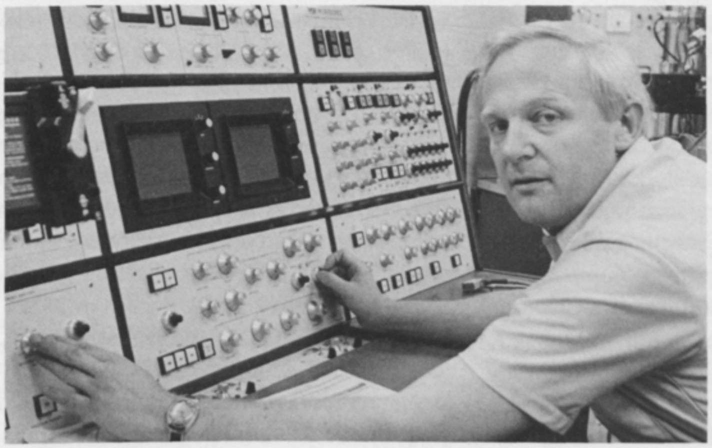
The researchers are using an ultra-high-vacuum scanning transmission electron microscope (STEM) capable of forming electron probes less than 2 Å (10^{-10} meter) in diameter, giving atom-structure images; the images locate the probe accurately for analytical electron microscope studies that give chemical information at a spatial level of 10–15 Å. This work is part of an overall program in electron microscopy and microspectroscopy.

Silcox is currently serving as director of the Materials Science Center at Cornell.

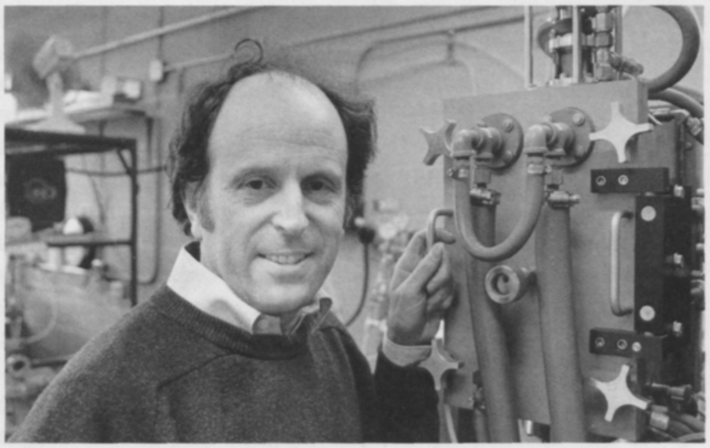
■ In the Department of Materials Science and Engineering, **C. Barry Carter** uses transmission electron microscopy to examine the microstructure of thin films of high-T_c superconductors grown on various substrates, and to investigate how structure is related to properties. Of special interest are grain boundaries within the film and at the interfaces. Specimens studied so far are $YBa_2Cu_3O_{7-x}$ materials grown (in collaboration with Buhrman's group) on $SrTiO_3$, YSZ, or MgO.

Working with **Grant Norton**, a postdoctoral associate, Carter has developed a technique whereby the superconductor is

Silcox



Carter



Mayer

Programs in areas such as electron microscopy, ion-beam technology, and thin-film techniques easily accommodated study of the new superconducting materials.

grown directly on a transmission electron microscope (TEM) sample; this allows the earliest stages of growth to be studied without further thinning of the sample.

■ Superconductivity is one of the research interests of **James W. Mayer**, the Francis Norwood Bard Professor of Materials Science and Engineering.

In one project, he and his group are characterizing superconducting thin films with the use of ion-beam techniques, in which beams of charged particles interact with the material under study. Rutherford backscattering and new techniques developed in Mayer's laboratory enable the researchers to determine the compositional profiles of high-T_c thin films as a function of depth. Mayer is also participating in a cooperative study of how ion beams can modify the structure and composition of superconducting thin films. In a collaborative project with industrial researchers, his group is studying how oxygen moves in and out of high-T_c superconductors—information that will be crucial for making devices out of these materials.

Mayer serves as director of the SRC Program on Microscience and Technology, which receives support from the Semiconductor Research Corporation.

■ **Francis C. Moon**, professor and director of the Sibley School of Mechanical and Aerospace Engineering, directed the development of a new kind of bearing, one of the first commercially viable applications of high-T_c superconductors. A patent for this device was recently issued to Moon and Rishi Raj of the materials science and engineering faculty, and assigned to the Cornell Research Foundation, Inc. Also patented to Moon is a device for measuring magnetic forces in new superconducting materials.

Moon is also interested in the use of superconductors for magnetic levitation of vehicles, an area of study in which he has been active for some years.

Both of these applications are discussed by Moon in articles in this issue.

■ **Rishi Raj** and **Emmanuel P. Giannelis** of the materials science and engineering faculty are interested in developing techniques for synthesizing superconducting materials in the form of useful shapes such as whiskers or platelets. For example, thin films of high-T_c materials might be grown on various substrates by chemical vapor deposition or sol-gel or solution-growth techniques.

In work with Moon on the high-T_c superconducting bearing, Raj used free-sintering and sinter-forging techniques to prepare the material. Now he is experimenting with multi-layered structures made up of stacks of thin films. These are among the methods he discusses here.

■ Potential applications of high-T_c superconductors in computers are of interest to **J. Peter Krusius** and his research group in electrical engineering. As explained in his article here, the packaging of computer systems is currently under study. Using superconducting connections rather than metallic lines, particularly in large-sized structures, might enable computers to operate two hundred times faster, he believes.

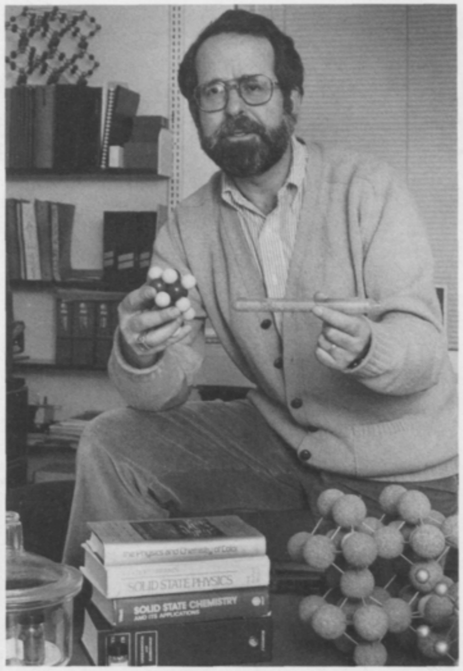
■ Another electrical engineering research group, headed by Professor **Richard C. Compton**, is working on the development of high-speed electronic circuits containing elements made of high-T_c superconductive materials. These researchers are using a new superconducting oscilloscope that can make measurements several times faster than previous instrumentation could, and they are developing techniques for using the oscilloscope in electronics research. This work is discussed in an article by Compton in this issue.

Compton is the recipient of a Presidential Young Investigator Award from the National Science Foundation, and the research is supported under that program. Materials are provided by Advanced Technology Materials, Inc.

■ Improving the performance of electromagnetic resonant cavities in electron-ring accelerators is a major aim of research directed by **Hasan Padamsee** of Cornell's Laboratory of Nuclear Studies.

The Superconducting Radio Frequency Group, with which Padamsee works, has been conducting research on superconductivity for sixteen years. This work has

DiSalvo



importance both for study of the fundamental nature of matter, and for current and potential applications such as future free-electron lasers.

An article by Padamsee appears here.

■ For the past few years, **Albert Sievers**, professor of physics, has integrated the study of high-T_c superconductors into his overall research program. Since his interests include the physics of condensed matter, the dynamics of the optical and infrared properties of solids and surfaces, solid-state vibrational lasers, and pure and applied far-infrared photonics, a result has been contributions in such areas as measurement of the superconducting energy gap and the infrared properties of superconducting thin films. Sievers' group was the first to grow single-crystal samples of high-T_c superconductors and analyze them using infrared techniques.

■ Rather than working on the copper-oxide superconductors, Chemistry Professor **Francis DiSalvo, Jr.** and his group are looking for new superconductors among the nitride compounds. These researchers are in the early stage of a study of the magnetic, electric, and thermal properties of both nitride and oxide materials, with a view of identifying the factors that are critical to superconductivity.

THIN FILMS
Progress in Superconducting Materials

by Robert A. Buhrman

When the discovery of high-temperature superconductivity was announced, just over three years ago, there was great excitement and sweeping predictions were made about the impact the discovery would soon have on a wide range of electrical and electronic technologies. Unfortunately, as many superconductivity experts realized at the time, these expectations were rather unrealistic.

In large part, the excitement stemmed from the fact that at least in principle, superconducting systems, with their property of zero electrical resistance, could be operated at temperatures at or above the boiling point of liquid nitrogen (77 K or −196 C). All other things being equal, such temperatures are much easier to obtain than the required operating temperatures of previously known superconductors, which are of the order of the boiling point of liquid helium (4.2 K or −269 C). Unfortunately, for many of the potential applications of superconductivity, raising the required operating temperature from 4.2 to 77 K does not necessarily enhance their overall economic or technical feasibility.

It was also quickly apparent to superconductivity researchers that developing the new high-temperature superconductor (HTS) materials to a state at which their performance would even begin to approach that of conventional low-temperature superconductors would be difficult indeed. This is because the electrical, structural, and metallurgical properties of this new class of superconductor present formidable challenges.

These problems, which I will discuss, have proven particularly difficult to the physicists and materials scientists who are trying to develop bulk HTS materials to the point where they could be used in large-scale current-carrying applications. Progress in this area has been slow indeed, and it appears that it will be quite some time before HTS materials can be seriously considered for large superconducting magnets or for applications in large-scale electrical equipment. But a major effort is being made in research all around the world, and we certainly should not assume that the goal of developing commerically viable bulk HTS materials will not be realized eventually.

Fortunately, however, there is an area in which progress has been much more rapid. In work with thin films—coatings of HTS materials on the order of 1 micrometer thick, formed on the surface of another material—we have been able to advance much closer to serious contemplation of HTS applications. I will discuss the work in this area that is being done at Cornell and other places, and where these studies may lead.

THE BASIC PROBLEMS WITH THE NEW SUPERCONDUCTORS

The properties of the new HTS materials that are better than those of the low-temperature superconductors are their much higher *transition temperature*, T_c (at which there is a change from normal-metal conductivity to superconductivity), and their much higher *critical magnetic field* (below which superconductivity is exhibited.)

The difficulty with the new high-temperature materials is that they have essentially none of the other properties that are desirable in a practical superconductor. The HTS materials—which are rather complex copper oxide compounds—are ceramics and exhibit none of the attractive ductile properties of ordinary metals and ordinary superconductors.

Moreover, the materials proved to be

"The difficulty with the new high-temperature materials is that they have essentially none of the other properties that are desirable in a practical superconductor."

difficult to make because the constituents of the compounds, and the compounds themselves, are extremely reactive at high temperatures. Initially, synthesis was accomplished at temperatures approaching 1,000 C through solid-state reactions that are often very difficult to control.

Another problem is that the HTS properties are very sensitive to slight changes in chemical composition. If the proportions of the constituents are not quite right, secondary phases can form during the synthesis and become imbedded in the material. These secondary phases are often insulating and thus can reduce or even block the zero-resistance supercurrent that would flow through a uniform specimen.

But perhaps the most important and fundamental problem with HTS materials is that their electrical properties are highly anisotropic—that is, they are different in different directions. This is illustrated in Figure 1, which shows the unit cell, or atomic building block, of $YBa_2Cu_3O_7$, the first compound that was discovered to have a transition temperature above 77 K, and the one that is still the most studied and developed member of the HTS family.

While the details of the normal and superconductive properties of this material are far from understood, it is clear that they are different in different planes of the crystal. Above T_c, the material exhibits quite good conduction—similar to, though somewhat less than, that of a metal like copper—when the current flow is in a direction that coincides with one of the copper oxide planes. But when the current flow is in the perpendicular direction, along what is known as the c-axis of the crystal structure, the material exhibits very poor, semiconductor-like conduction. Below T_c, it is apparent—although the numbers have yet to be determined precisely—that the maximum supercurrent that can flow without experiencing electrical resistance is at least two orders of magnitude less along the

Figure 1

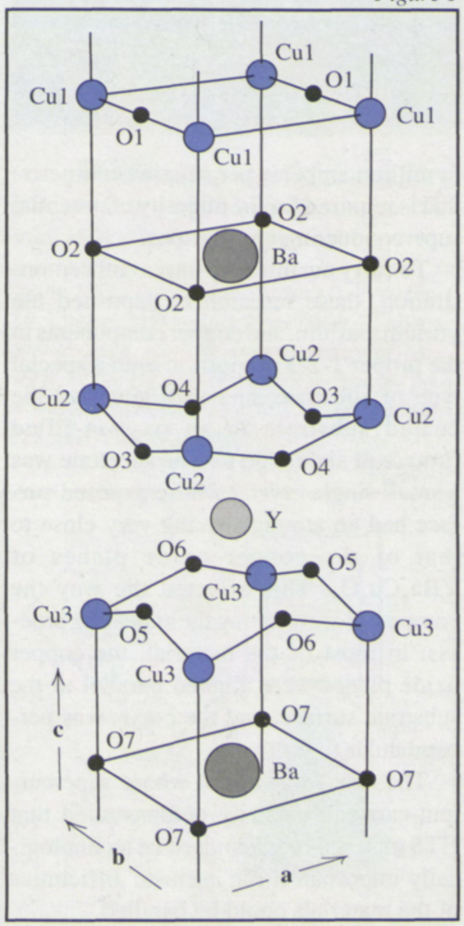
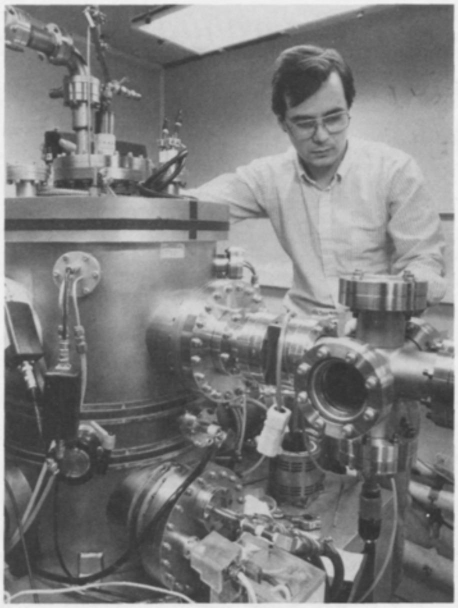


Figure 1. The crystal structure of the high-temperature superconductor $YBa_2Cu_3O_7$. In both the normal-conducting and the superconducting state, the current flows most readily along the copper-oxygen planes that are sandwiched about the central yttrium atom. These planes define what are known as the a-axis and b-axis of the crystal. In the c-axis direction, which is defined by the line connecting the outer, barium atoms, the electrical conduction is much poorer.



Right: Daniel Lathrop, a graduate student in applied physics, works with a vacuum evaporator. This evaporator was used for the first in-situ formation of a HTS thin film.

c-axis than it is in the directions of the copper oxide planes.

Unfortunately, all the other HTS materials that have been studied have similar, though often more complex, crystalline structures, and they all exhibit this "two-dimensional" anisotropic behavior, usually to an even greater degree.

As a result, it appears that for high-performance applications, the imposed current flow will have to be predominantly in the direction of a copper oxide plane. The big challenge is to process materials that meet this requirement. Fortunately, growing HTS thin films is one way in which this requirement can be met.

DEMONSTRATING THE FEASIBILITY OF THIN-FILM MATERIALS

The first major accomplishment in work with HTS thin films was achieved by a group of IBM scientists who showed that a thin film of $YBa_2Cu_3O_7$ could sustain a supercurrent at the level of current density (a million amperes per square centimeter) that is required for the majority of potential superconducting applications.

To carry out this very important demonstration, these researchers deposited the yttrium, barium, and copper components in the proper 1-2-3 proportion onto a special type of substrate, and then annealed the coated substrate in an oxygen-filled furnace at about 950 C. The substrate was a small single crystal whose exposed surface had an atomic spacing very close to that of the copper oxide planes of $YBa_2Cu_3O_7$. This affected the way the compound grew during the annealing process: in most of the material, the copper oxide planes were aligned parallel to the substrate surface, and the c-axis was perpendicular to it.

The result was a film whose supercurrent-carrying capacity demonstrated that HTS materials could indeed be technologically important if the intrinsic difficulties of the materials could be handled.

DEVELOPING MORE PRACTICAL THIN-FILM TECHNIQUES

Following this important existence proof, attention turned to the development of new techniques for forming thin films. The aim was to find methods that would be more compatible with potential applications.

The process that was initially used had two steps: deposition and then high-temperature solid-state reaction. But because of the extreme chemical reactivity of the components at high temperatures, and the difficulty of controlling the growth process, this two-step procedure was an interim solution at best.

Working in our superconductivity thin-film lab, a graduate student, Daniel Lathrop, demonstrated a workable alternative. He found that if the yttrium, barium, and copper atoms were evaporated in a chamber filled with a partial atmosphere of oxygen and exposed to a carefully heated substrate, the atomic vapor would react with the oxygen, and the $YBa_2Cu_3O_7$ would grow on the substrate, atomic layer by atomic layer. This one-step, or in-situ, process allowed the processing temperature to be lowered to the 600–700 C region, and resulted in the formation of properly oriented films with superior integrity and structure. It also allowed the use of a wider, though still limited, range of substrate materials.

Today similar types of in-situ HTS thin-film deposition processes are being very actively developed at major laboratories all over the world. One objective is to further reduce the necessary process temperature. Another is to discover how to grow high-quality films on technologically important substrates, possibly including a flexible substrate that would eventually permit the use of HTS films in large-scale applications such as a superconducting magnet.

LASER ABLATION FOR MAKING HIGH-QUALITY THIN FILMS

In implementing the in-situ process, it is crucial that the composition of the metallic components be carefully controlled and that the material reacts fully with the oxygen. This is because if there is a deficiency in oxygen content, the result is a semiconducting or even an insulating state.

One technique that is particularly successful in dealing with this problem is *laser ablation*. In this process a short high-energy pulse rapidly heats a small area of the surface of a bulk target, causing a small amount of material to essentially explode away from the surface and deposit as a film on a substrate (see Figure 2). Typically, one atomic layer or so is deposited with each laser pulse. If the target is a good-quality bulk polycrystalline $YBa_2Cu_3O_7$ specimen, such as those made here at Cornell by Professor Rishi Raj's group, and if the ablation chamber is filled with low-pressure oxygen, very high-quality $YBa_2Cu_3O_7$ thin films can be readily produced.

Laser ablation is one of the HTS-film-deposition techniques currently being developed by members of our group, and is by far the most successful approach we have used so far. This effort is being led by graduate students Stephen Russek, Brian Moeckly, and Dan Lathrop, and involves extensive collaboration with the research groups of Professors Albert Sievers, John Silcox, C. Barry Carter, James Mayer, and Rishi Raj.

THIN-FILM MICROSTRUCTURE AND HOW IT AFFECTS PROPERTIES

The growth, structure, and superconductive properties of HTS thin films are critically dependent on process parameters in ways that are not completely understood. Consequently, we are making a detailed study of the growth process. Since the atomic microstructure of the resulting films affects the superconducting properties in subtle but profound ways, this study involves examination of the crystalline microstructure.

Cornell is an ideal site for such research, since it is a world center of interdisciplinary materials science. We have a number of leading experts in electron microscopy, which is a particularly effective tool for studies of this kind. Three groups are currently contributing to the work on thin-film microstructure:

- Carter's group is using innovative electron microscopy techniques to examine the early stages of nucleation and growth in the laser ablation process. This research helps us find out how to better prepare substrates—for example, how to maximize the amount of material that grows with the c-axis normal to the substrate surface.
- Silcox's group is using a unique analytical electron microscope technique to probe for compositional variations in our films on a 1-nanometer scale, as well as examining the films for variations in microcrystalline orientation and size.
- Mayer's group employs high-resolu-

Above: Working with an apparatus used in the laser ablation growth of HTS thin films is Brian Moeckly, a graduate student.

Figure 2. The laser ablation process. Very short (10-nanosecond) pulses from the high-energy laser ablate or explode a small amount of material from the HTS target. When it deposits on a properly heated substrate, this material forms a HTS thin film of very high quality.

Figure 2

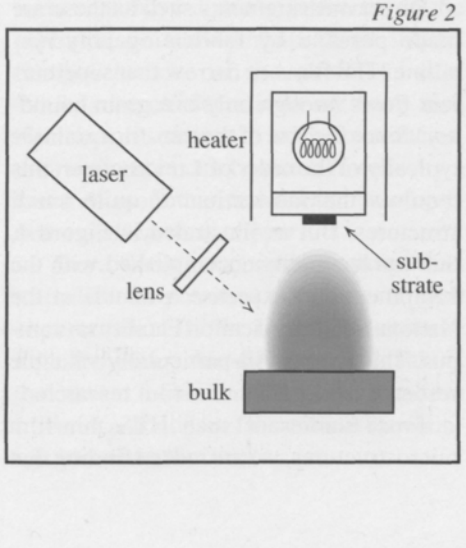
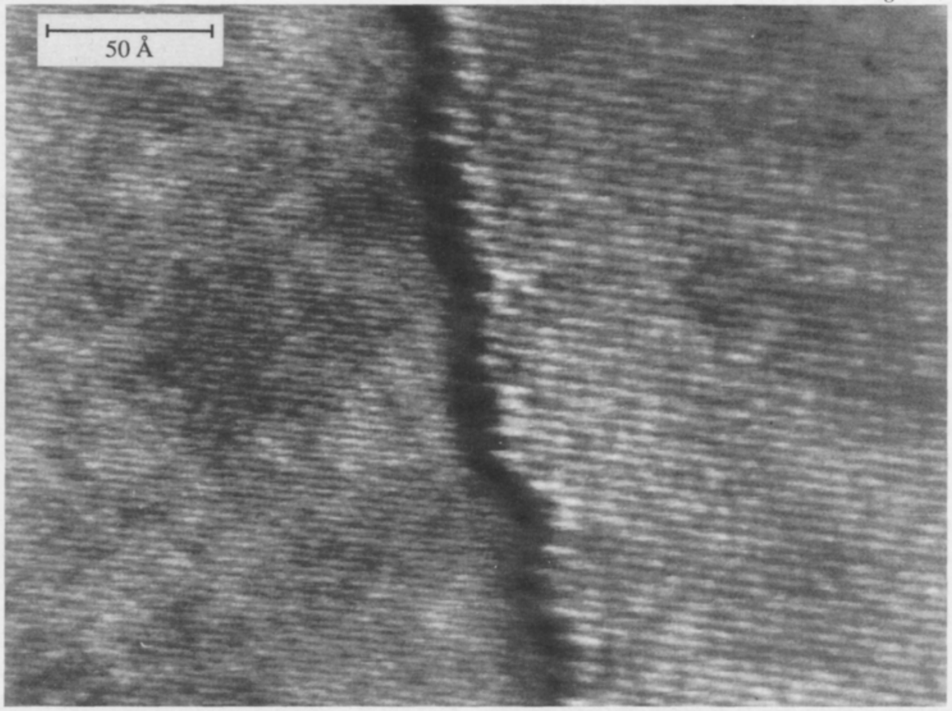


Figure 3. A very-high-resolution scanning transmission electron microscope picture of a boundary between two $YBa_2Cu_3O_7$ thin-film microcrystallites or grains. This boundary is formed by the relative rotation by 45° of two grains, each of which has its c-axis perpendicular to the image. The lines in the picture are caused by the atomic planes of the crystal. Such grain boundaries appear to significantly reduce the amount of supercurrent that can flow in the thin film.

