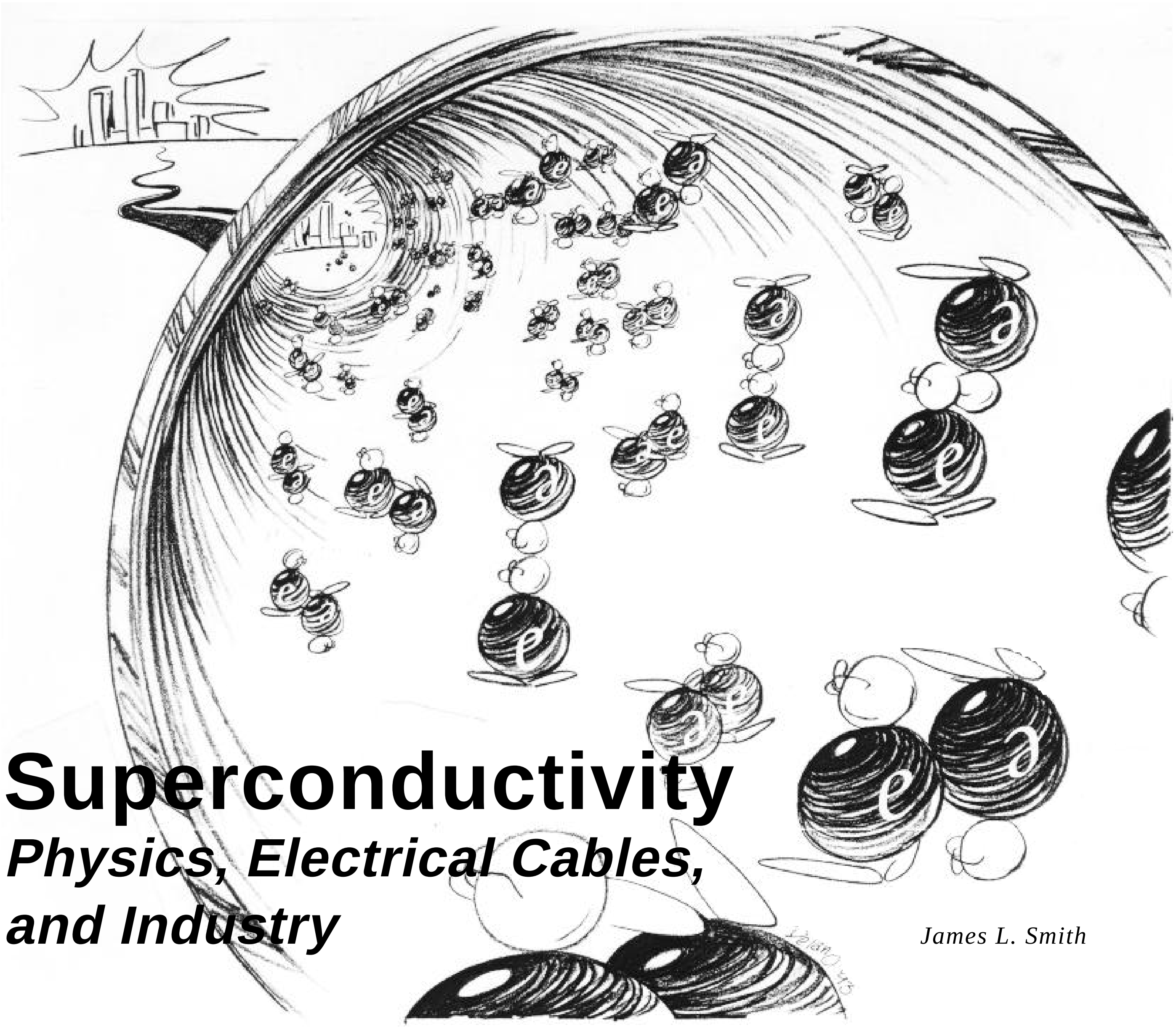

# Superconductivity
## *Physics, Electrical Cables, and Industry*

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It does not surprise us that we can see through glass. After all, we say, glass is transparent to the light that travels to our eyes from objects on its far side. But what does it mean to say that glass is "transparent" to photons of visible light? It means that the photons interact very little with the electrons in glass. And why do they interact so little? Because the spectrum of possible energy levels of the electrons has a gap extending over the range of energies possessed by photons of visible light. Similarly, the electrons of a superconducting material that move through the material under the influence of an applied voltage do not undergo collisions within the material because the spectrum of possible energy levels of the mobile electrons has a gap at an energy such that the collisions cannot occur. A superconductor is "transparent" to the flow of electricity.

Since collisions between the mobile electrons and the fixed electrons within a conductor are the source of the conductor's electrical resistance, superconductivity is certainly a property to be desired of wires used to carry electricity. But superconductivity has its drawbacks: The phenomenon occurs only at low temperatures, in low magnetic fields, and when currents are low. However, during the eighty-two years since mercury was found to become superconducting at about 4 kelvins, many superconducting materials have come to light for which those limitations are reduced. For example, in 1987 a material was discovered that becomes superconducting at a temperature above the boiling point of liquid nitrogen (77 kelvins, or –320°F). The discovery of "high-temperature" superconductivity was a momentous event because liquid nitrogen is very much cheaper than the helium required to cool previously known superconductors to their transition temperatures.

By July of 1988 Congress was infused with high-temperature-superconductivity fever—a feeling that the technology of high-temperature superconductors, unlike that of semiconductors, must not be lost to foreigners, that the United States had another chance to do it right, that here was an opportunity for government to help industry. The efforts of New Mexico Senator Pete