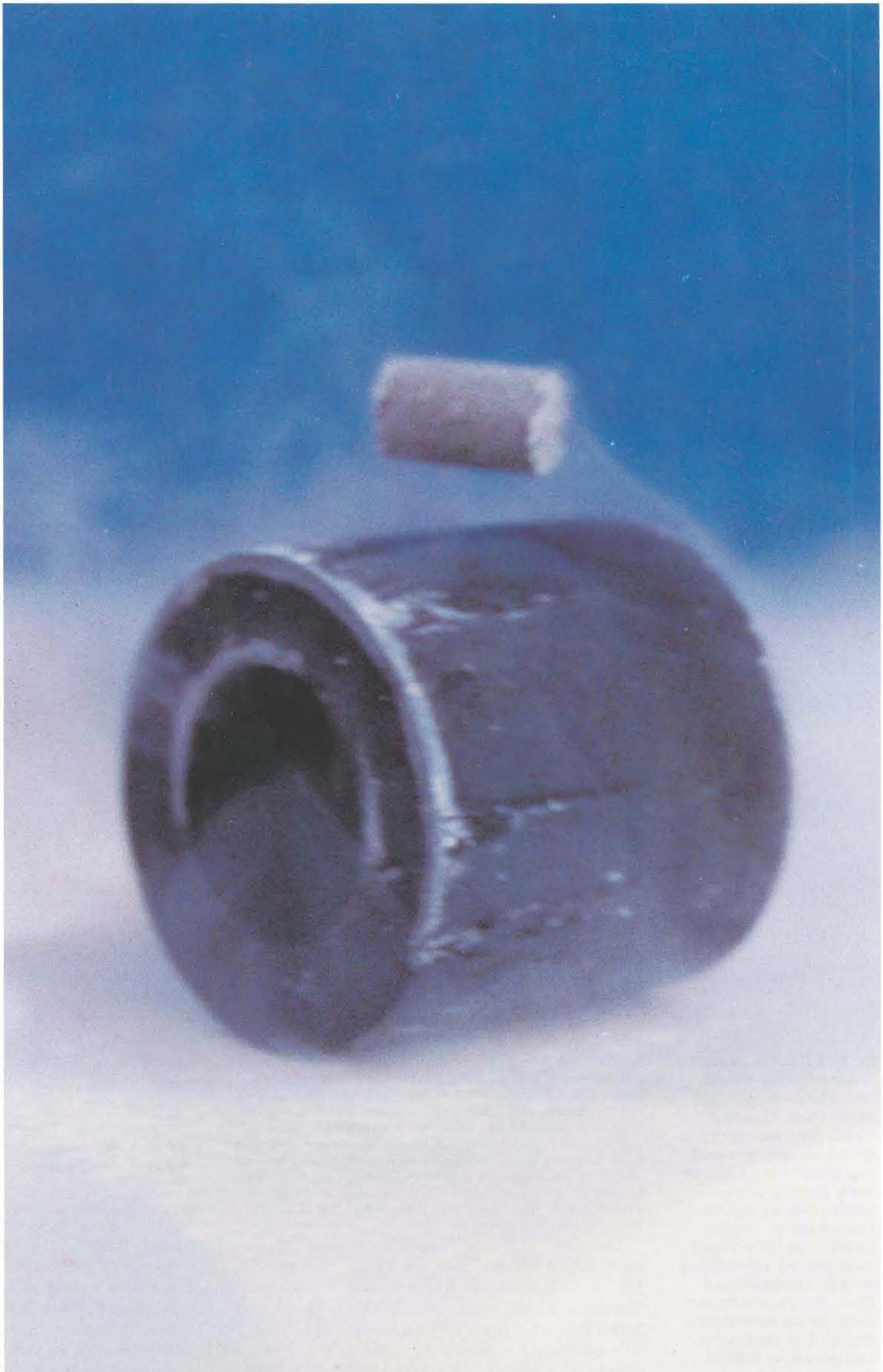


High Temperature Superconductivity

by David L. Goodstein

There is a good deal of excitement because some people suspect that somebody may someday find something to do with this stuff.

In a cloud of liquid nitrogen, a small piece of high temperature superconducting material hovers above a permanent magnet.

The two researchers who discovered the phenomenon of high temperature superconductivity in 1986 were working in a field in which most people had given up hope. In fact, J. Georg Bednorz and A. Karl Mueller at IBM in Zurich, Switzerland, had to disguise their work from their own supervisor in order to be able to do it. And even after they had made their discovery, the poor guys had to wait nearly an entire year before they got their Nobel Prize. The discovery was quickly confirmed in unexpected places such as China and Japan, and especially in Houston, Texas, and Huntsville, Alabama, where Paul Chu and his students and associates and former students not only confirmed the discovery but soon found a new class of materials that became superconducting at even higher temperatures. And that's when all the excitement really began.

The program for the 1987 meeting of the American Physical Society in New York City had gone to bed in December before the discovery was announced, so it contained nothing about high temperature superconductivity. But the organizers of the meeting, sensing that there was some interest in the subject, obligingly arranged for a special evening session to be held in case anyone had anything to present about the topic. That session was held in the hotel where the meeting took place. Four thousand people attended; it began at 7:00 in the evening and finally broke up at 6:00 the next morning. *The New York Times* front page story called it a "Woodstock for physicists." One month later, in April 1987, the whole scene was repeated at the annual meeting of the European Physical Society in Pisa and, although I was in Italy at the time, I declined to go. Once had been enough.

Since the discovery was made, there has been an absolute torrent of scientific papers on the subject—so many that some journals have had to bypass the normal peer-refereeing system; instead, a special panel reads the flow of papers on the subject as they come through. One consequence of this was that I found myself on the high temperature superconductivity panel of a journal I had never seen a copy of.

Of course, the news of this great discovery got into the press, and everyone who reads a newspaper must have read about the discovery during the past couple of years. It even became sound bites on TV. In August 1987 the U.S. government organized a conference at which businessmen and scientists got together to explore the commercial possibilities for the future competitiveness of our nation. Foreigners were not permitted to attend. Presumably this reflected the all-American origins of the subject in such American principalities as Switzerland, China, and Japan. There has been a flood of extremely expensive seminars—not for scientists, but for businessmen who feel they need to keep up on the latest developments in this field in order to keep their companies competitive. There has also been a flood of very expensive newsletters (again, not for scientists but for businessmen) and scientific journals (not for scientists but for libraries who feel obliged to buy every scientific journal that comes out). So far as I know, these seminars, newsletters, and journals

This curiosity has suddenly become cardiac country for CEOs, and the question is: What's going on here?

have been the only successful commercial applications of high temperature superconductivity.