This picture was taken by D. H. Shin of Professor Silcox's research group.

Figure 3



tion ion-scattering measurements for the precise determination of film composition and overall film quality.

- All of the above information is then coordinated with the superconductive properties of the films as measured in my laboratory and in Professor Sievers'.

MEASURING CURRENT FLOW ACROSS THIN-FILM BOUNDARIES

One of the many challenges in the study of HTS materials is to understand how crystalline orientations influence the amount of supercurrent that can flow. Early on, we knew that for best results, any imposed current must flow in the direction of the copper oxide planes. But to make matters worse, it now appears that any significant misorientation between two c-axis-perpendicular microcrystals (grains) will also reduce the flow.

The first explanation we arrived at is that in bulk HTS materials, secondary phases that are often insulating are likely to form at these boundaries during high-temperature processing, greatly attenuating the supercurrent. But we also found that attenuation occurs in high-quality thin films as well—films in which the grain boundaries are quite clean, free of secondary phases, and coherent (see Figure 3). Direct measurements of supercurrent density showed that the supercurrent flow across such a clean boundary can be reduced by more than a factor of ten, as compared to the amount that can flow in a single grain.

Direct measurements such as these are made possible by fabricating polycrystalline HTS films so narrow that supercurrent flows through only one grain boundary. Since the size of the thin-film grains is typically of the order of 1 micrometer, this requires the fabrication of quite small structures. But as illustrated in Figure 4, this can be readily accomplished with the equipment and expertise available at the National Nanofabrication Facility on campus. This facility is a particularly valuable resource in our HTS thin-film research.

From studies of such HTS thin-film microstructures, we are indeed finding that the superconductivity at these in-plane grain boundaries is weakened in a systematic way that is yet to be fundamentally understood. This "weak-link" behavior can be utilized to make particularly sensitive magnetic field detectors, known as SQUIDs, but in general this effect is harmful with respect to most potential applications. A major focus of our current research is to develop a better understanding of this weakening effect of grain boundaries, and to seek ways of eliminating or at least ameliorating it.

POSSIBLE APPLICATIONS USING SINGLE-CRYSTAL THIN FILMS

Of course, one way to deal with the grain-boundary effect is to simply eliminate all such boundaries. Indeed, this is an approach that is being taken in many HTS thin-film research programs.

Figure 4

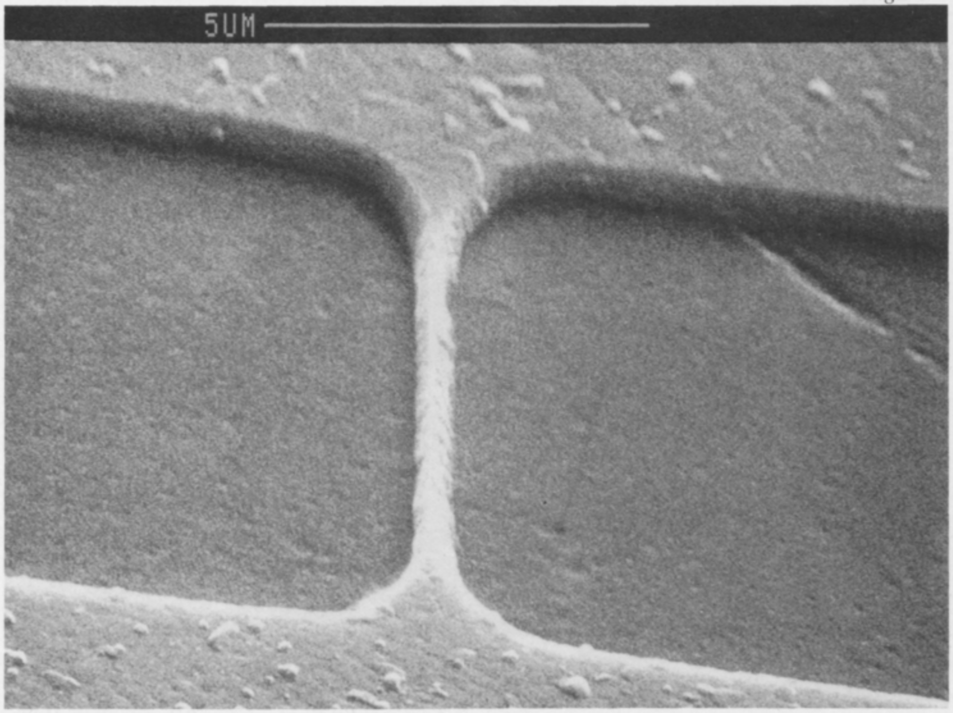


Figure 4. A scanning electron microscope picture of a $YBa_2Cu_3O_7$ thin-film microbridge that was fabricated at the Cornell National Nanofabrication Facility.

Such microbridges are sufficiently small that the superconductive properties are dominated by individual thin-film grain boundaries such as that shown by the higher-resolution image of Figure 3.

Through studies of such microbridges, Buhrman's group is seeking to determine how to improve the properties and hence the supercurrent-carrying capacity of polycrystalline high-temperature superconductors.

The method is to grow an HTS film on a single-crystal substrate whose exposed surface has an atomic structure matching that of the copper oxide planes; if this is done carefully, an essentially single-crystal HTS film can result. In fact, such films have been grown on substrates larger than two inches in diameter. They can sustain supercurrent densities of the order of 10^7 amperes per square centimeter at 77 K; and at lower temperatures they can sustain currents nearly ten times larger than that.

This thin-film single-crystal approach will limit the possible HTS applications to comparatively small-scale systems such as high-performance electronic devices, but it is this area of research and development that appears to hold the greatest promise for early application of high-temperature superconductivity.

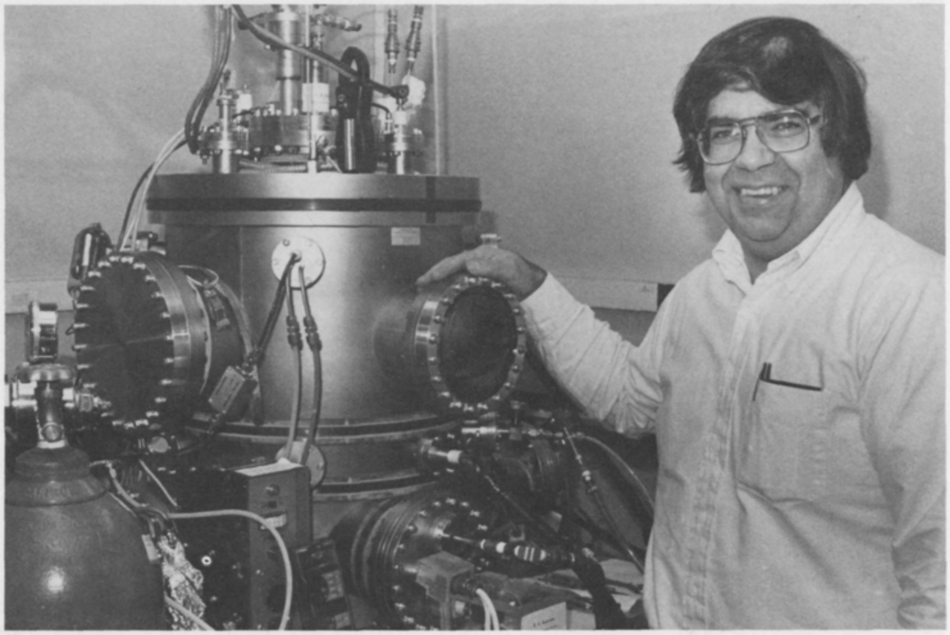
An example of a possible application is in circuits in the very-high-frequency (microwave or millimeter-wave) range, for communication and radar systems. In such circuits the resistive losses of the normal-conducting material that is used to produce filters, resonators, and other circuit elements can have a strong influence on the performance and—perhaps more importantly—the size of the overall circuit. While superconductors do not have zero electrical resistance at such frequencies, their resistance can be much lower—by a factor of more than ten—than that of normal metals such as copper.

There is now a major and growing effort to realize the potential advantage of such superconductors in high-performance high-frequency thin-film circuits. This is the current focus of much of the thin-film research activities at labs around the country, including our own.

EXPECTATIONS FOR HIGH-TEMPERATURE SUPERCONDUCTORS

In the three years since the discovery of high-temperature superconductivity, the basic properties of HTS materials have been established, potential applications have been examined, and a fairly fundamental understanding of the problems that are entailed has been reached. Extensive experiments have established that superconductivity in these new materials is generally the same as that seen in low-temperature superconductors, when properly scaled by the much higher critical temperatures and magnetic fields. We still have incomplete understanding of the microscopic origin of superconductivity in these materials, however, and much to discover about how to synthesize new materials with improved properties.

Recently there was a spate of reports in the popular scientific press suggesting that high-temperature superconductivity was proving useless. The reason given was the inability of single crystals of these materials to sustain a high supercurrent density in the presence of a significant magnetic field, which would almost always be present in real applications. But now that



high-quality thin films have been made, we have proof that properly fabricated HTS materials are capable of carrying technologically useful electrical currents in high magnetic fields at high temperatures.

As I have indicated, the most fundamental obstacle I see is the extreme anisotropy of the materials. Other major problems are their nonductile nature, and the strong sensitivity of their superconductive properties to imperfection in the crystalline structure.

The use of single-crystal HTS films—which we can expect to be in routine production soon—is one approach that can avoid the anisotropy problem, and thus possibly meet the needs of a particular, and potentially very important, application niche: that of high-performance high-frequency circuits and specialized superconductor sensors.

Larger-scale applications will almost certainly require the use of either polycrystalline thin or thick films, and/or polycrystalline bulk HTS materials. This in turn will require a systematic and extensive research effort directed at obtaining a fundamental understanding and control of the anisotropy and imperfection effects.

This is a particularly challenging physics and materials research problem, and we can expect to be at it for quite some time. But given the scope of the current activity and the significant progress that has already been achieved in a comparatively short time, steady progress can be expected in the years to come.

Robert A. Buhrman has been a member of the Cornell applied and engineering physics faculty since he received the Ph.D. degree here in 1973, and he has been director of the School of Applied and Engineering Physics since 1988.

His research interests include superconducting devices, solid-state and low-temperature physics, and submicron lithography—all areas that are involved in the research he discusses in this article.

He currently serves on the technical advisory boards of the New York State Institute for Superconductivity, and of the Science and Technology Center for Superconductivity, which is a multi-university research consortium centered at the University of Illinois. He is also a consultant for several companies active in high-temperature superconductivity research.

At Cornell Buhrman has been closely associated with the National Nanofabrication Facility since its beginnings in 1978; he served as associate director from 1981 through 1983. He is associated also with the Materials Science Center and the SRC Program in Microstructure Science and Technology.

He received his undergraduate education at The Johns Hopkins University.

THE POWER OF MAGNETIC LEVITATION

I. A Nearly Frictionless Superconducting Bearing Invented at Cornell

by Francis C. Moon

A device developed in our laboratories at Cornell demonstrates that useful applications of superconducting ceramics are already at hand.

The device is a high-speed superconducting bearing that operates by magnetically levitating a rotor. Speeds up to 120,000 revolutions per minute have been achieved without the need for feedback control, and the prospects are good for reaching a million rpm in vacuum. By comparison, currently available magnetic bearings allow speeds of more than 100,000 rpm in a vacuum, but require complex feedback circuits to maintain stability.

The new bearing, remarkable for its simplicity, stability, and nearly frictionless operation, could lead to the development of superior rotors for such products as gyroscopes, computer disk drives, scanning systems, and high-speed shutters. For example, conventional gyroscope systems run at speeds of around 12,000 to 36,000 rpm; but speeds in excess of 100,000 rpm, achieved with superconducting bearings, would allow smaller rotor mass for the same angular momentum. Disk-drive storage systems now run at speeds well below 10,000 rpm; but increasing the speed by a factor of 10 or 100 might permit smaller discs or faster access times.

Superconducting magnetic bearings might also have usefulness for nonrotating devices. Such applications might include linear bearings for small translation devices, and levitated stages for electron microscopes or optical instruments.

HOW MAGNETIC LEVITATION IS ACHIEVED BY THE BEARING

The essential feature of the new bearing is its material, a yttrium-barium-copper oxide superconducting ceramic of the kind that was developed in 1987 at the University of Houston. Much excitement followed the discovery that this material exhibits superconductivity at temperatures considerably above the near-absolute-zero temperature previously required—in fact, the temperature of liquid nitrogen is sufficient. An enticing goal has been to develop materials that would be superconducting at normal operating temperatures. In the meantime, though, there are applications—such as the new bearing—that are feasible at liquid-nitrogen temperature.

The reason the bearing can levitate a rotor containing permanent magnets is that superconductors repel magnetic fields; the phenomenon is called the *Meissner effect*. In our laboratory setup (Figure 1) the rotor, made of nonmagnetic metal, carries permanent rare-earth magnets (of samarium-cobalt, for example), which induce magnetization in the liquid-nitrogen-cooled superconducting bearing. This magnetization opposes the inducing field, and the resulting repulsion causes the levitation.

The permanent magnets can be thought of as creating magnetic flux lines that start at the north poles and return at the south poles of the magnets. Superconducting material repels some of these lines of flux to produce repulsive levitation force, while attracting and pinning other flux lines. This pinning of flux lines is responsible for the lateral stability of the rotor. (Pinning has an additional effect, evident in some new superconducting materials: rather than levitating as a result of repulsion, magnets can actually be suspended as a result of attractive forces.)

In our experimental device, the magnetic forces appear to be unaffected by the high rotation speeds. Furthermore, the system can be designed so that the levitating effect is self-stabilizing.

"The reason the bearing can levitate a rotor containing permanent magnets is that superconductors repel magnetic fields. . . ."

Figure 1

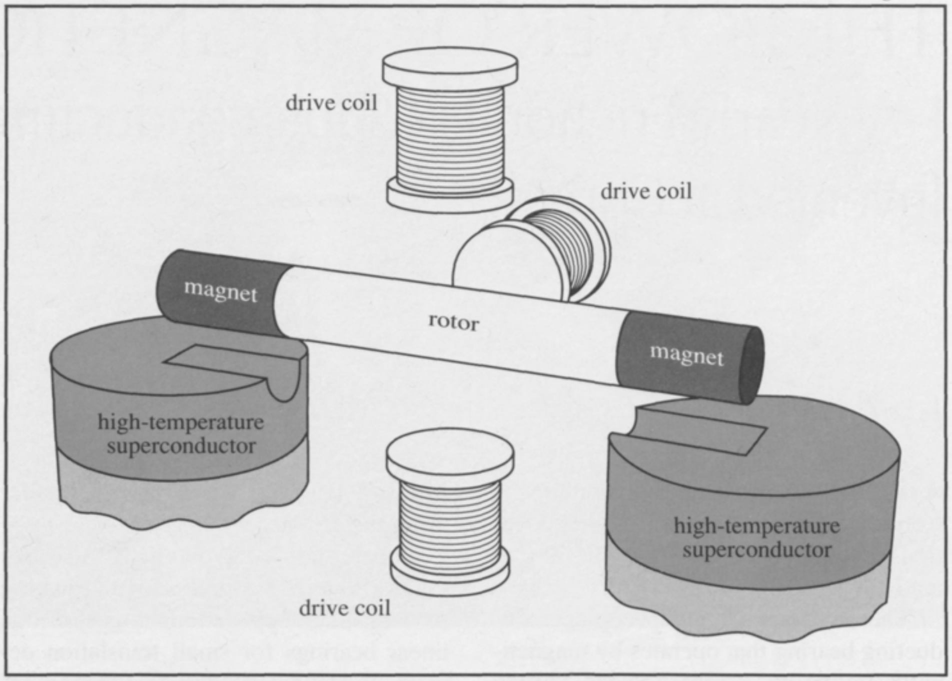


Figure 1. How the experimental superconducting bearing works. The nonmagnetic rotor contains permanent rare-earth magnets, which induce an opposing magnetization in the superconducting bearing material, $YBa_2Cu_3O_7$. Liquid-nitrogen cooling makes the material superconducting. The induced magnetization repels the rotor, which is thereby levitated. The rotor can be spun, with almost no drag, either by electromagnetic torque, as in a conventional motor, or by a small gas-turbine wheel attached to the rotor. Both methods have been used in Moon's laboratory.

The experiments have been conducted with rotors weighing 10–40 grams. The cylindrical bearings are about 14–16 millimeters in diameter. The rotor is levitated about 1.3 millimeters.

PREPARATION OF THE SUPERCONDUCTING CERAMIC

Work on the experimental bearing began with processing of the superconducting ceramic. This was carried out under the supervision of my colleague, Professor Rishi Raj of the Department of Materials Science and Engineering. (An article by Raj on processing methods for superconducting materials begins on page 23.)

The material for the superconducting bearing, $YBa_2Cu_3O_7$, was processed by two methods—free sintering and sinter forging. In the free-sintering method, the material was prepared by solid-state reaction of Y_2O_3, CuO, and $BaCO_3$. Finely ground powders were calcined for twenty-four hours in an oxygen atmosphere at 920 C, reground, pressed into pellets, and then free-sintered at 950 C for twelve hours. The density of the samples was about 90 percent of the theoretical value. The pellets, which were in the shape of cylindrical disks, were carefully machined to provide the optimal shape for the bearing.

We are now working on superconducting material processed by a new method, called *Quench-Melt-Growth* (QMG), which was developed in both the United States (at Catholic University) and Japan. At present the QMG method seems to produce forces at least two or three times greater than the force achieved with superconducting ceramics that have been processed by sintering.

The fact that different processing methods lead to different levels of magnetic force in the superconductor implies that improvements in processing may lead to higher magnetic pressure and therefore a wider range of applications. For example, improved processing might allow the use of heavier rotors.

IMPLICATIONS OF MAGNETIC FORCE MEASUREMENTS

In designing the pads for the bearing, our chief object was to obtain maximum lateral and axial stability without loss of lift force.

Figure 2

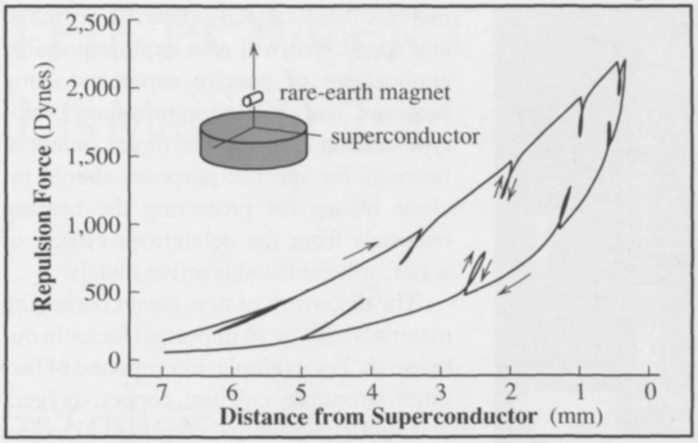


Figure 2. Hysteretic behavior observed with the experimental bearing and rotor assembly. In these experiments, magnetic force was measured against vertical displacement of the rotor. Lower values were obtained when the force diminished than when the force increased.

Figure 3

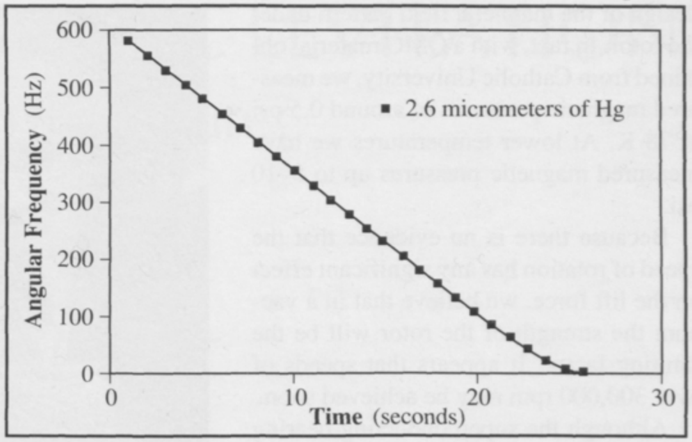


Figure 3. Decay of the spin rate of the rotor with time. Measurements were made under vacuum. The constant deceleration is evidence of a constant drag torque on the rotating magnets; the source of this magnetic drag is not obvious.

In the light of measurements of the magnetic force between a bulk superconductor and small permanent magnets, we were able to determine an optimal shape. (The instrument used to make the measurements has been patented.) The measuring technique not only helped us with the bearing design, but revealed something about the underlying physics.

In one set of experiments, we measured the magnetic force between our permanent magnets and a number of high-T_c superconductors, including thallium-based and bismuth-based materials. (T_c refers to the critical temperature below which superconductivity is exhibited.) We measured forces both normal and tangential to the superconductor surface.

These experiments indicated that there is a small magnetic stiffness for lateral, axial, and heave motions of the rotor which gives the bearing a "soft" or low-frequency suspension. The source of this magnetic stiffness is believed to be related to flux pinning. A beneficial consequence is that small periodic forces due to imbalances of the rotor are filtered out when the rotation torque is above 10 hertz; below 10 hertz, however, complex dynamics, including chaotic vibrations, have been observed.

Magnetic force plotted against either vertical or lateral displacements were shown to be hysteretic—that is, dependent on the previous history of the motion. A large hysteresis loop results when there are cyclic gross displacements (Figure 2), while minor loops result when there are small displacements. These minor loops seem to give a slope proportional to the magnetic stiffness and are probably indicative of flux pinning.

A central thesis of our research is that the motion of a rotor about an axis with magnetic-field symmetry offers near-zero torque resistance to rotary motion. Numerous experiments have confirmed this. However, we have not encountered perfect symmetry: every permanent magnet with circular symmetry that we have measured showed about 1–5 percent asymmetric flux. This would be expected to result in a small amount of flux drag, and in fact, measurements of rotary speed show a linear decay with time (Figure 3).

In experiments run in air or gaseous nitrogen, the initial decay appears to be governed by viscous air drag, but for smaller velocities the cause appears to be magnetic drag. Other measurements indicate that the drag force is essentially independent of the speed of rotation and of the amount of lateral motion.

THE EXPERIMENTAL MODEL: PROGRESS AND PROSPECTS

The rotors we are now using weigh 10 to 40 grams, and the effective magnetic pressure on the rotor ends is around 0.15 newton per square centimeter (about 0.1 psi). Since the magnetic pressure is proportional to the square of the magnetic field, it seems possible that a 50- to 100-fold increase in magnetic pressure between the rotor and bearing might be achieved through further improvements in the material and clever design of the magnetic field pattern under the rotor. In fact, with a QMG material obtained from Catholic University, we measured magnetic pressures of around 0.5 psi at 78 K. At lower temperatures we have measured magnetic pressures up to 5–10 psi.

