TECHNOLOGY WATCH

With Martin Pipe

We got the power!

It seems incredible as we tuck into the 21st century, but the physical property we know as 'superconductivity' was discovered way back in 1911, by the Dutch physicist H. Kamerlingh Onnes. At least he won a Nobel Prize in 1913 for his efforts. To recap, superconductivity is the characteristic of certain materials to conduct electricity with no resistance and no losses, when cooled to extremely-low temperatures. Kamerlingh Onnes discovered that the electrical resistance of mercury disappeared when the metal was cooled down to 4K (-452°F/-269Celcius). Superconductivity depends on three interdependent properties. The first is the 'critical temperature', which is defined as the maximum temperature below which a superconductor shows superconductivity at zero magnetic field and current. The second is the 'critical current', or the maximum current below which a superconductor demonstrates superconductivity at a given temperature and magnetic field. The critical current is defined by means of an electric field or resistivity (i.e., 1 μV/cm). Finally, we have the 'critical magnetic field', which specifies the maximum magnetic field below which a superconductor shows superconductivity at zero current and temperature. Figure 1 shows how the three are inter-related.

There has been significant research into superconductivity since this initial discovery, because there are obvious electrical engineering advantages. One can imagine electrically-powered public transport systems where energy wastage is reduced considerably. Another obvious contender is power distribution, which would be made vastly more efficient if superconductors were to be called into effect. Annually, megawatts of power are lost over the 13,891 km of power transmission lines operated by the National Grid company. It's much the same story elsewhere around the world. With natural energy resources dwindling, cutting down those losses makes a lot of sense. Superconductivity was only completely described in 1957, thanks to research conducted by J. Bardeen, L.N. Cooper and J.R. Schrieffer. The importance of their work was recognised in 1972, when they received a Nobel Prize. Much research was subsequently devoted into investigating materials that would exhibit superconductivity at higher temperatures. The practical implication is that less expensive cooling systems are required. K.A. Muller and J.G.Bednorz won the Nobel Prize in 1987 for discoveries made the previous year. Also in 1987, P.Chu and M.Kuev Wu discovered a new ceramic compound $YBs_2Cu_3O_7$-x. This material allowed cooling temperatures to be increased from 4Kelvin to 77Kelvin. Today, high-temperature superconductors (HTSs) that exhibit superconductivity at temperatures ranging from 20K (-423°F) to 130K (-225°F) are available.

Pirelli is a company best known for its tyres. The company also happens to be a major player in the power transmission cable market, and its products are supplied

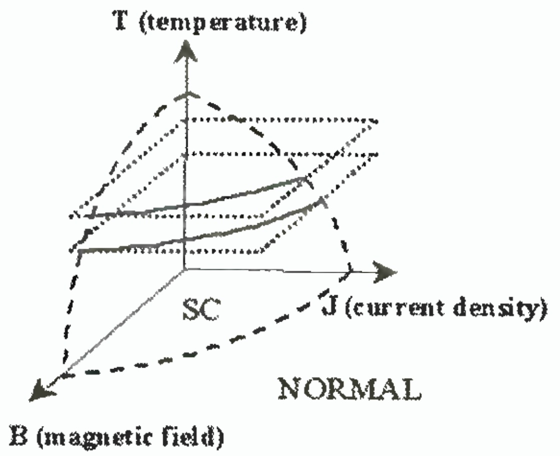

Figure 1. The interrelationship between critical current, critical temperature and critical magnetic field.

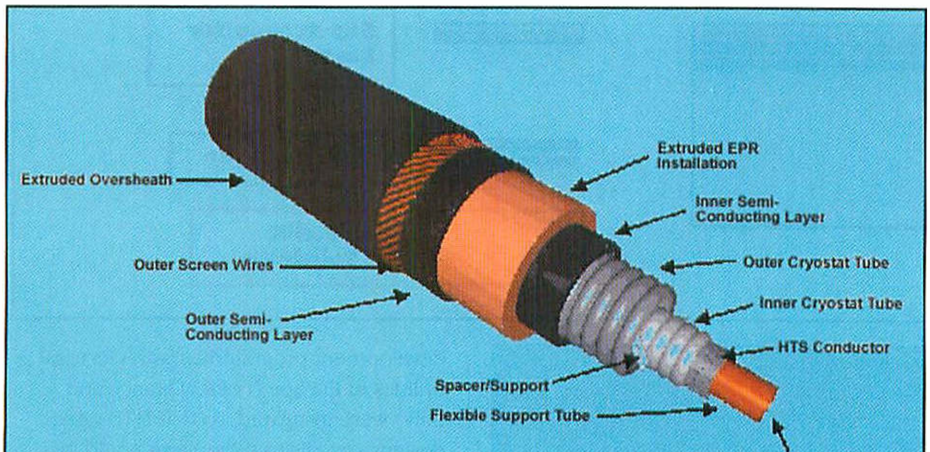

Figure 2. Component view of 'warm-dielectric' superconductor cable.