My favorite remark to come out of all this was made at the federal conference in Washington, where Clayton Yeutter, the U.S. trade representative said, "Chief executive officers are paid to succeed." This was in reference to superconductivity, a subject that had been a mere scientific curiosity a few months before. This curiosity has suddenly become cardiac country for CEOs, and the question is: What's going on here?

To try to answer this question, I'll first explain what superconductivity is; then I'll define what we mean by high temperature in regard to superconductivity; then I'll describe what the new discovery is; and finally I'll discuss whether anything might be made of it.

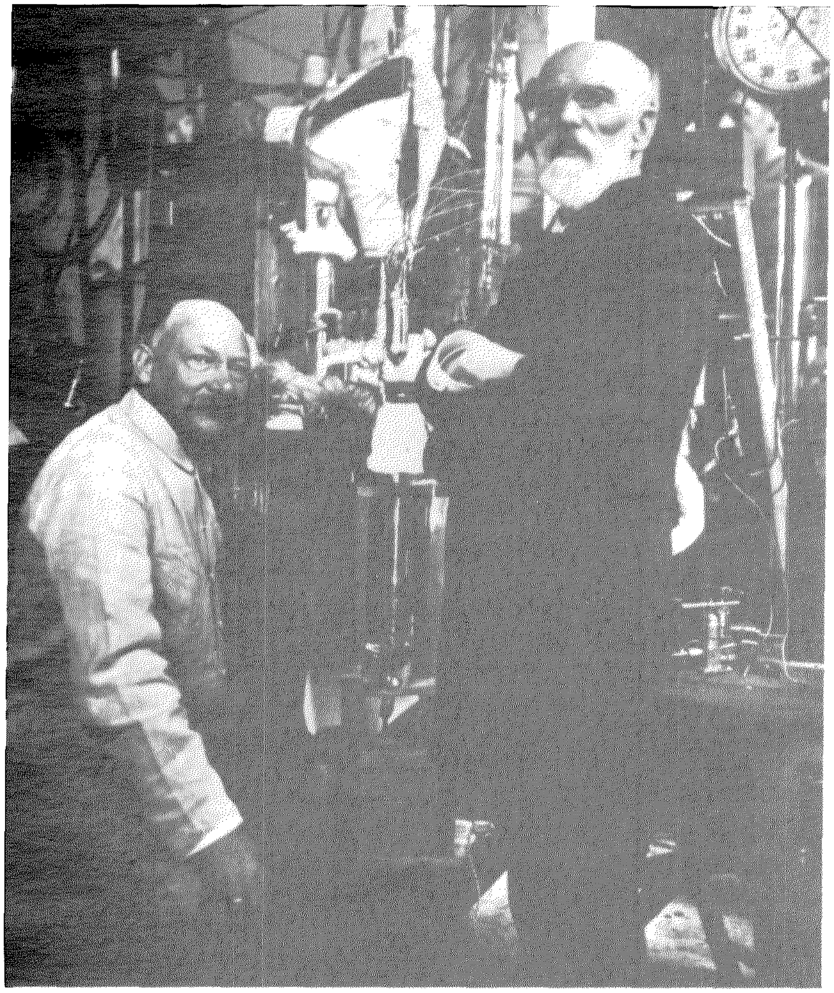
The phenomenon of superconductivity was discovered in 1911 by the Dutch physicist Heike Kamerlingh-Onnes. Three years earlier Kamerlingh-Onnes had succeeded in becoming the first person ever to liquify the element helium, and in liquid helium he had a bath in which he could cool things to the lowest temperature ever achieved on earth. So any measurement he decided to make would be the first measurement ever made at this new lowest temperature. The measurement he decided on was the resistance of a sample of metal. He chose mercury, because he could distill it and make it very pure. The experiment is done by passing an electric current through the sample and measuring the voltage that develops across the sample in order to push the electric current through it. The ratio of voltage to current is called the resistance. Kamerlingh-Onnes wanted to find out how the resistance of mercury behaved as a function of temperature when it was cooled down to this very low point.

It was well known at the time that, at higher temperatures, as the temperature went down the resistance went down in a nice, smooth curve. You might wonder why this man, with a whole new world to explore, would choose to add a few more points to a well-known curve. The answer, I think, was that he didn't expect to do that at all; he expected to make a spectacular discovery. His mental image of how a metal worked would have been much the same as ours today—a metal is basically a container full of a fluid of free electrons that can move around inside and give the metal its familiar properties, such as its shiny surface, electrical conduction, and so on. He also would have known that all fluids freeze if you cool them down enough, so he might have thought that if he got a metal like mercury cold enough, the electron fluid would freeze, and it would cease to be a metal. If that happened, then at the point where it ceased to be a metal, the resistance would suddenly jump up to infinity. I think that must have been the dramatic discovery he expected to make. But when he made the measurement, what he found instead was exactly the opposite—the resistance jumped down to zero. And that was the discovery of superconductivity.

Superconductivity has, we now know, three principal properties associated with it. One is that the electrical resistance is zero; the second is that superconductors are destroyed by magnetic fields; and the third is called tunneling.

In saying that the electrical resistance is zero, I mean really zero, not just very small. The way to find that out is not by Kamerlingh-Onnes's method; in that case all you find out is that the resistance is smaller than you're able to measure with your instruments. There's a better way of doing it, which is to take a doughnut of superconducting material, such as lead, and induce a current to run around in the ring with nothing driving it. If you did this with the very purest and best ordinary conductor—for example very pure copper at low temperature—the natural resistance of the material would cause the current to decay away to zero in a tiny fraction of a second. But when this experiment is done with superconducting lead, the current flows with no noticeable decrease for a period of years. So the resistance to the flow is really zero.

Superconductors are destroyed by magnetic fields. If you apply a magnetic field to a superconductor, the superconductor actually expels the magnetic field—keeps it outside so that the inside has no magnetic field and can remain superconducting. Of course, if you make the magnetic field stronger, it becomes harder for the superconductor to expel it, and if you make it strong enough, the superconductor can no longer do it. The field collapses and the material ceases to be superconducting.