Because there is no evidence that the speed of rotation has any significant effect on the lift force, we believe that in a vacuum the strength of the rotor will be the limiting factor. It appears that speeds of over 300,000 rpm may be achieved soon.

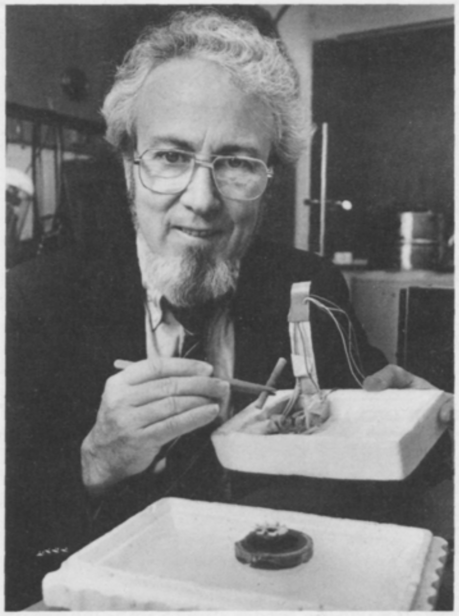
Although the superconducting bearing pads must be cooled below 95 K, we have found that indirect cooling with liquid nitrogen is sufficient. Indirect cooling has the additional advantage of allowing the system to be operated in a vacuum. Operation at atmospheric pressure is, of course, possible, provided that one has the input torque to counter the viscous torque between rotor and bearing.

With the lightweight rotors we are currently using, levitation can be achieved without putting any external current through the bearing. The superconducting currents in the $YBa_2Cu_3O_7$ pads are induced by the magnetic fields from the rotor magnets.

ONGOING RESEARCH ON SUPERCONDUCTING BEARINGS

In our continuing program of research, a fundamental objective is is to gain a better understanding of the physics of passive superconducting bearings. (By passive I mean without the use of feedback forces to achieve stable levitation. Active nonsuperconducting magnetic bearings are now in use, but require sophisticated electronic feedback to obtain stable performance.)

For example, we do not know whether the induced superconducting currents that produce the magnetic forces in the superconducting material are confined to individual grains or whether there are macroscopic current paths in these new materials.



Moon demonstrates the levitation of a permanent rare-earth magnet by a superconducting ceramic cooled by liquid nitrogen. (A close-up of the floating magnet is shown on the cover.)

Also, the nature of flux pinning is not understood; a theory is needed to explain and predict the hysteretic behavior of the magnetic forces. Models would also lead to more rational and optimal designs of superconducting bearings.

Another property to be understood is magnetic damping. Damping of lateral vibrations of levitated rotors has been measured; a theoretical model for this behavior is needed.

In our experimental work, we intend to explore different materials and processes that will improve the performance and capabilities of the bearing. The goals are to increase load capacity, bearing stiffness, and speed. We will also explore possible applications of passive superconducting bearings, and develop appropriate prototype bearing systems. The development of bearings for specific purposes should include means for protecting the bearing materials from the deleterious effects of water, solvents, and reactive metals.

The discovery of new superconducting materials may be an important factor in our research. For example, a compound of bismuth, strontium, calcium, copper, oxygen, and a little aluminum is reported to have a critical temperature of 114 K. When such new materials become available, they should be tested for magnetic force capability and other properties relevant to magnetic levitation applications. Of course, the development of really-high-temperature superconductors would greatly expand the possible applications.

A major goal of much research today is the development of high-temperature superconducting wire with current densities greater than 10,000 to 100,000 amperes per square centimeter (A/cm^2). An encouraging recent development is that high current densities—at least 35,000 A/cm^2 in a 1-tesla magnetic field—have been achieved in bulk ceramic superconductors made by the QMG process. The availability of high-current-density wire would permit the development of magnetic bearings with higher load capacity, capable of lifting rotors with weights corresponding to magnetic forces of 100 to 1,000 newtons. And, of course, high-temperature superconducting wire and magnets would permit levitation of even larger objects, such as MAGLEV high-speed vehicles.

Bearings, valuable as they are, are only a beginning.

THE POWER OF MAGNETIC LEVITATION
II. Is Magnetic Transportation in the Future?

by Francis C. Moon

In combination, some seemingly unrelated stories that have appeared recently in the nation's press send a message to the United States. The headlines shown in the box illustrate the convergence of three interrelated developments that pose both problems and opportunities for the nation.

The first three headlines concern the nation's growing airline traffic in the face of zero growth in airport capacity. No new major airports have been built in the past fifteen years, and only one major new one—for Denver—is scheduled to be built in this decade. In addition, there is the problem of upgrading existing facilities. It would take billions of dollars to improve our aging air-traffic-control system, and more billions to replace aging aircraft.

The next two headlines point up a second development: improvements in ground transportation by the French, Germans, and Japanese. Not only is the United States' domination of the aircraft trade being challenged by European countries, but France, Germany, and Japan are poised to sell to the United States new high-speed trains worth billions of dollars and thousands of jobs.

The third trend is the emergence of magnetic technology. New superconducting materials and engineering advances in magnetic levitation could give the United States an edge in international competition for the sale of manufactured transportation goods.

> **SOME RECENT HEADLINES**
>
> **Air Traffic Delays Increase in 1989**
> **Air Passengers to Increase 50% by End of Decade**
> **Air Traffic System Upgrade Could Cost Billions**
>
> **French Set New Train Speed Record**
> **Japan and Germany Set to Build Magnetic Trains**
>
> **New Superconducting Material Discovered**
> **Senator Pushes Bill for Magnetic Transportation Research**

The message of these stories and of this article can be summarized as:

- New magnetic-levitation (MAGLEV) transportation technologies can be used to relieve airport congestion.
- New superconducting materials may improve the cost/benefits ratio for some MAGLEV systems.
- Postponement of research in MAGLEV technology in the United States will mean the loss of jobs and worsening trade balances near the end of the decade.

Supporting the first of these premises is a recent study by the Argonne National Laboratory. The conclusion was that new MAGLEV technology need not be a competitor to air-travel service, but could be a complementary component, taking short-distance flights out of the air-traffic system near major airports. (Up to 40 percent of the flights out of major airports are for trips of less than six hundred miles.)

OPTIONS FOR FAST GROUND TRANSPORTATION

To be competitive, any ground transportation system must be fast. Fortunately, several systems that could meet this requirement have emerged.

During the 1970s, three technologies were in the competition: air-cushion technology; improved steel-wheel-on-steel-rail systems; and MAGLEV.

Air-cushion technology was deployed by the French, but was later abandoned because of complaints about the noise.

Recently the French and the Germans

"Germany and Japan have invested millions of marks and yen over the past two decades in the development of MAGLEV systems."

The French TGV (Train à Grande Vitesse) runs with steel wheels on a steel track. The TGV Atlantique, which has attained a test speed of over 416 kph, is in competition with the comparable German ICE (Inter-City Express). The operating speeds of these trains may be limited to around 320 kph because of problems of noise, wear, and maintenance.

have been competing to build the world's fastest rail trains. A French TGV (Train à Grande Vitesse) has achieved a test speed record of over 260 miles per hour (416 kilometers per hour) and is expected to achieve operational speeds of 300 kph. The German ICE (Inter-City Express) is capable of comparable speeds. These systems seem to be technically successful in the 250 to 320 kph range, but it remains to be seen whether regular operating speeds of more than about 320 kph can be achieved without excessive noise, wear, and maintenance problems. In tests of the ICE at very high speeds, very high noise levels were measured at a distance of one hundred meters from the track.

The third competing technology, magnetic levitation, does not have these drawbacks. MAGLEV systems have been shown to be capable of operating in the 200–300 mph (320–480 kph) range of speed.

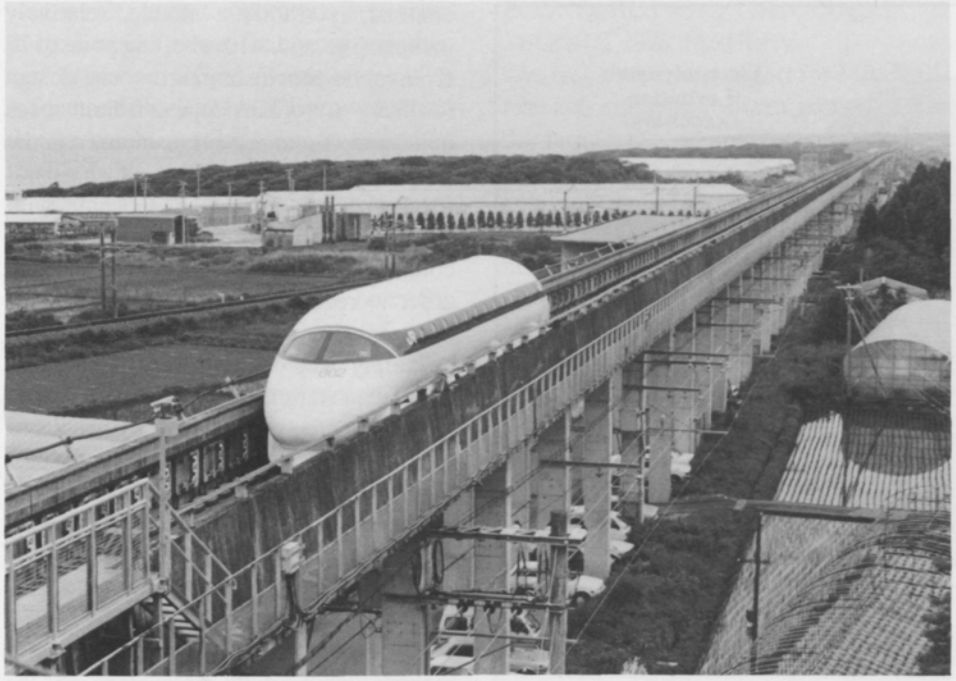
There are two competing MAGLEV technologies. One of them, typified by the West German Transrapid 07, relies on conventional electromagnets and sophisticated computer control of the air gap between vehicle and guide rail. The other, developed by the Japanese and implemented in their Linear Motor Car, uses superconducting magnets.

Germany and Japan have invested millions of marks and yen over the past two decades in the development of MAGLEV systems. The United States bowed out of the competition in the early 1970s, before the oil embargoes.

HOW CAN MAGNETIC FIELDS LEVITATE VEHICLES?

Objects can be magnetically levitated in several ways. For MAGLEV transportation, there are two major competing systems, based on the principles of *electrodynamic levitation (EDL)* and *electromagnetic levitation (EML)*. These two principles are illustrated in Figure 1.

In the EDL method, sometimes called the *repulsive* method of MAGLEV, superconducting magnets on the vehicle create



Left: Japan and West Germany are currently the competitors in developing and marketing MAGLEV trains. The Japanese Linear Motor Car (above) uses superconducting magnets. The German Transrapid (below) uses conventional electromagnets and electronic feedback control.

high magnetic fields, of the order of 2 to 3 tesla. The track or guideway carries two types of nonsuperconducting windings or coils. One set of windings is passive, and as the vehicle moves past these passive coils, the moving magnetic field generates eddy currents in the track coils. This pushes the vehicle up. The other set of guideway coils are used to pull the train forward. Wayside stations, spaced many kilometers apart, supply electrical power to these linear motor coils. This is the technology used in the Linear Motor Car, which the developer—the Japanese National Railways—is already seeking to deploy in Japan and to market worldwide.

EML, also known as the *attractive* or *suspension* method, does not use superconducting magnets. Instead, it uses iron and ordinary copper coils to create electromagnets which try to pull the vehicle up to an iron-alloy track. Sensors and feedback currents are used to achieve stability, with the vehicle hanging about one centimeter below the track. Another set of coils is used to pull the train forward. Both West Germany and Japan have developed low-speed versions of this system, and the Germans are ready to deploy a high-speed (500 kph) model called the Transrapid 07.

Both methods have advantages and disadvantages. EML does not require exotic superconducting technology, but it does require high-power feedback electronics and a more precisely aligned guideway. EDL can run with a large gap between

Figure 1

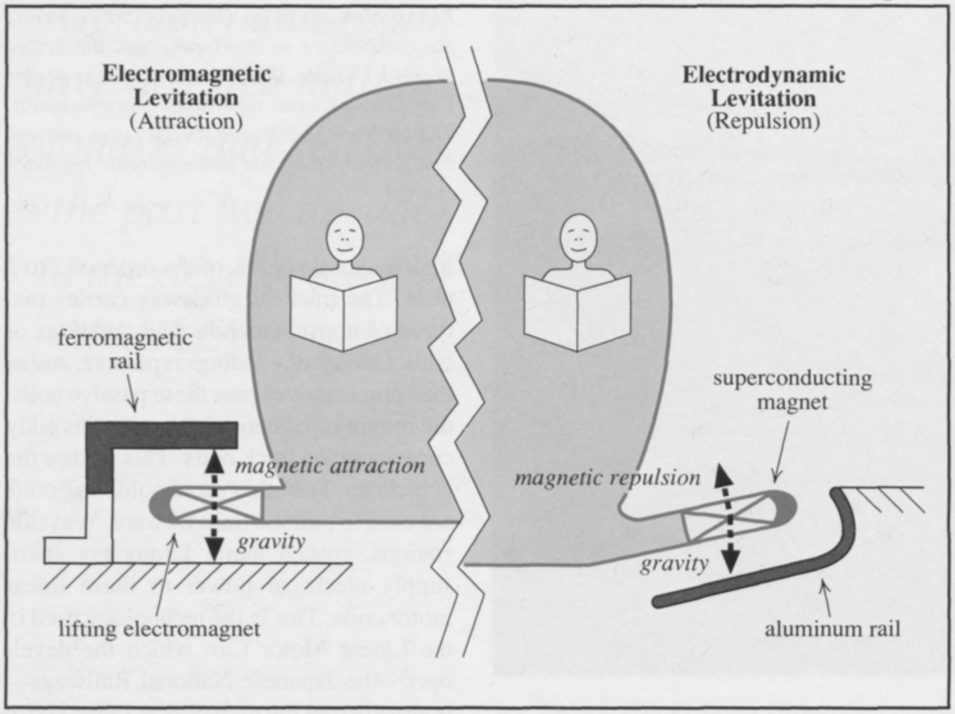


Figure 1. Two ways of levitating vehicles. Superconducting magnets are used in the method based on repulsion.

guideway and vehicle (up to 20 centimeters), but has the disadvantage of stray fields (around 10 to 100 gauss) in the passenger cabin, necessitating heavy magnetic shielding.

THE IMPACT OF NEW SUPERCONDUCTING MATERIALS

As I have noted, in the present superconducting MAGLEV train, superconducting coils of wire, cooled to liquid-helium temperature (4.2 K), are carried on the vehicle. When and if high-temperature superconducting materials in the form of wire or tape become available, several important benefits are likely to result for MAGLEV transportation applications.

Clearly, new high-temperature superconducting materials are not what engineers call "enabling" technology—the feasibility of the MAGLEV concept was demonstrated more than twenty years ago. Instead, the new materials will be an "enhancing" technology that could spur interest in a superconducting MAGLEV transport system, and brighten the prospects for its economic operation.

One advantage, of course, would be the higher operating temperature for the superconducting magnets. Liquid helium, the coolant that is currently required for the superconducting magnets, is expensive and not easily available, and the cryostats that are needed are high-tech items, requiring careful operation and maintenance by skilled technicians. Liquid nitrogen, by contrast, is readily available, relatively inexpensive, and, with a boiling point of 77 K, involves much simpler cryostat design (ordinary styrofoam cups can hold it for quite some time). The cryostat used in the Japanese MAGLEV train provides a basis for comparison. The Japanese design, with liquid-helium cooling, requires a unit for collecting and liquefying the cryogen in order to recirculate it. If low-cost liquid nitrogen were used instead, the gas could be simply vented and replaced with liquid at the next station.

Another advantage of using high-temperature superconductors at liquid-nitrogen temperature is a beneficial scaling effect. Cryostats impose a weight penalty on the design; to minimize that penalty, the size of the magnets must be increased. At liquid-helium temperature, this is an important factor: the Japanese design calls for racetrack coils with dimensions on the order of 1 x 2 meters. High-temperature superconducting material might allow an alternative: the use of a larger number of smaller coils, of the order of 1/4 x 1/4 meter. These coils could be made modular so that defective ones could simply be pulled out of the coil array and new ones pushed in. The smaller coils would probably entail less total cost, and if they were placed in alternating-polarity arrays, they would result in lower fields in the passenger cabin.

Reducing the likelihood of so-called *thermal quench failures*—in which the material suddenly becomes nonsuperconducting—is another potential advantage if high-temperature superconductors can be used. Conventional superconducting coils are subject to thermal quench, but it is expected that the different thermal properties of the new materials will make them less susceptible to this problem.

Overall, high-temperature superconductors would reduce the cost of manufacture, operation, and maintenance of vehicle magnets and make MAGLEV more attractive to operating companies. In summary, the likely benefits are:

- magnets of reduced weight;
- lower maintenance costs for magnetic service and repair;
- greater level of acceptance by operating companies;
- lower stray magnetic field in the cabin because of the smaller magnets;
- lower risk of thermal quench.

SUPERCONDUCTING PERMANENT MAGNETS FOR LEVITATION

Proposals have been made to use permanent magnets instead of superconducting coils to generate the magnetic pressure needed to levitate vehicles.

The problems with room-temperature conventional permanent magnets are their weight and the fact that they generate fields of the order of only 1 tesla. The new high-temperature superconductors might make it possible to substitute superconducting permanent magnets—bulk forms that retain superconducting circulating currents after the applied field is removed. It is thought that fields as high as 1.5 tesla might be achieved, and since magnetic pressure is proportional to the square of the magnetic field, such superconducting permanent magnets at liquid-nitrogen temperature could generate more than twice the levitation pressure achieved by room-temperature permanent magnets, and thus decrease the weight penalty of the magnets.

This would mean that vehicles could be levitated without the need for wire or tape forms of the new superconductors. This is a radically new concept still in the exploratory stage.

ECONOMICS AND THE GLOBAL MARKET FOR MAGLEV

The lack of federal support for MAGLEV research in the past fifteen years has been due largely to economic forecasts showing an insufficient market here for MAGLEV vehicles, and high operating costs. Now there is revived interest that seems to be driven by three nontechnical factors.

The first is the growing realization by several state governments, including Florida, Nevada, and Texas, that they must invest in new transportation systems to satisfy projected growth.

The second factor, which I have already mentioned, is the near-saturation capacity of major hub airports. Landing slots are very tightly scheduled at peak hours.

But the most important factor is the prospect for new jobs and exports. There is a growing awareness that the projected market for new trains is not just North America, but the world. This realization has led the state of Pennsylvania, for example, to fund a study at Carnegie Mellon University of how Pittsburgh, a city with closed steel mills, might become a major manufacturer of MAGLEV technology.

MAGLEV NEWS

- West Berlin will soon open a new Magne Bahn people-mover. The 50-mph elevated train is suspended by permanent magnets and guide wheels.
- The American subsidiary of the German firm AEG, an arm of Daimler-Benz AG, is planning to build an $80-million, 1.1-mile Magne Bahn for Las Vegas.
- The West German government has made a commitment to build an EML MAGLEV system either between Hamburg and Hannover or between Essex and Bonn. The new train, called Transrapid 07, is expected to achieve speeds of 310 mph.
- The Japanese government recently decided to build a 45-km MAGLEV demonstration project outside of Tokyo. The new train, called the Linear Motor Car, is based on the superconducting EDL system and will run at speeds of 310 mph.
- Officials at Frankfurt Airport are studying a proposal from AEG to construct an airport people-mover based on the Magne Bahn concept in West Berlin.
- The French have extended their TGV service with a new train called the TGV Atlantique between Paris and Le Mans. The train is expected to run at speeds of more than 180 mph. The French expect a 40 percent drop in airline passengers for the same route.
- The French transportation agency is trying to sell a TGV system to several governments. Lines that would be served are Miami–Tampa in Florida, Montreal–Toronto in Canada, and Seoul–Pusan in Korea.

An old Dick Tracy cartoon, reprinted by permission of Tribune Media Services.

To develop MAGLEV technology, I would propose starting with a core of engineers and scientists from industry, universities, and government labs such as DOE and NASA to decide on the best configuration for high-speed transportation. This might take two years. The next steps would be to build a full-scale prototype vehicle, and to conduct a feasibility study for a demonstration project.

The advances in superconducting materials make MAGLEV technology more promising than ever, but the new discoveries in superconductivity, exciting as they are to scientists and engineers, will not bring a new age of transportation unless there is commitment from our national leaders, Congress, and the voters.

A bill that has been proposed by Daniel P. Moynihan in the Senate would help get the United States back into the MAGLEV technology competition. So far this bill has generated only mild interest, but as new technology is imported into this country from France, Germany, or Japan, interest should grow. The United States is now behind in MAGLEV development, but it still has opportunity to enter the international competition.

"It is impossible to imagine the height to which may be carried, in a thousand years, the power of man over matter. We may perhaps learn to deprive large masses of their gravity, and give them absolute levity, for the sake of easy transport."

—Benjamin Franklin

Professor Francis C. Moon, the director of the Sibley School of Mechanical and Aerospace Engineering at Cornell, began conducting research in the area of magnetic levitation more than twenty-five years ago. The recent availability of superconducting ceramics has been an added incentive for further work.

In his study of magnetic levitation for trains, Moon has visited developers in West Germany and Japan. He testified before the Senate Committee on Environment and Public Works concerning a bill that has been introduced by Senator Moynihan in support of MAGLEV development.

Moon's research interests span a wide spectrum of problems in the dynamics of solids and structures, including the mechanics of solids in magnetic fields, magneto-mechanics problems in fusion reactors, wave propagation in composite materials, and nonlinear vibrations. In the past few years he has conducted research on chaotic dynamics, as well as nonlinear problems in structures.

Moon studied at the Pratt Institute for his baccalaureate degree in mechanical engineering, and at Cornell for the M.S. degree and the Ph.D., granted in 1966. After teaching at Princeton University, he returned to Cornell in 1975 as a member of the Department of Theoretical and Applied Mechanics. He became director of the Sibley School in 1987.

Recently he received an Alexander von Humboldt award to visit West Germany, where he lectured and inspected the West German MAGLEV facility. He is a consultant to Argonne National Laboratory on superconductivity and MAGLEV.

Moon is the author of two books, Magneto-Solid Mechanics *(1984), and* Chaotic Vibrations *(1987), both published by Wiley.*

INNOVATIVE PROCESSING OF CERAMIC SUPERCONDUCTORS

by Rishi Raj

The discovery of high-temperature superconducting yttrium barium cuprate has changed the way we think about ceramics.

It has broadened the perception and the definition of ceramic materials, and has attracted new workers from other fields such as chemistry, physics, and engineering, adding to the diversity of techniques used for synthesis and characterization.

And whether or not the superconductors themselves lead to new technologies, their discovery has introduced a fundamental change in how ceramics will be made and used in the future. For example, the thin-film technologies that are being developed to make near-single-crystal films of ceramic superconductors can be used to make films of ferroelectric ceramics that may impact the development of the optoelectronics technology well into the twenty-first century.

