HIGH TEMPERATURE SUPERCONDUCTORS AS A TECHNOLOGICAL DISCONTINUITY IN THE POWER CABLE INDUSTRY.

T P Beales and J S McCormack

BICC Cables Ltd, Superconductivity Group, Hedgeley Road, Hebburn, Tyne and Wear NE31 1XR, England.

ABSTRACT

The advent of superconductivity above 77 K represents to the power cable industry a technological discontinuity analogous to that seen in the copper telecommunications industry by the arrival of optical fibres. This phenomenon is discussed along with technical criteria and performance targets needed for high temperature superconducting wire to have an economic impact in transmission cables.

1. TECHNOLOGICAL DISCONTINUITIES: A COMPARISON

Analysis of the emergence of high temperature superconductivity in the cable industry has strong parallels with that already seen for optical fibres [1]. Both innovations represent a discontinuity in which a known technology can be displaced by a new process which is superior in at least one performance criteria. This presents both new opportunities for business but is also a threat to established markets and careful management of the technological change with adoption of appropriate technological strategies is required for commercial success [2,3].

Utterback and Kim have defined technological discontinuities invading stable businesses as four basic types [4]. Type 1 can be described as a Product-Process discontinuity which involves a brand new product and manufacturing process. An example of this is the introduction of transistors to replace vacuum tubes in the electronics industry. Type 2 is a Product discontinuity where a new product using similar or existing manufacturing skills replaces an existing one. An example is the replacement of components with discrete transistors by integrated circuits. Type 3 is the Process discontinuity where an old product is made using a new manufacturing route. An example is the replacement of open hearth furnace by oxygen processing in steel making. Type 4 is the Process-Product in which an existing product is made by a radical new manufacturing route which totally changes the companies' manufacturing. An example of this is the introduction of quartz watches over clockwork products.

High temperature superconductivity can be defined as a totally new product *vis à vis* copper wire. The manufacturing methods used to form high temperature superconductors from MOCVD to powder-in-tube are established manufacturing routes in industries as diverse as semiconductors to fire-proof cabling but not in an established electro-ceramic superconductor industry. We can define high temperature superconductivity as a type 1 case ie a Product-Process discontinuity which is the most difficult type to manage successfully. Each of the industry players will regard this transition as being different in magnitude and scope and will enter into it carrying a different technological baggage. This will affect their psychology of perception as to the threats and opportunities of high temperature superconductors.

Using the analogy with the development of optical fibres we can group the industry players into five categories based on each companies technology background in telecommunications or power industry for the case of optical fibres and high temperature superconductivity respectively. Group 1 is the outsiders, typically materials manufacturers. In telecommunications these were companies like Corning, Du Pont, Hereas and Pilkington, in electrical transmission they are Du Pont, ICI, Hoechst, Merck etc. Group 2 are the service industries. In telecommunications these were AT&T, GTE, GPO and in power transmission these are US utilities, National Power in the UK, EDF in France and ENEL in Italy. Group 3 are the cable manufacturers which in telecommunications were Times Wire and Cable, Belden, General Cable, BICC, Pirelli and GEC and in Power transmission are BICC, Pirelli, Siemens, Alcatel, Sumitomo. Group 4 can be classed as traditional companies which for the telecom case were the illumination fibre companies such as American Optical Corp and Galileo and in superconductivity are the conventional superconductor companies such as Oxford Instruments, IGC and Furukawa. The final category Group 5 are start-up companies. In telecoms these were companies like Spectran, Fibronics and Valtec and in superconductivity are represented by companies such as American Superconductor Corp.

In optical fibres of the five groups above, the ones who perceived the smallest product-process discontinuity were the first to move. Companies like Corning had relevant R&D expertise in glass technology and so the transition for them was smaller than for companies like Times Wire and

Cable who did not. The most radical innovations in optical fibres came from groups 1 and 5. In high temperature superconductivity, close parallels are being observed and the most successful alliances for power cables are likely to be cablemakers allied to a non-cablemaker who perceives a small technological discontinuity in the introduction of high temperature superconductors.

