# What high-temperature superconductors promise

*Already, existing types of computer chips can be made one million times more powerful with no significant increase in cost. Charles B. Stevens, Robert B. McLaughlin, and Roland P. Hagge report.*

Generally speaking, it is often the case that not until many decades after a specific technology has first emerged and found application throughout the economy that we become fully conscious of the revolution that it has engendered in human existence. The case of the "compressed air revolution" provides the exception which proves the rule. Reading encyclopedias from the turn of the century, one would come across articles touting the forthcoming technological revolution about to be generated by "compressed air," which would shortly provide a convenient means of powering lightweight engines. As we know today, "compressed air" did not quite make it. Instead, the internal combustion engine emerged on the scene. And shortly thereafter, planes and cars were everywhere.

About 10 years ago in a private interview at the New York headquarters of the United Nations, Yevgeni Velikhov, who was leading the U.S.S.R. delegation for a conference on energy R&D at the time, and who is currently the chief science adviser to Soviet leader Gorbachov, told Fusion Energy Foundation director of research, Uwe Henke v. Parpart, that what was needed in the energy field was what was being maintained in the field of computers—an order of magnitude decrease in unit costs a couple of times per decade. Prospects for achieving this in the energy field still involve great difficulties. But, with the recent developments in the field of high-temperature superconductivity, the rate of decrease in unit costs for computers is about to be multiplied a thousandfold or more, with a millionfold drop immediately around the corner.

Disregarding, for the moment, the most interesting nonlinear possibilities which these recent breakthroughs in high-temperature superconductivity are immediately about to engender in computer and other technological applications, just simply applying the now eminently practical superconducting Josephson junction technology, together with rapidly advancing x-ray lithographic techniques means that existing types of computer chips, can be made upwards of 1 million times more powerful with no significant increase in cost. And, again, without taking into account more advanced possibilities, this single step would break through the essential barrier to economical, real-time automatic control of virtually every industrial and manufacturing process.

Even the linear impact of this single development, which derives from the most immediate applications of these recent developments in high-temperature superconductivity, should lead to a tenfold increase in productivity throughout the world economy. According to former Fusion Energy Foundation computer experts, the high-temperature Josephson junction chip should hit the market within the next year or two, and, if the U.S. economy still exists four years from now, chip proliferation will have reached saturation.

## The superconductivity revolution

The contemporary scientific community has never seen anything quite like this. Over the past few months, hundreds of researchers in laboratories around the world have dropped everything to study the recently realized high-temperature superconducting materials. Researchers are working day and night—holidays no longer exist. Marathon, "sardine-like" sessions are held at scientific meetings, with the overbooked schedule going into the wee hours of the morning. Everyone from full professors to novice graduate students has become infected.

The speed with which the high-temperature superconducting revolution has emerged is truly remarkable. It has virtually caught everyone in the technical world off-guard. For the past 75 years, progress in superconductivity R&D has been tortoise-like. At the turn of the century, it was discovered that some materials, when supercooled to temperatures near absolute zero—that is, 0° Kelvin which is the same as −273° Celsius and −461° Fahrenheit—begin to conduct electricity without any detectable resistance. And many of these superconducting materials cannot even begin to conduct electricity at ordinary temperatures.

It took scientists 62 years to raise the temperature at which superconductivity can be produced from 4°K to 23.3°K. This progress was achieved through exploring pure metals or alloys like niobium-tin. And for the past 13 years little progress beyond 23.3°K has been made.

The breakthrough came at the beginning of this year when the superconducting transition temperature, Tc, was experimentally pushed to above 77°K with the new metal-oxide ceramic materials. The existing commercial superconductors, like the niobium alloys, don't reach the superconducting state until they are chilled below 23°K. That degree of cooling requires the use of liquid helium as a refrigerant. Helium condenses at 4°K and liquid helium is very expensive—it costs about $11 a gallon. It is also very difficult to use and refrigerate.

At a temperature above 77°K, liquid nitrogen can be used as a refrigerant. Liquid nitrogen costs only 22¢ per gallon and is quite easy to utilize. In fact the first MIT Alcator tokamak experiment utilized liquid nitrogen as a coolant without a refrigerator at all. A commercial truck would deliver the liquid nitrogen bottles once a week and the experimenters would simply pour the liquid nitrogen over the magnets and achieve the 77°K, while the nitrogen would bubble away into the atmosphere. Nitrogen is cheap, readily available, abundant, and clean.

Liquid nitrogen is far easier to handle and is a much, much more efficient coolant. Experts say, overall, the cooling power of liquid nitrogen is about 1,000 times greater than helium per dollar of investment. That is, liquid nitrogen refrigerators are thousands of times cheaper than helium ones.