This fundamental change in how ceramic materials have been and will be synthesized is reflected in our research here at Cornell. Whereas five years ago we were concerned with issues such as the effect of particle-packing on the sintering process, today we are seeking to synthesize ceramics in a near-single-crystal configuration, by thin-film as well as by powder-processing techniques.

Our view is broad. Rather than limiting our effort to the development of ceramic superconductors, we want to create a whole new class of material that may have wide-ranging applications, from sensors to optoelectronic devices to superconductive cables. In this article I will describe our approaches and some of our preliminary results. A superconducting magnetic bearing and a high-current superconducting cable are possible applications of our work.

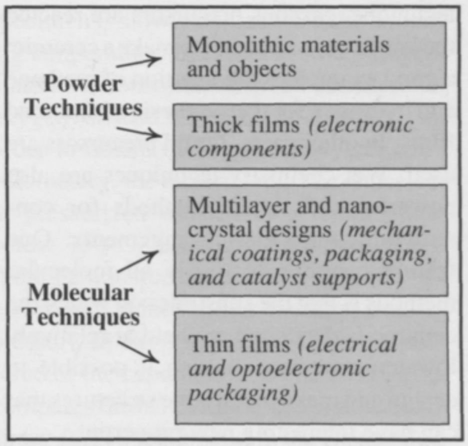
HOW CERAMICS ARE SYNTHESIZED

A simple classification of methods for the synthesis of ceramics is given in Figure 1. These methods fall into two broad categories: powder processing and molecular processing.

In powder processing, particles of very small size (about 1 micrometer in diameter) are packed into shapes and sintered at high temperature to produce dense structures. The method can be used to make monolithic objects such as cutting tools, or it can produce thick films for fabricating electronic components such as capacitors. (These films, ten to a few hundred micrometers in depth, are called thick in comparison to what are called thin films, of the order of a micrometer in depth.)

The molecular techniques are more recent. They differ from the powder approach in an important way and therefore pose new and interesting scientific problems. In the molecular approach, the compound is formed by deposition of its elements with gradual building up of a thin film a few to several thousand layers thick.

Figure 1. Techniques for processing ceramics, and some applications of the materials.



". . . their discovery has introduced a fundamental change in how ceramics will be made and used in the future."

The deposition is carried out at low temperatures so that the films will grow without large defects. This technology depends on a basic scientific understanding of the atomic steps that control the early growth—when the first layer of the new crystal is formed on a surface—and the subsequent growth.

Molecular processing is done in a variety of ways. In one method, metal atoms are evaporated under low oxygen pressure to grow oxide films; this is the technique that has been most often used to make highly oriented films of the high-temperature (high-T_c) superconductors. In another technique, gaseous precursors are reacted thermally or in a plasma to make a ceramic; a good example is the reaction of methane and hydrogen for the synthesis of diamond films. In other cases, liquid precursors are used. Wet-chemistry techniques are also powerful and simple methods for constructing molecular arrangements. One feature common to nearly all molecular methods is that the substrates on which the ceramic is deposited are held at relatively low temperatures, making it possible to design and make metastable structures that can have interesting new properties.

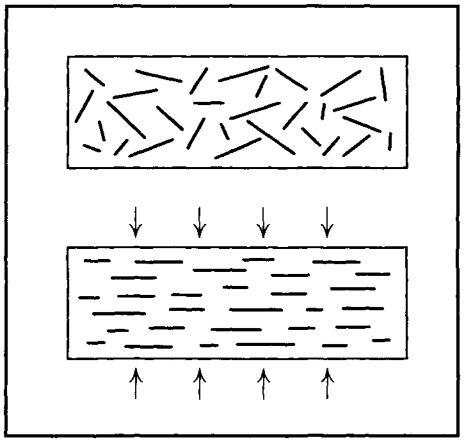


Figure 2. Making highly oriented ceramic superconductors: a uniaxial force applied during processing aligns the crystallites.

Molecular techniques can also be used to synthesize crystallographically oriented thin films, or to prepare films that are polycrystalline but have a grain size on the scale of a few nanometers (a nanometer is 10^{-9} meter). Such nanograin materials may have interesting properties of their own, and they could also serve as precursors for the preparation of textured films by thermal annealing, as discussed below.

The major aim of our research on the processing of ceramic superconductors is to fabricate materials that are highly textured—that is, materials that have highly oriented crystalline or crystal-like structure. This approach has resulted in significant improvement in materials made from powder, and it is now being applied to thin-film technology.

POWDER PROCESSING FOR CERAMIC SUPERCONDUCTORS

In powder processing of yttrium barium cuprate superconductors, the small particles are packed and "sintered" at a temperature of 900 to 1,000 C to densify the material.

Two variations of the method are *free sintering* and a technique we call *sinter-forging*. In free sintering the contact forces between the particles provide the driving force for densification. In sinter-forging a uniaxial force is used to increase the densification rate and—more importantly—to induce crystallographic texture. As illustrated in Figure 2, randomly oriented crystals can be aligned by the application of a uniaxial force; the thermodynamic driving force for the alignment is derived from the

Figure 3

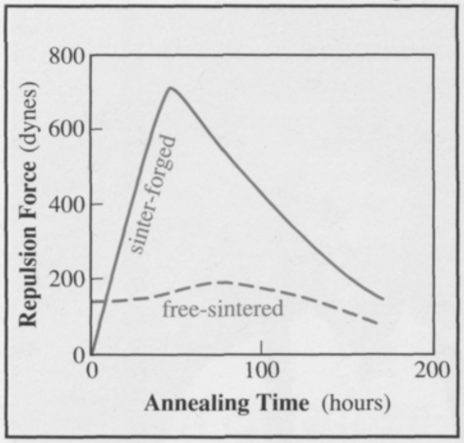


Figure 3. Levitation force in yttrium barium cuprate superconducting material as a function of annealing time in pressurized oxygen. Although a free-sintered specimen shows the greater levitating force before annealing begins, the optimum effect (corresponding to optimum orthorhombic texture) is obtained with a sinter-forged specimen after about fifty hours.

Oxygen pressure was 3 MPa, annealing temperature was 635 K, and the distance between superconductor and magnet was 1 mm.

Figure 4

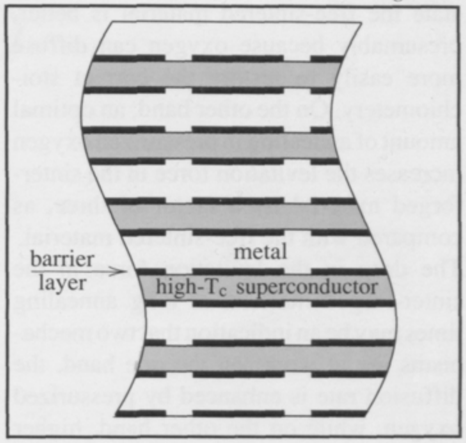


Figure 4. A multilayer high-temperature superconductor ribbon structure that might be used for large-scale electrical transmission.

Figure 5

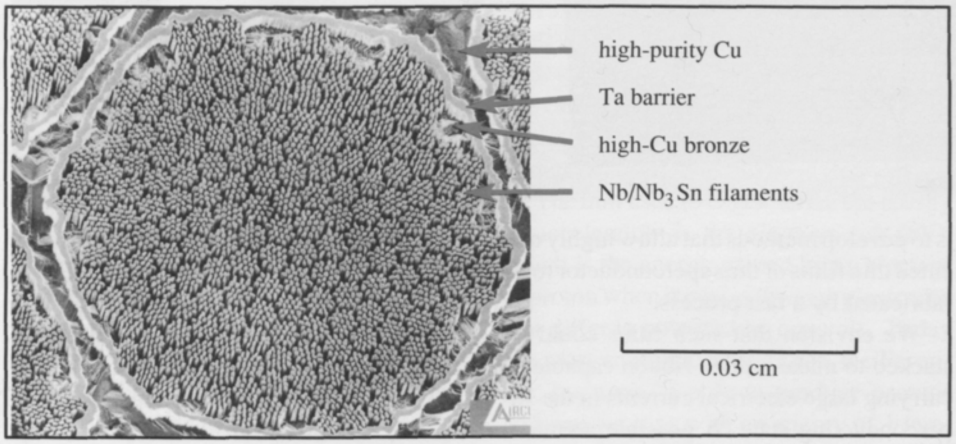


Figure 5. Photograph of the cross section of a multifilamentary superconducting composite. This was originally from a 1980 Ph.D. thesis by R. W. Hoard at the University of Washington.

higher mechanical compliance of the aligned as compared to the unaligned arrangement.

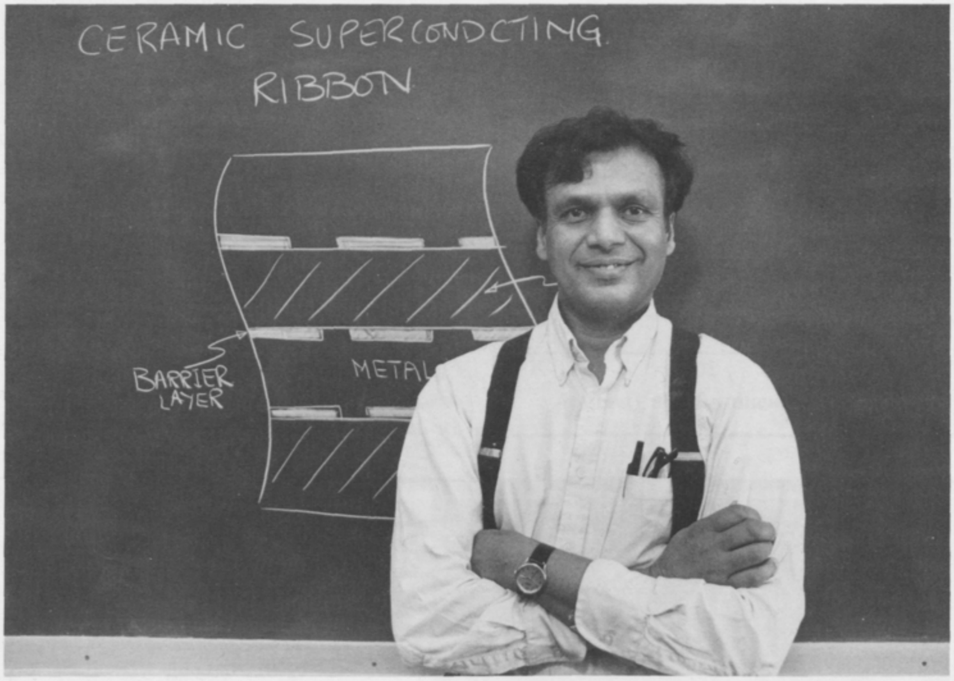
For at least one application—processing of material for the superconducting magnetic bearing that is discussed by Francis C. Moon elsewhere in this issue—we have found sinter-forging to be the better method. Figure 3 shows that sinter-forged specimens were able to produce more levitation force.

Two factors are especially important in establishing superconducting properties: the crystallographic structure (only the orthorhombic phase, which exists in equilibrium below about 750 C, appears to be superconducting) and the oxygen stoichiometry (a slightly deficient oxygen chemistry appears to be required).

Maintaining these necessary properties is difficult because of the high temperature needed for processing the material. One problem is that the tetragonal-to-orthorhombic transformation, which occurs during cool-down, is accompanied by a volume change that can produce microcracks. Optimizing the oxygen stoichiometry is also made more difficult by the high processing temperature; we must take into account the oxygen pressure in the atmosphere and the effect of temperature and structure on the diffusivity of oxygen.

The oxygen stoichiometry is affected differently in the two processing methods. Free sintering yields an incompletely densified and porous material; as a result of the porosity, oxygen can diffuse rapidly to restore the correct stoichiometry while the specimen is slowly cooled from the sintering temperature. In contrast, sinter-forged material is consolidated to full density, and oxygen diffusion occurs less easily; in order to obtain the required oxygen stoichiometery, the material must be annealed in pressurized oxygen at a temperature below 750 C, as required for the orthorhombic transformation.

Figure 3, which shows how annealing in pressurized oxygen changes the levitation force of the superconductor material, also compares the behavior of free-sintered and sinter-forged specimens. In the unannealed state the free-sintered material is better, presumably because oxygen can diffuse more easily to restore the correct stoichiometery. On the other hand, an optimal amount of annealing in pressurized oxygen increases the levitation force in the sinter-forged material by a factor of three, as compared with the free-sintered material. The drop in the levitation force in the sinter-forged material at long annealing times may be an indication that two mechanisms are at work: on the one hand, the diffusion rate is enhanced by pressurized oxygen, while on the other hand, higher pressure can produce oxygen concentrations that are greater than the optimum values. The best properties, therefore, are obtained by optimizing the time, temperature, and oxygen pressure.



CAN THIN FILMS BE PRACTICAL FOR POWER TRANSMISSION?

The best ceramic superconductors have been fabricated by *reactive vapor deposition* or by *laser ablation* (see the article in this issue by Robert A. Buhrman). Although these two techniques are different, they embody the same approach, which is to deposit the crystal one atom layer at a time on a substrate that can serve as a template for the growth of a single-crystal superconductor with its c-axis normal to the plane of the substrate.

The deposition rate has to be optimized so that the stoichiometry of the crystal is correct and so that there is enough time between successive monolayer depositions to allow the atoms to arrange themselves into a single-crystal order. Accordingly, these methods are slow. The possible deposition rate is about one monolayer per second, and this translates into about 0.1–1.0 micrometer of deposited material per hour. The objective of our research on thin films is to develop methods that allow highly oriented thin films of the superconductor to be fabricated by a fast process.

We envision that such films could be stacked to make a thick ribbon capable of carrying large electrical currents in the superconducting state. A possible architecture of such a ribbon is illustrated in Figure 4. Thin films of the superconductor and a metal (most probably silver) are stacked alternately, with a barrier layer (such as magnesium oxide) in between to provide long-term stability. This scheme may be compared with the design of current superconductors, in which filaments of superconductive niobium-tin alloys are embedded in copper alloys for mechanical stability (see Figure 5).

In Japan considerable headway has been made in fabricating high-quality wires made of ceramic superconductors sheathed in silver; the Japanese are now the leaders in the development of superconductive-wire technology. As we proceed in our research, we must remain cognizant that developments in Japan may overtake those in our laboratory, but we believe that our multilayer ribbon structure has a good chance for realization.

Rishi Raj is a professor of materials science and engineering at Cornell.

He received a B.S. degree in pure science from Allahbad University in India and subsequently a B.Sc. in electrical engineering from Durham University in England. He received a Ph.D. in materials science from Harvard University in 1970.

He joined the Cornell faculty in 1975 after teaching at the University of Colorado. He has also had several years of industrial experience. He has been a Guggenheim fellow and a senior visiting fellow at Cambridge University.

SUPERCONDUCTORS AND ACCELERATORS

by Hasan Padamsee

Superconductivity is at the heart of new accelerator technology needed in the search for a deeper understanding of the fundamental nature of matter and the forces of the universe.

An outstanding example is the Superconducting Super Collider (SSC) now under construction near Dallas, Texas. More than ten thousand superconducting magnets will be used in the SSC to guide beams of protons as they accelerate in their circular orbits and collide to produce the highest energy levels ever achieved artificially. These beams will be able to probe subnuclear structure on a scale of less than a trillionth of a millimeter.

A parallel quest is for accelerators that use high-energy electrons to probe the nature of matter. Here the need is for a technology that will improve the performance of electron-ring accelerators. This is the technology of *microwave cavities*, a field in which Cornell's Floyd R. Newman Laboratory of Nuclear Studies is doing pioneering research. I will mainly discuss this work on microwave cavities, and also our research on *high-temperature superconductors* (those that function above the temperature of liquid helium).

SUPERCONDUCTING MAGNETS FOR PURE AND APPLIED SCIENCE

In developing new accelerator technology, the object is to push beyond the current energy frontier to create particles of even higher energy.

The unit used to characterize the energy of accelerators is the *electron volt* (eV), which is the energy gained by an electron or proton when it passes through electrodes that differ in potential by one volt. Today the most energetic accelerator, the Fermilab Tevatron, is able to produce protons and anti-protons with an energy of 1 teraelectron volt (TeV), which equals one trillion, or 10^{12}, electron volts. A comparison with electron microscopy gives an idea of the precision of a TeV beam: an electron microscope with a 10^4 eV energy beam is capable of resolving structures such as viruses with micrometer (10^{-6} meter) precision, whereas a proton beam with an energy of 1 TeV can probe into the subnuclear structure of matter at the scale of 10^{-14} meter, 100 million times smaller than the electron-microscope scale. The Superconducting Super Collider, which will be the world's most powerful accelerator, was designed on the basis of the success of the superconducting magnets of the Tevatron. The SSC, with a circumference of 90 kilometers, will produce colliding proton beams at an energy of 20 TeV.

Although the development of superconducting magnets has been driven largely by the purely scientific need for high-energy accelerators, there are also practical spinoffs. Superconducting magnets for Magnetic Resonance Imaging (MRI) machines are available in many hospitals, where they are used for whole-body imaging, detection of tumors, and medical research.

Other applications, although not as common as MRI is today, could prove vital to our energy and transportation industries. Superconducting generators offer outstanding technical and economic advantages over conventional machines. At various places around the world, eighteen feasibility-demonstration models of superconducting generators have been built and successfully tested. The feasibility of using superconducting magnets in land and ship transportation systems has also been demonstrated; for example, a Japanese magnetically levitated test vehicle has attained a speed of 500 kilometers an hour over a

Figure 1

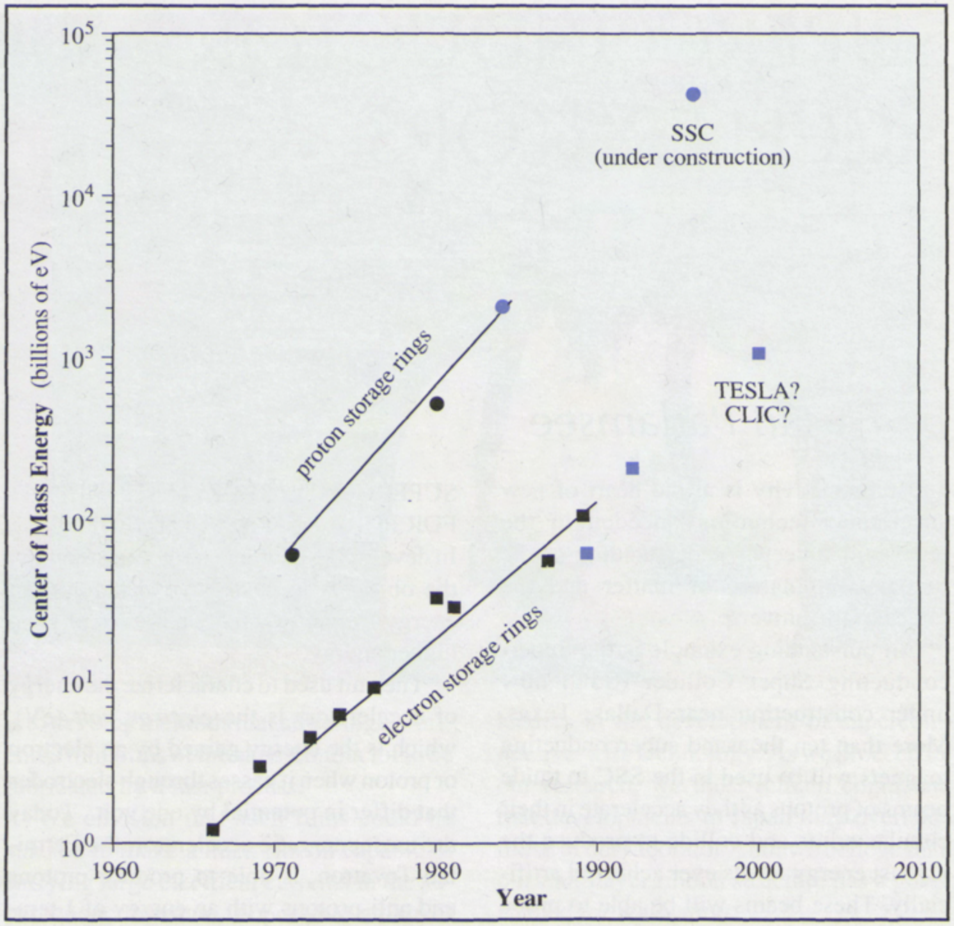


Figure 1. The Livingston Chart showing how energy attainable in proton and electron storage rings has increased by a factor of about ten every decade since 1960.

Accelerators indicated in color use superconducting technology to reach the top of the energy scale. A line is drawn through existing machines. By the turn of the century, the Superconducting Super Collider (SSC) will use over 160 kilometers of superconducting magnets to collide protons. Among the electron machines, 50 meters of superconducting cavities were installed in 1989; by 1992, plans call for over 650 meters of superconducting cavities. Advances in superconducting-cavity technology could make it the basis of a 1-TeV electron-positron collider (TESLA? CLIC?) to keep pace with the proton line. For a machine like TESLA, 30 kilometers of superconducting cavities would be required.

Nuclear physics machines are not included in this high-energy-physics picture. Presently, these machines use 50 meters of superconducting cavities, and the quantity is expected to increase to more than 300 meters by the year 2000.

seven-kilometer test track. Magnetic fusion, which is the leading candidate technology for controlled thermonuclear power, is practicable only with superconducting magnets.

THE USE OF SUPERCONDUCTORS FOR MICROWAVE CAVITIES

In all particle accelerators, a key component is the device that provides the accelerating kick. The simplest such device would be an insulated tube with a high voltage across the ends, as in electrostatic accelerators, but severe difficulties arise as the voltage approaches a million volts. High voltages produce corona discharges and lightning-like sparks outside the accelerator, and these dissipate the potential needed to accelerate the particles.

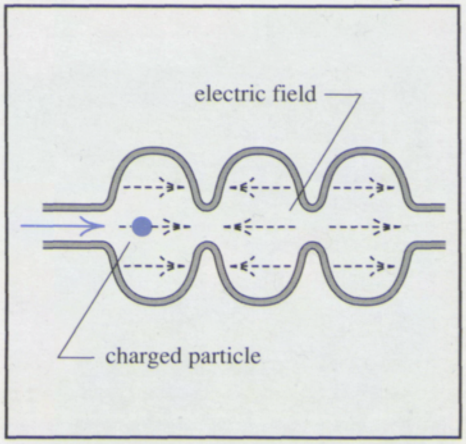
In 1928 Rolf Wideroe in Germany showed how to use alternating high voltages for acceleration. The basic idea is that by means of induction, one can accelerate particles without needing equivalently high static voltages. The changing flux linked by the particle beam induces an electric field parallel to the trajectory of the charged particles. Microwave frequencies are used, and a cylindrical metal pipe serves as a waveguide for the accelerating field. The phase velocity of the accelerating wave in the guide is slowed down by shaping the pipe into a long chain of coupled resonant cavities (Figure 2), so that the particle rides, like a surfer, always on the crest of the wave. The microwaves are produced by large high-frequency vacuum-tube amplifiers called klystrons.

Most existing accelerators are operated with normal-conducting cavities made of copper. These provide energy gains of 1 to 2 million volts per meter, consuming close

Figure 2. A chain of alternating resonant cavities for accelerating particles.