2. SUPERCONDUCTING CABLES

The market for power cables is a large one, in the UK alone for low and high power cables the market size is above £ 13,000 million [5]. Studies and prototypes in the 1960s and 1970s using niobium alloys targeted superconductivity having an impact on the high power end of the transmission network. This is serviced by supertension cables which can be defined as a cable which operates with a conductor above ambient temperature at an operating voltage of 132 kV and power rating of 300 MVA and above. In this design heat flows out from the conductor to the external ambient and the conductors are subject to thermal expansion forces. The cable may need to be force cooled by using oil or gas down a central duct. We can compare this with a superconducting cable which has a conductor far below ambient and so has a net heat flow from the ambient to the conductor, requiring an insulation layer, and is always force-cooled. The operating voltage is not as well defined yet but is certain to be lower than for a conventional cable. For conventional cables at levels of 1 GVA the heat generated in a supertension cable may be as high as 2×10^5 Wkm^{-1} making force-cooling inevitable and therefore a superconducting design an attractive alternative. Low temperature superconducting cables were and are uneconomical except at power levels higher than needed (3-5 GVA) [6,7].

The advent of the new ceramic high temperature superconductors changed the operating temperature of a superconducting cable and the situation was reviewed once again in the hope that the reduced refrigeration costs may alter the economics of superconducting cable installation. Also in the interim period between low and high temperature superconducting cables, environmental aspects regarding siting of overhead lines and right-of-way issues in congested urban areas have become prominent. In this aspect a superconducting cable has advantages in (i) no soil contamination from oil leaks (ii) thermal insulation superconducting cables do not affect surface vegetation, (iii) for the same power a superconducting cable is smaller than a conventional cable occupying less land, (iv) external magnetic fields can in principle be eliminated in a superconducting cable and (v) there is a low fire risk with a superconducting cable.

3. TECHNICAL REQUIREMENTS FOR SUPERCONDUCTING TAPES IN CABLES

The technical challenge for high temperature superconducting cables remains in the fabrication of the superconductor itself. The past work on helium-cooled cables has solved many of the problems with cooling and design and advances in dielectrics since the 1960s have answered many questions regarding suitability at cryogenic temperatures.

Techno-economic studies of the performance requirements for high temperature superconducting wires to be economical in transmission cables have taken place in Europe [8], Japan [9] and the USA [10]. The European study concentrated in two areas (i) a newly installed high power cable at 1 to 3 GVA optimised for maximum efficiency and (ii) a medium power rated cable of 0.5 GVA optimised for maximised efficiency at a fixed diameter. In this study, the values for an economical breakthrough for transmission cost (expressed in MVA per km) of the critical current density of the superconductor wire would need to be 2 x 10^9 Am^{-2} at 77 K and self-field [11]. For the three oxide superconductor systems these Jc values have been reached using thin film deposition techniques. However, problems with scale-up to long lengths seem to be very problematical for techniques used. The most promising for making long lengths of viable conductor seem to be techniques such as Doctor Blade [12] and powder-in-tube [13]. The jury is out on the thallium containing compounds at present but high Jc values of 9 x 10^8 Am^{-2} have recently been reported using a spray pyrolysis technique [14] which could be envisaged to be easily scaled up to longer lengths.

By far the greatest effect on economics is the Tc value and if this can be increased even nearer to room temperature then the breakeven point becomes much lower. Recent reports on a Tc value of 250 K in the bismuth-containing cuprate system may prove to be another breakthrough in this area [15].

In the absence of any new breakthrough in Tc, the system most likely to be used in a cable system appears to be the (Bi,Pb)-2223 system with a Tc of 108 K and operable at 77 K in a high current low-field application like a transmission cable. This material is also amenable to powder-in-tube manufacture, a well-known technique industrially and relatively cheap for a high-tec operation and already 1 km wires are being made [16]. The powder-in-tube technique is also preferred as it allows a degree of mechanical integrity to the superconductor either by increasing the number of filaments or by alloying the silver with another metal such as magnesium [17] showing bend strains up to 0.2 %. Ac losses in filaments have also been found to be acceptable for ac cable operation at 50 - 60 Hz using a braided multistrand approach [18].