## The break

The first breakthrough came at the IBM Zurich Research Laboratory in Switzerland. Drs. K. Alex Müller and J. Georg Bednorz had decided to explore a new class of materials, the metal oxides, for indications of superconductivity. A few examples of these metal oxides, known as perovskites, were already known to be superconductors at 13°K.

Müller and Bednorz extended their research to metal oxides that contain rare earth elements, like lanthanum in a barium-lanthanum copper oxide which had been developed by French chemists as potential chemical reaction catalysts.

As Müller and Bednorz noted in their April 1986, *Zeitschrift für Physik B* article, in January of 1986 this particular oxide exhibited superconductivity at a temperature of 35°K. Within a few weeks, this Müller-Bednorz work was extended by researchers at the University of Tokyo and at Bell Labs in Murray Hill, N.J. These groups got the onset of Tc at 40°K through replacing the barium with strontium.

Shortly after this, other groups got into the act and University of Houston and Bell Lab teams had succeeded in getting Tcs into the 50°K range, with the Tokyo team and a new team in Beijing, China in hot pursuit. Then on Jan. 29, 1987 the Houston group headed by Ching-Wu Chu zoomed to the range of 90-100°K, well above the 77°K liquid nitrogen threshold. The details of this breakthrough were presented in the March 2 *Physical Review Letters*. But the secret to the Houston success leaked out long before. This was the use of yttrium in the rare earth oxide, i.e., yttrium barium copper oxide (Y-Ba-Cu-O). Within days, a dozen groups had duplicated Chu's results.

At this point, all hell broke loose. These new superconducting materials can be easily synthesized by anyone equipped with a mortar, pestle, and a small, kitchen-variety microwave oven—though, a higher temperature pottery kiln would be most helpful. Even more significantly, with superconductors above 77°K, anyone can produce the required temperatures just as the Alcator tokamak group did, without a refrigerator. All you have to do is order a bottle of liquid nitrogen which costs 22¢ a gallon.

Since that time, which seems to many researchers in the field to be centuries ago, a lot of time has been spent concocting recipes for these oxides, these ceramics. Rate of cooling has turned out to be the most critical factor. At the Nuclear Research Center at Karlsruhe, West Germany, Dr. Constantin Politis and his colleagues prepared materials whose oxides are replaced by fluorines, which have Tc's at 120°K. These results are still somewhat controversial and are being checked.

At Wayne State University the Chen-Wenger team saw evidence that Tc was going to 240°K. This occurred when they irradiated samples of Y-Ba-Cu-O with microwaves. The microwaves induce an alternating current in the material, but Chen and Wenger measure a constant DC voltage at 240°K. This is the so-called reverse AC Josephson junction effect which can only occur in a superconductor. More recent work by a New York company shows indications of superconducting at 9° Fahrenheit and even as high as room temperatures.

## Recent developments

A crucial breakthrough came recently from the IBM group working at the Yorktown Heights, New York center. This group led by Roger H. Koch has succeeded in surmounting the most essential barrier to immediate practical applications of these high-temperature superconductors, the electric current density barrier. All previous results had been at extremely low current densities, which meant that the new materials were not immediately useful. But Koch and company produced thin films, like those needed for Josephson junctions, that carried hundreds of amperes of current per square centimeter of conductor at a Tc of 77°K. This was later extended to 1,100 amperes per square centimeter by the Bell Labs group. (In contrast, commercial 4.2°K niobium alloy superconductors can handle 50,000-500,000 amperes per square centimeter.)

But as Dr. Murphy of Bell Labs notes, this existing lower performance with the high-temperature superconductors is only an artifact of fabrication. The same problem confronted the niobium alloys when they were first discovered. Because only a small number of researchers were involved in the field, it took a few years of investigation into innovative fabrication techniques to get the current density up. It is expected, especially with the unprecedented number of researchers and groups flooding the field of high-temperature superconductor research, that this will only take a year or two at most.

Besides current density, the other critical parameter for many applications of superconductors, such as magnetically levitated trains, magnets for fusion reactors and magnetohydrodynamic (MHD) generators, and windings for superconducting motors and energy storage devices, is that of the critical magnetic field. The magnetic field generated by a superconductor—in fact any conductor—is proportional to the electric current it carries. The conductor is thus exposed to its own generated field. The critical field for superconductors is the magnetic field intensity at which the self-generated magnetic field will penetrate into the superconductor and interrupt the current flow. That is, at the critical field, the superconductor flips back to a non-superconducting state. This critical field, therefore, limits the total field that a superconductor can generate.

