Superconducting Cables for a.c. and d.c. Power Transmission

J. A. Baylis

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Superconducting cables for a.c. and d.c. power transmission

By J. A. Baylis
Central Electricity Research Laboratories, Leatherhead, Surrey

The growth of electricity demand has led to a steady increase in the power-carrying capacity of underground power transmission lines. Some present cables are water cooled to increase their current rating, and further increases could be achieved by refrigerating the conductors to reduce their resistivity. The ultimate and best use of refrigeration is to cool to a few Kelvins above absolute zero so that superconductors can be used.

The technical problems of both a.c. and d.c. superconducting cables are described, with particular attention to the choice of superconductor and the choice of dielectric. The conductor choice is heavily influenced by fault current requirements. Some possible cable designs are then discussed, and present progress towards such designs briefly summarized. The electrical parameters of superconducting cables are deduced, and tentative economic assessments put forward. For high-power levels, exceeding 2 GVA, superconducting cables may offer real advantages; on the other hand, it may be 20 years before substantial requirements for such cable will arise.

1. Introduction: underground transmission in the U.K.

The past few years have seen a rapid growth in high voltage underground cables installed in England and Wales. However, it is already evident that the next few years will show a slackening in the rate of cable installation, and this offers an opportunity for the development of new cable types. As can be seen from figure 1, cables comprise about 12.5 and 9 % of the 132 and 275 kV transmission systems of the C.E.G.B.: these are high percentages internationally speaking. The figure also shows that installation of cables at a particular voltage tends to follow the building of overhead lines by about a decade. At present the percentage of 400 kV cable is only 0.5 % and one might expect installation of some long lengths of 400 kV cable in the late 1970s, or early 1980s. Looking further ahead, cables with higher power ratings than those used at present, corresponding to another step up in transmission voltage, may be required in the 1990s.

When making comparisons between different types of cable, circuit length is almost as important as circuit power rating. A diagram showing the lengths of the present C.E.G.B. major 275 kV cables is shown in figure 2. About 50 % of the total circuit length is contained in seven routes with lengths of more than 12 km. Six of these routes transmit power in and around London, and this function of power transmission in large conurbations is likely to be the main possible application of superconducting cables. With the growth of conurbations and of the size of overhead transmission structures, cable circuits might increase in length.

All high-voltage cables installed in the U.K. have paper-in-oil insulation. As described in Endacott's paper (this volume, p. 193), these cables have been successfully developed to match the thermal ratings of the corresponding overhead lines (375 to 900 MVA at 275 kV and 845 to 2620 MVA at 400 kV for single circuits). With increases in voltage, the maximum electrical working stress in the dielectric has been steadily improved from 10 to 15 MV m^{-1}, and better methods of removing the heat generated in the conductor and dielectric have been developed. To achieve the highest ratings, the cables are placed in pipes, through which water is pumped.

A bevy of new cable types are now jostling one another for acceptance (Corry 1972, Nicol

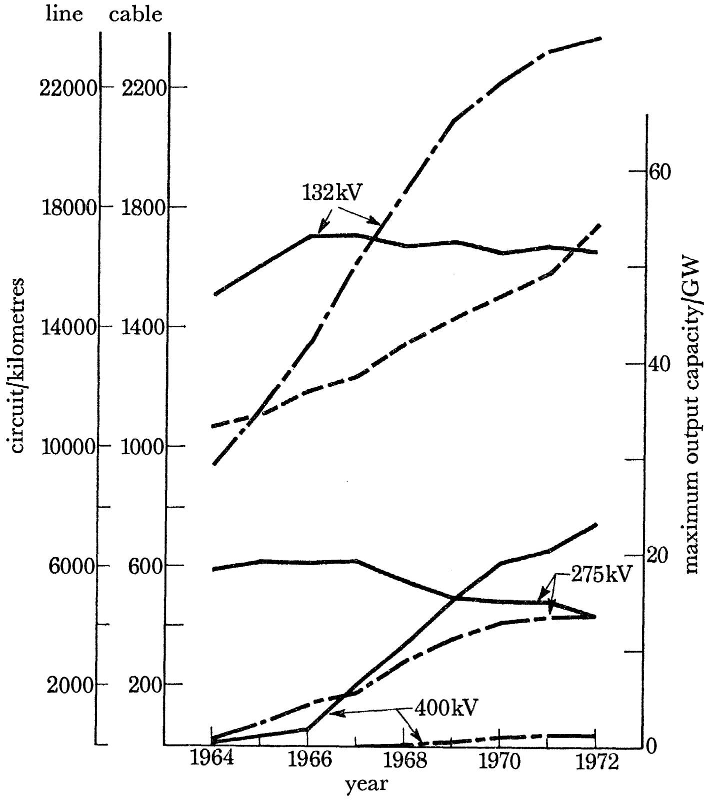


Figure 1. Maximum output capacity of the C.E.G.B. and circuit kilometres of overhead line and undergound cable in service with the C.E.G.B. on 31 March each year. (The 275 kV lines were built between 1954 and 1964; the 132 kV lines doubled during 1950–65.) ——, overhead lines; —·—·—, underground cables; ————, maximum output capacity.

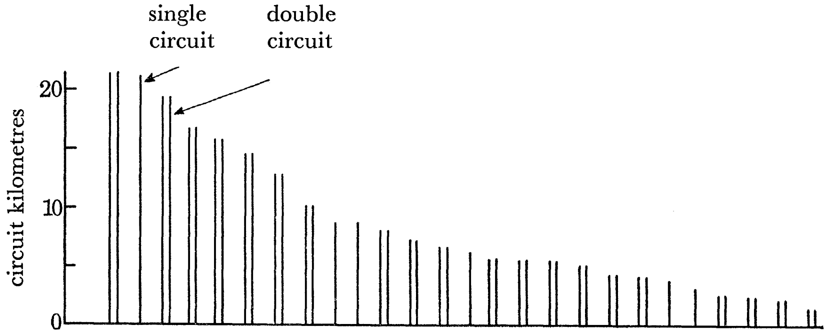


Figure 2. Lengths of major 275 kV underground cable circuits in service with the C.E.G.B.