So the technical objectives for the implementation of high temperature superconducting wires in operational transmission cable systems appear to be close to being achieved. There are many factors that influence this. One analysis has been to calculate the cost of the superconductor using a powder-in-tube process with "bulk" powder values and estimating associated conductor losses.

Fig 1 shows a graph of the calculated transmission cost in units of ecu $kW^{-1}km^{-1}$ against the cost of producing the conductor for cables in units of ecu $kA^{-1}m^{-1}$. These costs are for the optimised high power cable in the European study [11]. For clarity these have been simplified in this graph to show three cases with Jc values of 1×10^9, 1.5×10^8 and 0.5×10^8 Am^{-2} respectively. These results are compared to a single core oil-filled cable 400 kV, 1000 MVA rating (solid line). The most interesting fact found by relating the conductor costs in units of ecu $kA^{-1}m^{-1}$ is that a breakeven Jc can be estimated for a range of wire properties and operating conditions. These results show that for conductor costs below 100 ecu $kA^{-1}m^{-1}$ the transmission costs are dominated by the ancillary equipment such as installation and coolers etc. For values near to 1000 ecu $kA^{-1}m^{-1}$ the wire would constitute near to 60 - 70 % of the cost of the cable, while at values near to 10 ecu $kA^{-1}m^{-1}$ the wire would be less than 5 % of the total cost of the cable.

Fig 2 shows a plot of operating Jc in Am^{-2} against the cost of the conductor in ecu $kA^{-1}m^{-1}$ for the optimised high power cable at a rating of 1000 MVA and the replacement medium power superconducting cable operating at 400 MVA *compared with the equivalent copper cable system*. The European study [11] found that there were three factors in high temperature superconducting wire manufacture that may influence the use of the product in cables:

1. Advances in the critical current density toward 10^9 Am^{-2} for a process that can be scaled to industrial production

such as powder-in-tube. This would tend to move the graphs up the y axis in Fig 2.

2. Process route economies that reduce the overall cost of production for the superconductor tape ie reduction of processing time of the (Bi,Pb)-2223 tape for example. This would move the curves to lower conductor cost values along the x axis in Fig 2.

3. Identification of new products that could benefit from the technology as it know exists. Such an approach is the EPRI-cable to retro-fit pipe-type cables [10]. This has the effect of moving the two curves closer together in Fig 2.

Fig 3 is a further representative breakdown which shows the conductor Jc in Am^{-2} versus the absolute cost per unit length of the conductor in $kA^{-1}m^{-1}$. This was taken to be a typical monocore tape of the type made in most laboratories by rolling or pressing with dimensions of 2 mm x 50 μm. It was also assumed that a factor of 2.5 in the ratio of superconductor cross-section to current density to allow for uneven current distribution. These curves give a good idea of the actual manufacturing costs needed for a high temperature superconducting tape to be economical in power cable systems.

4. CONCLUSIONS

High temperature superconductors represent a technological discontinuity in the power cable industry and a potential threat to the high power supertension cable area especially.

Technical requirements of powder-in-tube samples are nearer the specification required for economical operation at 77 K.

The best performance so far of these wires is in the order of 6 x 10^8 Am^{-2} for short pressed samples, and in long lengths (100 m +) this has been shown to be 1 to 2 x 10^8 Am^{-2}. These values are close to the Jc(operational) values needed for transmission cables which typical one would expect to be near 50 % Jc at 77 K, 0 T. The European cablemakers view is that an operational Jc for a new optimised high power cable would be 2 x 10^8 Am^{-2} for a wire price of 60 ecu $kA^{-1}m^{-1}$ and for a retrofit medium power fixed diameter cable the same Jc would need wire price of 400 $kA^{-1}m^{-1}$ making it an attractive first solution for high temperature superconducting cables.