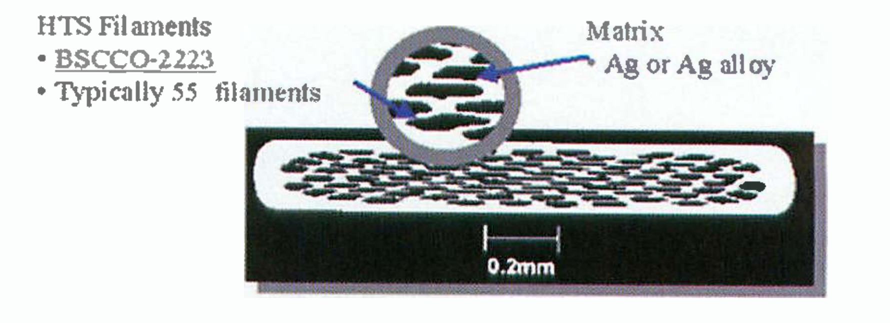

Figure 3. Construction of tape based around BSCO2223 HSC material

Figure 4. Construction of BSCO2223 HSC material.

to the National Grid amongst others. The discovery of HTSs prompted Pirelli to start its own HTS research programme with the eventual aim of commercially exploiting them as lossless power transmission lines. There were three phases, the first of which was to educate a new generation of researchers and engineers in the investigation of HTSs. They would then be encouraged to develop technologies for incorporating them into practical wires. Emphasis was given to the development and manufacturing of HTS 'tapes' that could stranded using machinery derived from that used for conventional cables. These tapes must be manufactured in long continuous lengths, and possess the mechanical and electrical characteristics to withstand cabling operations. In 1994, the second phase of the programme began. Pirelli completed the design of a 115kV, 400 MVA superconducting cable based around these tapes. The cable could be retrofitted to existing ducts with a diameter of 8 inches.

In 1995, Pirelli - together with the California-based Electric Power Research Institute and US Department of Energy - worked to develop this cable design into a working prototype. The temperatures involved are still extremely low (a few tens of K), and for this reason the ceramic superconductor is surrounded by a liquid nitrogen coolant. The cable in question was a 'warm-dielectric' type, shown in Figure 2. Here, only the HTS conductor assembly is enclosed in a cryogenic environment. An electrical insulation is applied over the flexible 'cryostat', which encloses the superconducting core and coolant. In addition to the required cryogenics, the partnership also worked on suitable joints and terminations. Similar development programmes with electrical utilities in Europe (notably France and Italy) were instigated, so that HTS cable designs specific to their needs could be developed. In 1998, the third phase began. This centred around setting up the first 'real world' HTS field trial in the US. A three-phase HTS system, currently being installed in Detroit Edison's electrical grid, is planned to start operation by the summer.

In this trial, a single three-phase cable circuit will replace three parallel sets of conventional three-phase cable. Superconductors can be thinner than conventional cables, on account of their lossless nature. Set against this, of course, is

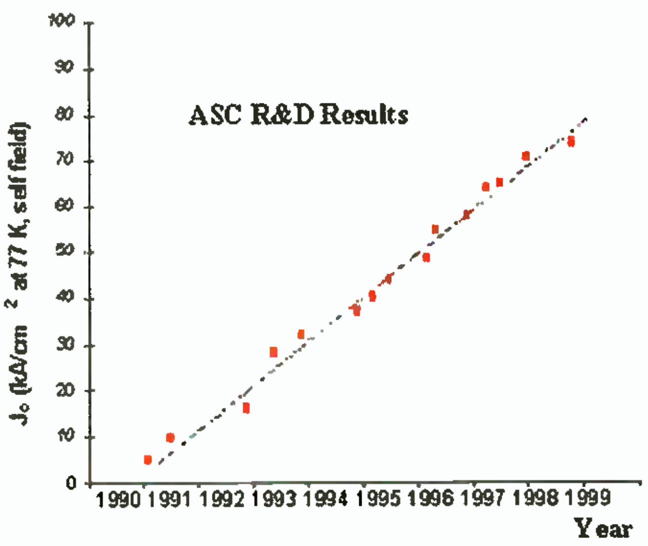

Figure 5. How American Superconductor Corporation's research has improved critical current density over time.

