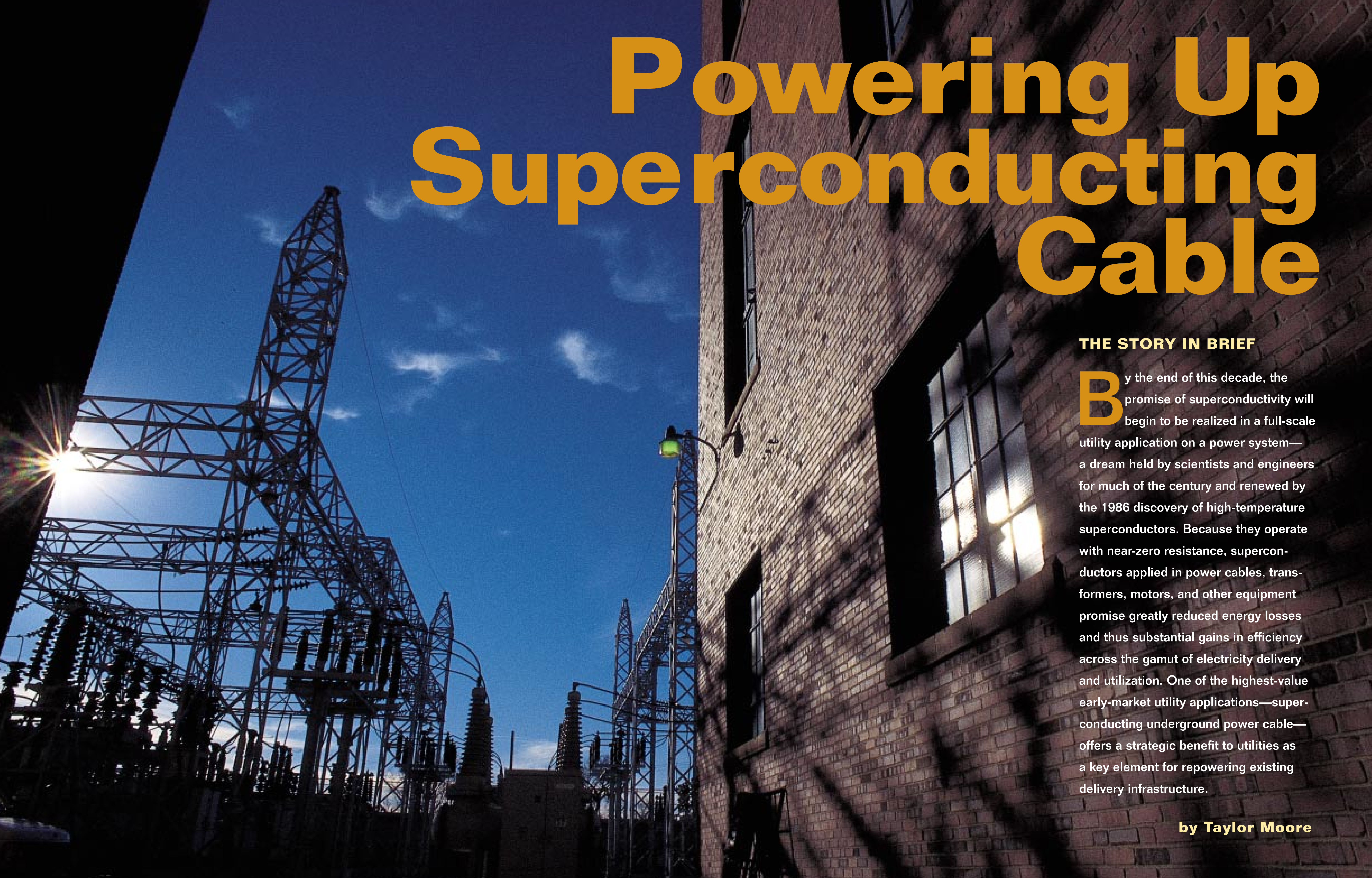

Powering Up Superconducting Cable

THE STORY IN BRIEF

By the end of this decade, the promise of superconductivity will begin to be realized in a full-scale utility application on a power system—a dream held by scientists and engineers for much of the century and renewed by the 1986 discovery of high-temperature superconductors. Because they operate with near-zero resistance, superconductors applied in power cables, transformers, motors, and other equipment promise greatly reduced energy losses and thus substantial gains in efficiency across the gamut of electricity delivery and utilization. One of the highest-value early-market utility applications—superconducting underground power cable—offers a strategic benefit to utilities as a key element for repowering existing delivery infrastructure.