Happily, the new ceramic oxides have already demonstrated an extremely high critical field. The barium-yttrium-europium-copper oxide reaches critical field at 500,000 Gauss at 77°K. This is already better than that achieved with the best niobium tin alloy, which has a critical field at 350,000 Gauss. Chu and his co-workers have projected that Y-Ba-Cu-O optimal critical field is near 2 million Gauss. Even higher values are estimated by the MIT and Bell Communications groups.

## In the bag

One immediate result of the Bell Labs and IBM Yorktown Heights crashing of the current density barrier is that Josephson junction supercomputing chips are now in the bag. For some time, the general technological basis has existed for realizing a computer-generated "third industrial revolution"—the second came with electricity and the internal combustion engine. Naturally, this presupposes the plasma and directed energy technologies as well.

Computers can dramatically enhance the ways we capture, store, retrieve, and transmit information. If fully implemented to provide real-time, automatic control of all industrial and manufacturing processes, computers would radically increase labor productivity throughout the economy. Advanced planning techniques could be harnessed by a single person, that previously took, massive, slow-moving 10,000-scale bureaucracies, to run complex industrial and other organizations. The general population will have the tools to access almost any aspect of human knowledge and keep abreast of the most recent developments.

And while computer technology has already made enormous strides over the past three decades, its impact has been virtually infinitesimal, compared to today's potential of putting supercomputers on a single chip.

The cost-performance of computers has fallen steadily over the last 30 years. Today a plurality of households contain mini-computers which easily match the full performance of million-dollar business computers *circa* 1955.

## Josephson junctions

In 1962, Brian Josephson developed a superconducting device which has since been known as the Josephson junction. The Josephson junction is not a semiconductor phenomenon. The Josephson effect occurs in superconducting materials where the free electrons—the conduction electrons—act as though they are in very efficient "quantum" orbits, macroscopic orbits. According to existing theory, the Cooper electron pairs (see page 21) exist in discrete quantum energy states, instead of an apparently continuous energy spectrum found with ordinary conduction electrons.

Because of this, when two superconducting layers form a junction with a very thin electrically insulating oxide layer sandwiched in between—about 0.0040 microns thick—a very low energy "gate" can be achieved (see **Table 1** for the Speed-Power Product). A very small amount of energy, about 300,000 times less than the existing ECL-II semiconductor gates, can get electrons to flow across the insulating layer. This very efficient quantum "tunneling" derives from the

TABLE 1

### Comparison between current semiconductor gates (ECL-III) and Josephson junctions (CIL)

| Technology | Gate delay (ns) | Power (mw) | Speed-power (pj) | Density (gates per sq mm) |
|---|---|---|---|---|
| ECL-III | 1.1 | 60 | 66 | 30 |
| CIL | .03 | .006 | .000180 | 10 |

# BCS standard theory of superconductivity collapses

One of the first victims of the new high-temperature superconductors has been the existing standard theory of superconductivity, which was known as BCS theory. This theory was developed by John Bardeen, Leon N. Cooper, and J. Robert Schrieffer—thus BCS—in 1957. It says that an electron moving through a crystal lattice, as in a metal, tends to transiently distort or "pucker" the "elastic" chemical bonds of the lattice slightly. This is due to the negatively charged electron attracting the positively charged ion nuclei of the lattice atoms.

A second passing electron will be attracted to the excess positive charge created by the higher density of ions in the "pucker" region. Thus, according to BCS, the first electron in effect "attracts" the second electron via the pucker.

This weak attraction is then said to bind the two electrons into a so-called "Cooper pair." And because electrons, like people, generally like to cohabitate in pairs with opposite spins, the Cooper pair of "free" electrons in the superconductor act in unison with matched and opposite spins and momenta like those stable pairs found in atomic orbits.

According to the BCS theory the transition from electricity conduction within the crystal lattice based on "single" free electrons to that based on Cooper pairs is quite dramatic. The general reason given for this dramatic change in electrical conductivity is that uncoupled, free electrons strongly resist increases in electron population density—that is, the single electrons resist compression to higher electric current densities. This is said to be the case because the electrons follow Fermion-like behavior. According to E. Fermi, single, free electrons have a fundamental "quantum" behavior which only allows one electron to populate any given quantum energy state. This is supposedly the source of the "single" free electron's resistance to condensation.

But when the electrons form Cooper pairs, the two coupled electrons act like a single particle with a totally different behavior than that of Fermions. In fact the Cooper pair acts like a photon—the quantum cell of electromagnetic radiation, light. Photons are theoretically capable of being relatively easily compressed to very high population densities. In this case the elementary particle—the photon or Cooper electron pair—are said to act as Bosons. And in theory, an infinite number of Bosons can populate a single quantum energy state as opposed to only one for the Fermion.