The cavities resonate in a mode such that there is a strong electric field on axis. At any instant, the field vectors in adjacent cells of the chain point in opposite directions. A charged particle traveling at nearly the speed of light takes one period to travel across one cell. In the next cycle the electric field in the adjacent cell reverses, so the particles continue to see an electric field in the same direction and continue to accelerate.

Figure 2



to half a megawatt of radio-frequency (RF) power. But since the losses increase as the square of the accelerator voltage, so does the demand for electricity. As researchers call for higher energies, the cost entailed by copper cavities becomes exorbitant.

Here superconductivity comes to the rescue. The microwave surface resistance of a good superconductor is five orders of magnitude lower than that of copper. After allowing for the refrigerator power that must be provided to maintain liquid-helium operating temperature, the use of a superconductor instead of copper results in a very attractive net-gain factor of several hundred.

Whereas superconducting magnets economically provide the strong magnetic fields to guide high-energy protons in "small" circular orbits, superconducting RF cavities provide the high voltages needed over "short" lengths. Electron-ring accelerators, in particular, need very high voltages. This is because electrons moving in circular orbits lose energy rapidly via synchrotron radiation—an effect that is greater for electrons than for protons because of their lower mass. Losses due to synchrotron radiation increase as the fourth power of energy, and so to increase the energy of existing electron-ring accelerators, superconducting cavity systems providing voltages of several hundred million to a billion volts are needed. Niobium cavities provide accelerating voltages of 5–10 million volts per meter.

DEVELOPING SUPERCONDUCTING MICROWAVE CAVITIES

The phenomenon usually associated with superconductivity is that DC currents flow without dissipation when a superconducting material is cooled below its *transition temperature*, T_c. The currents are carried by *Cooper pairs*, which are condensates of charge carriers and have the property that they can move through the material without friction. Only at T = 0 K are all the charge carriers condensed into Cooper pairs. At higher temperatures, some carriers are unpaired; the fraction of unpaired carriers increases exponentially with T until none of the carriers are paired above T_c.

In this somewhat simplified picture, known as the *two-fluid model*, when a DC field is turned on, the pairs carry all the current, shielding the applied field from the normal (unpaired) electrons. Hence, the electrical resistance vanishes completely. When the current is alternating, however,

". . . to increase the energy of existing electron-ring accelerators, superconducting cavity systems providing voltages of several hundred million to a billion volts are needed."

Figure 3

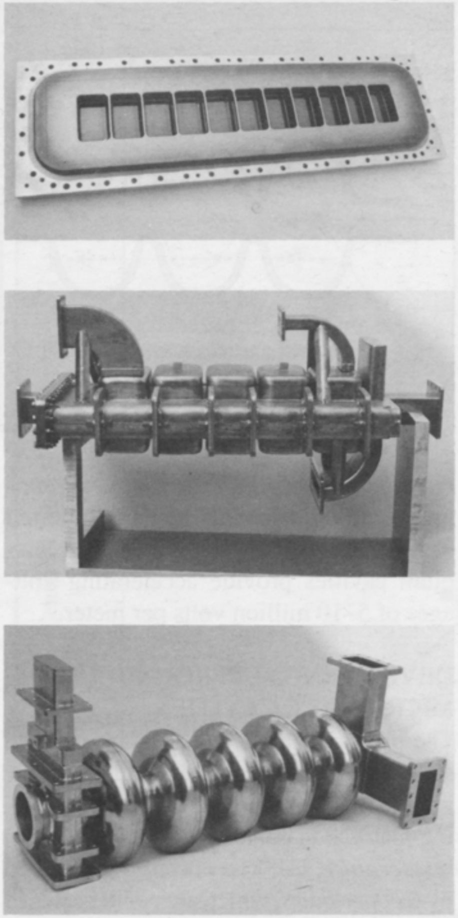


Figure 3. Superconducting cavities developed at Cornell's Laboratory of Nuclear Studies.

Top: One-half of a superconducting cavity machined out of solid niobium. This was tested in 1974 in the 12-GeV electronic synchrotron at Cornell. The cell chain is six centimeters long.

Middle: A half-meter section of the "muffin tin" superconducting cavity developed for high-current storage rings. Prototypes tested in the Cornell Electron Storage Ring (CESR) in 1982 were the first superconducting cavities ever used in high-energy, high-current electron storage rings. Waveguides protruding from the cavity bring in power from the klystron to the beam and remove beam-induced power in nonaccelerating modes to room-temperature absorbers.

Bottom: Second-generation superconducting cavity for high-current electron storage rings. Prototypes were tested in CESR in 1984 to achieve world-record performance. The section is a half-meter long. Three hundred sixty identical cavities are in production for CEBAF, an accelerator for nuclear physics under construction in Virginia.

there is some resistance, even at temperatures below T_c. The cause is readily seen in terms of the two-fluid model: While Cooper pairs can move frictionlessly, they do have inertial mass, which means that for alternating currents to flow, forces must be applied to bring about the alternating directions of flow. Hence, electric fields are present in the skin layer and they continually accelerate and decelerate the normal electrons in the layer, leading to a finite resistance. Nevertheless, a high T_c is an advantage for a material to be used for microwave cavities.

The most popular superconductor for accelerator cavities is niobium; it has the highest T_c of all the pure elements and is the most amenable to obtaining high quality and uniformity over the square meters of accelerator-cavity surfaces. The *Q* value of a niobium cavity at 2 K is typically several times 10^9 for a resonant frequency of 1.5×10^9 hertz. This means that the stored energy in the cavity takes a billion cycles to decay by a factor of 1/e! Such high-*Q* resonators have other applications besides accelerators—for example, in ultra-stable oscillators.

CORNELL RESEARCH ON SUPERCONDUCTING RF CAVITIES

Our Superconducting Radio Frequency Program at the Laboratory of Nuclear Studies is geared toward designing, building, and testing superconducting cavities for accelerators. We also pursue basic research to understand the present limitations in the high-field performance of superconducting RF cavities and to develop new techniques to reach ever higher voltages.

The first test of a superconducting cavity in a high-energy accelerator was conducted in 1974 in the Cornell 10-GeV Electron Synchrotron. This pioneering experiment showed that superconductivity is robust in the harsh environment of a high-energy accelerator, particularly in the presence of synchrotron radiation and high-energy electrons that stray from the main beam carrying hundreds of microamps of current.

Superconducting cavities for storage-ring colliders followed as the next target application. In a collider, all the energy of the particles in two counter-rotating beams is available for interesting reactions at collision; this is in contrast to a fixed-target synchrotron, in which more than half the beam energy is lost to the kinetic energy of the particles after collision. But to obtain interesting reaction rates in the absence of dense targets, the beam currents are increased by a factor of 1,000, to many tens of milliamps, and stored for long times.

This imposes new demands on superconducting cavities: they must provide 100 kilowatts of RF power to the beam through the delicate cryogenic environment, without losing more than a few watts to the liquid helium. (One watt evaporates a liter of precious liquid helium per hour.) The repetitive passage of intense beam bunches through the cavity present another chal-

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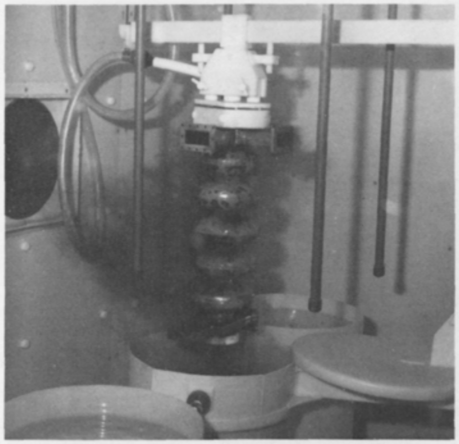

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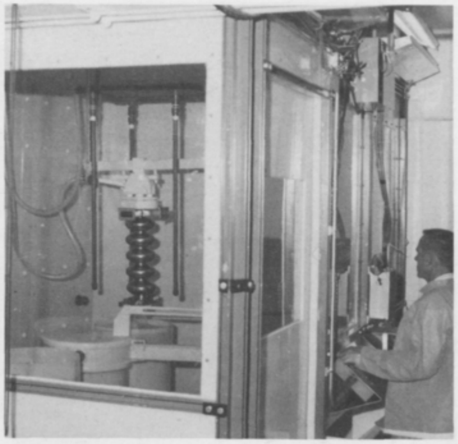

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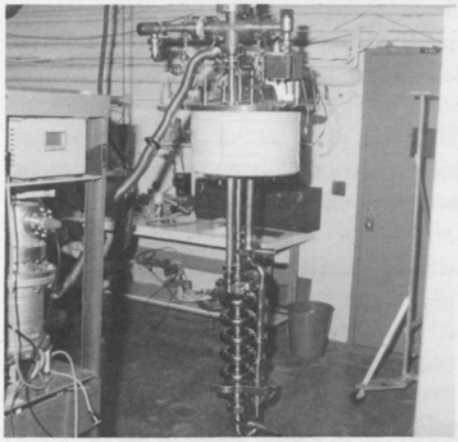


4

Steps in the preparation of superconducting cavities are illustrated in the photographs. The work is all done in the Laboratory of Nuclear Physics.

(1) A cavity has just been withdrawn from the acid etch bath and is being moved to an adjacent water tank. The acid dip removes a surface-damage layer 50 micrometers thick.

(2) The RF surface must be kept free of any superficial contaminants. Here technician Ralph Lobdell is operating the remote-handling chemical-treatment equipment.

(3) Each cavity is tested in the laboratory before being installed in the accelerator. For the lab test, the cavity is suspended from a vacuum pipe and immersed in a vertical Dewar for cooling to 2 K with liquid helium under subatmospheric pressure.

(4) After laboratory testing, the cavities are taken to a dust-free room and assembled into a horizontal cryostat for accelerator operation. Dust contamination is known to limit the performance. Here technician Skeeter Heidt is completing a vacuum joint.

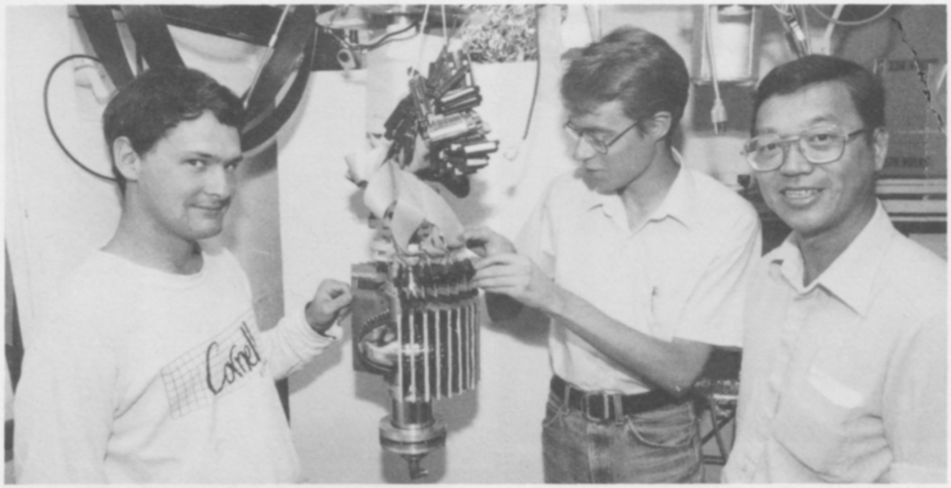
lenge arising from the shock excitation of nonaccelerating higher modes of the resonant cavity. To properly damp these modes without damping the accelerating mode, as well as to meet the high power demands, special devices called high-power couplers were invented and engineered. In 1982 the first test of a superconducting cavity system in a high-current storage ring was successfully carried out in the Cornell Electron Storage Ring (CESR).

A second-generation, improved design was developed, and in 1984 it was tested in CESR with impressive results. A world-record accelerating field of 6.5 million volts per meter was achieved, and a beam current was accelerated to a record level of more than 20 milliamps. The milestone test heralded the maturity of superconducting cavity technology for particle accelerators.

At the same time, plans for the world's most powerful nuclear physics research machine, the Continuous Electron Beam Accelerator Facility (CEBAF) were switched from normal-conducting to superconducting technology. The Cornell cavity and technology were adopted as the basis for this machine, and 180 cavities are presently under construction by industry. The facility is being built in Virginia.

DEVELOPING TECHNOLOGY FOR FUTURE ACCELERATORS

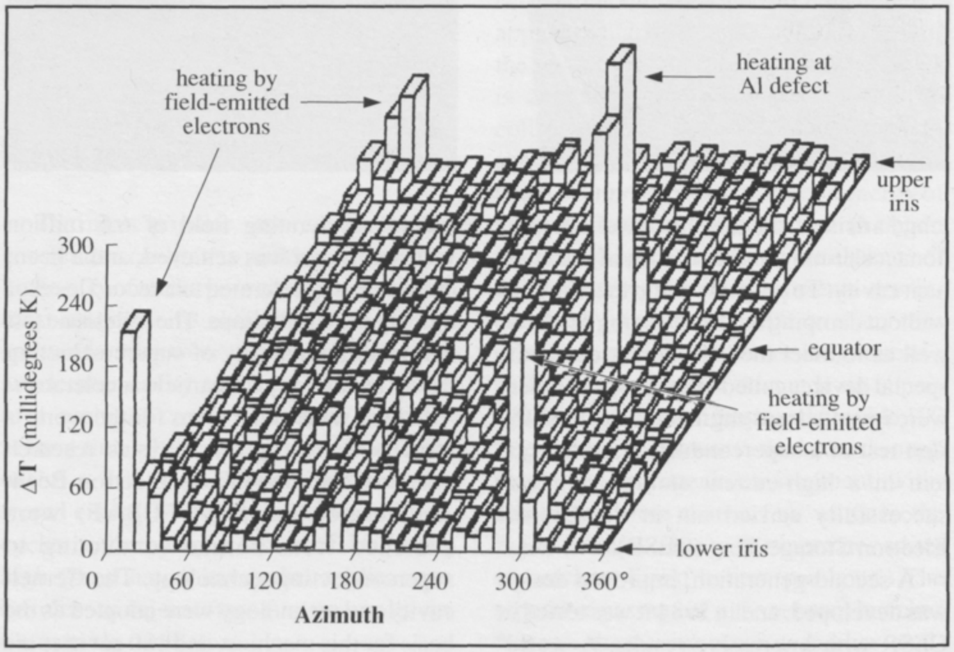
At the Laboratory of Nuclear Studies we are continuing to develop superconducting RF technology and cavity structures for future accelerators. These include superconducting cavities to be used in an advanced storage ring (called the B-factory) with a beam current that is higher by yet another factor of 100—in the range of several amperes.



Above: Preparing to cold-test a cavity are Keith Gendreau '89, then an undergraduate; Walter Hartung, a graduate student; and Q. S. Shu, a research associate. Surrounding the test cavity are thirty-six boards with nineteen low-temperature thermometers each. All 684 sensors are scanned within 15 seconds to give a temperature map (Figure 4).

Figure 4. A typical temperature map obtained in tests of a cavity. Heating in various regions of the cavity is caused by defects or impact from field-emitted electrons. Careful studies of such loss mechanisms are being conducted in the Cornell research program.

Figure 4



To resolve the unsettled questions raised by our present view of the fundamental nature of matter, it is anticipated that by the turn of the century, an electron accelerator with 1 TeV of energy will be required as a sister machine to the SSC proton collider now under construction in Texas. As is the case with the SSC, building such a large machine will entail a national or international collaborative effort.

To play a role in this grand venture, superconducting cavities will need to provide accelerating gradients of more than 30 million electron volts (MeV) per meter, as compared to the present capabilities of 5 to 10 MeV per meter. Our basic research on superconducting cavities is largely directed toward reaching this goal.

In principle, the fundamental limit to the accelerating field of niobium is about 50 MeV per meter, set by the critical magnetic field H_c, above which superconductivity is destroyed. In practice, many mechanisms keep the achieved accelerating field below the theoretical value. One of these mechanisms is the premature breakdown of superconductivity at local defects. If, because of excess heating at a surface imperfection, the temperature of any part of the

"The Cornell cavity and technology were adopted as the basis for [the world's most powerful nuclear physics research machine]. . . ."

current-carrying surface exceeds T_c, superconductivity is "quenched" and the energy stored in the cavity is completely dissipated as the normal-conducting region that has been created grows rapidly. For a long time, this form of breakdown was a major limitation to the reliable achievement of field levels above 3 MeV per meter.

Research on basic RF superconductivity at the Laboratory of Nuclear Studies spearheaded the effort to overcome this problem. The key was to improve the thermal conductivity of the niobium cavity wall by reducing the oxygen impurity to levels below 10 parts per million. With the help of the Materials Science Center in Bard Hall, we purified small test cavities by means of induction heating to 2,000 C in ultrahigh vacuum, and were able to prove the benefits of increased niobium purity.

With advice and encouragement from the Cornell laboratory, several commercial producers proceeded to raise the purity of niobium by a factor of 10 by improving the vacuum and melt conditions in their electron-beam melting furnaces. More than 30 tons have been purified, and more than 50 meters of high-purity niobium superconducting cavities have been industrially fabricated for particle acclerators around the world. The average accelerating gradient in acceptance tests for high-purity niobium cavities was 9 MeV per meter.

To reach the highest accelerating fields, the cleanest possible surface is required. This is obtained by heating cavities at 1,400 C in a vacuum of better than 10^{-7} torr. Here James Sears, a research support specialist, is dressed in clean-room gear to lower test cavities into the furnace. The dust particle count in the clean room is a factor of a million lower than in ordinary air.

Another field-limiting mechanism under investigation is related to the high surface electric fields terminating on the walls. (This is analogous to the earlier problem of supporting high DC voltages in electrostatic accelerators.) Electrons drawn by field emission from the wall are accelerated in the cavity and deposit their energy into the liquid helium as they impact the cavity wall. New treatments that will provide surfaces free of field-emission sites are under development; the procedure is to heat-treat finished niobium cavities in ultrahigh vacuum and subsequently handle them in dust-free environments. The best test cells so far have reached accelerating fields of 30 MeV per meter, the desired level for a future TeV collider structure.

RESEARCH WITH THE NEW HIGH-T_c SUPERCONDUCTORS

Ever since the discovery of superconductivity in 1911, raising the critical temperature of superconductors has been one of the important problems in physics. In 1986 the

Figure 5

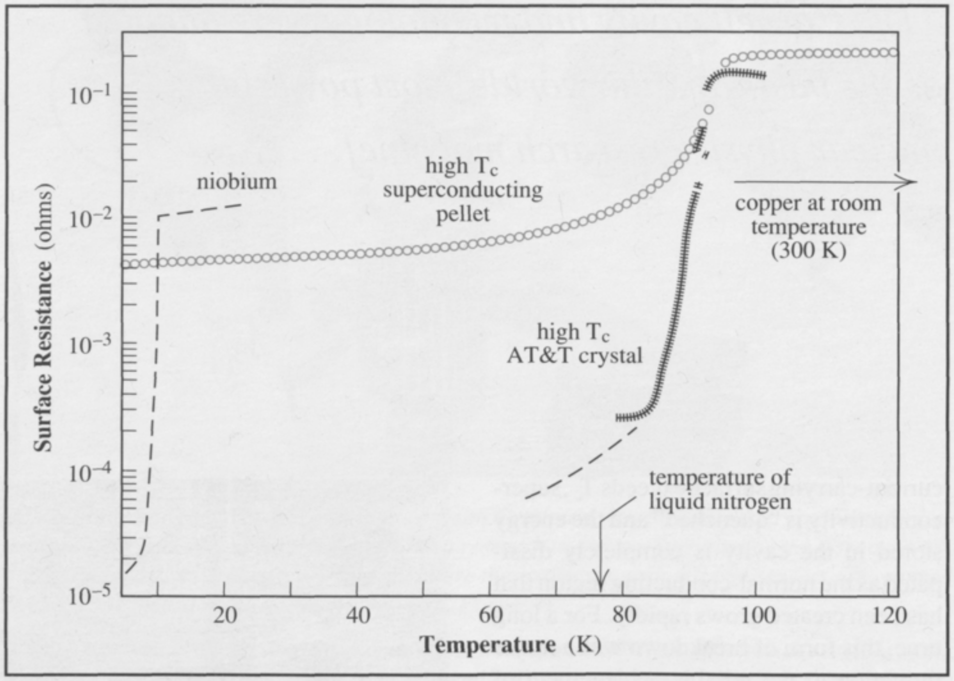


Figure 5. Microwave properties of high-temperature superconductors. The new superconductors are compared with copper and niobium in terms of surface resistance at 6 x 10^9 hertz.

The first available forms of high-temperature superconductive material were ceramic pellets that were only slightly better than room-temperature copper. High-quality crystals obtained from collaborators at AT&T were a factor of 100 lower in resistance than room-temperature copper, but not as low as niobium.

new oxide superconductors provided the long-desired breakthrough. The new materials have opened new vistas of possible applications, but there is a long road to the development of useful devices.

The Laboratory of Nuclear Studies, together with other Cornell units and our collaborators at AT&T Bell Laboratories, BellCore, and General Electric, is evaluating the RF properties of new high-temperature superconductors with a view to improving our basic understanding and developing technically useful materials.

High-quality crystals from AT&T Bell Laboratories are the materials with the best RF properties measured to date, and thin films prepared at BellCore by laser ablation are beginning to show comparable properties. For these films, we have measured, at liquid-nitrogen temperature, surface resistance values that are a factor of 20 better than those for bulk polycrystalline ceramic high-temperature superconductors, and a factor of 10 better than those for copper. Such films are attractive for passive electronic applications such as interconnects. For accelerator cavities, the resistance is still a factor of 40 higher than for niobium at liquid-helium temperature.

The Superconducting Radio Frequency (SRF) program at Cornell's Floyd R. Newman Laboratory of Nuclear Studies (LNS) is funded principally by the National Science Foundation, with supplementary support from the U.S.–Japan Cooperative Agreement. Professor Karl Berkelman is the director of LNS.

The research program is accompanied by graduate education. Students have the opportunity to work in a variety of areas, including microwaves, ultahigh vacuum, high-temperature techniques, scanning electron microscopy, energy-dispersive X-ray analysis, cryogenics, superconductivity, electrodynamics, accelerator physics, and accelerator technology.

SRF program members who work with students include Professors Maury Tigner and David L. Rubin, Senior Research Associates Hasan Padamsee and Joseph L. Kirchgessner, and Research Associates David L. Moffat and Quan-Sheng Shu. Current graduate students are Joel Graber and Walter Hartung.

"The foremost goal is a deeper understanding of the fundamental nature of matter; sure to follow are still unknown and unimagined benefits to humankind."

SPINOFF FROM PARTICLE-PHYSICS RESEARCH

Research in superconductors for accelerators has many valuable applications. A very large number of accelerators are used for radioisotope production, cancer therapy, sterilization of biological materials, polymerization of plastics, industrial radiography, and synchrotron-radiation light sources.

These useful "dividends" are a part of those derived for the broad field of particle physics. The practical spinoffs that flow from studies of atoms, nuclei, and subnuclear particles have come to benefit people in immeasurable ways. We tend to take for granted the "electronic age", sometimes forgetting its beginning in the discovery of the electron by J. J. Thompson in 1879. In our present nuclear age, a substantial fraction of society's energy needs is met by nuclear power plants (although we have not yet come to grips with the problems of nuclear waste or of the possibility of global destruction from nuclear weapons; every advance in civilization is accompanied by deep human problems that must eventually be resolved).