by Taylor Moore

IN THE HEART OF THE RENOWNED industrial city of Detroit, part of an aging electricity delivery infrastructure is scheduled to be retrofitted with what could be one of the most important technologies of the twenty-first century. The installation and energizing of the world's first high-temperature superconducting (HTS) power cables in a utility network, set for the year 2000 at Detroit Edison's Frisbie substation, will be a pioneering demonstration of a likely early-market utility application of superconductivity. And for Detroit Edison, the principal operating subsidiary of DTE Energy, the project will test a strategy for upgrading its downtown underground distribution system.

Three 400-foot (120-m) HTS cables, cooled to below 77 K (−196°C) by liquid nitrogen circulating in their cores, will each carry 2400 A ac at 24 kV—three times the current carried by a conventional copper cable. Installed in existing 4-inch-diameter (10-cm) ducts, the HTS cables together will replace nine conventional cables. The reduction in conductor mass will be dramatic: over 18,000 pounds (8200 kg) of copper will be replaced by less than 250 pounds (110 kg) of HTS conductor—helically wound, silver-sheathed wire tape made from a ceramic copper oxide compound (BSCCO) containing bismuth, strontium, calcium, and a small amount of lead.

The flexible HTS cables will be installed by personnel from Detroit Edison and Pirelli Cables and Systems. Originating at the lower-voltage terminals of a 120-kV/24-kV transformer in the substation yard, the cables will run in the underground ductwork through several 90-degree bends to the three-story substation building, where they will connect with switchgear on the top floor. The installation will provide a realistic learning experience for crews that may eventually perform similar jobs throughout the city's downtown area, where Detroit Edison has about 1000 miles (1600 km) of underground cables that are possible candidates for replacement.

Catalyzed by major funding from EPRI and the U.S. Department of Energy under its Superconductivity Partnership Initiative with private industry, the $5.5 million Detroit HTS cable project will culminate nearly a decade of collaborative science and technology R&D led by Pirelli, the world's largest manufacturer of power cables; American Superconductor Corporation (ASC), a leading producer of HTS wire and technologies for power applications; and EPRI. In addition, the project is expected to receive a critical technological contribution from the cryogenic experts of Lotepro Corporation, a subsidiary of the industrial gas technology company Linde.

PHOTO PAGES 8–9 BY JOE CRACHIOLA © 1999 DETROIT EDISON

Detroit is experiencing a downtown revitalization, with major building projects under way or on the drawing board. Significant growth and shifts in the demand for electricity are anticipated over the next decade.

"It's gratifying to see the results of R&D that EPRI began in 1989 finally come to fruition in a utility-scale demonstration on a power system," says Ralph Samm, the manager for underground distribution who initiated EPRI's early work on developing HTS power cables for utilities.

DOE and EPRI previously cosponsored the development of a 50-meter flexible HTS conductor assembly manufactured by Pirelli with wire made by ASC. In tests conducted in 1996, the conductor assembly carried 3300 A at 1 μV/cm dc and 77 K—a world record that still stands. Then, using the same conductor, Pirelli developed a 50-meter cable prototype for operation at 115 kV. This prototype, including terminal connections and a splice, was successfully tested last fall at the company's high-voltage laboratory in Milan, Italy. Energized at 69 kV, it carried 3300 A dc at 74 K and has since demonstrated an ability to carry 2000 A ac.

Last October, in announcing DOE's collaborative R&D award of $2.4 million to the Detroit cable demonstration, Energy Secretary Bill Richardson said the project would open "the gateway to the electricity superhighway of the future. The contract builds on the department's significant investment in developing HTS technology over the last decade and paves the way to commercialization of a technology that will transform the power delivery systems of the world." Richardson said the project "will help the United States build and increase its competitive position in the emerging world market for HTS electric power applications."

Superconducting cable technology has promise as a cost-effective means of at least tripling the current-carrying capacity of existing underground distribution or transmission circuits, and its availability in the next decade could fortuitously coincide with the emergence of competitive retail electricity markets that are likely to place greater power transfer demands on regional and urban networks. "High-capacity HTS cables will accelerate the growth and increase the value of an open and competitive marketplace for electricity," said Greg Yurek, ASC's president and chief executive officer, at the time of the DOE announcement. Yurek also emphasized the importance of the Detroit project in "the commencement of the growth of a significant commercial market for HTS products."