BCS describes this overall transition as the formation of Cooper pairs which can condense into a single macroscopic quantum state with long-range order throughout the lattice. But recent experiments with the new high-temperature superconductors prove that the BCS theory of "linear" sums of Cooper pairs is totally inadequate.

At first, the lanthanum-based copper oxide superconductors appeared to be following the BCS model at temperatures up to 50°K. But at 90°K the new superconductors exhibited behavior which was contrary to the BCS model and operates according to a supposedly unknown mechanism.

This problem came to a boil when two research groups announced that they had conducted an essential test of lattice puckering, one of the axiomatic characteristics of the BCS theory. The lattice puckering, which supposedly leads to the formation of the Cooper pair in the BCS theory, is really nothing more than lattice vibrations. And if the weight of the lattice atoms is changed, such as by utilizing a heavier chemical isotope (that is, the same chemical element with more neutrons in its nucleus), then the superconducting behavior, Tc for example, should significantly change.

At the April Materials Research Society meeting in Anaheim, California, the AT&T Bell Lab and the University of California, Berkeley groups announced that they had independently performed such an experiment with different oxygen isotopes. The experiment utilized two samples of the superconducting copper oxide ceramic which were identical except for the oxygen atoms. In one sample the more prevalent oxygen-16 isotope was utilized. In the other sample, the heavier oxygen-18, which has two more neutrons in its nucleus, but otherwise has the same chemical properties as oxygen-16, was used. The researchers cooled the samples and measured the temperature at which each one became superconductive.

According to the BCS theory, the superconducting transition temperature, Tc, depends on the frequency of the lattice vibrations. And it is well known that a lattice with heavier atoms will vibrate at a different frequency than one with lighter atoms. But the two experiments show quite convincingly that Tc does not change at all. Theorists are quite perplexed. The experiments indicate that the number and arrangement of the oxygens in the lattice is key to the superconducting behavior—that is, instead of the "elementary" quantum processes, such as Cooper pair formation, macroscopic lattice geometry and composition is primary.

same property found with electrons bound to atomic orbits. Electrons in atomic orbits act as if they have no resistive "mass." That is, normally, free electrons will emit electromagnetic radiation, and thereby lose energy, if they deviate from a linear trajectory or change their speed of motion. But this is not true for electrons bound to atomic orbits. (If it were, all atoms and molecules would rapidly collapse to infinite densities and absolute-zero temperatures.)

In effect, orbitally bound electrons act as perfect superconducting coils which operate without any loss—pure "reactance" with no resistance. As a result, bound electrons can act as perfect transformers for upshifting and downshifting electromagnetic wave frequencies without any detectable loss; without any radiation. This means that atoms and molecules can engage in photon "cross-talk" with each other without being easily overheard. This photon cross-talk becomes most efficient in the case of living matter, as seen in the experiments of Prof. Fritz Popp of West Germany.

The "free" Boson Cooper electron pairs in the superconductor act in a similar fashion. And this means that very small energies (femtojoules) can achieve measurable "cross-talk," quantum tunneling, on the macroscopic scale of the Josephson junction and thus reduce the "quantum of action" of turning on and off a gate—a switch—by more than a billion times. This billionfold reduction in the operation energy of the basic element of the computer, the gate, permits a much greater "population density" of gates and therefore a greater concentration of computing power.

IBM researchers have shown that, utilizing Josephson junctions, one can construct all of the elements needed for a digital computer: logical functions and memory. IBM, in fact, produced a whole family of Josephson devices known as current injection logic (CIL) and based on low-temperature superconductors. Gates in the Josephson technology are called superconducting quantum interface devices (SQUID).

Table 1 compares CIL to the currently fastest semiconductor technology utilized in supercomputers, the ECL-III. It will be noted that this CIL low-temperature superconducting technology has a very low gate density. This results from the cooling problems of low-temperature superconductors. The new, high-temperature superconductors have immediately transformed this entire circumstance.

IBM demonstrated with the low-temperature CIL Josephson-junction technology that random access memories (RAM), having gate densities in the same order as the existing semiconductor counterparts, were 20 times faster with an overall thousandfold increase in computing power.

Ironically, IBM's huge Josephson junction research effort over the past decade convinced most other computer companies that there was little that could be done to make ultra-low-temperature Josephson junctions practical. As a result, IBM has, until recently, had the corner on Josephson junction R&D. Now, with the shock-like emergence of high-temperature superconductors, IBM may once again become the single giant in the computing field.