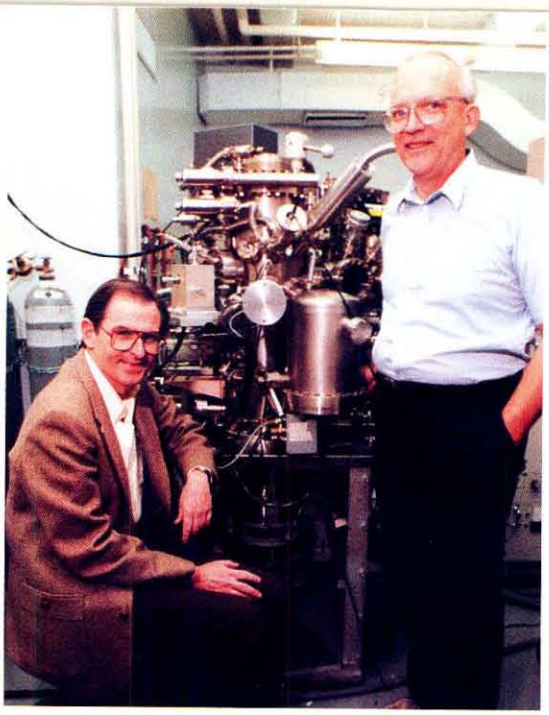


Heike Kamerlingh-Onnes (left) poses with the first helium liquifier. At right is Johannes Van der Waals, known for his theoretical studies of liquification. And lurking at far right behind the gauge is the unknown technician who probably did all the work. (Leyden Museum of Science, Caltech Archives)

In the early 1960s, however, somebody discovered that certain superconductors (not all of them, but some) actually could support extremely large magnetic fields before they were destroyed. Nobody remembers who discovered high field superconductors (well, I'm sure the discoverer remembers, but I don't), but I think that in the long view of history that might turn out to be a more important discovery than that of high temperature superconductivity.

If you have a superconductor that can exist in a high field, it can also be used to create a high field. To do that, you make the superconductor into a wire and make the wire into a coil; then you run a very large current through the coil, and that creates a magnetic field inside the coil. So the second property is that superconductors can be used to create magnetic fields and in some cases very large magnetic fields.

The third property of superconductivity is known as tunneling. If I put two pieces of superconductor very close together, then it's possible for some of that supercurrent (that is, the current that can flow with no resistance) to leak across from one to the other. Then, if you repeat Kamerlingh-Onnes's measurement, you



David Goodstein (left) and Robert Housley (visiting associate from Rockwell) pose with the CUSP (Caltech Universal Surface Probe), which combines in one machine "every surface analysis technique ever invented by the human mind—or at least more than half." Also involved in Caltech's work on high temperature superconductors is Ken Keester, member of the professional staff.

These new superconductors are complicated, composite materials of a type technically called ceramics. What we're dealing with here is pottery.

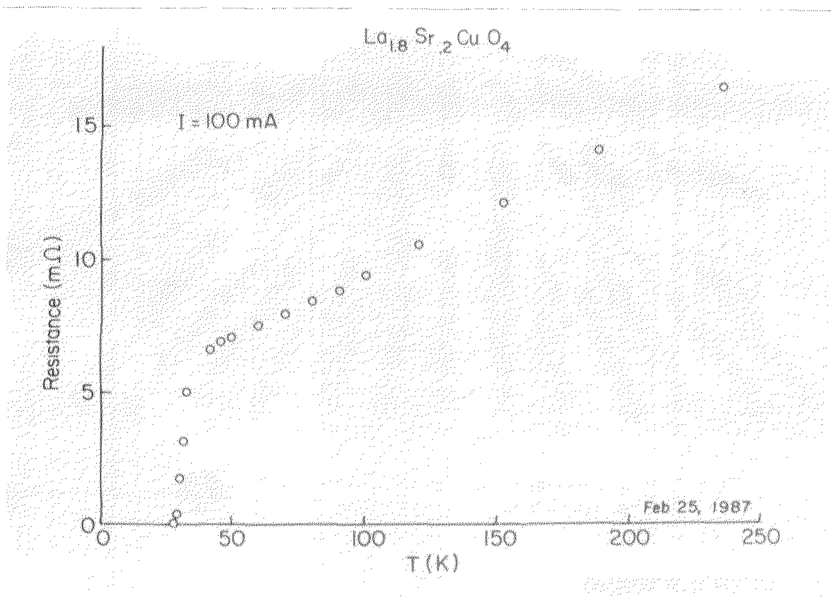
find the same result. The current flows and there's no voltage at all across the circuit, across what we call the tunnel junction. Unlike the case of a single piece of superconductor, however, when the current is flowing through a tunnel junction, the relation between current and voltage becomes exquisitely sensitive to tiny outside influences, such as very small magnetic fields, electromagnetic radiation, and so on.

Now that we know what superconductivity is, let's go on to temperature. In Kamerlingh-Onnes's mercury sample the superconducting transition occurred at a temperature of 4 kelvins. Absolute zero, that is, the lowest temperature that has any meaning, the temperature of a body from which all possible energy has been extracted, is 0 kelvins. That's very convenient; it means we never have to deal with negative numbers. (In the familiar Fahrenheit scale, absolute zero is −459°.) The size of a degree in the Kelvin scale was fixed by the very sensible idea that the freezing point of water should be 273. Once you've made that decision, then it follows that normal room temperature is about 294K and the temperature at which air liquifies is about 80K. At this temperature, which is −330° Fahrenheit, most of the air in the room would form a puddle on the floor. Of course, if the temperature in the room were −330°, other things would happen that don't bear thinking about.

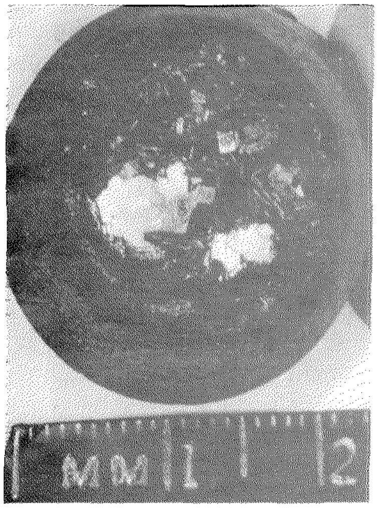
In 75 years of work on superconductivity, scientists managed to push the maximum temperature at which it occurred from 4K up to 24K. It held at that point for a long time, which is why Bednorz and Mueller were working in an obsolete field. The breakthrough that earned them the Nobel Prize was the discovery of material that became superconducting at 30K. The big discovery by Chu and his associates that caused all the excitement was a material that became superconducting at 93K, the crucial point here being that it's above the temperature of liquid air. So now you could cool a sample in liquid air and get a superconductor, whereas before you had to cool a sample in liquid helium.

There have been weekly rumors of discoveries in the room-temperature range ever since, but those rumors have not proved to be true. My colleague Bill Goddard (Caltech's Charles and Mary Ferkel Professor of Chemistry and Applied Physics) has recently published a new theory in the usual places—*The New York Times* and *The Wall Street Journal*—that makes a firm prediction that the highest temperature possible for this kind of superconductivity will be about 225K (−54°F).