Added Walter Alessandrini, chief executive officer of Pirelli Cables and Systems North America, "The Detroit Edison cable project is the first of several we expect to undertake in the next few years as the market for high-capacity HTS cables starts to grow."

Key for urban infrastructure renewal

Detroit Edison believes that high-current HTS cables rated at subtransmission and distribution voltage levels could be a technology solution for meeting the growing demand for electricity in Detroit's urban core while avoiding the wholesale replacement of underground facilities and the resulting disruptions at street level. "The cables will be installed in downtown Detroit to support the revitalization of this older urban area in a nonintrusive, environmentally friendly way," says Robert Buckler, president and chief operating officer of DTE Energy Distribution.

Buckler notes that major downtown building and renovation projects under way or planned for the near future—including casinos, office and shopping complexes, a new baseball park, and a new football stadium—will bring significant load growth and load shifts for the utility's downtown distribution system over the next decade.

"Having the capability to triple the current-carrying capacity of existing conduits will allow us to avoid digging up and disrupting the infrastructure," he says. "Soon after the turn of the century, the city's revitalization will have progressed to the point that we will need more power in the downtown area, and superconducting underground cables could have a very significant impact in bringing this extra power in."

Like Detroit, most other large U.S. cities are experiencing building booms and expect double-digit—in several cases, even triple-digit—population growth over the next dozen years, according to survey information reported at a recent conference sponsored by the Fannie Mae Foundation and the Brookings Institution. Such growth will undoubtedly increase the demand for electricity. But as John Howe, ASC's vice president for electricity industry affairs, notes, "The siting of new transmission lines has become progressively more difficult and is virtually impossible in many areas with high real estate values. And with downtown underground distribution, often there is simply no more room in the ground for new cable conduits."

Bill Carter, Detroit Edison's director of transmission and subtransmission planning, says the traditional approach would be to install new 120-kV pipe-type or solid-dielectric cables to increase power capacity in the downtown service area. "But that's pretty expensive," he notes. "If we can use existing ductwork and take advantage of the much greater current-carrying capacity of superconducting 24-kV cables, we may be able to avoid installing new 120-kV cables, eliminate the two transformation steps—from 24 kV to 120 kV and back down—and simply transmit power into downtown at 24 kV."

Energy losses that result from resistance in conventional conductors are reduced at higher voltage levels of power transmission and distribution. But this traditional solution for delivering more power requires new transformers and other substation equipment. In contrast, superconductors are nearly resistance free and can

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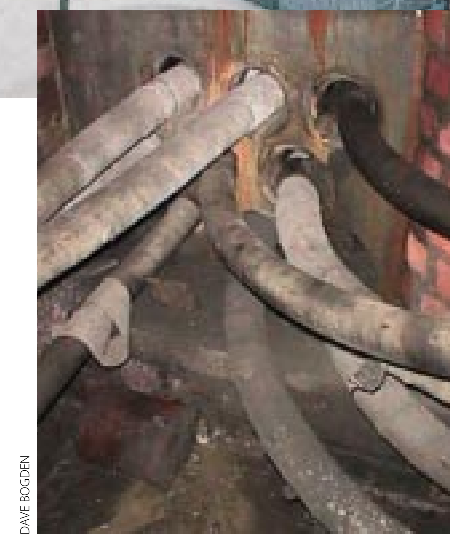


DAVE BOGDEN

Three 400-foot (120-m) flexible HTS cables will be connected to a spare transformer (foreground, top photo) in the yard of Detroit Edison's Frisbie substation, then will turn underground and snake through several 90-degree bends to connect with switchgear inside the substation. After conventional 24-kV copper cables have been removed from nine ducts in a substation duct bank (right), the 24-kV HTS cables will be installed in three of the ducts. Because these three cables can carry the same amount of current as the nine copper ones they will replace, six cable ducts will be freed up for possible use in meeting future load growth.

operate at high current levels with much lower losses. Thus the need for voltage transformation steps is reduced.

High-current HTS cables could help relieve transmission bottlenecks in existing corridors by eliminating the capacity limit posed by conventional underground cables (which can carry only about half as much current as overhead lines of the same voltage). Although more expensive than overhead lines, underground HTS cables could also serve as new circuits in existing overhead transmission rights-of-way where there is insufficient space for an additional overhead line.