1972). The incentive for new developments is strong: a double circuit of 400 kV overhead line costs £60k/km, but the equivalent underground cable installation is 13 times as costly. Some new designs of cable offer a dielectric with lower loss and permittivity, e.g. lapped tape or extruded polymers; some offer a dielectric of greatly reduced thermal resistance, e.g. SF$_6$ gas; and some a conductor of lower cost or resistivity, e.g. sodium, or cryocables with deeply cooled aluminium conductors. Two cables of the latter type, cooled with liquid nitrogen at 77 K, are under development in the U.S.A. One uses a lapped polyethylene tape dielectric impregnated with liquid nitrogen with a finely stranded conductor of fairly conventional appearance

(Jeffries, Minnich & Belanger 1972), while the other uses vacuum as dielectric: this vacuum also serves as the thermal insulation, and the conductors are rigid tubes which contain the nitrogen (Graneau 1970). The electrical resistivity of aluminium at 77 K is 10% of its room temperature value, while refrigerators consume between 6 and 8 W for each watt removed at 77 K. It is true of all deeply cooled cables that significant savings cannot be made by reducing the cost of the ohmic losses: the objective is a cable of higher current-carrying capacity for a given voltage.

Superconducting cables must be viewed against this background of rival systems, from which they stand somewhat apart. They offer conductors of minimal or zero resistance, but are furthest removed from present-day experience and rely on new technologies. They require expensive and elaborate thermal insulation and refrigeration, and as an indirect consequence become competitive only in long circuits and at power ratings of 2 GVA and above. At such powers several studies have shown that they should be cheaper than at least their cryocable counterparts (Deschamps & Schwab 1972; Rogers 1969). However, research into superconducting power transmission must be considered speculative, if only because of the long time scales for development and utilization.

Although superconducting cables have been introduced here in the context of the C.E.G.B in the U.K., similar conclusions have been reached by the majority of investigators in other countries. Discussion has also been limited to a.c., since long-term requirements for d.c. cables are less clear. The cost ratio between a.c. and d.c. superconducting cables at ratings of a few GVA is about the same as that between conventional ones, but d.c. superconducting cables have the unique ability to transmit enormous powers, up to 100 GW, underground in a single pipe. A.c. and d.c. will be considered together in the following sections, which describe some of the technical and economic factors which determine the prospects of superconducting cables. First of all, the relevant properties of superconductors will be outlined.

2. Superconductors

Superconductors show two different types of behaviour (Williams 1970). In the first type, all magnetic flux is excluded from their interior, and current is confined to a very thin surface layer, usually less than 1 μm thick. In this layer the magnetic field falls off exponentially from its value at the surface. The field at the surface, whether applied externally or due to transport current in the surface layer, has a critical value H_{c1}, above which the material *either* reverts to its normal resistive state, *or* changes to type II behaviour, described below. In all but two of the twenty-six elements which superconduct the former behaviour occurs. In niobium, vanadium and nearly all the superconducting alloys and compounds, of which there are many hundreds, the latter occurs. In type II behaviour magnetic flux can penetrate into the material, and superconductivity persists up to a higher critical value, H_{c2}. The material can also carry current in its bulk, and does so at a 'critical' current density, J_c, which is a function of field.

For a.c. cables, and probably for d.c., the superconductor will take the form of a thin surface layer on a normal metal substrate, necessary for structural and other purposes. The superconductor then acts as an electromagnetic screen for the normal metal, and ensures that no transport or eddy currents, due to a.c. or ripple in d.c., flow in the normal metal and generate heat. Current density, H, is expressed as A m^{-1} measured at the surface perpendicular to the direction of current flow, and hence is identical to the surface magnetic field.

Niobium is usually proposed for a.c. cables: it has the highest H_{c1} of any superconductor and the highest critical temperature of any element. Although niobium shows type II behaviour, it does not have a very useful J_c. Values of r.m.s. current density, H_s, corresponding to H_{c1} of pure niobium, are shown as a function of temperature in figure 3. Superconductors have no resistance to d.c. and ideally no resistance to a.c. at power frequency for fields below H_{c1}. In practice there is a small loss due to impurities and to irregularities in surface finish which locally enhance the field, and hence the losses are a function of the way the surface is made and prepared.

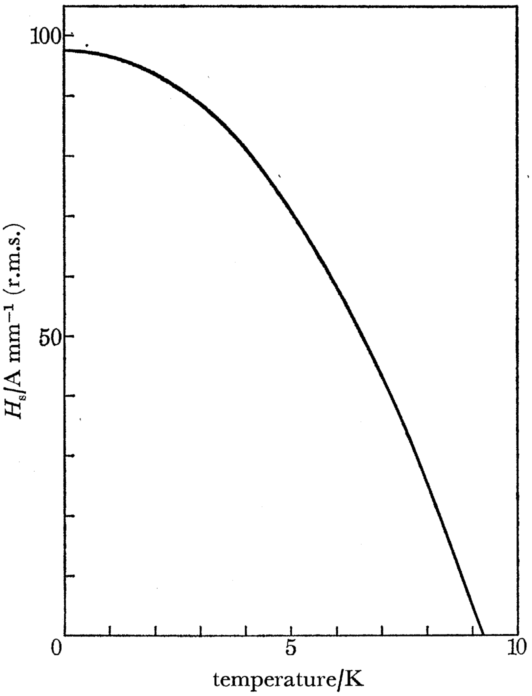


Figure 3. Critical surface magnetic field for pure annealed niobium as a function of temperature [Peak field = H_{c1}].