The cost of the required refrigerants is a good illustration of the difference between these temperatures. For the old-fashioned kinds of superconducting materials you have to use liquid helium. Liquid helium delivered to our door at Caltech with the morning milk costs $5 per liter—just about the cost of cheap vodka. It even looks a lot like cheap vodka—a colorless fluid. We get liquid nitrogen (liquid air and liquid nitrogen are pretty much the same thing, since air is 80 percent nitrogen) delivered to the door for about 12 cents per liter. I think that's



The graph at left shows the first Caltech measurement of a high temperature superconductor (lanthanum-strontium copper oxide). A closer look at the transition region shows that, unlike the original low temperature superconductors, the resistance doesn't drop suddenly but straggles gradually down to zero. This seems to be characteristic of all the new materials.



Newly baked crystals of high temperature superconductor emerge from the oven in a tiny crucible.

less than what we pay for bottled drinking water in the lab.

The first superconducting material, as I mentioned earlier, was mercury. But it turned out that many of the metallic elements (lead, tin, indium, aluminum, and so on) become superconducting at low temperatures. Certain materials, however, do not become superconducting; for example, the best ordinary conductors, such as copper, silver, and gold, never become superconducting no matter how low the temperature gets. Also, the magnetic materials—iron, cobalt, and nickel—don't become superconductors. (Magnetism is inimical to superconductivity.) High field superconductivity was discovered in the early 1960s in the material niobium-tin, and other high field superconductors, including niobium-titanium, and so on, were discovered later.

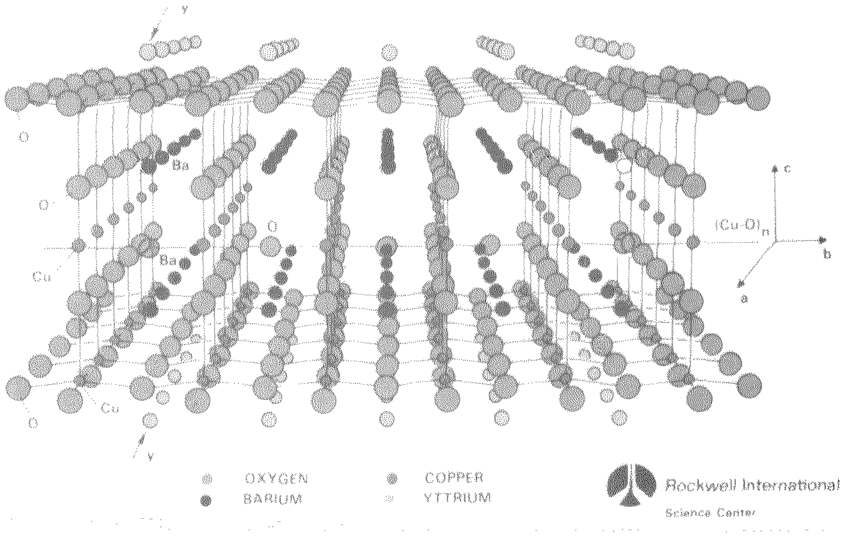
But the new high temperature materials are quite different from the metals and alloys that become superconducting at lower temperatures. Bednorz and Mueller made their breakthrough discovery (30K) in lanthanum copper oxide with a small amount of strontium impurity. The discovery by Chu and his colleagues at 93K was in the material yttrium-barium copper oxide, and more recently there have been a couple of discoveries of newer materials at even slightly higher temperatures—bismuth-strontium-calcium copper oxide at 107K and thallium-barium-calcium copper oxide at 125K.

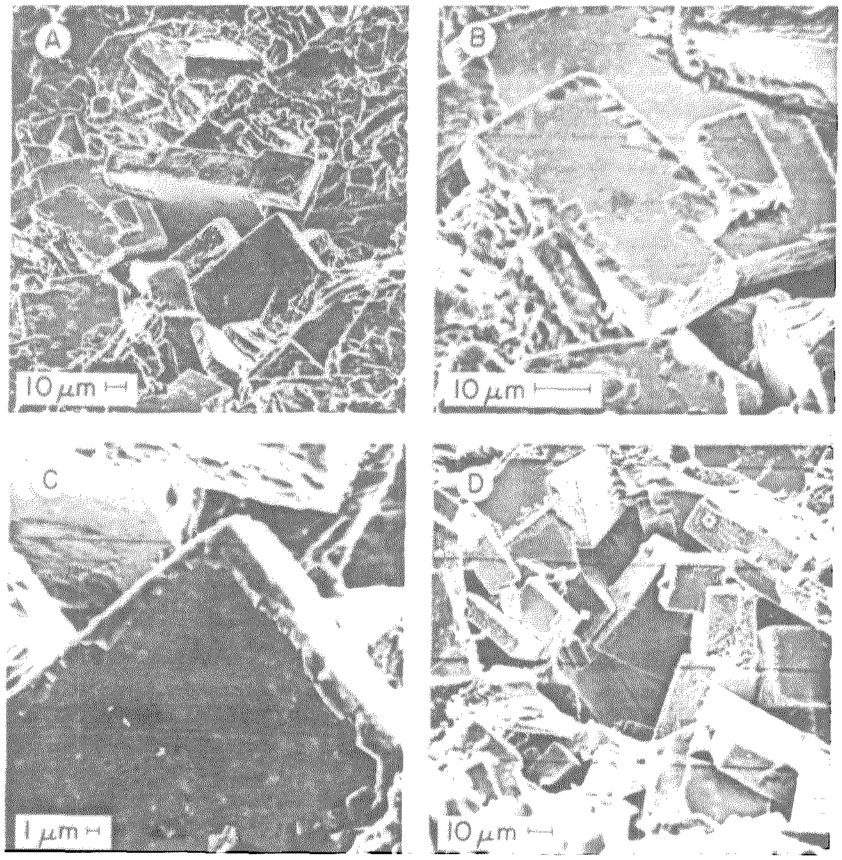
I remember that in the early days of all the excitement about this and of all the speculation about what kinds of materials would be involved in the highest temperature superconductor, Richard Feynman came into my office one day. We discussed the matter a little bit, and he made a prediction. He predicted that the highest temperature superconductor would be based on the element scandium. His first argument was that scandium came from roughly the right part of the periodic table to replace one of the exotic materials in these compounds; and his other argument was that, of all the elements in the entire periodic table, scandium is the only one for which no purpose had ever been found. When I told this to my colleague George Rossman, who is a Caltech professor of mineralogy with 92 personal friends on the periodic table (and that only counts the stable ones), he said that that was completely wrong—there *was* some use for scandium . . . but he couldn't remember what it was. The usefulness of scandium aside, these new superconductors are complicated, composite materials of a type technically called ceramics. What we're dealing with here is pottery.