In the broadest terms, there are three generally accepted parameters for measuring the performance of computer systems:

1) processing power as measured by instructions executed per second;

2) computer storage accessible at a particular speed; and

3) data rate of computer and communications links.

## Supercomputers

Just before the full "mini" and "micro" revolution hit, in 1976 the U.S. Army decided to define a general procedure for evaluating computers given apparently rapid rates of computer technology advances at the time:

> A survey of various Army laboratories showed that problems with over 50 nonlinear simultaneous differential equations were considered overly expensive to solve by digital techniques because of excessive computation time. . . . For problems requiring 600,000 operations/cycle of the highest frequency, effective bandwidth of present-day large-scale digital computers is less than 170 hertz. However, from our survey, there are real-time requirements for computers which can process problem bandwidths of at least 10 kilohertz and approach a performance capability of 600 million operations per second—three orders of magnitude faster than available computers.

And while this capability has now been reached by the largest supercomputers, these machines cost millions and millions of dollars and only a handful are in operation. Among the areas that were identified in this Army study of major high-power computer applications were signal processing, weather prediction, radar, sonar, seismology, biomedical analysis, image processing, simulation, power guide systems, and real-time automatic control.

High-speed computation in digital computers is measured as the number of operations a machine can execute within a given time-period. Usually this is expressed as millions of instructions per second (MIPS) or millions of floating point operations per second (MFLOPS), depending on the computer manufacturer. In either case, what is being measured is the product of the basic machine cycle time and the average number of operations that can be performed in a machine cycle.

For example, an IBM 3033 has a basic machine cycle of 57 nanoseconds (17.5 million cycles per second), and IBM says that it takes 3.9 cycles to perform the average instruction (0.256 instructions per cycle), giving a result of 4.5 MIPS.

The first of the more recent CRAY supercomputers, in contrast to the decade-old IBM 3033, has a cycle time of 12.5 nanoseconds, with scalar operations taking 4 cycles and vector operations taking 0.6 cycles to yield 20 and 140

MFLOPS, respectively.

The instruction rate is a function of the cycle time and execution efficiency. Cycle time is determined by the technology utilized to build the particular computer and the complexity of its circuitry. Execution efficiency is determined by the actual problem tested (instruction stream) and the design architecture of the machine.

There are no fewer than several dozen quite differently architected supercomputers now on the market, as well as scores of "scientific processors." The differences among these machines comes from differences in the way they carry out parallel computations.

Given that there is a fixed speed limit of circuit technology available to all machine designers, designers have focused in on various methods of executing multiple instructions simultaneously in separate, parallel computing elements. All the computers referred to in this section theoretically could execute at least one instruction per machine cycle, but by and large they fall far short of this ideal. In theory, some machines could produce much faster results, since they are constructed to have multiple execution units that independently and concurrently process machine instructions.

Theoretically, the maximal limit to parallel processing speed is never attained for any length of time, because in practice, instructions are not executed independently. For example, the IBM System 360 Model 91 (195) has four different types of execution units linked simultaneously to process 16 words or instruction for a maximum aggregate throughput of 70 MIPS. Interdependence of one instruction on others is much more the rule than the exception, and an estimated 60% of the Model 91's circuitry exists only to detect and resolve interdependence problems. In benchmark tests, the system attained only 14 MIPS on scientific applications and 3 MIPS on more general job streams where conditional branching and interrupts further affected throughput.

TABLE 2
## Gate characteristics

| Technology (year) | | Function | Gate delay (ns) | Power (mw) | Speed-power (pj) | Density (gates per sq mm) |
|---|---|---|---|---|---|---|
| ECL-III | (68) | NOR | 1.1 | 60 | 66 | 30 |
| ECL-1000 | (71) | NOR | 2 | 25 | 50 | 30 |
| S/TTL | (70) | NAND | 3 | 20 | 60 | 30 |
| LS/TTL | (72) | NAND | 10 | 2 | 20 | 30 |
| NMOS | (73) | | 100 | 1.1 | 10 | 130 |

ns = nanosecond; mw = milliwatt; pg = picojoule; sq mm = square millimeter

TABLE 3
## Rough estimate of characteristics for new supercomputer based on high-temperature Josephson junctions

| | |
|---|---|
| Performance | 2,000 FMLOPS |
| CPU cycle time | 120 picoseconds |
| Cache capacity | 1 megabyte |
| Main RAM capacity | 1 megabyte |
| I/O rate (max) | 1,000 megabits per second |
| Operating power | 100 kilowatts |
| Volume of mainframe | 4 cubic meters |
| Bit width | 512 |
| Address width | 512 |

Development of new basic technologies based on new physical principles for faster circuits is the key to increasing processor power. Existing computers are fabricated largely out of silicon semiconductor devices known as integrated circuits (ICs) or chips.