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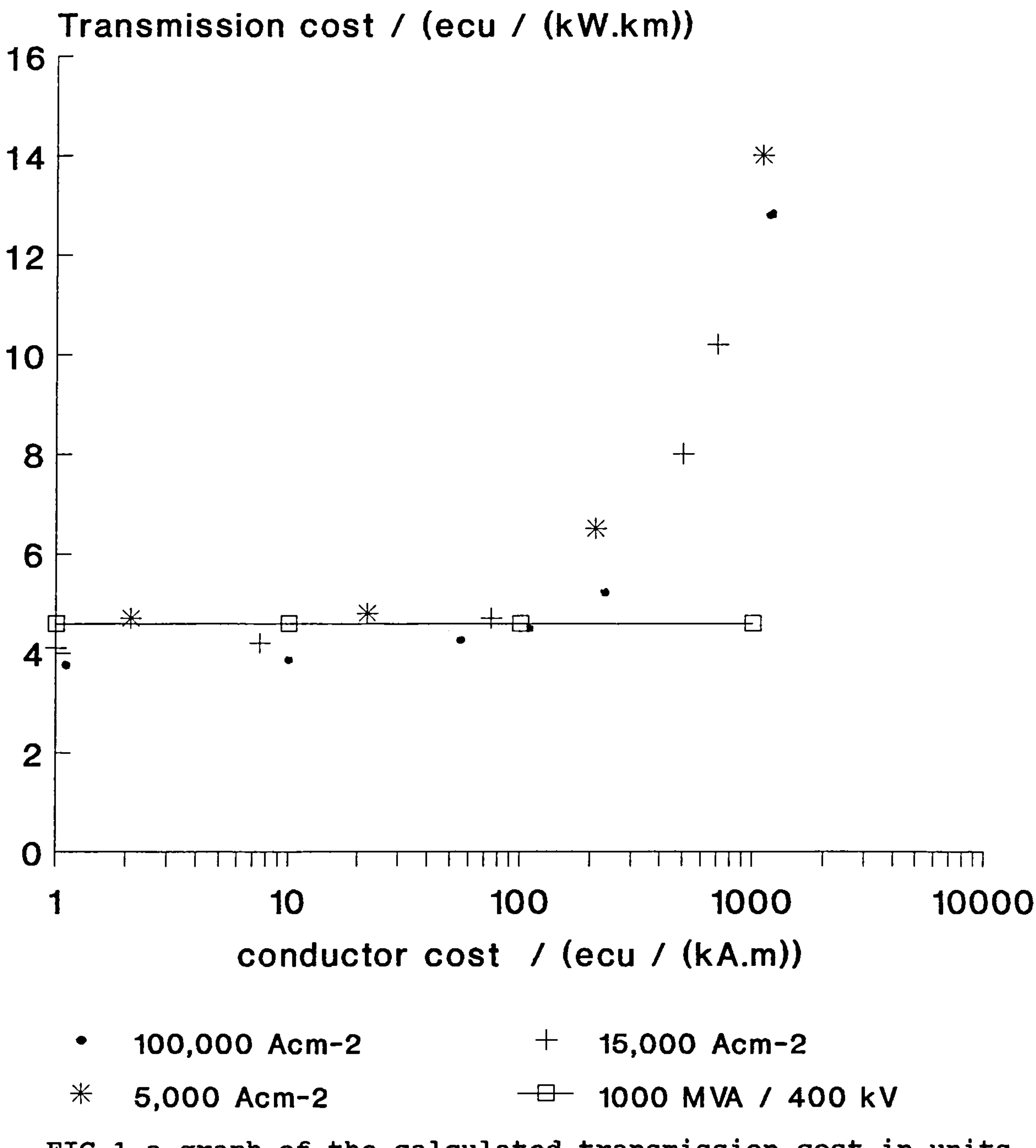

