Institute *of* **Physics**

RTRI

The Maglev train developed in Japan

Materials that conduct electricity with no resistance at accessible temperatures are poised to revolutionise communications, electronics and power supplies

Superconductivity

A copper wire looped with high-temperature superconducting tape which carries 100 times more current than an equivalent-size conventional copper wire

American Superconductor

VISIONS 9

BRIEFING PAPERS FOR POLICY MAKERS

Engineers examining the high-temperature superconducting coil for a 1000-hp motor

Superconductors come in from the

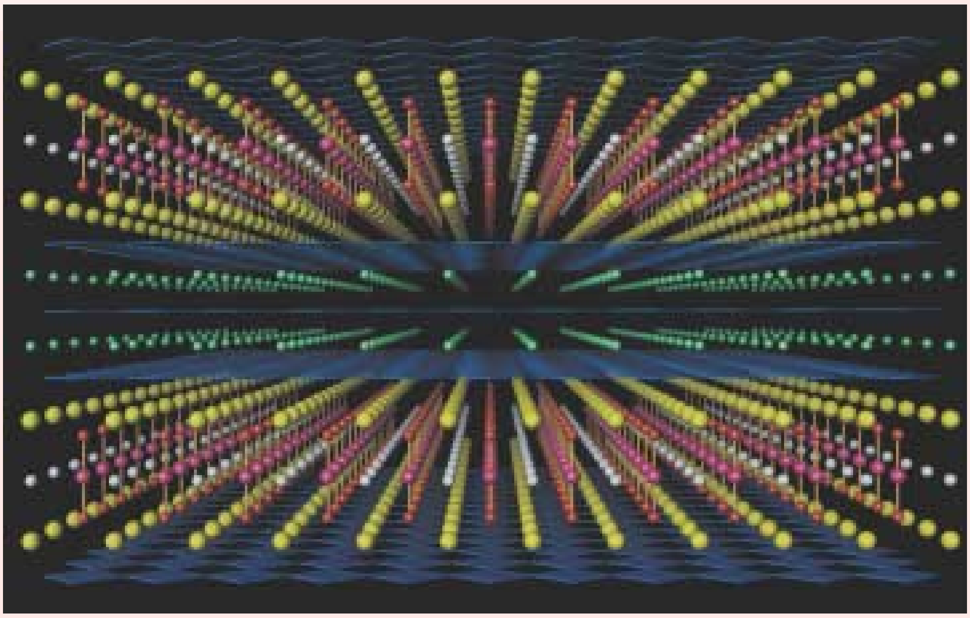
Ninety years ago a Dutch physicist Heike Kamerlingh Onnes showed that the electrical resistance of mercury when cooled below 4.2K (4.2 degrees above absolute zero) dropped to zero; the metal became 'superconducting'. Kamerlingh Onnes soon realised the practical and economic significance of this extraordinary behaviour. Electrical power could be carried by superconducting wires without loss, and incredibly strong magnetic fields could be created with superconducting electromagnets. In the following decades many other materials – mostly metals and alloys but also some unusual organic compounds – were found to have superconducting states, but only at very low temperatures attained by expensive cooling with liquid helium.

Then in the mid-1980s the physics world was set ablaze by news from two IBM scientists Georg Bednorz and Alex Müller that they had discovered a new class of ceramic superconductors. One of these compounds, containing yttrium, barium, copper and oxygen, became superconducting at the almost balmy 'critical' temperature (T_c), of 90K. In the ensuing frenzy of activity, more members of this layered cuprate superconductor family were identified, with T_cs ranging up to an astounding 133K. These discoveries opened the door to superconducting conductors and devices cooled by much cheaper liquid nitrogen.

Superconducting magnet technology using liquid helium was already well established for specialist applications. Companies such as Oxford Instruments make powerful low-temperature superconducting magnets, based on conventional superconducting alloys, for hospital scanners, analytical equipment and particle accelerators (see *Visions* 6 and 7). And the Japanese have already developed an ultra-high-speed train using superconducting magnets to levitate and drive the train. The high-temperature superconductors looked set to revolutionise not only these applications but also to create exciting new technologies. There were snags, however – the materials were initially less easy to fabricate than metals, and because of the poor contacts between the irregular fine grains of the early ceramic materials, they could support only a small supercurrent.

Many of these problems have since been overcome. Thin films supporting very high supercurrents can now be grown. Wires can be made by packing a bismuth-based superconductor into silver tubes which are then heated and rolled to make a more uniform microstructure.

The structure of the highest T_c superconductor so far discovered – $HgBa_2Ca_2Cu_3O_8$



M.O. Jones, I. Gameson and P.P. Edwards

Thanks go to Colin Gough of Birmingham University, Andy Mackenzie and Stephen Lee of St

These wires also have poor thermal conductivity and are already used as current leads for the ultra-cold superconducting magnets, much reducing the refrigeration power required.