Domenici and Laboratory Director Sig Hecker led to legislation that established Superconductivity Pilot Centers at Argonne, Los Alamos, and Oak Ridge national laboratories. Special agreements between the pilot centers and industry were allowed that gave more rights to industry, more protection to ideas. This was to be a test case of marriage between government and industry.

But making wire capable of carrying practical amounts of current from the high-temperature superconductors proved daunting. Nature had charged a price for superconductivity at higher temperatures. Among the possible wire materials are the copper-oxide compounds $YBa_2Cu_3O_7$, $Bi_2Sr_2Ca_2Cu_3O_{10}$, and $Tl_2Ba_2Ca_2Cu_3O_{10}$ and many doped versions of those compounds. They all exhibit "weak links" or "flux creep." Weak links—the imperfect bits of material between the perfect crystalline grains that make up all wires—are so called because their superconductivity is more subject to degradation by magnetic fields and currents than that of the perfect grains. The solution is to find a processing protocol that will at least partially align the imperfect grains and reduce the amount of intergranular material. Some progress has been made. Flux creep refers to the motion of magnetic-flux quanta—tiny whirlpools of current that exist throughout a current-carrying superconducting material. The motion occurs when the material is carrying a practical current. Flux creep has the same effect as electrical resistance and thus defeats the purpose of using a superconductor. Progress has been made in combating flux creep with line-like (one-dimensional) imperfections that "pin" the flux quanta against movement. Acting on ideas from IBM, workers at Oak Ridge and Brookhaven national laboratories have made tiny holes in superconductors with energetic, highly ionized atoms and found that such holes do pin flux effectively. The fact that each known high-temperature superconductor exhibits either weak links or flux creep but rarely both is tantalizing, as is the lack of any scientific reason to rule out the possibility of a high-temperature superconductor that exhibits neither problem. It is important to note that over the last five years incremental success at licking those difficulties has occurred around the world. There have been no touchdowns, but progress has been steady.