EPRI and Pirelli originally envisioned 138-kV-class, pipe-type underground transmission cables as the most likely early-market entry for HTS cables. Indeed, many utilities still view high-voltage underground transmission as the most promising future application for HTS cables. But a more immediate need for which superconducting technology could provide a solution emerged in discussions with some utilities about hosting an HTS cable demonstration on a power system.

"Although EPRI and Pirelli had previously focused on transmission applications, from our joint studies we learned that several utilities were interested in high-current HTS cables as a means of doing things on their distribution networks that they had been unable to do before," says Don Von Dollen, EPRI's manager for underground transmission. "One of the utilities identified an application in which 13-kV HTS cables, carrying the same amount of power as conventional 69-kV cables, could eliminate a voltage transformation step in bringing power into its high-density-load downtown area. That, in turn, could eliminate some expensive substations and allow for more-compact substation designs."

Continues Von Dollen, "Another utility needed to tie several of its downtown substations together to enhance system reliability. Space constraints in the substations precluded using conventional 69-kV cables, and there was not adequate space in existing duct banks to install multiple 13-kV circuits. But 13-kV HTS cables could be installed in the banks to carry the additional current."

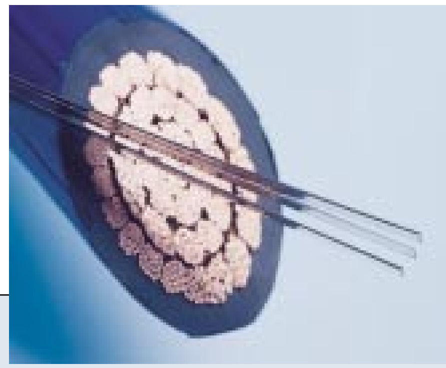
Given this utility feedback, it came as no great surprise when Detroit Edison's Carter described system operation challenges that called for high-current, 24-kV cables. "In some ways, our demonstration will be even more of a challenge for Pirelli than the 138-kV-class cable they have already designed, because now they have to fit a single-phase conductor into a 4-inch duct," says Carter. "For us, the greatest economic appeal is in maximizing the use of our existing infrastructure. The result will be reduced costs that ultimately will be reflected in lower rates for customers. If we can increase the distribution capacity downtown for less money largely by using existing assets, it will allow us to grow our system to meet customers' needs and better control our costs."

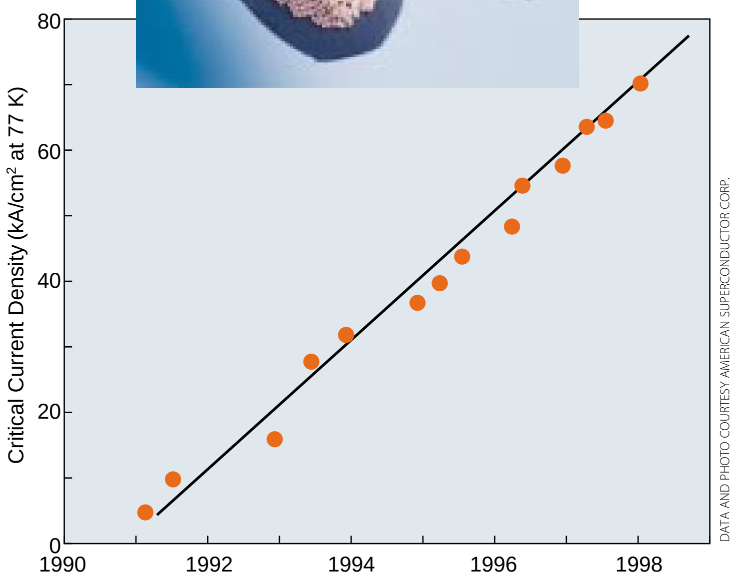
Realistic test environment

EPRI's Von Dollen says the Detroit Edison substation offers an almost ideal utility environment for demonstrating HTS power cable, including its installation, testing, routine operation, and maintenance. The three cables will be connected to a spare transformer that, when switched into the utility network, will expose them to surges and transients typical of a utility distribution system.

The substation's 60-year-old underground concrete duct banks are the same as those throughout the city. Replacing nine conventional cables with three HTS cables will leave six conduits available for possible future use. A manhole at the midpoint of the 400-foot (120-m) cable run will have just enough room for installing a splice on one of the three HTS cables—an invaluable demonstration exercise, since many splices will be necessary in longer, permanent installations. In the substation yard, there is room near the transformer at one end of the HTS cable run to install a liquid nitrogen refrigeration system, to be built by Lotepro Corporation.