Within a month of the announcement of Bednorz and Mueller's discovery, we had made our own measurement of the superconductivity of lanthanum-strontium copper oxide in our lab. That's not a tribute to how clever or fast we are, but a tribute to how easy the stuff is to make. It was made in a hundred laboratories around the world as soon as the discovery was announced. We also measured the resistance of the yttrium-barium copper oxide material, which drops to zero at about 90K.

The powdered substances from which these

Yttrium-barium copper oxide is made up of repeated planes of yttrium atoms, planes of barium atoms, and chains and planes of oxygen and copper atoms. The superconductivity takes place in the buckled plane of oxygens and coppers near the bottom; the rest of the structure just serves to keep the planes apart and in the right relation to one another.





These electron micrographs of yttrium-barium copper oxide show crystals stacked together like the ruins of a bombed-out building. The supercurrent has to find ways of tunneling from one piece to another, which is why the resistance doesn't drop sharply to zero. The scale is indicated below each micrograph.

things are made—carbonates and oxides of the materials you want in the final compound—are put into a magnesia crucible. Then the magnesia crucible is put into a porcelain crucible, and the porcelain crucible is put into a quartz tube, from which we can pump out the air and substitute pure oxygen (because these materials like to be made in oxygen). Then the quartz tube is put into an oven and heated up under the control of a little microprocessor at whatever rate we set, until it reacts and the compound is made. So, basically, you just buy these powders from the chemistry stockroom, and you shake and bake, and you have a high temperature superconductor. There's a little more sophistication to it, but that's the basic idea.

In the electron micrograph of the yttrium-barium material at left you can see that the crystals (the rectangular-shaped boulders) are stacked together like the ruins of a bombed-out building. Whatever supercurrent passes through this complicated material is actually finding ways of tunneling from one piece to another. Because of this, the transition temperature doesn't drop sharply as it did in the original superconductors; it just sort of straggles down to zero.

Above is an illustration of what the yttrium material looks like at the atomic level. You can see the repeated planes of yttriums and the chains of oxygens and coppers. The important feature is the buckled plane of oxygens and coppers, which is where the superconductivity takes place. The rest of the structure just keeps those planes apart in the right way and in the right relation to one another so that

Crystals of yttrium-barium copper oxide grown recently are larger than those on the opposite page and appear to be homogeneous single crystals when taken out of the crucible. But reflected polarized light reveals "twinning," or breaking up into pairs of different crystal orientation. Each striation here is a change from one orientation to another. The sample is about .1 mm across. (David Marshall, Rockwell International.)

the superconductivity can occur.

(Incidentally, physicists write the name of the compound thus: yttrium 1, barium 2, copper 3, and call it the 1-2-3 compound. Chemists and people from Los Angeles write the barium first and call it the 2-1-3 compound, because that's the area code.)

So that's what high temperature superconductivity is all about. Why all the excitement? I think that there are a number of reasons for it: the first one is the history of the subject. For 75 years people tried mightily to find materials that would become superconducting at a slightly higher temperature but, after inching it up to 24K, couldn't move it up any more at all for 15 years. Just about everybody gave up on the possibility of getting any higher. There was even a theory that predicted that the highest possible temperature for superconductivity was 35K. Then all of a sudden came the discovery at 30K. Within weeks it was up to 40K, and then came Chu's discovery at 93K, and everyone expected it to be up to room temperature within a month at the most. So this generated a great deal of excitement.

The second reason has to do with a mystery. There are two parts to the mystery. One is that we physicists are taught to believe that there is no such thing as a frictionless surface or a liquid with no viscosity—or, for that matter, a conductor with no resistance. Then superconductivity is discovered and, sure enough, there *is* a conductor with no resistance, but because it exists only under such bizarre conditions of extreme low temperature, perhaps that compensates in some sense for something happening that wasn't supposed to. Now all of a sudden we've got stuff becoming superconducting at 100K and above—maybe even at room temperature; who knows? Somehow it seems wrong; it goes against all our instincts, and so it makes us feel that there is a mystery there to be solved. The second part of the mystery is that we don't understand why it occurs. That's not to say there's no theory. I mentioned Bill Goddard's theory, and there are lots of others—in fact, one theory for every theorist. What is lacking is a consensus; that is, there is no agreement among physicists as to what this is all about.

Finally, there is a good deal of excitement because some people suspect that somebody may someday find something to do with this stuff. There may be some practical application for all this. If there is to be any practical application of high temperature superconductivity, it will make use of superconductors' three properties: zero resistance, the ability to create magnetic fields, and tunneling.

When you think of something that conducts electricity with no resistance at all, the first idea that comes to mind is electrical power transmission. Suppose we could make the national power grid out of superconducting material. Wouldn't that be wonderful? In order to think about this seriously, we have to compare three possible types of systems. One is the system we have now; the second is a national power grid of the old-fashioned kind of superconductor; and the third one is a national power grid of high temperature superconductor.

The first thing to think about is the losses in the system. The line losses in our present power grid amount to about 10 percent of all the power generated in the U.S. In other words, the grid we have now is well designed and works very nicely, and a 10-percent loss is not very much. If you could substitute a power grid made entirely of superconductor, one that was completely lossless, you would save that 10 percent. Actually, you might do better than that because, if you were designing from scratch a power grid made of superconducting material with no losses at all, you might design it differently from our present one. Our present one is very efficient because it's designed to use the normal conductors that we actually have. If you have lossless superconductors, you might think of locating the power stations, where the power is generated, farther away from the population centers, where the power is used. Then the power stations could be more radioactive, or more polluting, or whatever. So you might not want to just replace the present system with superconducting materials and leave the stations in place.

A superconducting power system would probably work on direct current, however, not the familiar 60 cycles that we are accustomed to getting when we plug into the wall. This is because superconductors are truly lossless only when the current drifts in one direction, not when it switches directions. The technology does exist for a d.c. power grid, but a.c. is somewhat more convenient. It's a little easier to step up the voltages for long-distance transmission and to step down the voltages at the other end for safe use. So one thing to take into consideration is that a superconducting power grid would be a d.c. system.

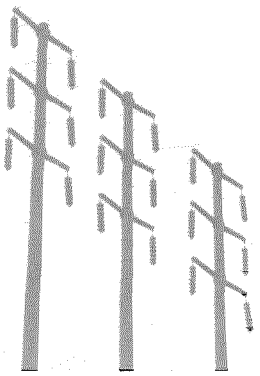
Of course, there is the issue of refrigeration, because that's the whole point: The advantage of the high temperature superconductors is that they require less refrigeration than the old-fashioned kind. In the 1960s extensive engineering studies were done to examine the possibility of a superconducting power transmission system. This was long before the discovery of high temperature superconductors, and the system was to be cooled with liquid helium. One of the findings of that study was that the cost of refrigeration was a negligible part of the cost of the system. You don't have to cool the system down from room temperature every day; if you get it cold once, it will stay cold forever. You just have to compensate for the small amount of heat that leaks into a well-insulated system by building refrigerators that tap out a little bit of the power that the system is being used to transmit. So, since refrigeration was never a serious problem, the savings in refrigeration by using high temperature superconductors represents only a fraction of what was already a negligible cost.