A number of different processes are used to construct and manufacture semiconductor chips. Broadly speaking, the silicon semiconductor families are known as metal oxide semiconductor (MOS) and bipolar. MOS family members include CMOS, NMOS, VMOS, HMOS, and others. Historically, the MOS technologies have been slower but consume less power than their bipolar counterparts. The bipolar family contains technologies known as TTL, STTL, LSTTL, ECL, I2L, FAST, AS, and LS2 technologies.

The circuit speed is given by the time delay incurred by a signal passing through the elementary component of digital logic, which is known as the gate. The so-called natural gate differs for different technologies and is defined as the Boolean operation that requires the minimum number of transistors while giving maximum speed.

**Table 2** summarizes the principal gate characteristics of many of these technologies.

By and large, the logic circuits of supercomputers are implemented in ECL integrated circuits. Table 2 shows that the price paid for this high-speed technology is both high power-consumption and low gate density. Both of these factors will have to be significantly improved by any future circuit fabrication technologies. There is, in fact, a relationship between the two since power consumption—heat—limits gate density.

High-performance ECL chips consume and therefore dissipate so much heat that special precautions have to be taken to keep circuits within operating temperature range. These cooling systems add significant bulk to computer architecture. The largest IBM machines were water-cooled and the latest CRAY is cryogenically cooled. The CRAY-

## The layered geometry of the new superconductors

The geometry of the new 90°K superconductor Y-$Ba_2$-$Cu_3$-O is related to an important class of minerals known as the *perovskites*. These minerals contain three oxygen atoms for every two metal atoms. The yttrium-barium-copper-oxide has six metal atoms in its unit cell. Therefore, if it were an ordinary perovskite, there would be nine oxygens. But, in fact, most samples have between 6.5 and 7 oxygens. That is, one quarter of the oxygens are missing in the case of the new high-temperature superconducting ceramic oxides.

These missing oxygens transform what would otherwise be an ordinary three-dimensional crystalline lattice into a unique, two-dimensional layered structure. The unit cell can be thought of as three cubes, piled on top of one another. Each cube has a metal atom at its center: barium in the bottom cube, yttrium in the middle one, and barium in the top one. At the corners of each cube are copper atoms. In an ideal perovskite, each copper would be surrounded by six oxygens in an octahedral arrangement. And the $CuO_6$ octahedra would be linked at each oxygen. Each barium and yttrium would then be surrounded by 12 oxygens.

But x-ray and neutron diffraction studies have shown that the new superconductor unit cell does not conform to this simple picture because some of the oxygen positions are vacant. For example, all of the oxygens in the plane of the yttrium atom are missing. Thus, the yttrium is surrounded by eight—instead of 12—oxygens. And the copper atoms on either side of the yttrium are surrounded by only five oxygens, making a square pyramid. The yttrium can be thought of as being sandwiched between two slightly puckered two-dimensional sheets of copper and oxygen atoms. This is actually layers of square pyramids. This feature has never been seen before.

Oxygens are also missing from the top and bottom copper layers of the unit cell. The vacancies occur in some of the equatorial positions of the $CuO_6$ octahedra, leading to the formation of square planar arrangements ($CuO_4$) that are perpendicular to the other copper-oxygen sheets. The bariums are surrounded by 10, not 12, oxygens.

Actually, the crystal structure is much more complicated than this simple description, much like the case as seen in the recently developed quasi-crystals. For example, some of the vacant or oxygen-deficient sites are occasionally occupied by oxygen, but in an arbitrary man-

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1 is literally a computer built inside an air conditioner, with each circuit-board frame containing freon pipes. The heat-sinking of ECL circuits adds to the already low density permitted for fabricated integrated circuits. This bulk further limits systems' speed, since electronic impulses traveling at the speed of light will move only 1.5 centimeters in 100 picoseconds.