The most common use of superconductors is in high field d.c. electromagnets (Hadlow, Baylis & Lindley 1972), and the most common material is an alloy of niobium and titanium (Nb–Ti). Nb–Ti is one of a class of alloys and compounds called the Hard Type II superconductors. These materials are characterized by a very high H_{c2} and J_c, and negligibly small H_{c1}. Typical properties of Nb–Ti are shown in figure 4 and in table 1: the critical temperature is similar to that of niobium. Nb–Ti is ductile, and can easily be coprocessed with copper to make composite superconductors: indeed it requires substantial amounts of cold work to give it a good J_c. The alloy Nb–Zr is also a hard type II superconductor and, as can be seen from table 1, has a higher T_c and much higher J_c for low fields than Nb–Ti. However, it is more difficult to coprocess and has lower H_{c2} than Nb–Ti, and is therefore less used in magnets. Some hard type II compounds, known as the high T_c materials, have higher H_{c2} and critical temperature than the Nb alloys, and also have a very high J_c. The only one in common use is Nb_3Sn, and its properties are also given in table 1. The high T_c materials are brittle, are more difficult to prepare in composite form and cannot be cold-worked.

A d.c. cable will use a hard type II superconductor. It is also possible to consider their use for a.c. The way a.c. penetrates into a type II is shown in figure 5, together with the resulting magnetization loop. The area enclosed by the loop gives a hysteresis loss, which is equal to $\mu_0 \omega H_m^{3+n}/3\pi J_c$ W m^{-2}, where $0 < n < 1$ and H_m is the peak current density. Loss as a function

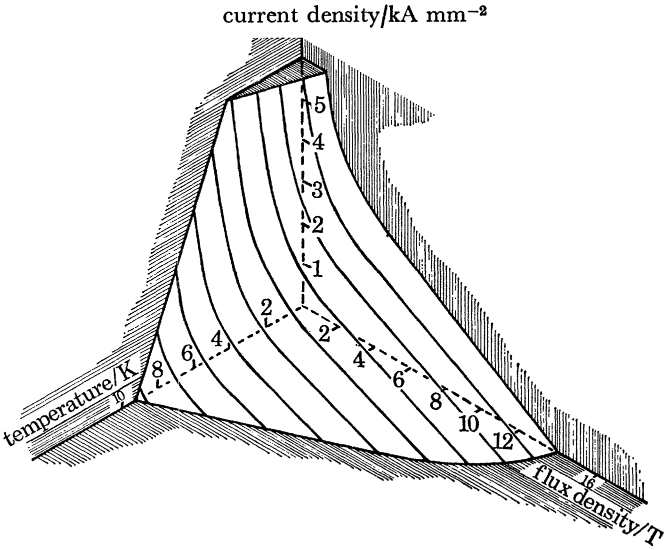


Figure 4. Three-dimensional plot of bulk critical current density, magnetic flux density, and temperature for a niobium–titanium hard type II superconductor.

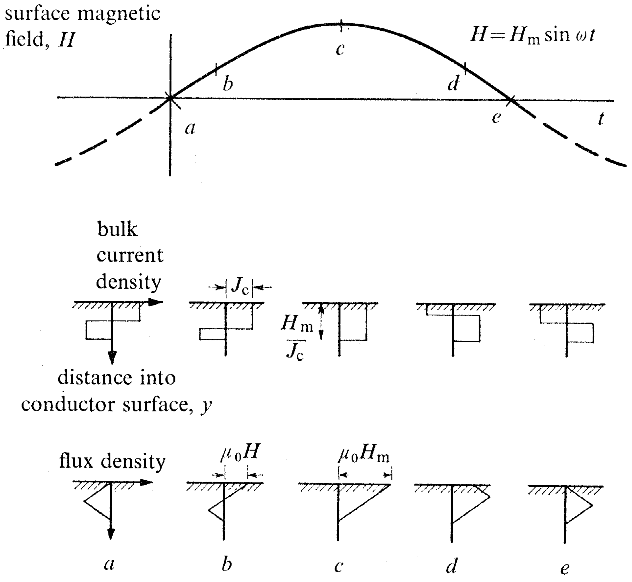
of H_s for typical Nb and Nb–Ti are shown in figure 6. It will be shown later that a loss < 0.1 W m^{-2} at 5 K is desirable, giving a working current density between 30 and 40 A mm^{-1} in Nb. Nb_3Sn and Nb–Zr can approach this performance: an alternative is to use Nb_3Sn at 8 to 10 K, where refrigeration is less costly and losses up to about 0.3 W m^{-2} can be tolerated.

Table 1. Properties of some superconductors

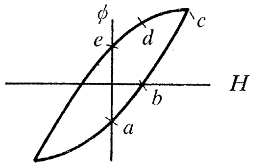
(*Note*: Cold work and impurities decrease H_{c1} and increase H_{c2} in Nb. All values of J_c are very dependent on the way superconductor is made and treated.)

	T_c at $B = H = 0$	H_{c1} at 5K / T	H_{c2} at 5K / T	J_c/A m^{-2} (at 5K and 0.5 T)
pure Nb	9.2	0.126	0.23	normal
Nb-25 mass % Zr	10.9	~ 0.02	7.0	2×10^{10}
Nb-44 mass % Ti	9.3		9.0	3.5×10^{9}
Nb_3Sn	18.0		20.0	2×10^{10}

A more severe requirement is the ability to withstand fault currents. During a fault the amplitude of the a.c. wave may momentarily rise to about fifteen times the usual value, with a quickly decaying d.c. offset of similar magnitude, and the cable must still be operational immediately afterwards. If Nb is used for the rated current, it will obviously be driven normal during the fault and an alternative current path must be provided. The simplest alternative is the normal metal substrate; of the commercially available metals, the most suitable are pure annealed aluminium and copper. Their resistivity, ρ, starts to rise with temperature between 10 and 20 K, and resistance ratios (ρ_{273}/ρ_5) of about 2000 and 250 can be obtained fairly easily in Al and Cu. These would give the losses shown in figure 6. The electrical skin depth, δ, $= (2\rho/\mu_0\omega)^{\frac{1}{2}}$, is < 1 mm, while the substrate thickness will usually be > 1 mm. Hence the losses are $\sim \frac{1}{2}\mu_0 \omega \delta H_s^2$. The specific heats of all metals at low temperatures are extremely small and hence most of the heat generated in the substrate during the fault must be absorbed by the helium coolant, whose bulk temperture at the end of the fault must not rise above about 6.5 K, and whose pressure must not rise above 1.5 MPa, say. Magnetoresistance in the substrate, and details of the heat transfer process to the helium must also be taken into account. A further difficulty is the low mechanical strength of annealed materials.



current and flux penetration during half an a.c. wave (Bean–London model, J_c independent of field, $n = 0$)



magnetization loop: $\phi = \int B \,dy$, and loss per cycle $= \oint H d\phi$, $= \dfrac{2\mu_0 H_m^3}{3J_c}$

FIGURE 5. A.c. loss in hard type II superconductors.