The disappearance in high-temperature superconductors of both weak links and flux creep at temperatures well below their transition temperatures demonstrates that those phenomena are indeed the price that must be paid for high-temperature superconductivity. At temperatures in the vicinity of the transition temperatures of the older superconductors (say below 20 kelvins), the high-temperature superconductors do retain their lack of electrical resistance in record high magnetic fields. That property may prove to be very useful when the cost of cooling to the lower temperatures must be paid for other reasons, and we are working to optimize wire for such applications. For example, the ability of high-temperature superconductors to maintain their superconductivity in very high magnetic fields at temperatures below their transitions temperatures might prove advantageous for the Superconducting Super Collider, which must be cooled to very low temperatures to maintain its high vacuum. At the Laboratory last winter, we used very high magnetic fields (produced by compressing copper carrying a large current with explosives) to measure the field required to drive $YBa_2Cu_3O_7$ out of its superconducting state at the lower temperatures. We found that the field required is very high indeed—140 teslas, or 3 million times the earth's magnetic field. Only the Russians at Arzamas-16 (one of their nuclear-weapons laboratories) have carried out a similar experiment; they reported a slightly higher magnetic field. Apparently the competition between the weapons laboratories in the United States and Russia has not stopped with the end of the Cold War.

The excitement created by the discovery of high-temperature superconductivity has now faded, and Edison's 99-percent perspiration is somewhere near half spent. American Superconductor and Intermagnetics General, industrial partners of the three national laboratories, are producing strips of flexible, silver-clad tape more than a hundred meters long that can carry over 10 amperes even after being wound on a drum and then unwound. It is clear that the cost of feeding electricity to a major new building (one requiring, say, 20 megawatts of power) in a crowded city (Boston or New York, say) with an underground cable of such superconducting wire would be similar to the cost of feeding with an oil-cooled cable, the type of cable now used despite the risk of oil leaks. In a city where electricity generation is physically distant from new construction (such as Baltimore, where electricity generation is to the south and growth is to the north), superconducting cables with twice the current-carrying capacity could replace existing underground cables and thus eliminate the need for overhead lines around the edge of the city or for miles of new excavation through the city. Furthermore, construction of new high-voltage overhead lines may be halted by concerns of the American public about their aesthetics and safety, and underground superconducting cables now offer a solution at the right time.

In the future, when weak links and flux creep are licked and materials are available that maintain their high-temperature superconductivity in higher magnetic fields, electric motors can be lighter and more efficient and electric energy can be accumulated at night as a magnetic field in large coils and used in the day when demand is greater. Here much work and the risk of failure remain. Even the effects of mechanical strain and the details of propagation of thermal transients through coils made of high-temperature superconductors are subjects that remain largely untouched by researchers. The modeling capabilities of the national laboratories and their abilities to field large-scale tests can help industry, and we have been talking to companies about those areas of concern.

There remain "cultural" differences between national laboratories and corporate America. We tend to want to understand down to the last detail; they need understand only enough to get a product on the market. And researchers at the national laboratories are not accustomed to paying attention to proprietary information. Yet company representatives all seem to want access to the enthusiasm, ideas, and capabilities of our scientists and seem willing to put up with managerial and legal obstacles to gain that access. They do understand that high-risk development can be the charge of the Laboratory, that the design engineering of a competitive product comes later, and that the Laboratory can therefore make most of its findings available to all.

The experiment of government helping industry is continuing, and apparently government has the most to learn, just as we expected. Steadily albeit slowly, the problems of high-temperature superconductivity are being solved. ■

**James L. Smith** received his B.S. in physics from Wayne State University and his Ph.D. in physics from Brown University. He is currently Chief Scientist of the Laboratory's Superconductivity Technology Center. During his twenty years at the Laboratory, he has received numerous awards, including two Distinguished Performance Awards from the Laboratory, the International Prize for New Materials from the American Physical Society, and an E. O. Lawrence Award from the DOE. He is a Laboratory Fellow, a Fellow of the American Physical Society, and the North American Editor of the venerable *Philosophical Magazine*. His continuing research interest is the study of superconducting materials from high to extremely low temperatures and in very high magnetic fields.