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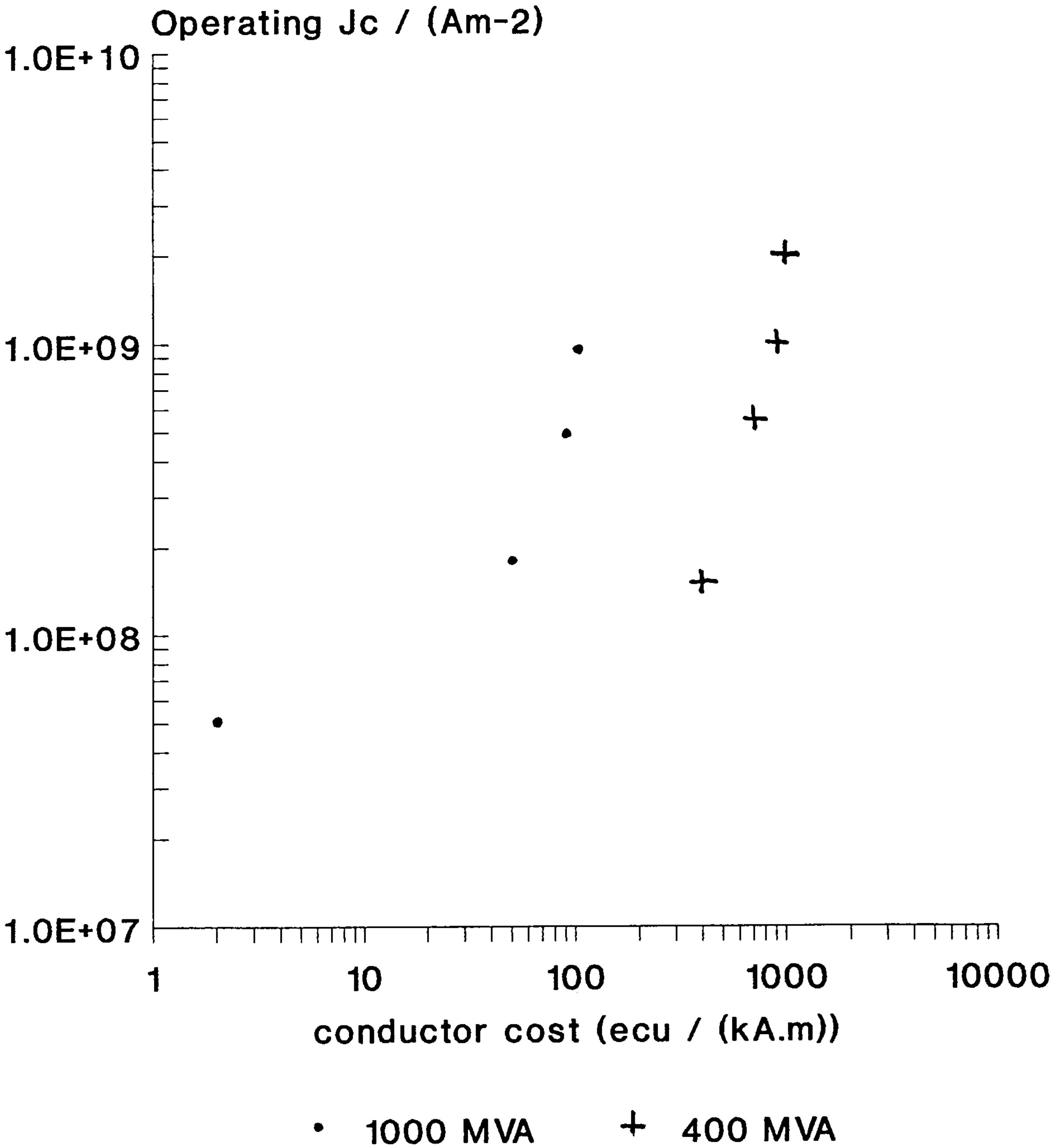

FIG 2 a plot of operating Jc in Am^{-2} against the cost of the conductor in ecu $kA^{-1}m^{-1}$ for the optimised high power cable at a rating of 1000 MVA and the replacement medium power superconducting cable operating at 400 MVA *compared with the equivalent copper cable system.*