A neater solution to the fault current problem is to place a layer of hard type II material between the niobium and the substrate metal (Taylor 1969). The reduced losses (see figure 6) give a better fault current capability and a reduced helium pressure rise. The only thermal condition is that the conductor temperature during the fault should stay below about 6.5 K, compared with 20 K for Al or Cu. The hard type II layer can also take a succession of minor faults, and gives no abrupt transitions as current is raised. A triple Nb/hard type II/Cu composite is, of course, more difficult and expensive to manufacture. However, if an alloy or Nb_3Sn with very high J_c is used, a simple double composite for both normal and fault currents may be obtainable.

A problem with any hard type II is the possibility of electrothermal instabilities or of frictional heating, both of which may drive the superconductor normal. The severity of the fault

3. Dielectrics

For an a.c. cable the prime consideration in the choice of dielectric is the dielectric loss, which should be equal or less than the loss in the conductors. Translated into terms of loss angle, a $\tan\delta < 10^{-5}$ is required ($\tan\delta$ = '$1/\omega CR$' for a sample of dielectric) (Swift 1971). Helium or vacuum both have $\tan\delta < 10^{-6}$ at electric stresses below half the breakdown stress, and hence are obvious candidates. Helium must be adjacent to the conductors in any case to provide cooling, and in some designs a vacuum gap between conductors can serve as thermal insulation between counter-flowing helium streams. The dielectric strength of helium depends on its density and pressure: figure 7 shows the d.c. strength of a 1 mm gap (Fallou & Bobo 1970; Gerhold 1972; Meats 1972). Typical fluid conditions in a cable are 5 K and 0.4 MPa, where the strength is about 38 MV m^{-1}. The strength of a vacuum gap over the range 5 to 20 K depends mainly on the nature of the surfaces: for unpolished niobium with some electrode conditioning a typical strength of a 1 mm gap is 30 kV (Swift 1972). At larger gaps, the indications are that breakdown stress falls slowly with gap size in helium and somewhat faster in vacuum (Klaudy 1972). A danger with vacuum is that any small leak of helium into the vacuum space will greatly encourage breakdown at the leakage site. With helium or vacuum there must be spacers to support the inner conductors of the conductor assembly, and the spacers will form the weakest part of the dielectric gap. In helium the deposition of conducting particles on the spacers may have a deleterious effect, as in room temperature SF$_6$ cables (Hampton 1973). In vacuum elaborate capacitive grading of the spacers may be necessary to prevent or control micro-discharges. These comparisons between helium and vacuum suggest that helium is probably the better dielectric for superconducting cables.

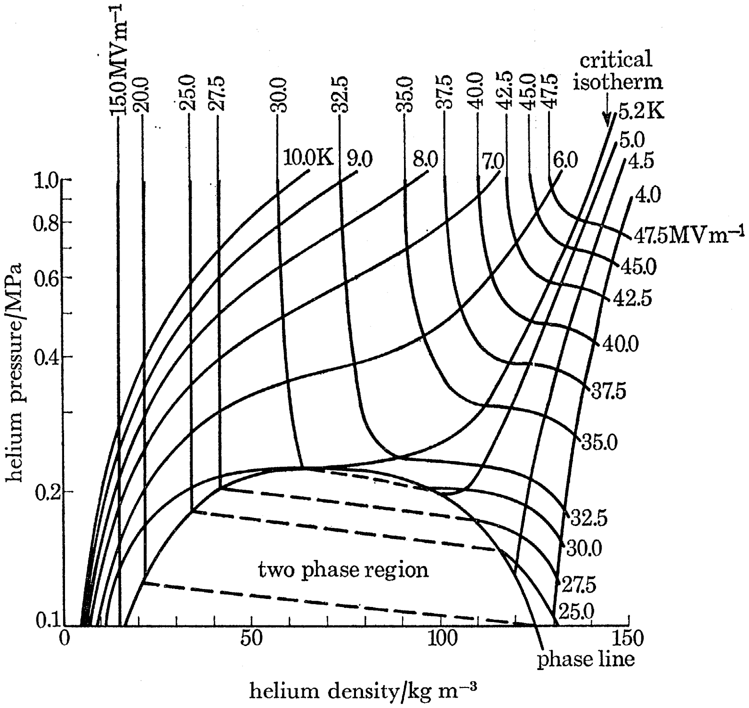


Figure 7. Contour plot for helium d.c. breakdown strength, brass electrodes with 1.0 mm gap (Meats 1972).