On the other hand, part of the reason that this system would have been extremely expensive to build in the 1960s was the high cost of the superconducting materials, which are tricky and difficult to fabricate into the kinds of wires that would be needed for a superconducting power transmission system. The new high temperature superconducting materials, even though they are easy to stir up in the lab, seem to be even more difficult to make into wires than the old materials were. So, in a sense, what seems to have happened is that we've solved the wrong problem. Refrigeration was not a problem, and what we've found is a material that doesn't need to be refrigerated as much; materials fabrication was a terrible problem, and what we've found is a material that is more difficult to make. So, all things considered, it doesn't seem to be a big step forward for high power transmission.

There's another problem with these new materials. If you're going to make a practical device out of them, such as a wire that goes into a power transmission system, then you have to be able to pass a very large current through the wire without destroying the superconductivity. In fact, you should be able to pass through about a million amps per square centimeter of cross-sectional area, which is what the old-fashioned superconductors are capable of. The new ones are capable of much less—perhaps a thousand times less current can be passed through without destroying the superconductor. The reason is the nature of the material. The optimists working in the field believe that this is only a temporary problem, and, when we get better at making these materials, it will be solved. For purposes of this article I'm assuming that that's true, because otherwise there's nothing to write about.

In addition, superconducting transmission systems are inherently unstable in the following sense: Just imagine that because of some accident (being struck by lightning, for example), some small portion of the superconducting system suddenly became normal—that is, became for a moment a normal conductor. Instead of cooling down again and becoming superconducting, it would start to get very hot. Essentially, it would become an electric heater—something with a big current passing through it that has electrical resistance. Because it's very hot, it starts to heat up the next section, which then also becomes normal and starts to get very hot, and that heats up the next section, and so on. The net result would be a meltdown of the national power grid, which would be regarded as embarrassing by most engineers. Early engineering designs had a complete backup system of conventional conductors to back up the superconductors, just to avoid that possibility. This was one reason the system would have been so expensive. I see no reason to believe that this would be any different in a high temperature superconducting system.

The second of the properties that we might want to apply is the ability to make high magnetic fields. The unit that most scientists use to measure magnetic fields is the gauss. (Actually, we're not supposed to use gauss any more; we're supposed to use a tesla, but most of us are old-fashioned and still use gauss.) The earth's field has a magnitude of about 0.5 gauss. The saturation field of an iron-core electromagnet is 20,000 gauss, and this was the strongest field



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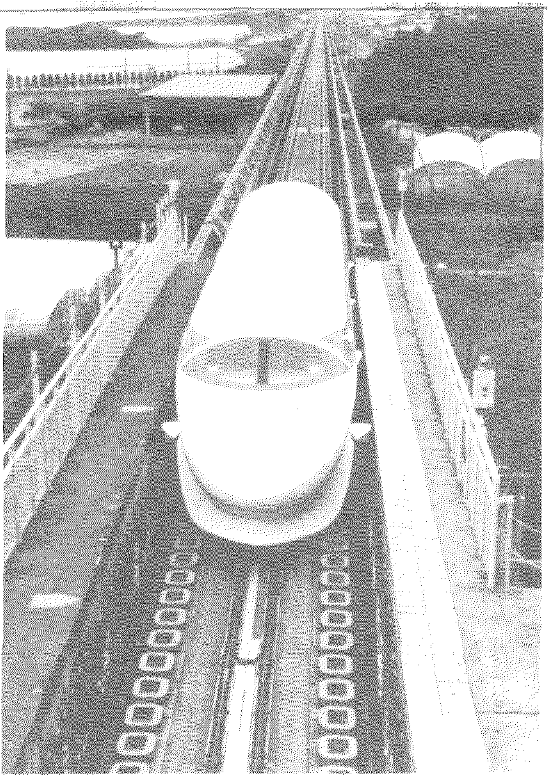

The Japanese MAGLEV train carries superconducting magnets that repel it above the track and propel the train forward. (Photo courtesy of Japan Railways Group.)

So what might we do with very large magnetic fields? My favorite by far is the magnetically levitated superconductor train.

you could get in the laboratory 20 years ago. There was perhaps one laboratory in the world that, by dedicating an enormous facility to that purpose, was able to create a field as high as 100,000 gauss for a scientific experiment. The great discovery in the early sixties of high field superconductors was that some of these can actually be used to create a field of 100,000 gauss, with the consequence that today you can just walk into your friendly neighborhood superconducting magnet store and buy one off the shelf, and you've got 100,000 gauss in your laboratory.

The new superconductors are also of the high field type. Furthermore, since the highest field you can get is related to the highest temperature you can get, the higher the temperature, the higher the field. Nobody knows yet how large a field will be possible with the new superconductors, but it's quite possible that it will be as big as half a million or even a million gauss. So when I say that we may have high fields available in the future, I mean very, very high fields.

So what might we do with very large magnetic fields? My favorite idea by far is the magnetically levitated superconductor train. The track on which this train rides is just an ordinary material—steel or some other ordinary metal, not a superconductor. But inside each car of the train there are powerful superconducting magnets. These magnets get turned on one after the other like the lights on a movie marquee. These fool the track into thinking that magnets are running backwards along the track. The track doesn't like that; it resists the motion of the magnets, and that gives the train an impulse to move forward. The track also repels the moving magnets, and so the whole train lifts up off the track by a few centimeters and rockets forward at a speed of 500 kilometers per hour. (That's an inch off the track at 300 miles per hour if you live in the U.S.)

If you've ever been in a truly high-speed train, such as the TGV in France or the Tokyo-Osaka bullet train in Japan, then you know how much fun it is to ride along in a train at ground level at 130 miles per hour. This thing will go more than twice that fast. It will put Disneyland out of business. If they ever build it, I will certainly be the first in line to buy a ticket, but I don't think we should start getting in line quite yet. There's no problem with the technology; the Japanese have had a few-kilometer, test-bed track running for many years to take VIPs on little rides to show them that it works. But there are a number of problems with building it, principally the expense. Among other things, the track must be very straight and very well maintained. When you're traveling at 300 miles per hour one inch off the track, you don't want any bumps and you don't want any hairpin curves. The capital investment for buying the right-of-way and building and maintaining the track and so on would be enormous, and because we already have ways of getting from one place to another—cars, airplanes, and so on—there's no driving economic force to build this thing.