Next year, under the supervision of Pirelli personnel, cable crews will install the HTS cables, and engineering personnel will develop operating and maintenance procedures that not only will be used for a two-year series of tests to determine cable reliability and O&M costs but also will serve as initial procedures for other utilities to follow. "This demonstration project is as real-world as it gets," says DTE Energy's Buckler. "It will encompass most of what we expect to encounter in the future if we decide to pursue a major HTS retrofit strategy.





American Superconductor continues to increase the critical current density of multifilament HTS wire manufactured with the ceramic copper oxide compound Bi-2223. Shown here are the values achieved in short lengths of the superconductor material, with a high of 70,500 A/cm^2 being reported last year. This steady progress has led to kilometer-length HTS wire tape that can carry 130 A; three such tapes now carry as much current as a 400-A conventional copper cable (photo).

Our people are excited at the prospect of learning how to do their work using the new, cutting-edge superconducting technology."

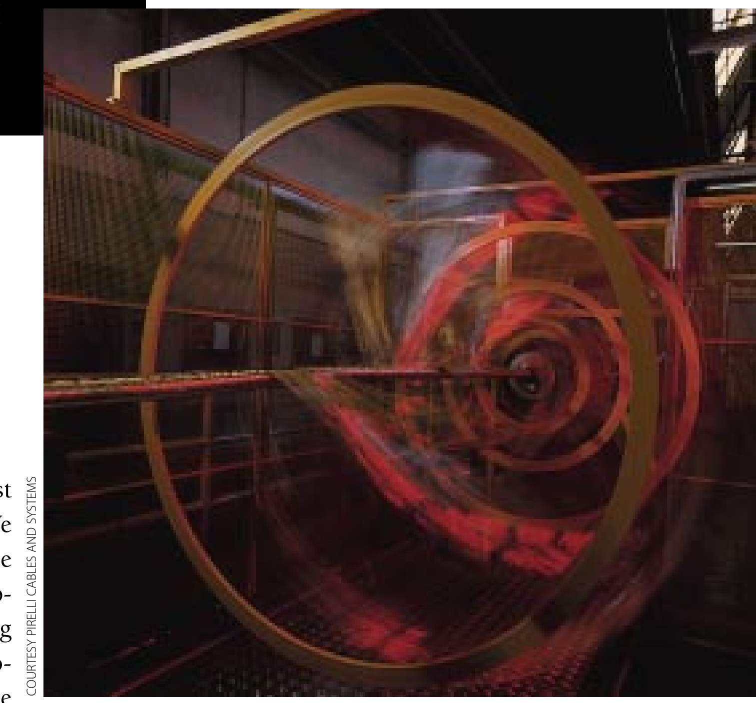
Adds Carter, "We will be one of the first utilities to get O&M experience with liquid nitrogen–cooled, HTS power technology—something we believe will be of significant value as HTS cables and other power products, such as fault current limiters and transformers, enter the commercial market. We've involved our O&M personnel from the outset in discussions with Pirelli and the project's other partners to address any safety concerns and procedures that must be worked out before the HTS cables are placed in service."

Notes Paul Grant, an HTS expert and science fellow in EPRI's Strategic Science and Technology group, "The most valuable, tangible results from the Detroit demonstration, in my opinion, will be the operating rules and insights that Detroit Edison will develop for using HTS cable technology. On the basis of prototype test results to date, I am confident that the technology itself not only will work but will be a slam dunk—with the possible exceptions of pulling the cable through the conduit bends and splicing a joint in the space previously used for conventional cables."

Cryogenic refrigeration technology based on cheap, environmentally benign liquid nitrogen is used in a wide variety of industrial and research applications. However, the utility industry's experience with the coolant has been limited primarily to its use for temporarily freezing dielectric oil in a cable to facilitate repair or splicing and as a spray for cleaning conductor insulators.

For the Detroit Edison HTS cable demonstration, Lotepro will engineer the refrigeration system to meet Pirelli specifications. The system will involve "well-proven and -tested components, although their arrangement in a system will be a first of a kind," says Hans Kistenmacher, president of Lotepro. In one likely configuration, he says, pressurized liquid nitrogen would be circulated in a loop and would be cooled at the refrigeration unit via heat exchange with pressurized helium. The helium would then be expanded in a high-speed turbine enclosed in a cryogenic coldbox before being returned to a compressor. The expansion turbine would run on frictionless gas bearings for highest reliability.