Discoveries in elementary-particle research are significant also because they form the basic tools of other sciences. Neutron activation for trace-element analysis, muon spin rotation for precise magnetic field measurements in the new superconductors, and pion therapy for cancer tumors are but a few of the established applications of recently discovered particles.

The primary requirement for continued vitality in particle physics is the building of the sophisticated facilities needed to push against the present frontiers of knowledge and understanding. The foremost goal is a deeper understanding of the fundamental nature of matter; sure to follow are still unknown and unimagined benefits to humankind.

Hasan Padamsee is a senior research associate at Cornell's Newman Laboratory of Nuclear Studies, where he heads the Superconducting Radio Frequency Program.

Before coming to Cornell in 1973, he earned a B.S. degree at Brandeis University and a Ph.D. in solid-state experimental physics at Northeastern University. He has been a visiting physicist at CERN in Switzerland, and has served frequently on national review, advisory, and program committees.

SUPERCONDUCTORS FOR FASTER COMPUTERS

by J. Peter Krusius

Smaller computers that run seven times faster than current models may be possible with the use of superconducting interconnecting wire.

This dramatic improvement is indicated by a novel analytical method, called *package system simulation*, that has been developed in my laboratory and used to assess the potential benefits, for computer hardware, of the new superconducting materials now available. This work is part of a systematic study of how various emerging hardware technologies could be used to improve the performance of computers.

Since their conception, the performance of digital computers has increased by many orders of magnitude, but much of the improvement has been achieved by means of hardware that implements the classical von Neumann architecture. Only more recently have new functional architectures been explored, and these have been intended for special purposes such as vector and parallel processing. But while architectural enhancements are often specific to a given class of computing problems, the hardware advances can usually be exploited in all computers. The goal of our research program is to explore the possibilities.

THE PHYSICAL STRUCTURE OF HIGH-SPEED COMPUTERS

The structure of a typical high-speed computer is shown in Figure 1. An array of silicon *integrated-circuit (IC) chips* is arranged in *multi-chip modules*, which in turn are positioned in a regular array on a *printed wiring board.* Typical sizes are of the order of millimeters for chips, centimeters for modules, and meters for boards. Anywhere from one to about one hundred chips can be placed into each module, and a similar number of modules can be mounted on the wiring board.

These parts are connected by means of networks of metallic *interconnect wires*. In a chip, the network of wires is arranged in planes separated by insulating material, and small *vias* filled with metal allow the wires in different layers to be connected (Figure 2). The same kind of interconnect structure is used in the modules to distribute signals among chips, and also on the board to connect the modules. With this kind of interconnect structure, each circuit can be made to communicate with any other circuit in the computer, whether it is on the same chip or on a different chip on another module.

WHY SUPERCONDUCTORS MAKE BETTER INTERCONNECT WIRES

Of the many interesting properties of superconductive materials, the most important for our purposes is the vanishing electrical resistance.

For zero resistance, certain conditions must be met: the temperature must be below a critical temperature T_c, and frequency must be well below the threshold for excitation across the superconductive gap. These conditions can be met in computer hardware in which the interconnects are made of the new high-T_c materials. The requirements are that the hardware must be maintained at liquid-nitrogen temperature (around 77 K) and frequencies must be well below 500 megahertz.

Consider a high-speed computer of the type in Figure 1, with all the normal-metal interconnects replaced with superconducting material. Two benefits accrue from the vanishing resistance.

The first, a trivial direct consequence of zero resistance, is that interconnect lines carrying the signals can be charged faster to full voltage values, and there is less attenuation of signal pulses. Thus, we expect the computer to run faster.

Figure 1

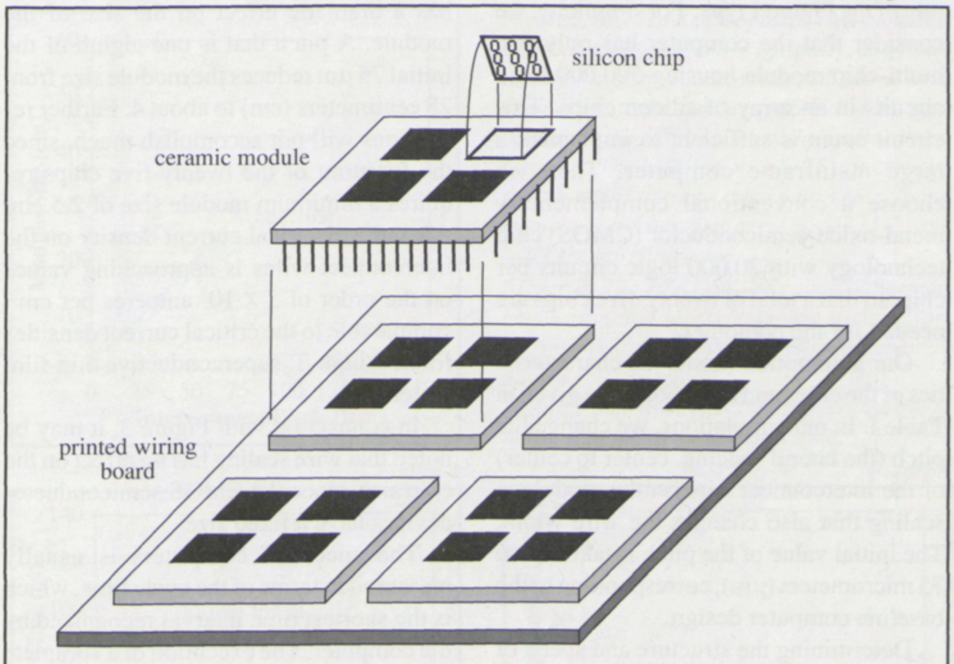


Figure 2

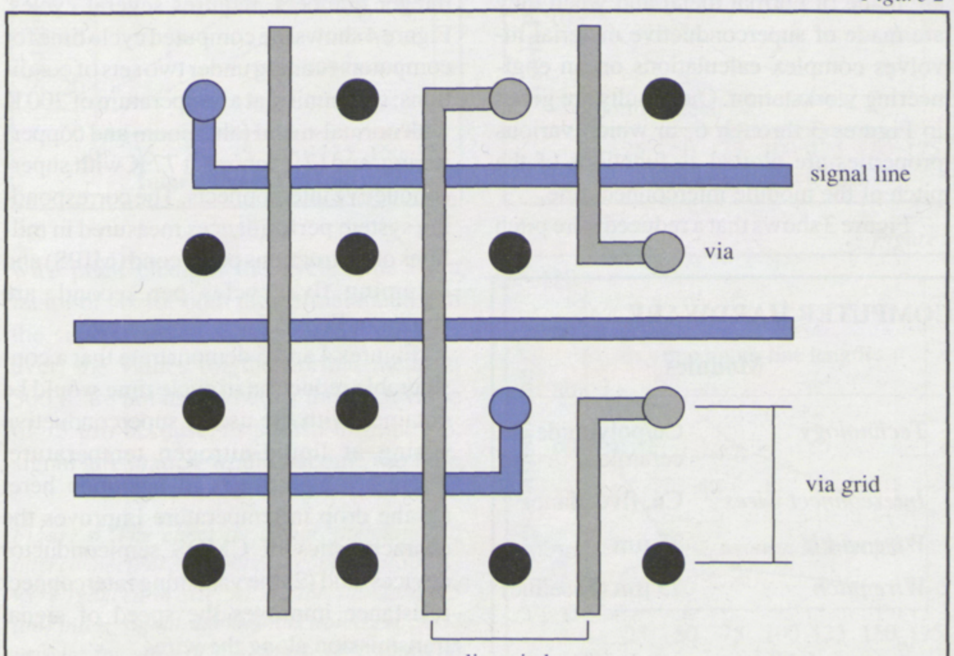


Figure 1. The structure of a typical high-speed computer.

An array of silicon integrated-circuit chips (each about 5–10 mm across) makes up a multi-chip module (about 5–10 cm on a side), and an array of modules is placed on a printed wiring board (typically 0.1–1.0 meter on a side).

The chips are attached to the modules by means of an array of small solder bumps with a pitch as small as 1/4 mm. The modules are connected to the board by means of an array of pins with a pitch on the order of 1.25 mm.

Figure 2. The planar interconnect structure of a chip. Only two levels of wires are shown (in gray and in color). The network of wires is arranged in planes separated from each other by a sheet of insulating material. In each layer the orientation of the wires is at right angles to the orientation in the adjacent layers.

Wires in different layers can be connected through small metal-filled vias *that extend through the insulator sheets. Vias are usually placed on a rectangular grid; wires generally run in orthogonal directions in adjacent planes.*

Typical choices for the wire metal and the interlayer insulator are: aluminum and silicon dioxide on the chip, tungsten and aluminum oxide on the module, and copper and glass-epoxy on the board.

Such a planar multi-layer method for interconnecting circuits is characterized by the width of the wires, the pitch of the wires, the spacing of the via grid, and the number of wire planes.

The second benefit, also a consequence of the vanishing resistance, is that the cross section of the interconnect lines can be reduced significantly. The entire interconnect structure, from the chip to the board, must be redesigned. The best way to do this is to keep the wire spacing constant, reduce the width of the wires, and decrease the thickness of the interlayer insulator. With this strategy, the electrical noise coupling between the wires will be unaffected and the electrical impedance of the wires will remain constant.

This redesign is important because the interconnect structure influences, in a complicated fashion, the partitioning of the computer and therefore its overall size. Because the scaled interconnect can be made much denser, the computer will become smaller and faster.

SIMULATION TECHNOLOGY FOR ESTIMATING SPEEDUP

Using our package-system simulation technique, we can calculate the improvement in computer performance that would be achieved by substituting superconductive interconnects for metal ones. The following example demonstrates the method.

First we must choose a specific structure of the Figure 1 type. For simplicity, we consider that the computer has only one multi-chip module housing 500,000 logic circuits in an array of silicon chips. This circuit count is sufficient to implement a large mainframe computer. Then we choose a conventional complementary metal-oxide-semiconductor (CMOS) chip technology with 20,000 logic circuits per chip, so that a total of twenty-five chips are needed for the computer.

Our assumptions about the characteristics of the chips and the module are given in Table I. In our simulations, we change the pitch (the lateral spacing, center to center) of the interconnect wire on the module, a scaling that also changes the wire width. The initial value of the pitch is taken to be 75 micrometers (μm), corresponding to the baseline computer design.

Determining the structure and speed of the computer when the interconnect wires are made of normal metal and when they are made of superconductive material involves complex calculations on an engineering workstation. Our results are given in Figures 3 through 6, in which various properties are plotted as functions of the pitch of the module interconnect line.

Figure 3 shows that a reduced wire pitch has a dramatic effect on the size of the module. A pitch that is one-eighth of the initial 75 μm reduces the module size from 28 centimeters (cm) to about 4. Further reductions will not accomplish much, since the footprint of the twenty-five chips requires a minimum module size of 2.5 cm. Also, the electrical current density on the interconnect wires is approaching values on the order of 5×10^5 amperes per cm^2, comparable to the critical current densities for new high-T_c superconductive thin-film materials.

In connection with Figure 3, it may be noted that wire scaling has no effect on the chip size, since the CMOS semiconductor devices have a fixed size.

The speed of computers is usually measured in terms of the cycle time, which is the shortest time interval recognized by the computer. The execution of a complete instruction, such as the addition of two integer numbers, requires several cycles. Figure 4 shows the computed cycle time for computers running under two sets of conditions: (1) running at a temperature of 300 K with normal-metal (aluminum and copper) wiring, and (2) running at 77 K with superconductive interconnects. The corresponding system performances measured in millions of instructions per second (MIPS) and assuming five cycles per second, are shown in Figure 5.

Figures 4 and 5 demonstrate that a considerable reduction in cycle time would be obtained with the use of superconductive wiring at liquid-nitrogen temperature. There are two effects in operation here: (1) the drop in temperature improves the characteristics of CMOS semiconductor devices, and (2) the vanishing interconnect resistance improves the speed of signal transmission along the wires.

We see in Figure 4 that the scaling of the

Table I. **PARAMETERS FOR COMPUTER HARDWARE**

Chips		**Modules**	
Technology	1.5 μm CMOS	*Technology*	Cu/polyimide on ceramic
Circuits	20,000	*Interconnect wires*	Cu, five planes
Input/output leads	378	*Wire width*	25 μm
Interconnect wires	Al, two planes	*Wire pitch*	75 μm (baseline)
Wire width	1.5 μm		
Wire pitch	4.0 μm		

Figure 3

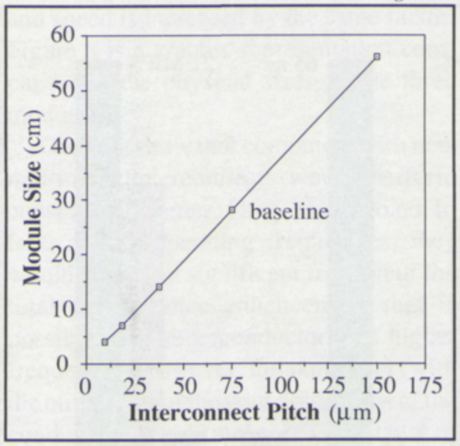


Figure 3. Size reduction of multi-chip modules, and therefore of the entire computer, as a function of the wiring size. Values obtained by a simulation technique are plotted. The wire parameter used is the pitch of the module interconnects. The baseline pitch is 75 μm, the current standard size. The other points correspond to module pitches that are 1/8, 1/4, 1/2, and twice the baseline value.

Figure 4. The effect on cycle time of normal-conducting and superconductive wiring. Normal metals are aluminum in chips and copper in modules.

Figure 5. The same effect measured in terms of millions of instructions per second.

Figure 4

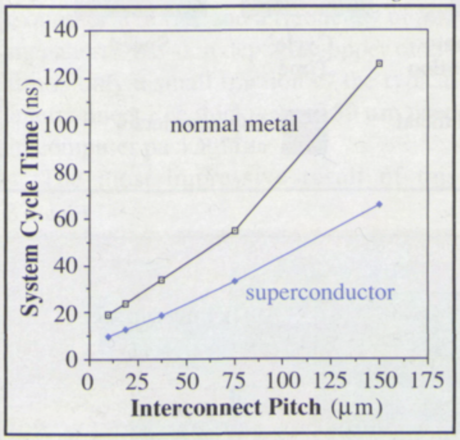
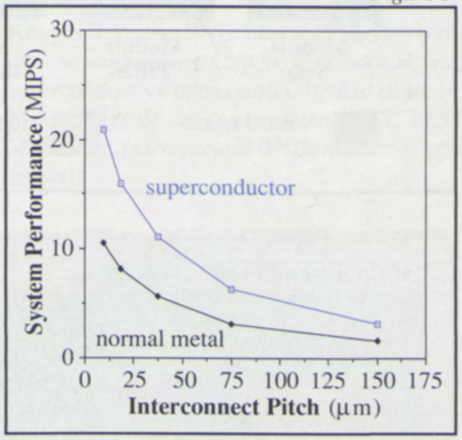


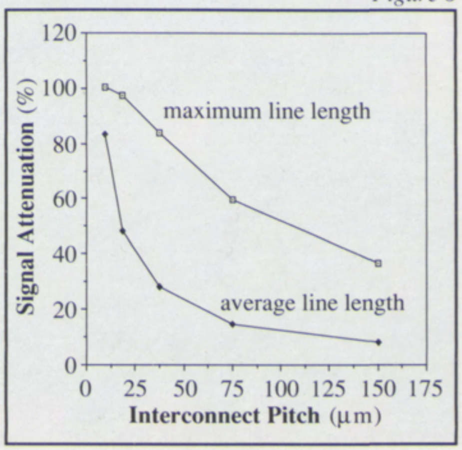
Figure 5



wire pitch changes the cycle time by a factor of six for both the normal metal and the superconductive interconnects. However, the values for the normal metal at 300 K are not useful below the pitch value of 75 μm because, as shown in Figure 6, signal attenuation would become too high

Figure 6. The effect on signal attenuation if interconnects of aluminum or copper (at 300 K) were reduced in size. At 1/2 the standard (75 μm) pitch, signal attenuation would reach 82 percent for wire of average length, and 100 percent for wire of maximum length.

Figure 6



"... considerable reduction in cycle time would be obtained with the use of superconductive wiring at liquid-nitrogen temperature."

Figure 7

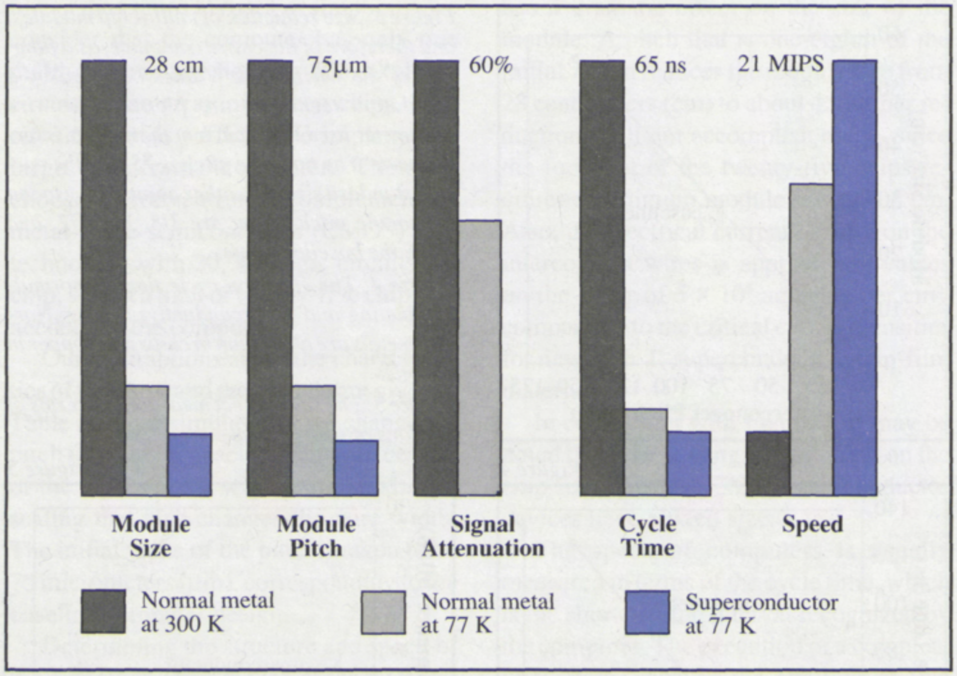


Figure 7. Comparison of characteristics of three computers with normal-metal and superconductive interconnect.

Figure 8

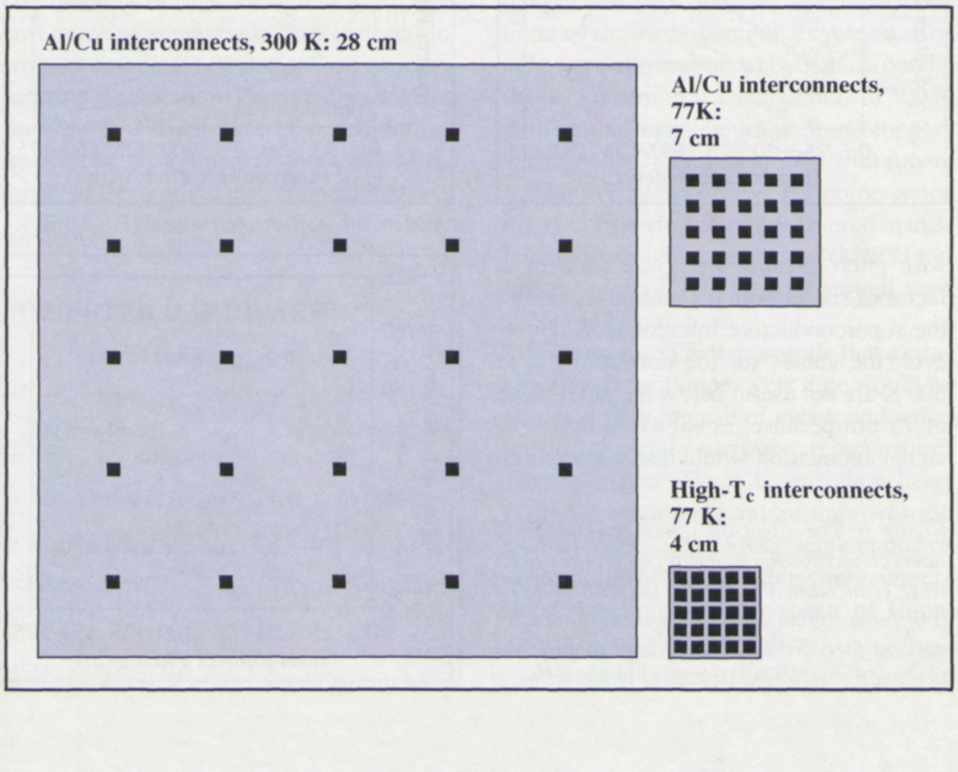


Figure 8. Relative size of multi-chip computer modules of comparable performance. Chips are shown as black squares.

and the computer would be inoperable. To assess the potential speedup possible with high-T_c interconnects, we would have to compare the 300 K aluminum/copper interconnect system at 75 μm pitch with the 77 K superconductive interconnect system at the pitch of 9.4 μm (1/8 of 75 μm).

IMPROVEMENTS PREDICTED BY SIMULATION TECHNIQUES

Performance parameters calculated for three hypothetical computers—one using interconnects of normal metal and operating at 300 K, one using normal metal and operating at 77 K, and one using superconductive metal and operating at 77 K—are given in Figure 7. With the superconductor, overall size is reduced by a factor of 7, and speed is increased by the same factor. Figure 8 is a graphic representation comparing of the physical sizes of the three modules.

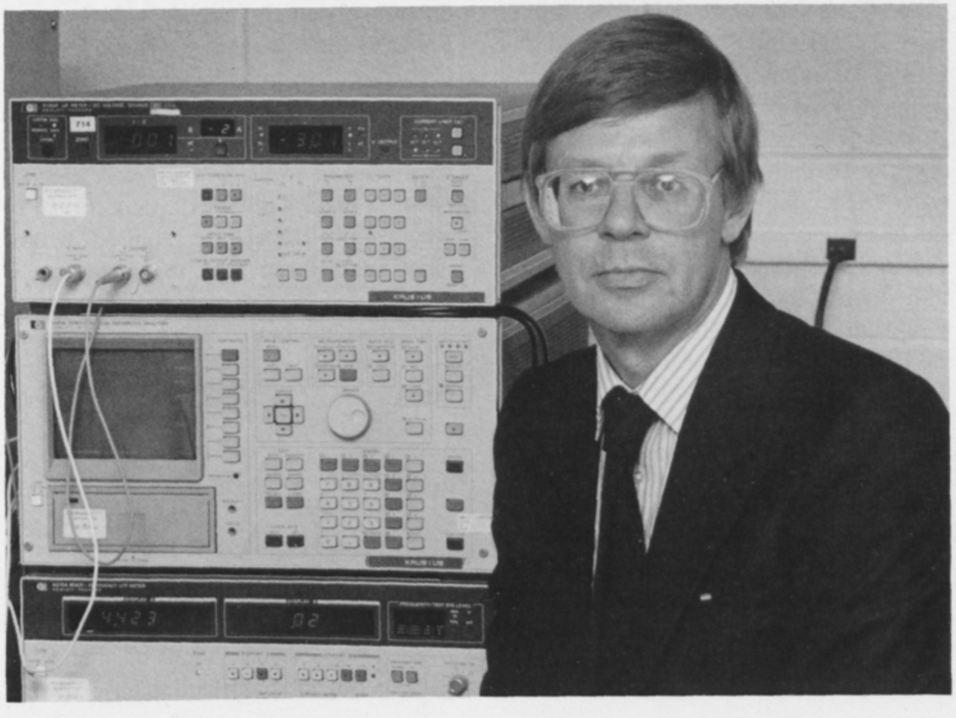
Our data show that computers with normal-metal interconnects would perform considerably better if they were cooled. In fact, at low operating frequencies, they would achieve a significant fraction of the total performance enhancement that is possible with superconductors. At higher frequencies, however, the *skin effect* (with the outer layer of the wire doing most of the conducting) would make the advantages of superconductive interconnect larger. For example, at 300 K and a frequency of 500 megahertz, the skin depth in copper of 2.9 μm is only a small fraction of the typical interconnect line thickness of 50 μm used in computer packaging.