Also, there's some concern about having 100,000-gauss magnets on a public conveyance. There's not a shred of evidence that large mag-

In projects such as a hypothetical manned mission to Mars, powerful magnets on board a spacecraft might be able to brake and steer it through the plasma created as the spacecraft enters the planet's atmosphere.

netic fields are dangerous to your health, but there's also not a shred of evidence that they aren't.

There are a number of other applications of high magnetic fields that are possible from these materials. One of them is the so-called superconducting supercollider. The SSC is to be the next generation of high energy particle accelerators, and it's barely small enough to fit in one state. Perhaps that's why Texas was picked as the site. As far as the designers and proponents of this $4.5 billion machine are concerned, the discovery of high temperature superconductivity was an acute embarrassment. The people who would like to slow down that very political project say, "Why build it now with obsolete technology? Why not just wait 10 years until the high temperature superconductors are ready and build it with them?" The last thing the proponents want to be told is to wait 10 years, so the plan is to build the SSC not with high temperature superconductors but with the old-fashioned low temperature kind.

Nuclear fusion, the promise of limitless energy from sea water or something, has been just around the corner ever since World War II and is still just around the corner. One of the schemes for performing this feat is called magnetic confinement. The plasma, the ionized material in which the fusion would take place, is contained in a powerful, shaped magnetic field, and it's conceivable that the magnetic fields available with the new high temperature superconductors could be strong enough to perform that trick and create magnetic confinement fusion. But there are some problems with that. One is that the new materials appear to be especially sensitive to radiation damage, and that's a property that you don't want to have in something that's going to be part of a nuclear reactor. The other problem is that magnetic confinement is no longer the system of choice. As a matter of fact, I don't think there is any major research group in the world now working on magnetic confinement. It's just not the way the problem is being approached these days.

If high temperature superconductivity is going to have an application, one of the most likely places is in space. For one thing, economics in space is different from economics on earth. If a communication satellite, for instance, costs $100 million to build, and you can save a little weight by using a component that costs $1,000 to replace a heavier component that costs $10, you do it. Weight is everything and cost means almost nothing. Also, there's a possibility that in a well-designed spacecraft, the ambient temperature will be low enough so that these materials will be superconducting without any active refrigeration at all.

Among the ideas that have been suggested for space applications is something called magnetohydrodynamic braking. When a spacecraft, a shuttle for example, reenters the atmosphere, there's so much heating that it creates a plasma (it ionizes the air through which it's passing), so what it's really doing is riding through a conducting medium. If you had a powerful magnet on board causing electric currents to flow through that medium, you might be able to

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direct those currents in such a way as to brake the craft and even guide its trajectory. When this idea was studied during the 1960s and 1970s, it was finally abandoned because there were no magnets strong enough to do the job. But it's just conceivable that these new materials will make magnets available that are strong enough.

With very powerful magnets you can accelerate charged particles, and it might be possible to come up with some exotic schemes for propulsion using these accelerated particles. People in the space business are always interested in exotic new schemes for propulsion. It's even conceivable that you might want to make ordinary electrical components such as motors and generators out of high temperature superconductors simply because this would substitute a lightweight ceramic coil for a heavy iron permanent magnet. Saving on weight makes the idea attractive. These are only a few of the possibilities; there is much potential application in space.

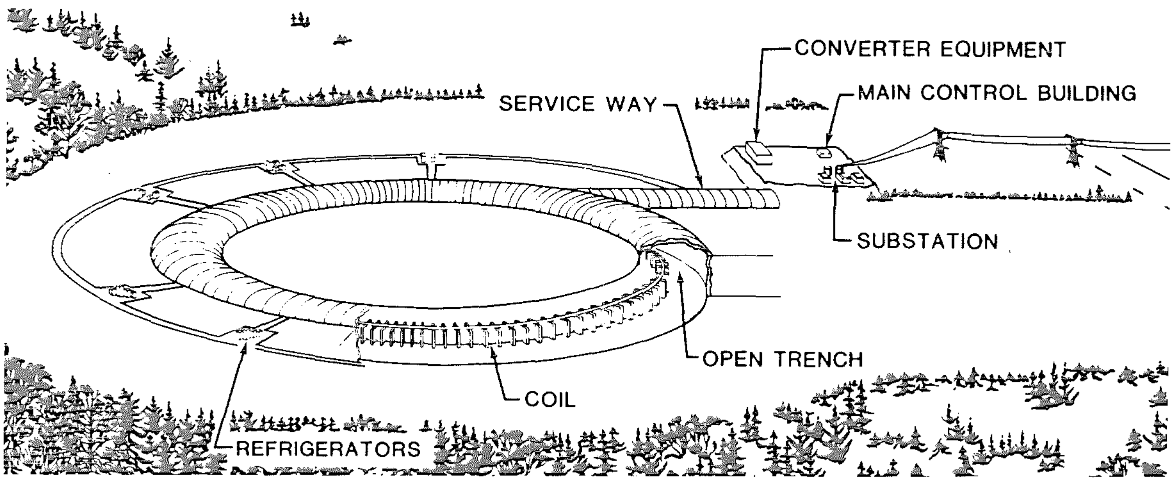
Finally, there's the possibility of using the high magnetic field properties of high temperature superconductors for energy storage. When the discovery was first announced, I started reading about it in the newspaper like everyone else. The newspapers said that all of this is going to change the way we live; we're going to have superconducting transmission lines, and magnetically levitated trains, and all sorts of things. And as I looked down the list of those other things, the one that seemed the least likely of all was energy storage. So I decided to look into it to see what that was all about. It turns out that it's not the least likely at all, and a project—SMES (for superconducting magnetic energy storage)—is already being planned by the Defense Nuclear Agency.

This project envisions the capability of releasing either 0.4 to 1 gigawatts (billion watts) of energy for a period of 100 seconds, or 10 to 25 megawatts for a period of 2 to 3 hours. You don't have to be a KGB agent to figure out what the first one is for; it's for Star Wars. The second one is to even out the peaks and valleys in the demand on the power grid for electric energy during the day and night. During the night, when people aren't using so much energy, you store it up in this thing, and during the day you release it for use.

An elementary calculation tells us that, if you're going to build this thing out of the old-fashioned high field superconductors and store the energy in a field of 100,000 gauss, then what you need is 2,500 cubic meters of high field volume. That's about an eighth of the volume of Beckman Auditorium. So we're not talking about the Grand Coulee Dam here, but we are talking about a fairly substantial engineering project, once you consider the coils and refrigerators and all the other stuff to go with them. I have seen the plans for one of these proposals, and the idea is to make a superconducting coil in the shape of a doughnut, 1 kilometer in diameter and buried underground.