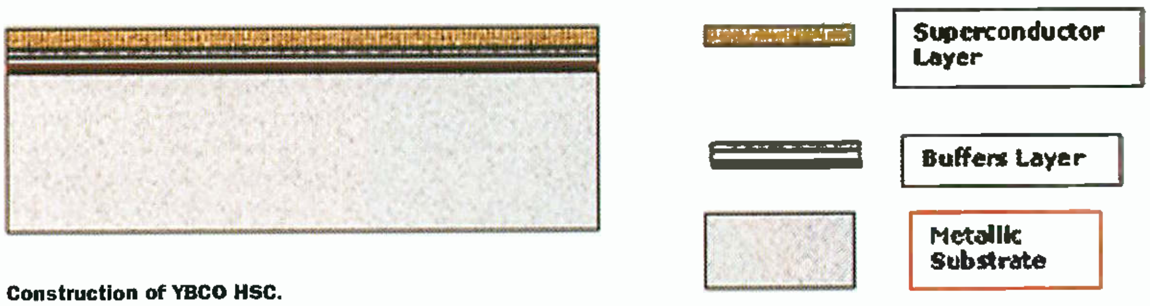

Figure 6. Construction of YBCO HSC.

Figure 7. Could conventional overhead cables be on their way out?
Photo courtesy National Grid Company

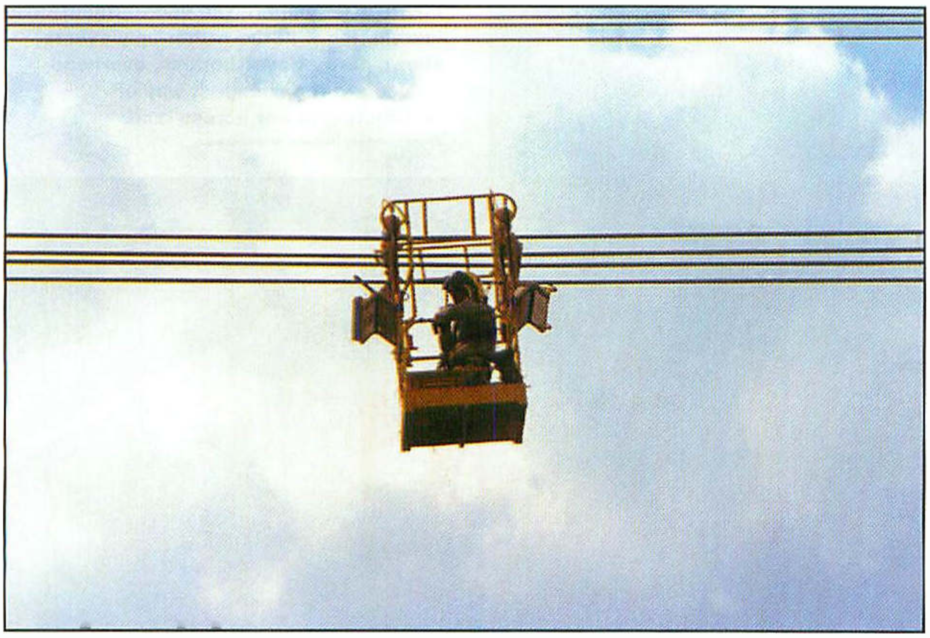

Figure 8. Checking conventional overhead cables. This job won't be as easy if they're buried underground!
Photo courtesy National Grid Company

Thickness	0.305 (+/-0.02mm)
Width	4.1 (+/-0.2mm)
Ic*	>100A
Je*	>8kA/cm2
Jc*	>37kA/cm2
Max Stress (@77K)	>300MPa
Max Stress	>265MPa
Max Strain**	>0.4%
Min. Bend Dia. **	<70mm

Ic = critical current, or the maximum current below which a superconductor exhibits superconductivity at a given temperature and magnetic field

Je = Engineering critical current density, or the ratio between critical current and tape cross-section

Jc = critical current density, or the ratio between critical current and superconductor cross-section

* at 77K   ** With 95% Ic Retention

Table 1. BSCCO-2223 specifications

all that cryogenic plant! Pirelli have developed two HTS materials. The first, BSCCO-2223, was developed in conjunction with the American Superconductor Corporation (ASC). It consists of HTS elements made up from a composite structure, where the superconductor filaments are embedded in a metallic matrix - refer to Figure 3. Power distribution cables need to be mechanically robust, and so tapes produced from BSCCO-2223 are reinforced by a thin layer of stainless steel on both sides of the HTS element as shown in Figure 4. Over time, research has improved the critical current density, or the ratio between critical current and superconductor cross-sectional area - refer to Figure 5. Development of the second material, YBCO, was started in 1999 - again in conjunction with ASC. YBCO, shown in Figure 6, is a 'coated conductor' - a ribbon-shaped wire, made by depositing thin films of intermediate materials (such as cubic zirconia) on ribbons of metals, followed by deposition of a thick (> $1\mu m$) superconducting layer.