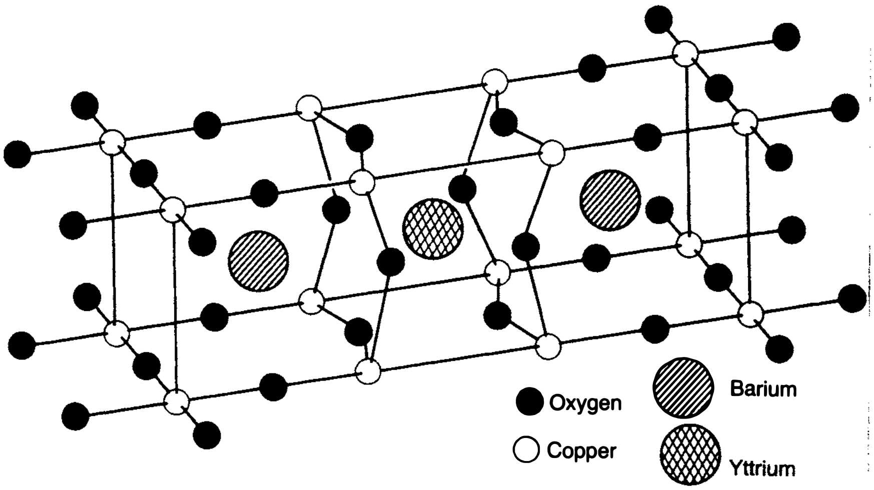
### Most probable development strategy

The first thing that will most probably be done with the new high-temperature Josephson junctions is to construct a new generation of supercomputers. **Table 3** gives a rough cut at what this would look like. The hardware performance of this Josephson junction-type supercomputer would be about 40 times greater than that of the existing top-of-the-line CRAY-XMP. More significantly, the much longer bit widths, 512 as opposed to 64 for the CRAY, and address widths, also 512, means that the existing barriers to fast program composition and parallel processing would be removed. This would increase the computers' applied computing power capabilities by a further several orders of magnitude.

This new supercomputer would then provide the essential tool for design and production of a new generation of chips, supercomputer chips—both general purpose and specialty items. According to leading computer design experts, development of such a new supercomputer is currently the main bottleneck to incorporating a large number of circuit miniaturization techniques currently available. Computers must be utilized in the design of these super-complex integrated circuits. But the existing supercomputers fall short of the required computing power needed. The imminent high-temperature Josephson junction supercomputer would fit the bill by more than an order of magnitude for what is required in chip design. Overall, experts expect that a millionfold increase in single chip power should result with the combined effects of incorporation of Josephson junctions into the chips and the realization of the first generation of Josephson junction supercomputer.

### SDI applications: plasma electronics

While more conventionally minded physicists have been increasingly perplexed by the new high-temperature superconductors, one community of scientists—plasma hydrodynamicists—have had their full expectations realized. These scientists have long predicted that "quantum phenomena" are not fundamentally acausal; that eventually, man could master



ner. Sometimes oxygens are found at other, unexpected positions in the lattice. Distortions also occur, such as in the case in which the yttrium "cube" is crushed relative to the barium cubes. This appears to occur because yttrium is smaller than barium. And that may explain why the oxygens are missing from the yttrium horizontal plane. That is, there is no room for them.

Many other interesting crystal lattice "defects" and "distortions" have also been found. For example, the unit cells normally are stacked in a Ba-Y-Ba—Ba-Y-Ba fashion, but sometimes a yttrium is inserted between them. Sometimes the smallest face of the unit cell, most usually a perfect square, is distorted very slightly into a rectangle. This particular distortion occurs when the ceramic is processed at high temperatures and then cooled. And it would appear that for the first time macroscopic geometry is seen to determine quantum behavior, i.e., the so-called crystal imperfections are producing superconductivity.

quantum phenomena with a sufficiently advanced hydrodynamics. And this hydrodynamics would be closely related to that found in energy dense plasmas, such as those explored for hydrogen thermonuclear fusion energy generation.

In fact, Dr. Robert Moon of the University of Chicago and editor of the *International Journal of Fusion Energy,* has long held that these type of materials, the doped ceramic oxides and rare earth doped ceramic oxides in particular, held great promise for high-temperature superconductivity. Dr. Moon pioneered the use of these materials in a more limited application in terms of developing materials for "cold cathodes." Dr. Moon has developed an extensive theory for a causal, "hydrodynamic" quantum theory derived from the early 20th-century work of Louis de Broglie and the later work of David Bohm.

Dr. Moon's work is also based on the most provocative applications of plasma hydrodynamics to "elementary" particle physics carried out by Prof. Winston Bostick of the New Jersey Stevens Institute and Los Alamos National Laboratory. In fact, the new high-temperature superconductors appear to function in a manner completely analogous to that of energy-dense, self-organized plasma pinches. When intense electrical currents are passed through a plasma, the plasma transforms itself into filamentary, "force-free" vortex structures. This permits the plasma to conduct huge current densities without significant dissipation—like that of a superconductor.

Within the high-temperature superconductor, it appears that internal waveguides are self-generated by the flow of the electron current. These waveguides appear as slight distortions in the lattice and form into a multi-layer, filamentary geometry—like that seen in the plasma pinch.