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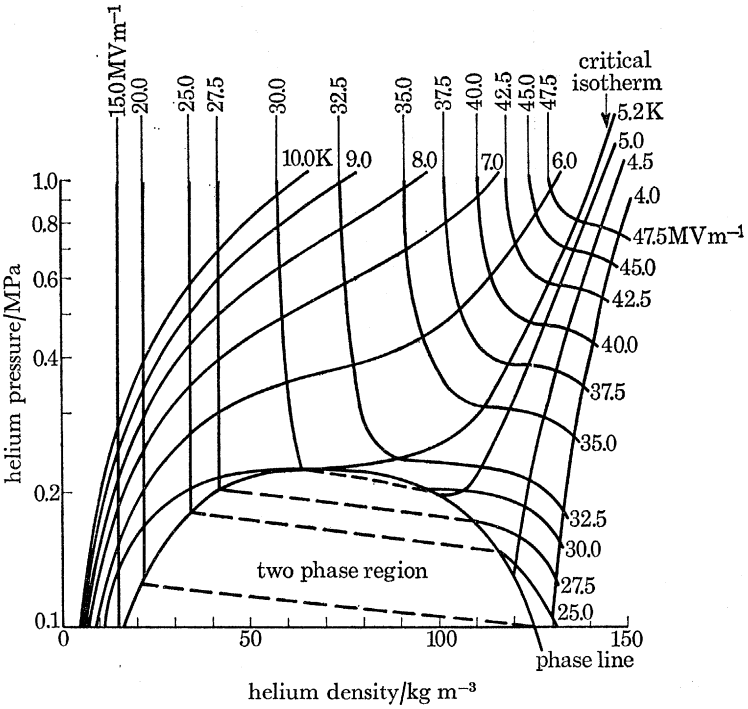

FIGURE 7. Contour plot for helium d.c. breakdown strength, brass electrodes with 1.0 mm gap (Meats 1972).

In addition to the working voltage, the dielectric will be subject to switching overvoltages and to impulse voltages from lightning strikes on external plant. The impulse specifications for conventional cables in the U.K. are 342, 640, 1050 and 1425 kV line-to-earth at line-to-line voltages of 66, 132, 275 and 400 kV. In designs with helium an impulse strength of between 15 and 20 MV m^{-1} should be achievable. In a d.c. cable the maximum voltage experienced is about twice the working voltage.

It has been shown that certain non-polar polymers, in particular, polyethylene and PTFE, can also satisfy the criterion $\tan\delta < 10^{-5}$ at temperatures around 5 K (Vincett 1969). These polymers could be used in thick extruded form, but because of thermal contraction problems it is more likely that the conductors would be lapped with tapes to build up a thick layer, as in a room temperature polyethylene tape SF_6 impregnated cable developed at C.E.R.L. (Gibbons & Stannett 1973), and as in the cryogenic cable described in § 1. In the present case the tape structure would be impregnated with helium, again at about 0.4 MPa pressure, and the weakest parts of the dielectric are then the butt gaps between parallel tapes. The breakdown strength of the tape itself is > 100 MV m^{-1}, but the stress at which micro-discharges start to appear in the butt gaps, whose size will be between 0.07 and 0.13 mm, the tape thickness, will be well below this. Any discharges slowly erode the insulation, as well as giving a loss, and hence the working voltage should correspond to not more than 70 % of the discharge inception stress. The dielectric must also not break down when subjected to the specified impulse voltages. Due to the long zig-zag path which a complete breakdown follows across the tapes and through the gaps, the impulse strength should be several times the discharge inception stress. In the cryogenic cable referred to, which was impregnated with pressurized nitrogen, the a.c. strength was 25 MV m^{-1} (435 kV line-to-ground for the cable) (Jeffries *et al.* 1972). On smaller samples with 1 mm of insulation, the a.c. strength was 34 MV m^{-1} (r.m.s.), and the impulse strength was about 2.7 times as great (92 MV m^{-1}) (Belanger 1971). The impulse strength of nitrogen alone was 56 MV m^{-1}, though higher strengths have been reported elsewhere (Lehmann 1970). Data on lapped tape structures in pressurized helium are urgently required. One set of published results (Dubois, Eyraud & Carbonell 1972) gave a.c. and d.c. breakdown strengths of 42 (r.m.s.) and 105 MV m^{-1} across 0.5 mm of tape insulation, and a recent experiment at C.E.R.L. on simulated butt gaps gave discharge inception stresses of between 50 and 25 MV m^{-1} depending on the number of tapes and the tape thickness (Sadanand 1972). It would seem that working stresses of 9 to 12 MV m^{-1} (r.m.s.), and an impulse strength between 45 and 60 MV m^{-1} can be hoped for in an actual cable dielectric: impulse strength rather than discharge inception stress would then be the limiting factor determining the rated voltage.

A further problem with a lapped tape dielectric is that a low-loss conductor screen must be developed. The function of the screen is to ensure that the inside and outside surfaces of the dielectric are in good contact with the conductors, and that no stressed butt-gaps occur adjacent to metal surfaces. A satisfactory screen has been developed for the polyethylene and SF_6 cable referred to above.

4. Cable design

Many designs have been put forward for superconducting cables, embodying different kinds of conductor and different dielectrics. Most early designs assumed the use of helium or vacuum as the dielectric. The conductors then take the form of rigid tubes to contain the helium, or to separate helium from vacuum. In an a.c. cable the tubes can be arranged in several different ways, of which three are shown schematically in figure 8. In each case the three phases of the