A guiding objective for a cable refrigeration system design is that it be economically optimal from the first unit's initial operation. "We want a system that will be practical for commercial operation, and so we are trying to achieve the optimal economic limit relative to the state of the art for copper cable in this application," says Kistenmacher.



American Superconductor's HTS tape is fabricated into a stranded conductor assembly by Pirelli Cables and Systems, using modified conventional-cable equipment. The machine on the right then wraps the conductor assembly with thermal insulation made of metallized polyester film.

Dielectric: warm or cold

Pirelli, which has identified superconducting power cables and fiber-optic communications as strategic technologies for its future business, is developing two basic HTS cable designs in separate efforts.

The design planned for the Detroit Edison project, an extension of previous work sponsored by EPRI and DOE, features a warm dielectric. In this design, hollow-core conductors contain pressurized liquid nitrogen, but the dielectric that electrically insulates the conductors operates at external ambient temperature and thus can be made from such conventional materials as fluid-impregnated paper, paper-polypropylene-paper laminate, extruded ethylene-propylene rubber, and cross-linked polyethylene. The flexible cables can be installed in a steel pipe and surrounded by pressurized dielectric fluid or gas or, as is the case in Detroit, encased with extruded solid dielectric.

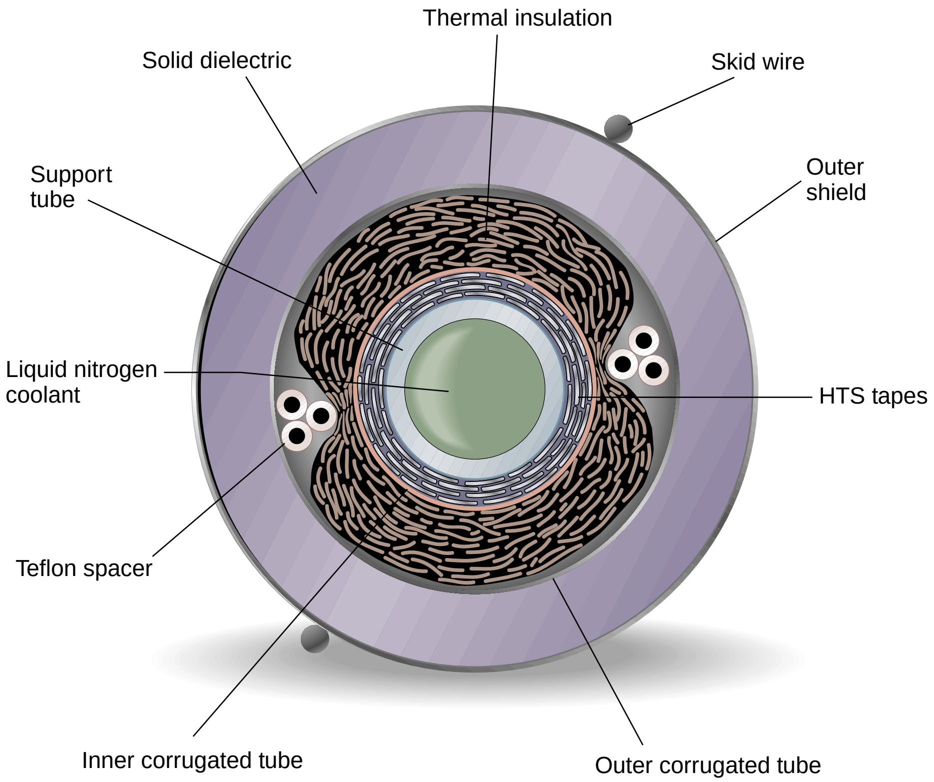
Also, under a 1997 agreement with Electricité de France (EdF), Pirelli is developing a 50-meter prototype of coaxial underground HTS cable in which the dielectric operates at cryogenic temperatures. In this design, one conductor is inside another; the two are separated by the dielectric, with liquid nitrogen circulating through the insulated pipe that contains the cable assembly. The neutral outside conductor creates a superconducting shield that repels the magnetic field from the primary conductor, meaning that electrical losses are even lower than with a warm-dielectric cable. Pirelli and EdF plan to test the cryogenic HTS cable prototype by late 2000. (In the United States, DOE is supporting a coaxial cable prototype development effort featuring HTS wire from Intermagnetics General. This effort is being led by Argonne and Oak Ridge National Laboratories and includes Southwire Corporation.)

