work in a regular array of parallel, square-based rectangular parallopipeds as b/a (height divided by base) varies. The volume fraction of porosity is calculated as a function of R , a and b , and the Rayleigh-type analysis predicts instability for $b = 2l_c = 4\pi R$. The analysis shows that for $b = a$ (an equiaxed grain) the critical porosity to permit a stable channel network is 5.2–5.5 per cent, in accord with experiment. But as b/a increases, the critical porosity for channel instability rapidly rises to 10 per cent for $b/a = 2$, and 40 per cent for $b/a = 4$.

In fact, practical fuel elements, with highly elongated grains, typically show porosities of only a very few per cent, and this can be so only if no channel network exists. The conclusion is that the very

pronounced grain elongation ($b \gg a$), that always accompanies the burn up of highly rated fuel is in fact an excellent natural safeguard for the integrity of the fuel, preventing the release of radioactive fission gases. Nature, it appears, does not have to be green to be benevolent. □

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Superconducting ceramics

Applications just beyond reach

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SUPERCONDUCTIVITY may seem to be a single topic of specialist interest, but a recent conference* was attended by solid-state physicists and chemists, materials scientists, and electrical engineers interested in microelectronics and power. This breadth of representation illustrates graphically the wide-ranging appeal of the new and exciting developments.

It was emphasized (M. Rice, ETH, Zurich) that transition-metal oxides are indecisive beasts, rarely content to remain as simple metals; instead, they are susceptible to spin-density waves, or charge-density waves, or some other form of electronic ordering. So, although some groups claim that undoped La_2CuO_4 is superconducting, others suggest that superconductivity occurs only if the sample is slightly off-stoichiometry, or contains impurities. $\text{YBa}_2\text{Cu}_3\text{O}_x$ appears to be an extraordinarily robust compound; by now it must have been made by hundreds of research groups, and all are agreed that it becomes superconducting within a degree or two of 92 K. But in its normal state, is it a simple metal? The normal-state resistivity is sufficiently high (Rice), approaching 10^{-3} ohm cm, that electron-phonon scattering is unlikely to be responsible for the observed linear dependence of the electrical resistivity on temperature.

Careful and systematic work (K. A. Muller, IBM, Zurich) has shown that both the $(\text{La}, \text{Sr})_2\text{CuO}_4$ and $\text{YBa}_2\text{Cu}_3\text{O}_x$ compounds have jumps in their specific heat capacity at the superconducting transition temperature. In sharp contrast to the behaviour of conventional superconductors, however, his data suggest that in the new

materials, a linear term in the electronic heat capacity survives to low temperatures. Although other mechanisms might be involved, this could imply that there are two mechanisms that co-exist, one with a gapless spectrum of electronic states and the other with the gap seen by tunnelling and other experiments.

The role of oxygen in the lattice is of vital importance and the details remain to be established. It appears that the highest transition temperature is in stoichiometric $\text{YBa}_2\text{Cu}_3\text{O}_7$, but that ordering of oxygen vacancies where they exist may be important. Perfect single crystals were not reported, but small crystals with parallel c -axes twinned in the basal planes were (G. Balistrino, Rome). As the difference between the a - and b -axes is small, these are good approximations to single crystals.

All the bulk samples contain grain boundaries that are relatively wide and amorphous. It is not clear at present whether this is because of impurities or because of disordering of the superconducting phase itself, but it has a crucial effect on the superconducting properties and is the main obstacle to the use of these materials.

In many ways it is not the high critical temperatures of the new materials, but their high critical fields (which quench superconductivity) that are their most spectacular property. At 9 tesla (T) the critical temperature for the perpendicular orientation was reported to be 87 K (H. Takagi, Tokyo), although an anisotropy of a factor of 5 means lower critical fields parallel to the base plane and thus it will be necessary to orientate the material to make the most of its properties. At 95 T, the magnetic energy is 4×10^9 J m $^{-3}$, corresponding to a pressure of 4,000 MPa.

Although the technical problems are formidable, these figures illustrate some of the potential of these materials.

The achievement of high critical-current densities remains the obstacle to the use of new materials. Magnetization measurements show that these are conventional type-II superconductors to which earlier theories can be applied, and therefore the problem is one of sample preparation. The material should be able to carry 10^4 A cm $^{-2}$ in 10 T. Current densities up to 10^6 A cm $^{-2}$ within the grains were measured at 4.2 K, but insulating or amorphous layers between the grains prevent the current passing between them. This problem also occurred in thin films (A.M.C.) and appears to be more acute in oxide superconductors than in traditional intermetallic compounds. There are several promising processing routes that should break up these layers (such as hot isostatic pressing) but much work is needed to get the conditions right. Considerable progress has been made in the production of multifilamentary wires, but again contact between grains is poor and, so far, current densities are low.

Rather surprisingly it has been found that lumps of oxide behave as superconducting quantum interference devices (SQUIDs) that are used for sensitive magnetic-field measurements, without any special processing (see Colclough, M.S. *et al. Nature* **328**, 47–48; 1987). Calculations show that they should have a similar performance to liquid-helium-temperature SQUIDs (C. M. Pegrum, Strathclyde Univ). For better control, and microcircuit applications, it will be necessary to produce thin films and one group (M. G. Blamire, Cambridge) was able to show sputtered films, or material, etched into device structures. The oxide barrier was too thick to show tunnelling characteristics and work is continuing in order to produce narrower resistive transitions and thinner barriers.

The large-scale applications for high-temperature superconductors depend upon the availability of wire or ribbon that can carry large currents and be wound into coils. If it is assumed that these materials are available it is possible to achieve some notable improvements in the marketability of large-scale devices. The key to this is that industry is used to handling liquid nitrogen but not liquid helium. In general, the cost of motors, generators, cables, levitated transport, fault-current limiters and so on will be reduced but the greater reliability that results from simplified designs will be the spur to greater investment. □

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