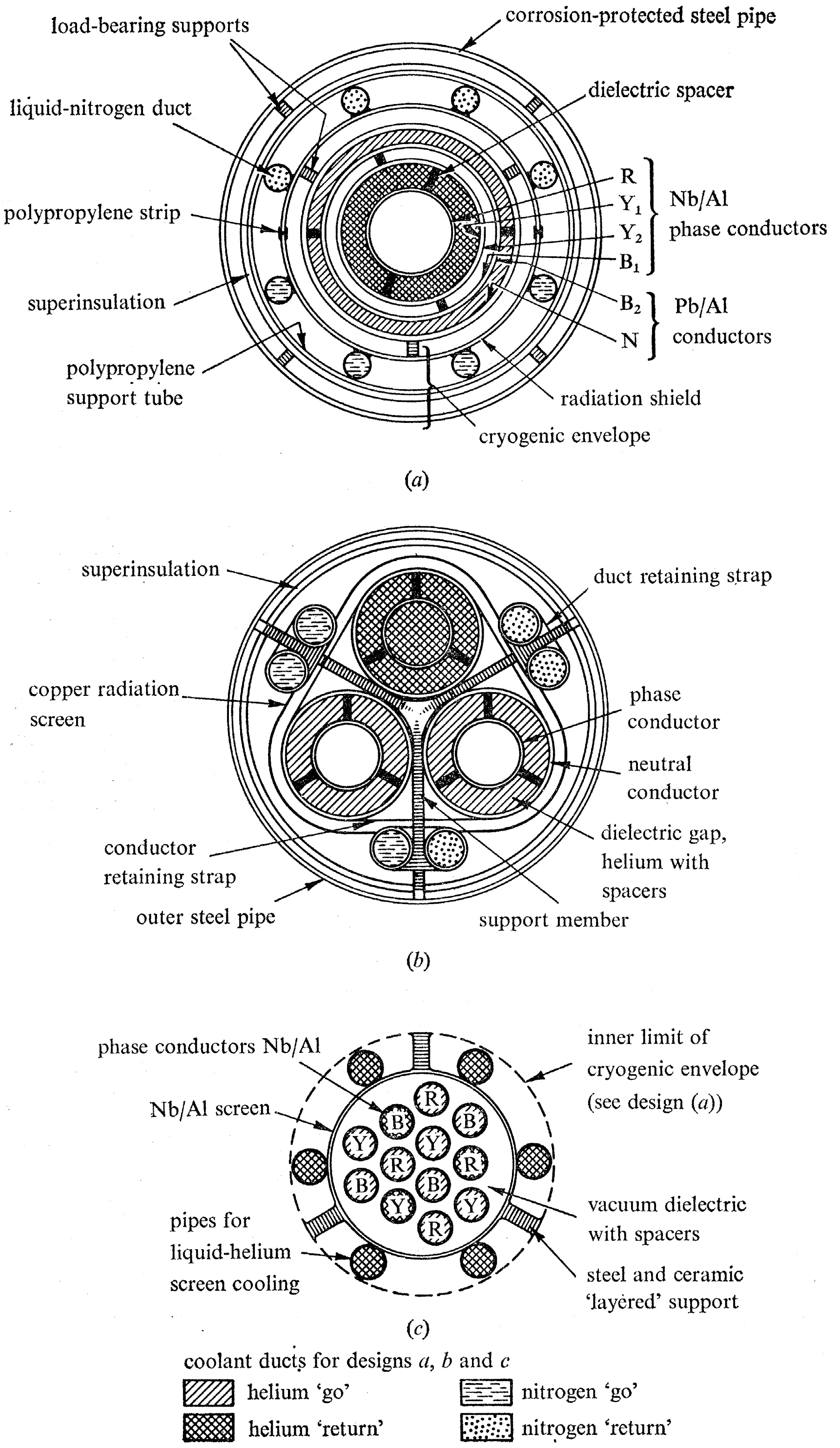

FIGURE 8. Three designs for an a.c. superconducting cable with tubular conductors. (*a*) All-coaxial design (Edwards & Slaughter 1967). (*b*) A trefoil design (other variants are considered by Bogner & Schmidt (1971), Eigenbrod *et al.* (1970) and Rogers (1969)). (*c*) Multitube design (Edwards & Slaughter 1967).

cable are enclosed in a single 'cryogenic envelope' which provides the thermal insulation: separate envelopes for each phase would be too costly. The envelope contains a screen to absorb the radiation and conduction down supports from 300 K: in this case the screen is cooled by liquid nitrogen. Between the screen and the outer pipe there is a 10 mm layer of 'superinsulation', many layers of aluminized mylar sheet, to reduce the radiative heat inleak. The supports for the screen and for the assembly of conductors should have minimum cross-section to reduce conduction, and the envelope is kept at a vacuum of $\leqslant 10^{-2}$ Pa to prevent convection. Heat inleaks to the screen and to the conductor assembly can be reduced to about 2 W m^{-2} and 0.1 W m^{-2} respectively (Rogers, Slaughter & Swift 1971). The loss in the conductors should, therefore, be kept below 0.1 W m^{-2}, though higher losses could probably be accepted for a few hours if it was required to temporarily overload the cable. The heat inleak to the conductors, and the dielectric and a.c. losses, are removed by the helium streams, of which there must be at least two – one 'go' and one 'return'. The go and return streams must be thermally isolated from each other to prevent temperature peaking effects between refrigerator stations (Edney, Fox & Gilbert 1967).

The all-coaxial conductor arrangement of figure 8*a* is the most compact, but would be difficult to assemble. The trefoil design is with good reason the most popular. Here each phase of the cable consists of a coaxial pair: the inner carries the phase current at the phase voltage and has superconductor on its outside, while the outer is grounded, carries equal and opposite current and has superconductor on its inside. The outer acts as an electromagnetic screen and as the helium wall. In the third design there are four tubes per phase and a common surrounding neutral screen. This design is not very practical, because large sideways electromagnetic forces act between the conductors during fault currents. Even in the other designs, slight axial misalinement of the conductors causes vibratory forces which during faults are several times the weight of the conductors, and these have to be considered when designing the spacers (Baylis 1972).

Tubular conductors must be assembled in lengths of 15 m or less, which entails many joints. However, a greater problem is the thermal contraction: aluminium and copper contract by 0.42 and 0.33 % respectively on cooling, while typical strains at the elastic limit are 0.06 and 0.1 %. To allow for contraction the tubes must be continuously corrugated, must follow a helical path, or must have large Ω bends at intervals along the conductor route (Baylis 1972). Satisfactory designs for aluminium are particularly difficult to obtain.

These problems can be avoided with a lapped tape dielectric and a conductor formed from helically laid strips as shown in figure 9. The inner conductor is laid on a helical non-conducting former, and the outer on the outside of the dielectric held down with skid wires. This construction is flexible, would accomodate thermal contraction, and could be pulled into the helium pipe in long lengths. The lapped tape also offers about three times the electric strength of helium alone, and hence a higher working voltage, a more compact cable, and lower total cost. The conductor plus dielectric would be very light, but would also be a mechanically weak structure. Satisfactory behaviour during drumming, pulling, cool down, and during pressure transients from fault currents may be a problem. The possibility of frictional heating referred to above may make the use of a hard type II superconductor more difficult than with simple tubes.