A disadvantage of the current Pirelli HTS cables is that they're designed for laying in stable ducts or 'pipes'. It's unlikely that they'll withstand the forces that overhead cables - strung from pylon to pylon - have to sustain. The major stress points would be the pylon-mounted moorings at either end of the cable. Then there's the practical upshot of getting the coolant up there. Unless the technology is developed further, this leaves the power distribution industry in a bit of a dilemma. The obvious place to lay

Figure 9. One cannot deny that underground installation of power transmission plant doesn't have its advantages in areas of natural beauty.
Photo courtesy National Grid Company

pipes would be underground, but digging up the landscape is an extremely expensive process. Then there are the practical upshots. It might be difficult to obtain permission to lay these cables along the most logical route - and underground cables run the risk of being accidentally severed! Here in the UK, major power distribution cables - notably the cross-country 132kV ones that link rural power stations to urban substations - are overhead, obviously for ease of maintenance and speed/relative cheapness installation. Effectively, this section of the network would have to be completely replaced. Although the switch to underground cables would undoubtedly

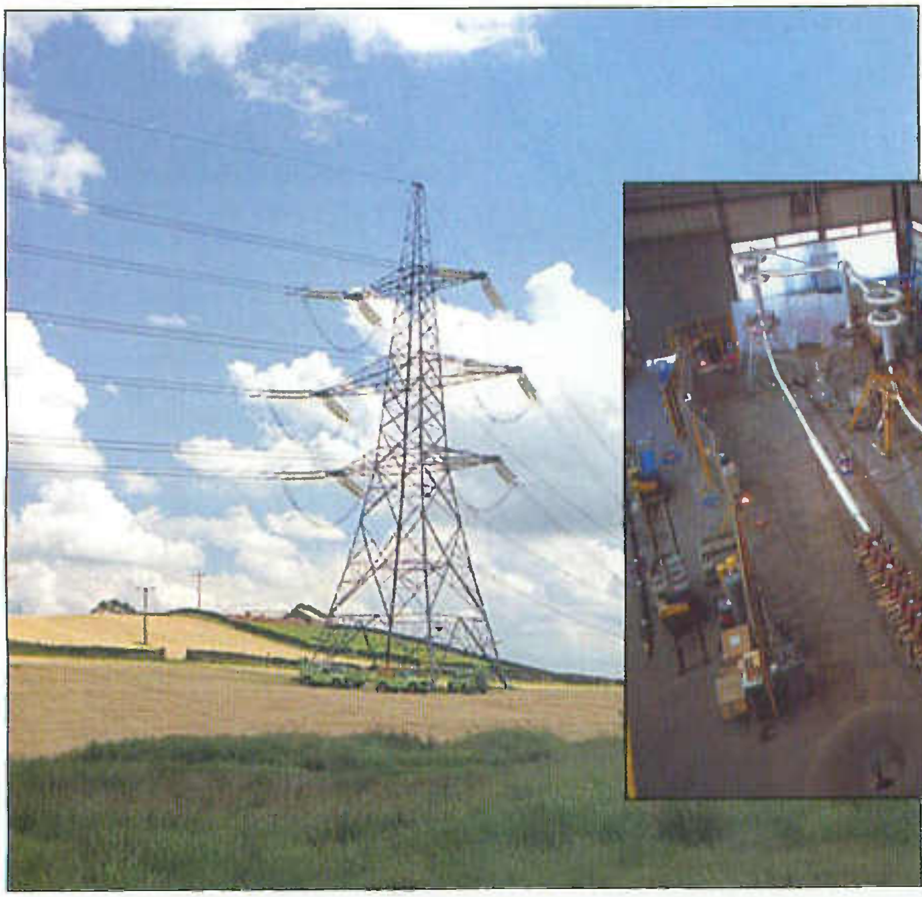

Figure 10. Compare the underground installation with the rather ugly pylons shown here. Nevertheless, overhead cables are the cheapest way of distributing power across land.
Photo courtesy National Grid Company

Figure 11. A length of finished superconductor power transmission cable, undergoing test.

make the landscape prettier, the costs would be astronomical. Would the privatised electricity industry be prepared to takes such steps? Although the increased efficiency - and elimination of some step-up/down transformers - would undoubtedly save money, the payback times would run into thousands of years! The cables alone aren't cheap. Pirelli's YBCO coated-conductor tapes have a projected cost of around $5/kA/m.

Figure 12. Applying the mylar insulation over the cryostat during cable manufacture.