But this similar behavior goes much further than that of a simple analog. The new superconducting materials offer the ideal external and internal interfaces for operating both delicate diagnostics and sensors, and, monstrously powerful relativistic beam weapons systems. The new superconducting materials offer potentialities for electromagnetic "machine" interfaces similar to that seen for the application of teflon to "greaseless" pumps and no-stick cookware. But in this case, it is high-temperature plasmas, and high-energy particle and laser beams that are interfaced with the minimum of "stick" and resistance.

More specifically, the new high-temperature superconductors would provide the ideal materials for all essential interfaces in high-energy particle accelerators and lasers. The

advance in reflecting surface technology would be stunning. Mirrors, beam splitters, beam multiplexing, and microwave cavity operation could be improved by many orders of magnitude.

The same holds true for much lower energy operation of delicate diagnostics and sensors.

For example, with high superconducting photodiodes and baseplates you would be able to easily detect single photons, even in the infrared. We now need an input of about $10^{15}$ infrared photons to get a single bit for the image. Potentially, we could have photodiodes that detect one infrared photon—a potential increase in resolution, in simple linear terms, of 15 orders of magnitude!

The potential for streak cameras, currently utilized most extensively in nuclear weapons and inertial fusion work, would be about three orders of magnitude increase in temporal resolution. The Streak Camera permits there to be a time-integrated picture of a photon input, like x-rays. For example, if during the implosion of a laser fusion target, we record the x-ray output of the imploding plasma on a moving film, we can get a streaked motion picture of the implosion. The existing Streak Camera have picosecond resolution—one-trillionth of a second. The new superconductors would make possible femtosecond—a thousandfold increase—temporal resolution. This would open up the possibility of single photon "sectioning" with interferometer studies.

Take holograms, for example. The resolution of a three-dimensional hologram—literally a three-dimensional picture, usually recorded and generated by coherent laser light—is fundamentally determined by the coherence length—not the wavelength of the light that is utilized. Given the long coherence length of biophotons measured by Dr. F. Popp, the self-alignment, etc., we could get everything with surface scanning, and throw away our x-ray machines. This is because these longer wavelength, very coherent biophotons are able to transit significant distances through tissues, if not the whole body. If high resolution holographic interferometry could be performed with the detection capabilities opened up by high-temperature superconductors, we could look inside the body just by scanning the surface of the body or tissue.

Many of these potential applications may take years to develop. But the possibilities opened up by the new physical principles—and some old, overlooked principles—manifested by the high-temperature superconductors, are rapidly expanding.

# Glossary

**bipolar:** a transistor consisting of a sandwich made of two different kinds of semiconductors—the P and N semiconductors.

**Boolean operation:** operations like AND, OR, NOT, and so forth. The fundamental "connectives" of logic first worked out in the modern period by Leibniz. Digital (binary) logic, i.e., yes and no, or one fold of the circle—circular action acting on circular action—is fundamentally determined by triply reflexive rotational action, as Leibniz showed for the case of 256 possible connectives for the case of three operants.

**byte:** 8 bits of data—i.e., 8 yeses or nos, i.e., an 8-digit binary number. In base 10, the maximum 8-digit binary number is equivalent to 256.

**conditional branching:** a computer instruction that redirects the execution flow based on evaluating a particular instruction.

**convolution:** a mathematical operation involving the integral of the product of two functions at different times or positions.

**current injection logic (CIL):** an IBM family of Josephson junction superconducting devices.

**cycle time:** the time period for the smallest complete cycle of a central processor logic; the fastest instruction usually takes one cycle to complete.

**execution efficiency:** the number of central processor cycles needed on the average to execute an instruction.

**gate:** a hardware implementation of a Boolean operation built out of transistors or Josephson junctions. In other words, a series of yes/no switches or decision points.

**integrated circuit (IC):** an electrical circuit that integrates a large number of gates on a single slab of material, silicon in the case of semiconductors.

**interrupt:** an interruption in the execution of a program that occurs at unpredictable intervals; interrupts are caused by such events as program errors or input/output events.

**logic:** the part of computer circuitry that performs logical or Boolean operations.

**natural gate:** the logical operation that can be formed by using the smallest number of transistors.

**parallel execution:** the ability to simultaneously execute two or more complete instructions.

**random access memory (RAM):** memory that can be read and written at equal speed independent of location; location-dependent memories are serial in access.

**scalar operation:** a single element of data, in effect a zero-dimensioned array.

**semiconductor:** a substance with electrical-conductivity properties intermediate between a metal and an insulator.

**vector operation:** a one-dimensional array of data.