A design for a 4 GVA a.c. cable is shown in figure 10*a*: the reasons for choosing this rating are given in §7. The dielectric is polyethylene tape, and each phase of the cable is cooled by

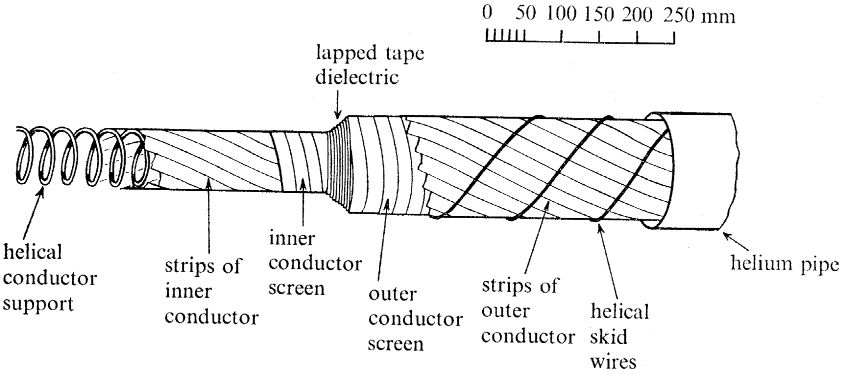

FIGURE 9. Details of cable construction with a lapped tape dielectric.

a flow of helium through the pipe in which it sits. The two smaller pipes carry the 'go' flow, and the larger pipe, which absorbs most of the heat inleak, carries the return flow. The screen is cooled by liquid nitrogen in eight ducts, four 'go' and four 'return', and the whole is enclosed in a single steel pipe of 465 mm o.d. All the interior pipes and ducts are straight tubes made from low thermal contraction alloy with bellows at joints. They are held in place by straps and spacers at intervals along their length, and are supported by studs which rest on the outer steel pipe.

The phase-to-phase voltage is 275 kV, and a working stress of 8 MV m^{-1} at the inner conductor is assumed. The corresponding stress under the impulse voltage of 1050 kV is 53 MV m^{-1}.

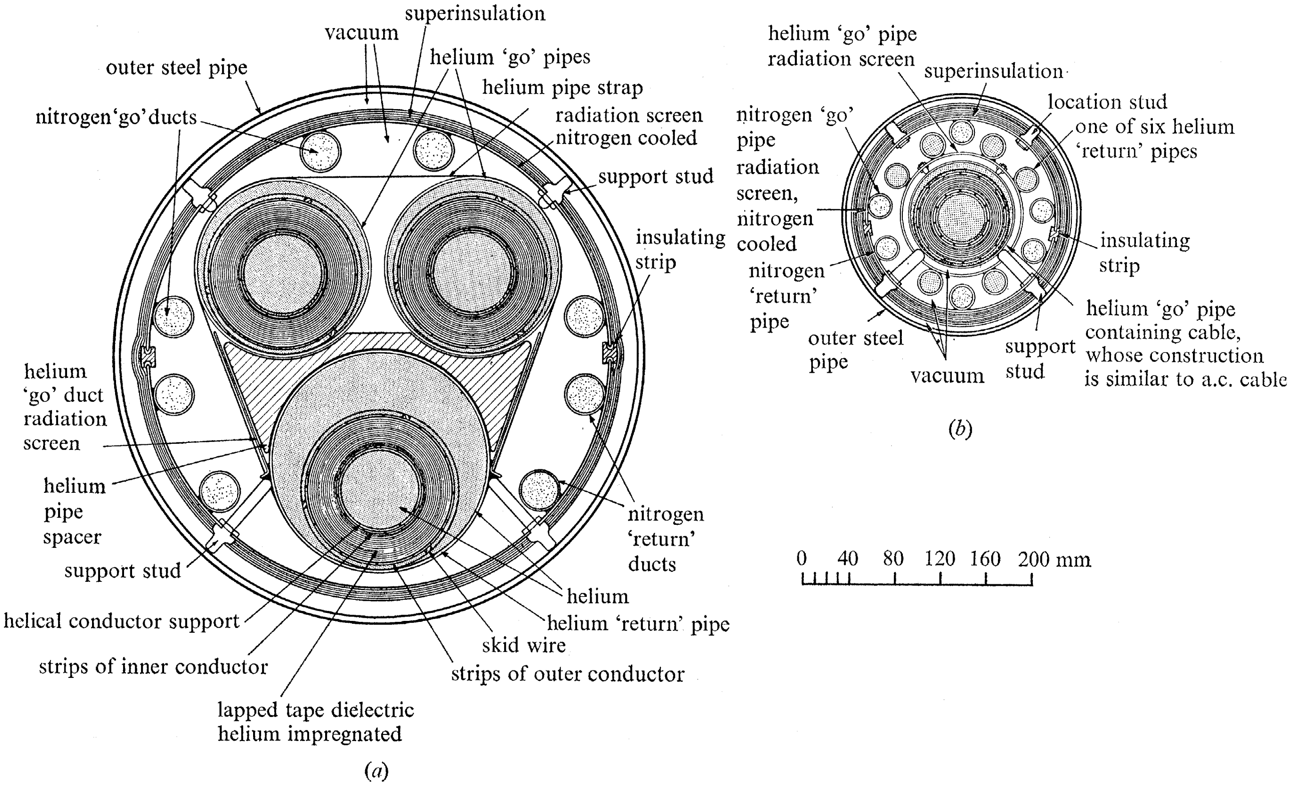

FIGURE 10. 4 GVA superconducting a.c. and d.c. cables. (*a*) 275 kV a.c. with conductor and dielectric as shown in figure 9; (*b*) 230 kV d.c.