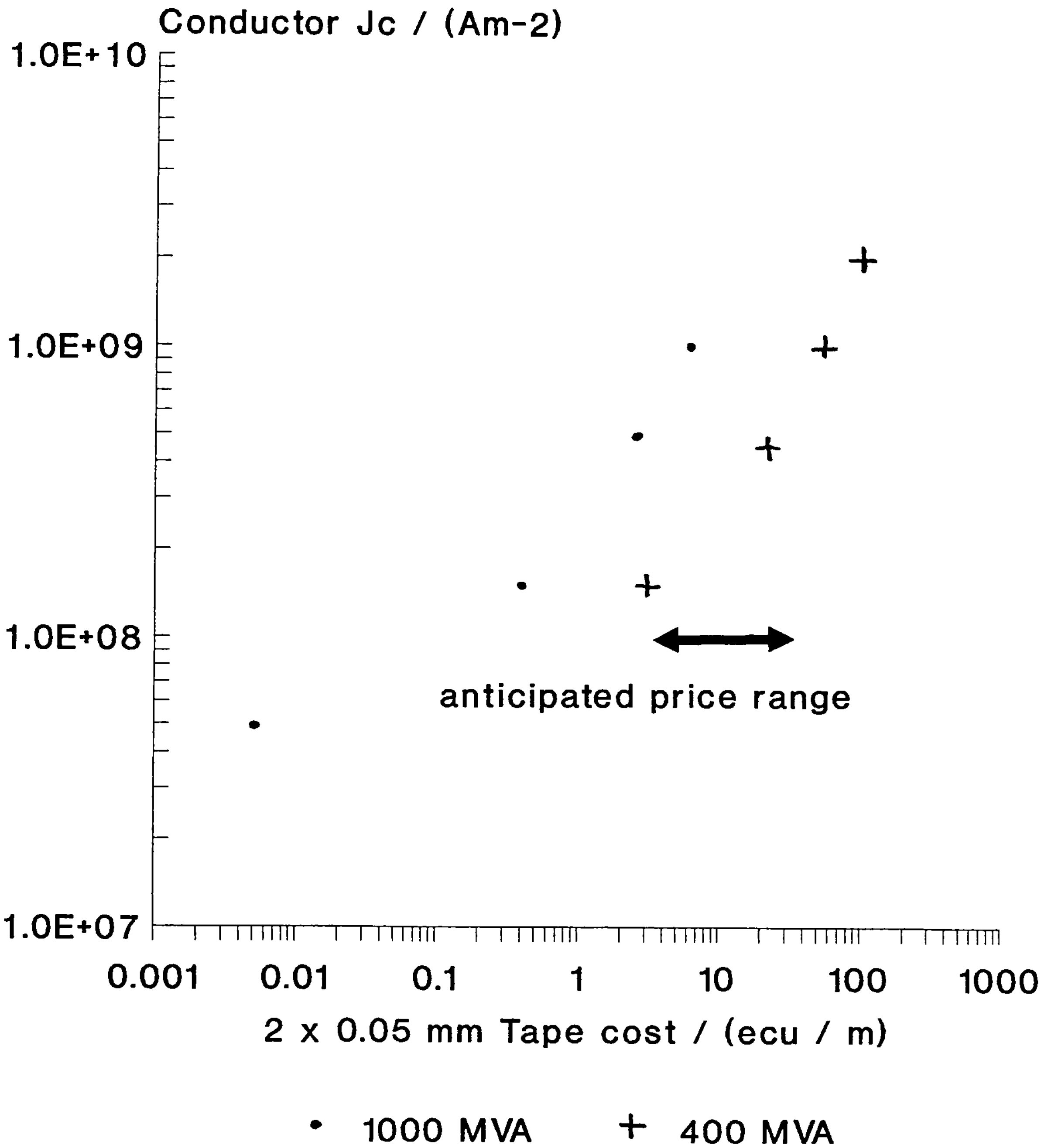

FIG 3 the conductor Jc in Am^{-2} versus the absolute cost per unit length of the conductor in $kA^{-1}m^{-1}$ - (2 mm x 50 μm conductor).