Pirelli envisions offering the warm-dielectric design for applications of up to several hundred megavolt-amperes and the cryogenic-dielectric design for applications of 225 kV and up and current levels as high as 1 GVA (1000 MW of power). Candidate applications for both types of design exist in many utility markets, said Steve Norman, Pirelli's manager for the Detroit Edison demonstration, in an interview last November. "EdF has a particular application for dense, high-power urban penetration, so we are talking about a system at 225 kV carrying 1 GVA per circuit or, alternatively, one at 90 kV that probably would carry about 600 MVA." Norman added that, as a result of its 1998 acquisition of Siemens' power cable business, Pirelli is also developing a coaxial cold-dielectric HTS cable prototype in Berlin, Germany, for eventual demonstration there.

Interviewed just after the first electrical tests of the warm-dielectric HTS cable prototype were conducted in Milan, Norman said that success in the laboratory had shifted the focus to proving HTS cable technology in a utility network. "We've done about all that we can in the laboratory. Now Detroit is going to be the proof of the pudding. We're going to put the cable in the field and demonstrate to users that it can be applied in their environment. Once we have installed the cable and then maintained the performance of the superconductors—which is no trivial issue—the emphasis will be on operation. A key issue undoubtedly will be the refrigeration plant and its reliability."

Goal is to meet or beat copper

Pirelli anticipates several field trials of HTS power cables with utility users, beginning with Detroit Edison, before the technology enters commercial markets (perhaps as soon as 2003). The early prototypes and demonstrations are not expected to have installed costs competitive with those of conventional cables, which have benefited from a century of manufacturing know-how. But owing to expectations that ASC's HTS wire will continue to improve in performance and that the demonstrations will give a clearer picture of total HTS cable costs, researchers are optimistic that in commercial installations the cables will have a cost-performance ratio equal to that of conventional cables.



The 24-kV, 2400-A warm-dielectric HTS cables that Pirelli is planning to use in the Detroit Edison demonstration are based on an earlier design for a 115-kV solid-dielectric cable. Liquid nitrogen circulates through the hollow core of the HTS conductor assembly, and multilayer thermal insulation surrounds the conductor. The solid dielectric for the demonstration will be either extruded ethylene-propylene rubber or Pirelli tree-retardant cross-linked polyethylene.

"We must compare the total owning cost of the new superconducting cable—including losses as well as O&M costs for the refrigeration system and for the cable system overall—with that of conventional cable," says EPRI's Don Von Dollen. "The bottom line is that the cost of HTS cable has to be better than that of conventional cable."

The cost of superconducting wire dominates the cost of HTS power cables. According to EPRI's Paul Grant, there has been a general belief in the HTS community that to be cost-competitive in power applications, the basic manufacturing cost of HTS wire for operation at 77 K can be no more than $10 per kiloampere-meter (kA-m). Today's HTS wire, based on the BSCCO compound Bi-2223, costs several times that amount.

In a recent paper submitted for publication in a professional journal, Grant and colleague Thomas Sheahen of Science Applications International Corporation suggest that the cost-performance target of $10/kA-m "may be extremely difficult to realistically achieve for silver-sheathed BSCCO produced by the oxide-powder-in-tube [OPIT] technique." ASC, meanwhile, asserts that with full exploitation of large-scale production economies, including automation, the cost-performance target is attainable with current HTS wire technology.

"We suspect—in fact, we are convinced—there is no single cost-performance market-entry value whose realization would constitute a declaration of victory," say Grant and Sheahen. As an example, they conclude that in the case of high-current HTS power cables for retrofit installation, the potential value of urban real estate formerly occupied by intermediate-voltage step-down substations could justify a cost-performance ratio 100 times greater than $10/kA-m.

In a separate, parallel part of the EPRI-DOE cable demonstration project, Pirelli will make and test a 1-meter multistrand conductor featuring ASC wire that differs from BSCCO-OPIT wire both in HTS material and in fabrication method. The work will build on a large private effort undertaken by ASC and EPRI to commercialize this so-called second-generation HTS wire, made by growing thick (>1-µm) biaxial films of an yttrium barium copper oxide (YBCO) compound on flexible metallic tape. (The original HTS material, this compound was discovered by researchers in 1986 to be superconducting at liquid nitrogen temperature.) The ASC-EPRI effort benefited substantially from work at DOE's Oak Ridge and Los Alamos National Laboratories that demonstrated possible approaches to producing coated YBCO conductor.