Applications

American Superconductor

The most important early application of high-temperature superconductors has been in communications. Combined with low temperature electronics at 60K, superconducting thin-film devices (microwave filters) enhance the performance of

cold

mobile telephone systems giving greater sensitivity, selectivity and protection from ‘drop-outs’. There are at least four American start-up companies successfully exploiting this technology, one of them using materials developed in the UK. A British company, Cryosystems, employing filters developed at Birmingham University, aims to commercialise such systems in Europe and Asia.

Another exciting application goes to the quantum heart of superconductivity. The magnetic field, or flux, passing through a small loop of superconducting material is quantised and can be used to represent the 1s and 0s on a digital computer. This is the basis of an entirely new kind of very low power switch, called a rapid single flux quantum (RSFQ) device, which could revolutionise computing. RSFQ circuitry operating several hundred times faster than today’s most advanced computers has already been demonstrated. It could be an attractive route towards the petaflop computer capable of doing 10^{15} arithmetical operations a second, requiring only a kilowatt of power rather than the megawatt quantity currently envisaged using silicon technology.

Related devices called superconducting quantum interference devices, or SQUIDs, can be used diagnostically to detect the minute magnetic fields produced by the brain or heart, while other variations of this superconducting technology are employed in ultra-sensitive microwave communications, astronomy, and analysis for the pharmaceutical industry.

Superconducting power

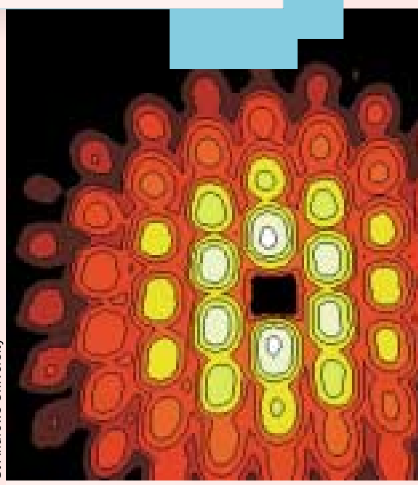
The real superconductor revolution that everyone is awaiting is the application of the high-temperature materials in the power industry. Thanks to the development of suitable wires, superconducting power cables are on their way. Companies in the US, Europe, Japan and Australia are producing nitrogen-cooled multi-wire cables that can carry up to around five times more power than conventional copper wires of the same dimension. Pirelli and American Superconductor are, for example, developing a major superconducting cable to replace old power lines going into the heart of Detroit.

High-temperature super-conductor coils are being developed for large industrial motors such as pumps and compressors which will be much more efficient, with much lower power losses. The compactness and lightness of these motors also makes them ideal for propelling ships. Other important applications include generators – a market worth $20-30 billion over the next 10 years, energy storage, transformers, and fault current limiters that protect power grids from current surges, like lightning strikes which can lead to large areas of network failing.

The future for all these superconducting technologies looks rosy. By 2020 they are expected generate markets worth many tens of billions of dollars. In the meantime, continuing investment at the research level is essential – not only in developing new materials, improved processing routes and creative engineering design, but also in understanding what gives rise to high-temperature superconductors (see Box). Progress on all these fronts could lead to even brighter prospects for applications.

A NEW ERA FOR CONDENSED MATTER PHYSICS

The high-temperature superconductors present a major theoretical challenge. Even their ‘normal’ conducting properties are a puzzle. In conventional low-temperature superconductors, superconductivity is successfully explained as pairs of electrons interacting with vibrations of the material’s crystal lattice. In the high-temperature superconductors the electronic pairing is still there but theorists don’t yet agree on its nature. The copper-oxide layers in the material seem to be the key, but unlike conventional metals and semiconductors, the electrons appear to interact very strongly, such that simple descriptions based on quantum mechanics developed over the past 70 years no longer work. Theorists have therefore had to develop more sophisticated models, which are equally applicable to a much wider class of materials in which these strong electronic correlations are important – such as the GMR (giant magneto-resistance) materials already in use in the magnetic digital recording industry (see *Visions* 5). These new mysterious insights into Nature’s workings are bound to reap rich rewards in the future. Just as exciting is the fact that new superconducting materials continue to be unearthed – such as the recently discovered magnesium diboride with a T_c of 40K which surprisingly behaves like a conventional superconductor.



St Andrews University

UK researchers are leading the world in studying and controlling the phenomenon of ‘vortices’ which arise in so-called type II superconductors (such as the high-temperature superconductors) and, if mobile, can severely limit their ability to conduct. The image here shows a triangular vortex lattice in superconducting niobium as revealed by neutron diffraction (similar to X-ray diffraction, but sensitive to magnetic structures)

ANDREWS UNIVERSITY AND SIMON BENDING OF BATH UNIVERSITY FOR THEIR HELP WITH THIS PAPER

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