The most impressive result of this demonstration of simulation technology is the prediction that the use of superconductive interconnects at liquid-nitrogen temperature could have a dramatic effect on the physical size and performance of computers. Beyond that, the exercise demonstrates how versatile and useful simulation can be in analyzing computer systems.

Acknowledgments:
The research discussed here was supported by the Semiconductor Research Corporation. The simulation method was developed by Krusius and William E. Pence, who was then a graduate student and is now at IBM, Yorktown.

Further Reading:

Krusius, J. P., and W. E. Pence. 1989. Potential of low temperature CMOS with normal and superconductive interconnect. Invited paper in *Proceedings of 6th International IEEE VLSI Multilevel Interconnection Conference*, pp. 233–40.



J. Peter Krusius is a professor of electrical engineering at Cornell, and director of the Joint Services Electronics Program.

He was educated at the Helsinki University of Technology, which awarded him the degree of D.Tech. in 1975. Subsequently he worked as a research associate at the Institute of Physics, University of Dortmund, West Germany, and then as a senior research associate and docent at the Semiconductor Laboratory, Technical Research Center of Finland, and at the Electron Physics Laboratory, Helsinki University of Technology. He came to Cornell as a Fulbright fellow in 1979, remained as a research associate, and was appointed an associate professor in 1981.

He was instrumental in bringing to Cornell one of the Centers of Excellence supported by the Semiconductor Research Corporation. He is active in the National Nanofabrication Facility at Cornell, and has served as associate director of that laboratory.

MAKING FASTER CIRCUITS USING SUPERCONDUCTORS

by Richard C. Compton

The faster a circuit can run, the more information it can process. And since the key to faster circuits is higher frequencies (or, equivalently, shorter wavelengths), the push is for circuits that operate at ultrahigh frequencies, in the microwave or millimeter-wave ranges.

In computers, ultrahigh frequency translates to more computations per second. In communications, it translates to more phone calls multiplexed onto a single fiber cable. For radar systems, the higher the frequency, the better the resolution. An added benefit of faster circuits is that the reduced wavelength often results in smaller, lighter circuits; this is particularly important in airborne and space applications such as satellite communication systems.

> *About the Units:*
> Ultrahigh frequencies are considered to be in the range of 1 gigahertz (GHz) to 1,000 GHz. For historic reasons, these frequencies are usually identified by the wavelength, which is inversely proportional to frequency.
>
> Circuits operating in the range 1 to 100 GHz are often referred to as *microwave* circuits because the wavelength (30-0.3 centimeters) is small compared to radio waves.
>
> Over the range 30 to 300 GHz, the wavelength varies from 10 to 1 millimeters, so this region is often referred to as the *millimeter-wave* spectrum.

Superconducting materials have unique properties that can be exploited in circuits operating at ultrahigh frequencies. For example, for switching and the detection of high-frequency signals, devices made from superconducting materials are far superior to their semiconductor counterparts. In fact, the difficulty with superconducting devices is not so much in making them go fast, but more in designing circuits and developing applications to exploit their high-speed capabilities. In the Cornell millimeter-wave laboratory, we are looking for such applications.

SUPERCONDUCTORS FOR MILLIMETER-WAVE DETECTORS

Materials whose resistance drops dramatically to zero at temperatures around 4 K—near the temperature of liquid helium—have been available for over a quarter of a century. The technology associated with these "low-temperature" materials is considerably more established than that of the recently discovered "high-temperature" materials that become superconductors around 77 K, the temperature of liquid nitrogen.

Interestingly, there are properties other than zero resistance that make superconductors extremely useful in high-speed devices. One of these useful characteristics is that in a superconductor, much as in a semiconductor, occupied electron-energy states are separated from the empty states by a band of forbidden energies; and because energy is inversely proportional to wavelength, the energy required to promote an electron over the band gap is approximately a thousand times smaller in a superconductor than in a semiconductor. (In a semiconductor the wavelength is just outside the optical spectrum, around one micrometer, while in a superconductor it is around one millimeter.) The smallness of the band gap makes it possible to build ultrasensitive detectors for millimeter-wave signals.

One of the main applications for such detectors is in astronomy. New stars are often formed within clouds of interstellar gas, making them difficult to observe with

Figure 1

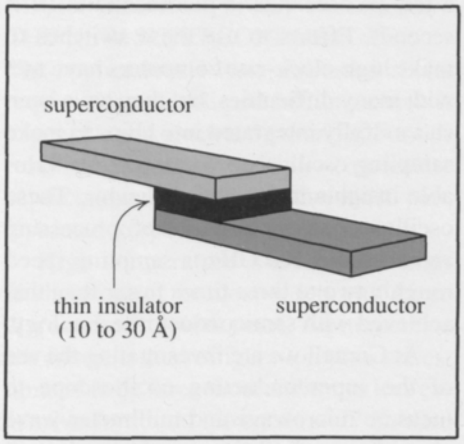
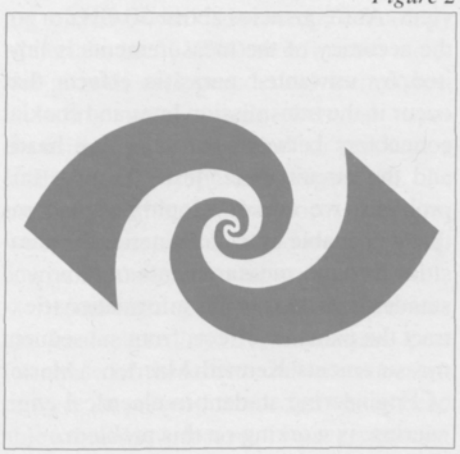


Figure 1. A Josephson tunnel junction. Two films of superconducting metal are separated by a very thin layer of insulator; the junction is at the area of overlap.

Figure 2. A log-spiral antenna used to detect signals in the millimeter/submillimeter range. The antenna funnels the signals into the center, where a detector is located. The logarithmic nature of the metal arms allows the antenna to operate over a large frequency range. Superconducting Josephson junctions are the most sensitive detectors at these frequencies.

Figure 2



optical telescopes; however, millimeter and submillimeter signals can penetrate through these clouds relatively unhindered. There are also many interesting rotational transitions in molecules that emit submillimeter waves and can be studied with the help of a suitable detector.

Superconducting detectors are made up of two superconductors separated by a thin layer of insulator. This forms a *Josephson tunnel junction* (Figure 1). The millimeter-wave signals excite an electron over the gap and into the unoccupied band. The electron is then free to tunnel through the insulator into the other superconductor, generating a current that can be detected.

The speed of the Josephson junction is limited by its resistance-capacitance (RC) time constant. The capacitance can be made small by fabricating detector devices that are very small—on the order of a few micrometers square. These small detectors can be used at frequencies up to 1,000 GHz. Their sensitivity is limited by how efficiently signals can be coupled into the device.

At Cornell's millimeter-wave laboratory we are investigating a variety of ways of integrating these detectors into receivers. Figure 2 shows a log-spiral antenna structure used to feed a Josephson junction. The signal to be detected generates currents in the arms of the spiral, and the currents propagate into the center of the spiral, where the detector is located. In order to get optimal coupling of the signal and the detector, the impedances must match. Also important is the antenna pattern: for astronomical observations, for example, the width of the pattern should match the aperture of the telescope.

The pattern is created when the signal from an antenna is received by a second antenna that is rotating. The measurements

"... for switching and the detection of high-frequency signals, devices made from superconducting materials are far superior to their semiconductor counterparts."

Graduate student Robert York measures an antenna pattern using high-frequency signals. The measurements are made in an antenna range—a large room with walls covered with a microwave-absorbing material—that was designed and built in the millimeter-wave laboratory at Cornell. (An electrical engineering major, Jodi Schwartz, helped design and build the range as a participant in the Undergraduate Research Program funded by James Moore '62.)

are made in a specially designed room called an *antenna range*.

One of the difficulties involved in this measurement is generating the high-frequency signals, particularly if measurements are required over a broad frequency range. Superconductors can be made into oscillators, but their output powers are too small to make accurate pattern measurements. Semiconducting devices can be used in conjunction with frequency doublers and triplers, but typically these are optimized to operate at a single frequency and do not work well over a broad range of frequencies. To address this problem, we are attempting to generate broad-band signals using a short-pulse laser, following techniqes developed at IBM. In collaboration with Frank Wise of Cornell's applied and engineering physics faculty, we are using a colliding pulse mode-locked dye laser that generates optical pulses only 70 femtoseconds (70×10^{-15} second) long. Photoconductive switches convert the optical pulses into electrical impulses.

SUPERCONDUCTORS FOR HIGH-SPEED SWITCHES

Josephson junctions can also be used to make switches with speeds on the order of a few picoseconds (a picosecond is 10^{-12} second). Efforts to use these switches to make high-clock-rate computers have met with many difficulties, but they have been successfully integrated into chips to make sampling oscilloscopes that provide valuable insights into circuit behavior. These oscilloscopes are capable of processing signals up to 100 GHz, a sampling speed roughly two to three times faster than that achieved with semiconductor technology.

At Cornell we are investigating the use of the superconducting oscilloscope to measure microwave and millimeter-wave circuits, a study being conducted by my group in conjunction with those of Noel C. MacDonald and J. Peter Krusius of the electrical engineering faculty. In this project, we use the oscilloscope in a time-domain mode: a 7-picosecond pulse is passed through the circuit and then back into the scope. By looking at the return pulses, we can draw specific conclusions about the circuit.

Care must be taken in analyzing the measurements, however. Superconducting oscilloscopes, like superconducting detectors, are limited not by the speed of the electronics, but by the circuit used to couple high-speed signals into and out of the devices. At frequencies above 50 GHz or so, the accuracy of the measurements is limited by unwanted parasitic effects that occur in the transmission lines and coaxial connectors between the sampling heads and the circuit under test. To meet this problem, we are developing algorithms that will enable us to characterize the parasitics through measurements of "known" standards, and to use this information to extract the parasitic effects from subsequent measurements. Kenneth Maerten, a Master of Engineering student in electrical engineering, is working on this problem.

Figure 3

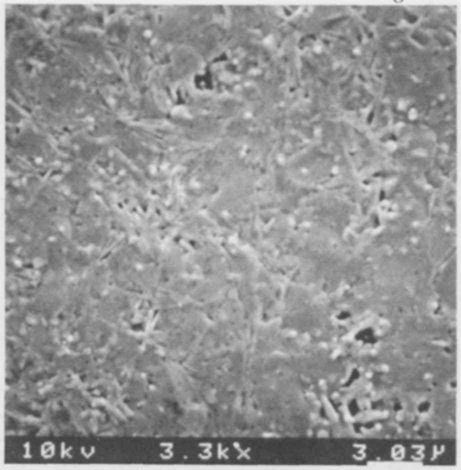


Figure 3. A sample of a Y-Ba-Cu-O superconductive ceramic grown by Advanced Technology Materials, Inc. The firm is investigating materials for various applications, including low-loss microwave transmission lines.

Figure 4

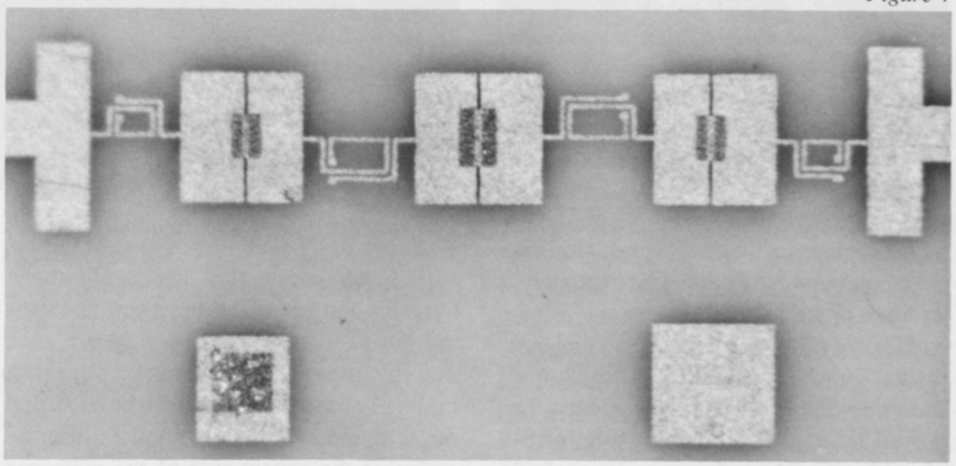


Figure 4. A good band-pass filter that could be better if its gold conductors were replaced with superconductors. The filter, which is a few millimeters across, operates over the band 2 to 20 GHz. It consists of an alternating series of inductors (spiral structures) and capacitors (metal patches separated by a layer of polyimide). It was made in the National Nanofabrication Facility by graduate students Katerina Hur and Mark Gitin in collaboration with Dan Swanson of the Watkins-Johnson Company.

MICROWAVE DEVICES THAT USE THE NEW SUPERCONDUCTORS

The applications I have discussed so far require the use of liquid helium, which is expensive and awkward to handle. For this reason, applications of low-temperature superconductors are, for the most part, restricted to specialized research.

High-temperature superconductivity has been one of the most widely publicized discoveries in recent years. An immediate advantage is that refrigeration costs are estimated to be three thousand times less expensive for liquid nitrogen (at 77 K) than for liquid helium (at 4.2 K). So far, though, no major products have been developed, although many have been targeted. Microwave integrated circuits have been identified as one of the key areas that may benefit from this breakthrough. Low-loss circuits, fast switching devices, and sensitive detectors are possible applications.

Initial efforts have been to develop economically feasible materials and processes. A number of high-temperature superconducting compounds containing copper, oxygen, and two or three other elements (usually yttrium and barium, but also bismuth, strontium, calcium, and tellurium) have been made. We are working closely with Advanced Technology Materials, Inc. (ATM) to refine the material-growth and processing techniques, including metal-organic chemical vapor deposition, that are used to produce a Y-Ba-Cu-O compound (Figure 3). To monitor the effect of new processing steps, we are developing standard tests for characterizing these materials.

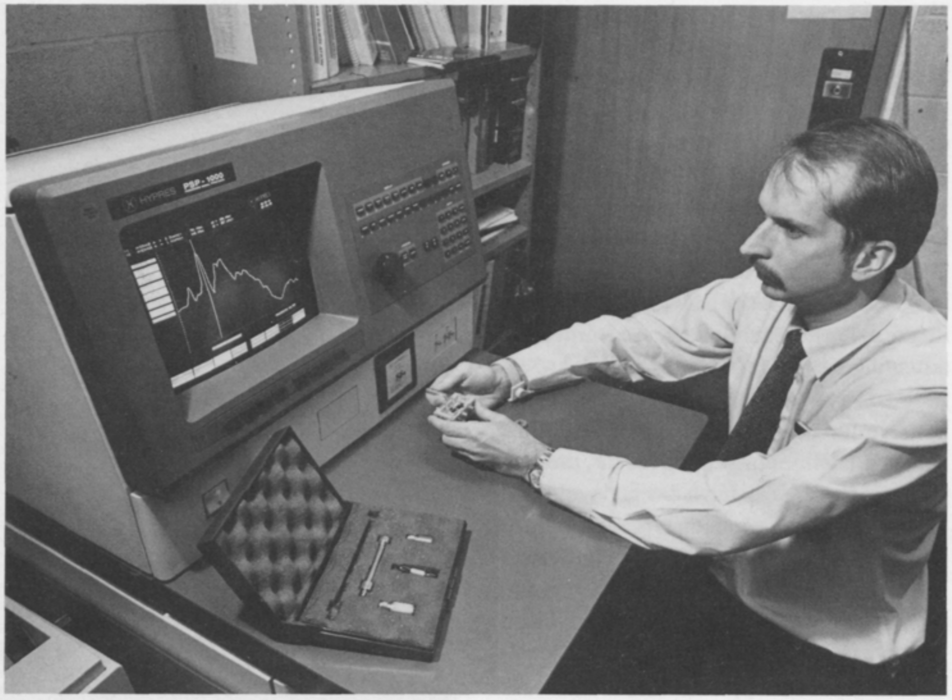
Before high-speed circuits and devices can become reality, the microwave performance of these materials must be improved. At present, researchers have been able to build low-loss microwave transmission lines with these new materials, but they have not been able to build useful Josephson junctions. Researchers at Cornell, ATM, and Avoca Laboratories, Inc., are cooperating in an effort to fabricate commercial microwave products that exploit the low-loss properties of the new materials.

Accurate measurement of the losses at microwave frequencies is quite difficult. A low DC resistance does not automatically translate to low losses at high frequencies—measurements at microwave frequencies are required. The necessary technique is to etch the material into a test pattern, place it into a custom test fixture, and measure loss as a function of frequency using a computer-controlled network analyzer. A number of undesirable circuit effects complicate the measurements, however, so we are working on a method that uses a series of resonator test samples: the losses of the superconducting samples can be inferred from measurements of the quality factor of these resonators.

We are looking at three main ways in

Right: Professor Compton prepares to connect up a millimeter-wave circuit for testing on a superconducting oscilloscope.

The instrument, one of a series of commercial models made by Hypres, Inc., uses liquid-helium-cooled Josephson junctions to measure circuits at frequencies up to 100 GHz. The Josephson junctions use niobium superconductors separated by an aluminum oxide insulator. Cooling is achieved by spraying the superconductive chips with liquid helium from a Dewar located in the instrument.



which the low-loss nature of high-temperature superconductors could be exploited to improve circuits:

- *Making filters with reduced conductor losses.* For example, the band-pass filter shown in Figure 4 could be greatly improved by using superconducting instead of gold connectors: the approximately 35 percent loss in the pass band—unacceptably high for many applications—could be reduced to less than 10 percent. With low-loss elements, more of them could be used before the losses became too large; and the more elements that were used, the sharper the filtering and the more sensitive the circuit.
- *Making high-quality resonators for stabilizing oscillator circuits.* The lower the loss, the higher the quality factor of the oscillator, and the more stable or quiet it becomes.
- *Fabricating smaller circuits.* Materials with lower conduction losses allow the transmission lines to be narrower. The scaling laws for microwave circuits are such that this means that substrates with much higher dielectric constants can be used; and because the wavelength in the substrate scales as the square root of the dielectric constant, the circuit size shrinks by approximately the same factor. To explore this application, we are working with a local company, Dielectric Laboratories, which has supplied low-loss ceramic substrates with dielectric constants high enough to make possible a fifty-fold reduction of circuit size.

A significant aspect of the Cornell research program in this area is the cooperative efforts with industry, which help make our work applicable to the development of useful products and processes. By striking a balance between basic and applied research, we can both strive for academic excellence and provide a valuable technology base for industry.

Richard C. Compton, an assistant professor of electrical engineering at Cornell, joined the faculty in 1988 after earning his Ph.D. from the California Institute of Technology. He received his undergraduate education at the University of Sydney, Australia.

While in graduate school, he worked as a Fulbright scholar on several projects, including the design, fabrication, and measurement of millimeter and submillimeter-wave circuits. He has been a consultant for the Hughes Aircraft Company, TRW, and Siemens.

Compton is a National Science Foundation Presidential Young Investigator.

REGISTER

■ **William B. Streett** will continue as dean of the College of Engineering for a second term, it was announced in January by Robert Barker, senior provost of the university.

Barker commented that university administrators agree with Streett's "long-term view of the leadership role the college must play in research, in university-industry collaboration, in graduate and professional study, and as one of the nation's leading undergraduate institutions."

Streett came to Cornell in 1978 as a senior research associate in chemical engineering. In 1981 he became a full professor and was also appointed associate dean of the college. In 1984 he served as acting dean, and in June 1985 he was appointed the Joseph Silbert Dean of Engineering. He is the eighth dean the college has had since it was instituted in 1921.

He earned a B.S. degree at the U.S. Military Academy at West Point in 1955 and served on active Army duty for twenty-three years. During that time, he earned M.S. and Ph.D. degrees in mechanical engineering at the University of Michigan.

He joined the West Point faculty in 1963. After teaching astronomy and astronautics for two years, he conducted research in chemistry as a NATO postdoctoral fellow at Oxford University, and then returned to West Point as associate professor of chemistry. In 1969, as assistant dean for academic research, he founded and became director of the academy's Science Research Laboratory. A Guggenheim fellowship in 1974–75 enabled him to return to Oxford for further research. He retired from the Army as a colonel in 1978.

Streett is author or coauthor of more than one hundred twenty papers in his specialties: the measurement of thermodynamic properties of fluids at high pressures, and computer simulation of molecular liquids. He has been an invited lecturer at six Gordon Research Conferences. He is a member of the honorary societies Tau Beta Pi and Sigma Xi.

■ Among administrative changes at the college that were announced by Dean Streett early in 1990 was the completion by **Richard N. White** of a term as associate dean for undergraduate programs. White has returned to full-time teaching and research as professor of civil and environmental engineering.

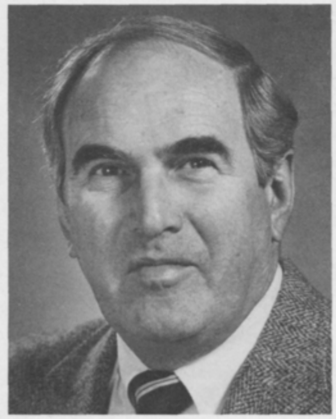

Streett

Electrical Engineering Professor **Christopher Pottle**, who has served as associate dean for computing since 1986, has assumed the responsibilities of the post in undergraduate programs for the rest of the academic year. A member of the faculty since 1962, Pottle holds a doctorate from the University of Illinois and is a specialist in computer-aided design, power-system simulation, parallel computer processing, and network theory.

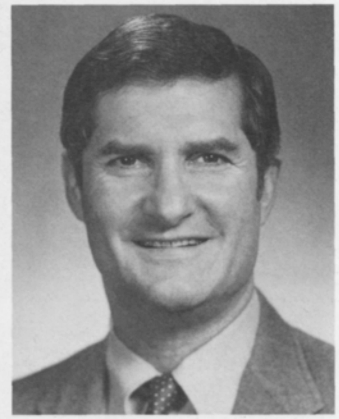
In announcing the administrative change, Streett commented on White's very active role as associate dean. "Dick White's leadership and hard work have greatly improved the quality of life and education for undergraduates at the college," Streett said.