The plan is to build it using conventional superconductors. Would there be an advantage in using these new high temperature superconductors? There is always a small savings to be had in the refrigeration. But as in all other big engineering projects, because we're really awfully good at making liquid helium and refrigerating things at those temperatures, the refrigeration is probably not a very serious problem. The question is, I believe, could we take advantage of the fact that we can make much stronger magnetic fields for the purpose of energy storage?

It turns out that the energy stored in a given volume is proportional to the square of the magnetic field. So if you can make a field 10 times stronger, which you may very well be able to do, you can store 100 times as much energy in the same volume. Or, conversely, you can store the same amount of energy in 100 times less volume. There's obviously a great advantage in doing that, but there's also a rather serious problem. The problem is that, if you have a coil carrying a current that creates the magnetic field, the field applies a force to the current that creates it. This is an outward force on the coil, as if it were trying to contain material under very



Bechtel's plan for a 5,000-megawatt SMES (superconducting magnetic energy storage) system places underground a superconducting coil in the shape of a doughnut 1 kilometer in diameter. (Drawing courtesy of Robert Lloyd, Bechtel Corp., and *Supercurrents* magazine.)

high pressure. That magnetic pressure, like the energy stored per unit volume, is proportional to the square of the field. So the magnetic pressure would also go up by a factor of 100 if you increased the energy density by a factor of 100. At 100,000 gauss the magnetic pressure in the system is about 400 times atmospheric pressure, or 400 atmospheres, which is a nice, well-known engineering pressure. It's the kind you might expect in a steam boiler, which engineers know how to handle with no problem. If we try to go up a factor of 10 in pressure from that—not 100, but just 10—we're talking about the kind of pressure generated in the barrel of a big artillery piece when it fires. That kind of pressure is contained for very short times by using special pre-stressed steel that is always under compression inside and not outside, so that the explosion just evens out the stresses and the barrel doesn't blow up. If you go up to 100 times this pressure, you're talking about a pressure that's never been contained before. If you ask engineers whether it's possible to contain that much pressure, they're reluctant to say that it's absolutely impossible but they will allow that it's never been done. And it's absolutely never been done using pottery.

Another problem associated with magnetic fields is a phenomenon you're familiar with if you've ever tried to open the switch on a circuit containing a big electromagnet. What happens is that the switch sparks over because the magnet doesn't like to be turned off quickly. If you do that with a very big magnetic field, the spark can be so violent that it vaporizes the switch itself. Since this would be the biggest magnetic field ever created, it seemed to me that there might just be some switching problems associated with such a thing. To find out whether or not that's true, I called up a friend of mine who is a knowledgeable and experienced power engineer and described the problem to him to get his opinion. I can't put in print exactly what he said, because these engineers can be pretty salty, but the gist of it was that "it's likely to be a challenging task."

The third property of high temperature superconductors is tunneling. If I put two pieces of superconductor very close together, some superconductivity can leak from one to the other, but the amount is acutely sensitive to such things in the environment as very weak magnetic fields or electromagnetic radiation. That means that you can use this property of tunneling as a detector of those things. Detecting infrared radiation is the one thing that superconductivity is now regularly used for outside the scientific laboratory. For example, in orbiting satellites superconducting tunnel junction detectors are used to detect infrared radiation, either in devices that look upward toward the sky for purposes of astronomy or downward toward the earth for purposes that are usually military secrets. (But not always—see page 24.)

The fact that the conducting state of one of these junctions is sensitive to small magnetic fields means that you can use small magnetic fields to manipulate it—to turn it on or off. This makes it possible to use these junctions for electronic logic and memory devices. In other

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words, it's possible to build a superconducting computer instead of the kinds we have now, which are based on semiconductors.

IBM, AT&T, and Sperry all abandoned their superconducting computer research projects in 1983. The reason was not that the superconducting technology was not advancing; it was. The reason was that the semiconducting technology was advancing much faster, and it seemed hopeless for superconductivity ever to catch up. The problem with superconductivity was not refrigeration; it was material fabrication. And, as I mentioned earlier, the fabrication problem with these new superconductors is even worse than with the old ones. In the long run, however, the superconducting computer will ultimately be the computer of choice. The reason is simple: The whole game in computers is to make them fast, and in order to make them fast, you have to make them small, because it takes time for the signal to travel any distance. So you want to pack the elements of the computer as tightly together as you can. When you pack a lot of semiconducting elements together, as is done in present computers, each of the elements is generating heat, because it's an electrical device, and devices using electrical conductors generate heat. When they're all packed together, they generate a lot of heat, and when too many of them are packed too closely together, the computer melts and that's no good. That's the ultimate physical limitation on how small, and therefore how fast, a computer can be. That limitation does not apply to superconducting circuit elements, because they don't dissipate heat the way semiconductor circuit elements do. So in the long run the superconducting computer will win—but it might take a very long time.

Let me end with a brief summary of human history. It starts with the Stone Age, when pottery was invented. It goes on to the Bronze Age, the Iron Age, modern times, and finally to the discovery of high temperature superconductivity —which is the second coming of the age of pottery.

This, of course, reminds me of a little story about the Second Coming and the Pope. I hope no one finds this offensive; I've spent quite a bit of time in Italy and consider the Pope to be sort of a friendly neighbor. The story takes place in the Pope's Vatican chambers, where he's talking with two of his assistants, who are both monsignors. One of the assistants notices a strange light coming from the window, so he goes to the window to investigate, and he sees the Second Coming. But he doesn't believe it at first because he's trained to be skeptical—not to accept things on first sight but to think about things and analyze them. So he does all those things and finally decides there's absolutely no doubt about it—what he's seeing is the Second Coming.

So he calls his colleague over to the window, and he looks out and says, "You're absolutely right. There's no doubt about it. This is the Second Coming." So the two of them spin around, fall to their knees, and say, "Your Holiness, it's the Second Coming."

The Pope races to his desk, sits down, and starts typing madly on his typewriter. One of the monsignors asks, "Your Holiness, what are you doing?" And the Pope says, "Well, I don't know about you, but I want to look busy."

I don't know whether high temperature superconductivity is really the second coming. But I do know that a lot of people are looking busy. □

This article was adapted from David Goodstein's Watson Lecture, which played to a standing-room-only crowd in October. Goodstein is no newcomer to show business; the prizewinning TV physics series, "The Mechanical Universe," in which he played a leading role, grew out of the witty freshman physics course Goodstein taught at Caltech from 1979 to 1982, a course that Richard Feynman had already made a legend (and a tough act to follow). Goodstein, whose BS is from Brooklyn College and PhD from the University of Washington, has been a member of the Caltech faculty since 1966. He is now vice provost and professor of physics and applied physics.