PAGES 14–15: ORIGINAL SCHEMATICS COURTESY PIRELLI; RERENDERED BY ROB FITZSIMMONS

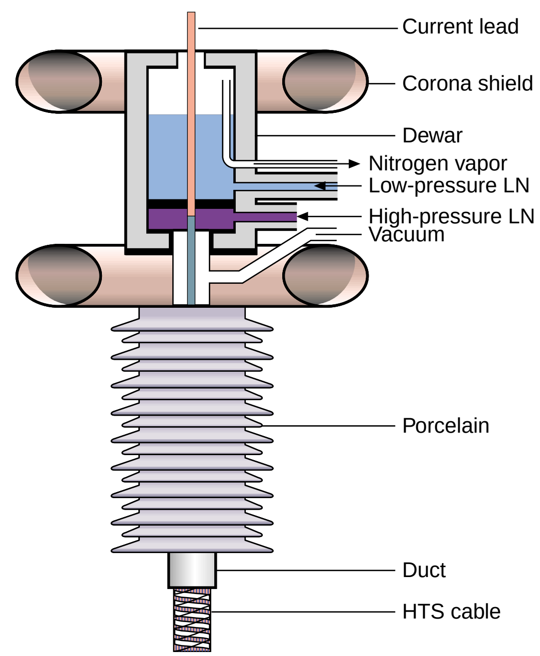
Pirelli successfully tested a 50-meter prototype HTS cable last November at its high-voltage laboratory in Milan, Italy. Designed for operation at 115 kV, the prototype system included terminal connections, a splice, and a pilot liquid nitrogen refrigeration unit. Energized at 69 kV, the cable carried 3300 A dc at 74 K and later 2000 A ac.

COURTESY PIRELLI CABLES AND SYSTEMS

According to Alex Malozemoff, ASC's vice president for technology, recent collaborative work by his company and the Massachusetts Institute of Technology—work sponsored under the alliance with EPRI—achieved low-cost deposition of YBCO films on single-crystal lanthanum aluminate. Films over 1 µm thick with a current density greater than 1 MA/cm^2 were produced. ASC has gone on to produce films 2 µm thick (carrying 1 MA/cm^2) and 0.8 µm thick (carrying 2.2 MA/cm^2).

"These results are important because they open up a new approach to achieving a truly low-cost manufacturing process for YBCO-coated conductor," Malozemoff and his colleagues reported at last year's Applied Superconductivity Conference. "Initial estimates indicate that at least a factor of two can be gained in cost-performance vis-à-vis BSCCO-OPIT. . . . YBCO-coated conductor technology lies further out in the development cycle but has the potential to open up a significant further increment in cost- or price-performance over BSCCO-OPIT, enabling a broader market for HTS wire in power and other applications."

The ASC scientists said that the different capabilities and characteristics of YBCO and BSCCO are likely to ensure an active market for both technologies in the future.



Pirelli has developed a basic termination design for HTS cables that channels the flow of high- and low-pressure liquid nitrogen (LN) and minimizes heat generation at the transition to conventional conductors.

Demonstrating the fruits of R&D

Phenomenal success in advancing the performance of high-temperature superconductors—discovered by IBM research physicists only 13 years ago—continues to spark media headlines and public interest. Yet definitive engineering conclusions as to whether these complex and even mysterious materials will, in fact, fundamentally reshape the technology of electricity delivery in the next century critically depend on the results of full-scale demonstrations in key applications—including power cables, transformers, and motors—over the next few years. EPRI is continuing a long-term commitment to commercializing HTS technologies that offer the greatest, most immediate benefits to electric utilities.

"EPRI focused early on a retrofit strategy for HTS cables—replacing copper cables in urban settings with high-capacity HTS cables, much as fiber-optic cables have been replacing copper communications cables," says EPRI's president and chief executive officer, Kurt Yeager. "Detroit Edison's leadership in opening up the urban market will provide a valuable experience base for all EPRI members, thereby helping to accelerate the acceptance of this new technology." ■

Background information for this article was provided by Paul Grant (pgrant@epri.com), Strategic Science and Technology, and Don Von Dollen (dvondoll@epri.com) and Ralph Samm (rsamm@epri.com), Energy Development and Utilization Division.