White's deanship was marked by the introduction or strengthening of several innovative programs. The Undergraduate Research Program, which now involves more than seventy-five students in faculty-directed research, was begun in 1987; White organized and developed the program, with funding support from James

White



Edminister



Sample

Moore, a 1962 alumnus. White also initiated the Teaching Assistant Development Program, which is required for all new TAs in the college. He helped expand and strengthen the Engineering Communications Program, which provides instruction in written and oral communication.

During White's term as associate dean, the Office of Admissions, Advising, and Counseling was reorganized and services to students expanded, and the Engineering Minority Programs were strengthened and features new to such programs were pioneered. White also supervised an extensive program to modernize undergraduate teaching laboratories, and he served on university committees that helped shape a broad program to improve undergraduate education.

A member of the Cornell faculty since 1961, White served for six and one-half years as director of the School of Civil and Environmental Engineering. In 1988 he was named the first James A. Friend Family Professor of Engineering. He has received numerous local and national awards for both teaching and research in his specialty field of structural engineering, and is a coauthor of five books.

■ **Joseph A. Edminister**, formerly the assistant director for corporate relations at the college, has been named director. In this position he succeeds **Charles Yohn**, who recently became associate dean and director of development for the School of Engineering at Duke University.

Since joining the corporate relations office in 1987, Edminister has worked primarily with companies and university groups in the areas of microelectronics and electrical engineering. He organized the highly successful summer short course that was offered by the National Nanofabrication Facility for the first time last year and will be repeated this summer.

The Office of Corporate Relations will work closely with college administrators in development and alumni affairs to help meet the goals of the Engineering Master Plan, Edminister said. The Master Plan, now part of the university's projected Campaign Plan, has as a top priority the Engineering and Theory Center Building, now under construction and expected to be ready for partial occupancy this summer.

Edminister came to Cornell in 1985 as assistant director of patents and licensing, and joined the College of Engineering in 1987. From 1957 to 1983 he was a professor of electrical engineering at the University of Akron, where he also served as assistant dean and acting dean of engineering. In 1984 he held an IEEE Congressional fellowship and served as technical adviser to an Ohio Congressman.

Edminister holds bachelor's and master's degrees in electrical engineering from Akron, is a registered professional engineer in Ohio, and is an author of books on circuit analysis and electromagnetic fields. He also holds a J.D. degree from Akron, and is a member of the Ohio bar and a registered patent attorney.

Yohn, a 1950 Cornell mechanical engineering graduate, spent thirty-four years with the Aluminum Company of America before joining the Cornell staff in 1984. During his tenure here as director of corporate relations, he established working relationships with more than forty companies, and gifts from industry totaled more than $38 million in cash and equipment.

■ Named director of continuing education is **Robert W. Sample**, who will supervise the ongoing development of a new program in which graduate-level courses will be transmitted via satellite to students at company locations.

In this position Sample succeeds Professor **Thor Rhodin**, who served as director of the program during its formative months and continues as chairman of the faculty Graduate Professional Programs Committee.

Sample will coordinate program development, corporate marketing, videotape and satellite transmission, academic support services, budgeting, and financial planning. A faculty advisory committee has also been appointed. The members are John A. Muckstadt, professor of operations research and industrial engineering (chairman); Rhodin; David Gries, professor of computer science; and Noel C. MacDonald, professor and director of the School of Electrical Engineering.

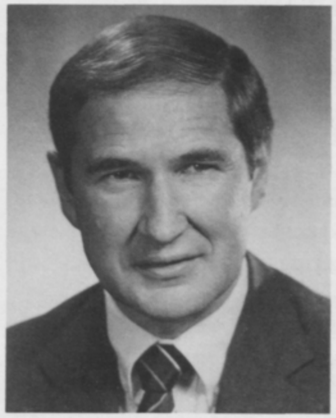
Sample holds a bachelor's degree in mechanical engineering from the U.S. Naval Academy and a M.S. degree in economics from the University of Rochester. During a twenty-four-year career in the Air Force, he served as an aircraft pilot and instructor and worked in the areas of information, education, budgeting, and personnel. In the 1970s he was a research associate at the Center for International Studies at the Massachusetts Institute of Technology, where he conducted research on arms control and the sale of American weapons. Subsequently he studied at the Industrial College of the Armed Forces. From 1979 to 1986 he held various Air Force posts, including executive assistant to the Deputy Undersecretary of Defense for Policy Review; commander of the 60th Military Airlift Wing; and chief of the Program Exercise Branch of the Joint Chiefs of Staff. From 1986 to 1989 he was a professor and chairman of the Department of Aerospace Studies of the ROTC unit at Cornell.

■ The new director of the SRC Program on Microscience and Engineering is **James W. Mayer**, the Francis N. Bard Professor of Materials Science and Engineering. Mayer succeeds Professor **Noel C. MacDonald**, who became director of the School of Electrical Engineering in July. SRC, the Semiconductor Research Corporation, is a cooperative organization of United States companies that provides support for research programs in several university "centers of excellence."

Mayer

Mayer, a B.S. and Ph.D. graduate of Purdue University, came to Cornell in 1980 from the California Institute of Technology, where he was professor of electrical engineering. He has also worked at the Hughes Research Laboratories, and as a visiting scientist at laboratories and universities in Germany, Canada, Italy, and Sweden. He is a specialist in ion implantation in semiconductors, thin-film reactions, and Rutherford backscattering and channeling techniques.

Mayer is a member of the National Academy of Engineering, a scientific member of the Bohmische Physical Society, and a fellow of the American Physical Society and of the Institute of Electrical and Electronics Engineers (IEEE). His honors include an honorary Doctor of Science degree from the State University of New York, Albany; the Von Hippel Award of the Materials Research Society; and the Silver Medal of the University of Catania.



MacDonald

MacDonald, a specialist in electron-beam technology and microfabrication, came to Cornell in 1984 from the Perkin-Elmer Corporation, where he held management positions in the areas of physical electronics and semiconductor equipment.

He received a doctorate from the University of California at Berkeley in 1967, and later attended the Harvard Business School's Program for Management Development. He taught at Berkeley for a year and spent two years at the Rockwell International Science Center. In 1970 he joined Physical Electronics Industries, Inc., as an entrepreneur, instrumentation engineer, and manager.

MacDonald, who was instrumental in developing the Scanning Auger Microprobe, received the 1973 Victor Macres Memorial Award of the Electron Probe Analysis Society of America. In 1975 he received a Young Engineer of the Year Award from the IEEE.

Hale

■ **Richard Hale** has been named an assistant dean and director of admissions at the College of Engineering. He came to the college in 1984 as assistant director of admissions, and has been serving as acting director.

Hale is a graduate of Antioch College and received a master's degree in aeronautical engineering from Cornell in 1958. He spent six years at United Aircraft (now United Technologies) and then returned to Ithaca to work at Therm Advanced Research. In 1968 he was a partner in forming Sage Action, Inc., a research and development company. (One of the products Hale helped develop is the bubble generator, a tool for visualization of air flow.) He also spent three years as director of management information systems at Tompkins Cortland Community College.

■ **Thomas Coleman**, associate professor of computer science, was recently named the first director of the Advanced Computing Research Institute (ACRI) at Cornell's Center for Theory and Simulation in Science and Engineering (the Theory Center).

According to Malvin H. Kalos, director of the Theory Center, the new position is in recognition of the increasingly important role of parallel processing in computational science and in the center's program. Approximately fifteen computer science faculty members and postdoctoral associates are already involved in research on parallel computing methods, and the presence of the ACRI is expected to facilitate funding and collaborative efforts.

Coleman has made extensive use of Theory Center facilities for research on parallel algorithms for optimization.

■ **Ravi Sudan**, the IBM Professor of Engineering, has received the James Clerk Maxwell Prize in Plasma Physics from the American Physical Society. The $5,000 prize is generally regarded as the highest honor in the field of plasma physics.

Sudan, a member of the faculties in electrical engineering and in applied and engineering physics, was cited for "wide-ranging contributions to the theory of plasma stability and turbulence and pioneering work on the generation and propagation of ion beams." His research, the citation read, has had "considerable impact on ionospheric and magnetospheric physics, on confinement and heating in field-reversed ion rings, and on light-ion-beam drivers for inertial confinement fusion."

Sudan has been a member of the Cornell faculty since 1958. He was director of the Laboratory of Plasma Studies for ten years (1975–85) and subsequently helped found the Theory Center and served as its deputy director during its initial period. He is a fellow of the American Physical Society and of the Institute of Electrical and Electronics Engineers.

■ **Michael L. Shuler**, professor of chemical engineering, won the 1989 Food, Pharmaceutical and Bioengineering Division Award of the American Institute of Chemical Engineers. He was cited for "pioneering work on engineering aspects of plant cell tissue culture and bioreactor strategies for utilizing genetically-modified cells" and for "developing a new class of computer models used to describe growth and product formation from living cells."

Shuler was recently elected to the National Academy of Engineering. Several years ago he won an award from the Microbial and Biochemical Technology Division of the American Chemical Society. He is the founding editor-in-chief of *Biotechnology Progress*.

■ Two members of the geological sciences faculty, **Jack E. Oliver** and **Sidney Kaufman**, have been chosen as joint recipients of the 1990 Hollis D. Hedberg Award from the Institute for the Study of Earth and Man. The award recognizes fundamental contributions to the understanding of the earth and its resources; Oliver and Kaufman were honored for their studies of the continental crust using seismic reflection profiling.

Oliver is the Irving Porter Church Professor in Engineering. He joined the Department of Geological Sciences as chairman in 1971. In 1981 he founded Cornell's Institute for the Study of the Continents (INSTOC).

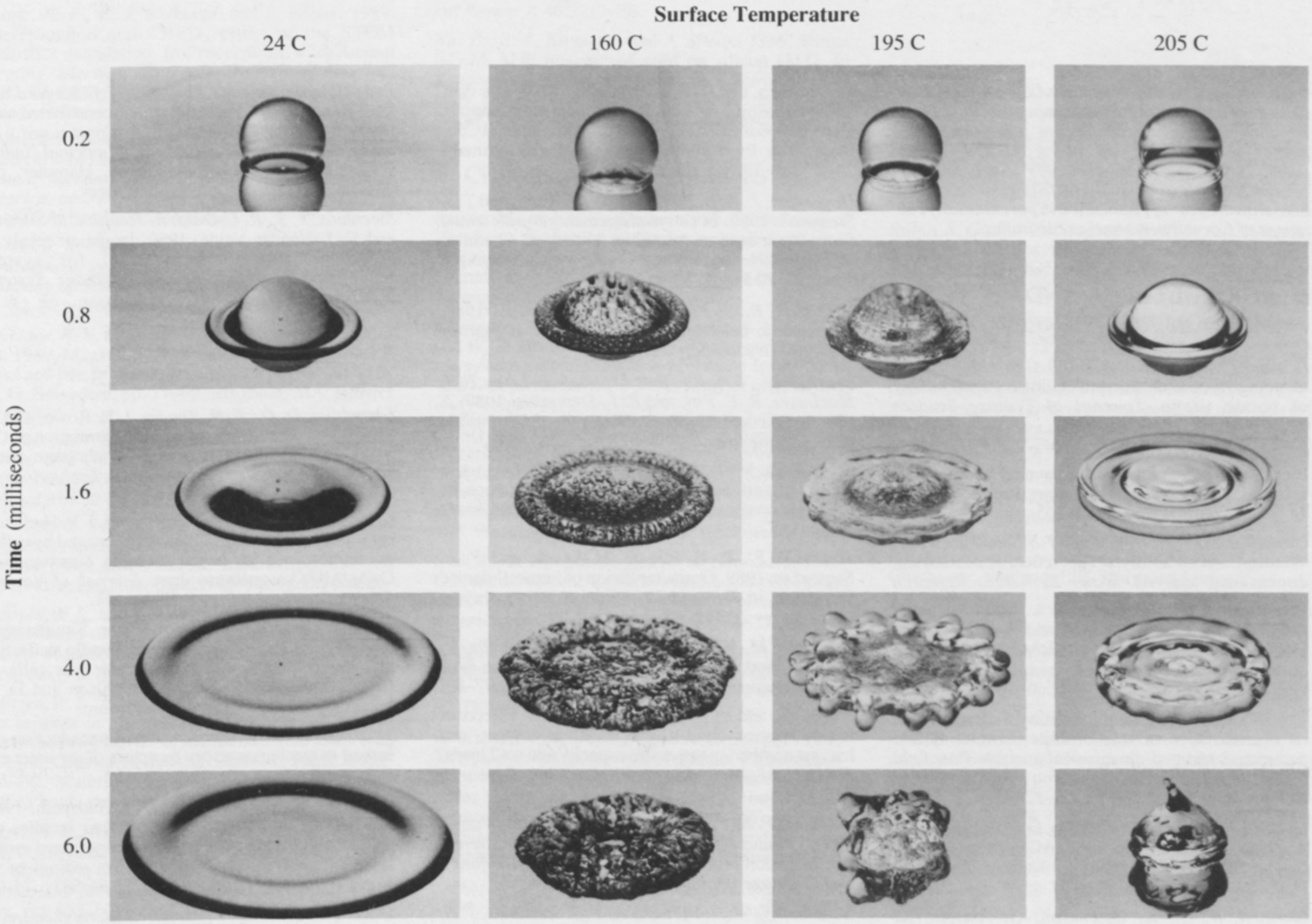
Kaufman, an acting professor, has been at Cornell since 1974, when he retired from the Shell Development Company. During his career at Shell, which began in 1936, he was a geophysicist and a leader in the area of exploration research and development. Currently he is executive director of the Consortium for Continental Reflection Profiling (COCORP), which involves specialists from academia, industry, and government and is centered at Cornell.

■ Photographs of droplets impacting on surfaces won a Gallery of Fluid Motion Prize for two researchers in mechanical and aerospace engineering. Associate Professor **C. Thomas Avedisian** and his graduate student **Sanjeev Chandra** were awarded the prize by the American Physical Society Division of Fluid Mechanics for flow visualizations obtained from experiments and computer simulation.

The citation commended "both the artistic beauty of the visualization and the original contribution to the understanding of fluid mechanics."

The study is relevant, Chandra said, to such applications as sprinklers for extinguishing fires, liquid sprays for cooling electronic equipment, and spray-fired waste incinerators. The research is supported by the National Science Foundation.

The examples below show the impact, spreading, and boiling of heptane droplets on a stainless steel surface, starting from 0.2 millisecond into the impact. The droplets are initially 1.5 mm in diameter, their initial velocities are 1 meter per second, and the view is looking down at an angle of about 30°. The effect of surface temperature on droplet shape may be seen by reading across any row; the evolution of droplet shape at various temperatures may be seen by reading down any column. Vigorous bubbling, rather like that of droplets sizzling on a frying pan, is seen at 160° (the boiling point of heptane is 98°), but the bubbles disappear at higher temperatures because the droplet becomes levitated above a cushion of its own vapor.



FACULTY PUBLICATIONS

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the three-month period July through September 1989. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

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LETTERS

Engineering in Context

Editor:

I always enjoy reading *Engineering: Cornell Quarterly*, but I particularly wanted to congratulate you on the Autumn 1989 issue.

Engineers play such a preeminent role in society that it is imperative that all our graduates are able to successfully integrate all the technical, scientific, social, political, and human values of their profession.

The Autumn 1989 edition has helped to raise the level of discussion of these important issues. I am circulating it to all our engineering faculty.

D. R. Rossington, Dean
School of Engineering, New York State
College of Ceramics, Alfred University,
Alfred, New York

Editor:

Thank you for sending me the current issue of *Engineering*. I was glad to see the reference to Henry [the late Henry Guerlac, professor of the history of science, referred to by J. M. Prausnitz]. More than that, I enjoyed the whole issue and, to my surprise, read it from cover to cover.

Of course, I especially enjoyed Professor Prausnitz' article. Henry would have loved it. Not only the knowledge that one of his students still holds the ideas he himself believed in so strongly, but the style and content of the article (the Apollo-Prometheus image appealed to this old classicist). Henry himself was both scientist and humanist. . . . Professor Calado's article is one to keep. Engineering, poetry, and art. I don't think even Henry knew all those wonderful paintings. . . . And I liked reading about Steinmetz, who, like Gertrude Stein's Darwin, was "all over my childhood."

It's an elegant journal, your *Engineering*, from the handsome cover with its well-chosen photographs all the way through.

Rita Guerlac
Ithaca, New York

From Apollo to Prometheus

Dean William B. Streett:

Dean Richard Seebass brought to my attention the efforts of Cornell's engineering college to broaden the education of its students. I have read the debate stimulated by Professor Prausnitz's presentation with great interest. I enclose a pamphlet describing the nature of our own efforts here in Colorado.

Athanasios Moulakis
Herbst Professor of Humanities
College of Engineering & Applied Science
University of Colorado at Boulder
Boulder, Colorado

(Professor Moulakis' pamphlet is titled, "The Place of Liberal Studies in Engineering Education—Thoughts Relating to an Educational Experiment at the University of Colorado".)

Dean William B. Streett:

Engineering: Cornell Quarterly came this week; I read your article first and then became involved in the one by Professor Prausnitz. I cannot resist [commenting on his remark that] ". . . the current situation in the humanities can cause confusion and despair because everything seems to depend on everything else; it is difficult to know where to start." In my opinion, this is one reason for *not* emphasizing the "Humanities". Engineers are taught exact sciences and results must be proven. . . . Apparently the "Humanities" change from generation to generation and can only influence the engineer's private life. I would vote for at least as much time for public speaking and the use of the English language.

Norman E. Elsas
Atlanta, Georgia

Professor Richard N. White:

I enjoyed your observations in *Engineering: Cornell Quarterly* and wonder if you had a certain sense of deja vu as I did. Since we started Cornell together ('60), I'm sure you remember that we were the last class to start "engineering" in our first two years. Seems that, at least to some extent, we've come full circle. I particularly enjoyed your dicussion of the poetry experiment. I remember having to rant and rave in order to take a general history course. . . . It was one of the very few true liberal arts courses I had in five years.

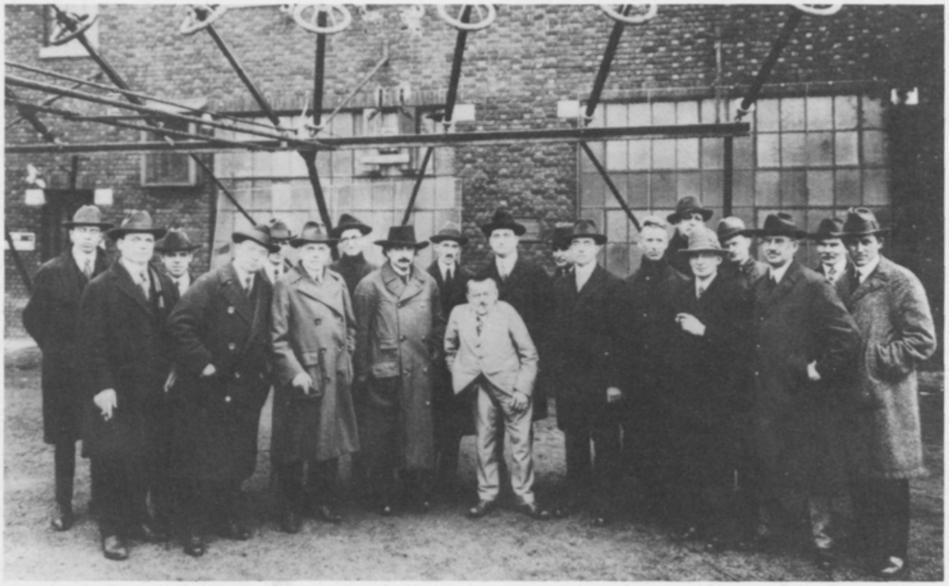
Harold R. Evensky
Coral Gables, Florida

Steinmetz as Modern Jove

Editor:

Upon reading the published version of my paper, "Manufacturing a Legend: Charles Proteus Steinmetz as Modern Jove" (*Engineering: Cornell Quarterly*, Autumn 1989), I was dismayed to see the photograph of Einstein and Steinmetz on page 50. When I referred you to the General Electric public relations department for photographs to illustrate the article, I never thought they would send that picture. Historians who write about GE are well aware that this photograph has been significantly altered and given a caption to leave the erroneous impression that Einstein visited Steinmetz at his GE office in Schenectady.

The original photograph (from the RCA archives courtesy of the IEEE Center for the History of Electrical Engineering in New York City), contemporary newspapers, and articles in the *World Wide Wireless* and *Wireless Age* for June 1921 tell a different story. Einstein came to the United States in early April 1921 with a prominent Jewish group to help raise money for the Zionist movement. His unfathomable theory of relativity, briar pipe, and violin made the German scientist a great hit with the New York City newspapers. On the morning of April 23, Einstein toured the New York City office of the Radio Corporation of America, in company with Steinmetz and others, and witnessed a demonstration of high-speed wireless commu-



nication between the United States and Germany. Einstein then toured the RCA transmitting station in New Brunswick, New Jersey, which had sent the messages, in company with leading scientists and engineers from GE, AT&T, Western Electric, and RCA (RCA was then owned by GE and AT&T).

The group photograph (reproduced above) was taken that day under the antenna of the New Brunswick station, not in Schenectady as stated by the caption accompanying the brushed-out photo. The airbrush artist removed some fairly prominent people. To Einstein's immediate right are Ernst Berg, head of the electrical engineering department at Union College and Steinmetz's assistant for many years; and, leaning into the picture, David Sarnoff, later president of RCA. Standing beside Steinmetz is Irving Langmuir, who won the Nobel Prize in physics in 1932. Next to the last on the far right side is Ernst F. W. Alexanderson, chief engineer of RCA and Steinmetz's protégé, who designed the radio-frequency alternator for the station.

The original photograph was published in *World Wide Wireless* in 1921 and in at least two later books: John Ryder and Donald Fink's *Engineers and Electrons* (1894); and A. Michal McMahon's *The Making of a Profession* (1984). The caption in *Engineers and Electrons* incorrectly identifies the man between Einstein and Steinmetz as Nikola Tesla. Research by Joyce Bedi at the IEEE History Center indicates that he is John Carson of AT&T.

The retouched photograph first appeared, as far as I have been able to determine, in John Winthrop Hammond's *Charles Proteus Steinmetz: A Biography*, published one year after Steinmetz died in 1923. Hammond was a public relations man for GE.

It is ironic that the retouched photograph resurfaced in my article on how GE helped "manufacture" Steinmetz's image as Modern Jove. I felt as though the company was manufacturing it again in my article! I hope the GE public relations department will correct the caption on the brushed-out photograph and inform future clients of the history and existence of the original picture.

Ronald R. Kline, Assistant Professor
History of Technology, College of
Engineering and Program in the History
and Philosophy of Science and Technology,
Cornell University

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Opposite: Cascadilla Creek in February, photographed by Richard N. White, the James A. Friend Family Distinguished Professor of Engineering.

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