A simple Nb/Al strip conductor is assumed with a current density of 34 A mm^{-1}: the niobium thickness is about 10 μm, as thin as can be manufactured, and the aluminium thickness is about 1 mm. The optimum radius ratio for a superconducting cable is $\surd e$. Hence for the given voltage the inner conductor radius is 40 mm, the phase current 8.5 kA, the outer conductor radius 65.5 mm, and the power 4.05 GVA.

A design for a d.c. cable of 4 GW rating is shown in figure 10*b*. The go and return helium streams are in separate pipes, though in some cases the solid dielectric may be able to provide the thermal isolation (Carter 1973), giving only one helium pipe. The electric stress at the inner conductor is 20 MV m^{-1}, and the current density 120 A mm^{-1}. The superconductor is assumed to be a niobium alloy with a J_c of 6×10^9 A m^{-2} at $H = 1.2 \times 10^5$ A m^{-1}. Following Carter, the thickness on the inner conductor is then 52 μm if fault currents are carried in the superconductor, and the thickness of aluminium substrate is 1.0 mm (or 2.4 mm of copper). If fault currents are taken by the normal metal, smaller thicknesses are obtained. In the design of figure 10*b* the power is carried by a single cable operating at 230 kV, and the radii of the coaxial pair are 23 and 38 mm. The current is 17.4 kA. The absence of stress inversion effects in the dielectric and the ability of superconductors to carry very large d.c. currents gives a most compact cable: a d.c. cable with radii 40 and 65.5 mm, as in the a.c. case, would transmit 12.5 GW, and three such cables as in figure 10*a* would transmit 37.5 GW. The d.c. to a.c. power ratio for similar cables is therefore about 9, compared with between 2.5 and 3 for conventional cables.

5. REFRIGERATION

Niobium or niobium alloys must be maintained at a temperature below 6.5 K to make adequate use of their superconducting properties, and to allow a margin for fault currents the helium in a cable would have an outlet temperature of about 5 K. The helium would be pressurized to avoid 2-phase flow conditions and the rapid changes in properties which occur just above the critical pressure. The dielectric strength of helium also increases with pressure (see figure 7).

Each watt dissipated at 5 K requires at least 300 W of compressor power at the helium refrigerators, and the helium itself costs about £1 per litre as liquid: the refrigerators and helium together comprise up to 35 % of the total cost of the cable. The sources of heat to the helium for the designs of figure 10 in watts per kilometre of cable are given below:

	a.c.	d.c.
heat inleak by radiation and conduction/W km^{-1}	127	51
a.c. loss (0.05 W m^{-2} at inner conductor)/W km^{-1}	52	0
dielectric loss ($\tan \delta = 5 \times 10^{-6}$)	30	0
loss in conductor screens/W km^{-1}	15	0
pumping and pipe friction/W km^{-1}	64	15
total heat to helium/W km^{-1}	288	66
optimum refrigerator spacing/km	12.0	7.8
flow velocity inside inner conductor/m s^{-1}	0.25	0.23
equivalent heat inleak at a termination/W	410	210

Refrigeration is cheaper the larger the refrigerator size, and hence the further they are apart. However, for a given helium temperature rise between refrigerators, the flow velocity, and hence pipe friction, also increases with refrigerator spacing. There is, therefore, an optimum spacing (Swift 1968), which can vary between 5 and 30 km for different cable ratings and designs. At the cable terminations there is a heat inleak down the conductors equivalent to about 6 mW/A per conductor for d.c. and slightly more for a.c. These two factors make superconducting cables uneconomic for short circuit lengths.

In the designs of figure 10 the pipes are sized to give equal pressure drops in the go and return streams, and the total heat loads to each are arranged to be approximately the same. Pipe friction will be increased and heat transfer decreased by the former and skid wires: some allowance has been made for this. In the go pipes approximately equal flow areas are provided inside and outside the conductors. Finally, the pipes must contain sufficient helium to satisfy the fault current specification: for a typical a.c. specification with Nb/Al conductors there must be about 0.02 m^2 of coolant passage cross-section adjacent to each metre of conductor periphery carrying 36 A mm^{-1} (Rogers *et al.* 1971). If a hard type II superconductor is used, this requirement is removed, and it is only the heat transfer coefficient which is of interest.

The major problem with refrigeration and thermal insulation is one of reliability. Considerable spare refrigeration capacity has to be provided, even if it is assumed that improvements are made over the reliability of present plant. Within the cable, a single leak to the vacuum space will put the cable out of commission, and during cable construction elaborate testing of all pipe and duct joints will have to be carried out to ensure vacuum tightness. Gross damage to the outer steel pipe could lead to bursting of the helium pipes, and loss of much helium, even if stop joints are installed at intervals along the cable route.

6. ELECTRICAL CHARACTERISTICS OF A.C. LINES

The basic electrical parameters of a coaxial pair are easy to determine (Forsyth *et al.* 1972). The series inductive impedance per metre, Z_{l}, and the shunt capacitive impedance per metre, Z_{c}, are given by

$$Z_{\mathrm{l}} = \frac{\omega\mu_0}{2\pi}\ln\phi\ \Omega\ \mathrm{m}^{-1}; \quad Z_{\mathrm{c}} = \frac{\ln\phi}{2\pi\omega\epsilon\epsilon_0}\ \Omega\ \mathrm{m},$$

where ϵ is the relative permittivity of the dielectric and ϕ is the radius ratio of the outer and inner conductors. The phase current, I, and line-to-neutral voltage, V, are $2\pi r_1 H$ and $Er_1\ln\phi$, where r_1 is the inner conductor radius, and H and E are the current density and electric field at the inner conductor. With a base impedance Z_{b} defined as V/I, the per unit series inductive impedance $\bar{Z}_{\mathrm{l}}$ and the per unit shunt capacitive impedance $\bar{Z}_{\mathrm{c}}$ are then given by

$$\bar{Z}_{\mathrm{l}} = \omega\mu_0\frac{H}{E}\ \mathrm{m}^{-1}; \quad \bar{Z}_{\mathrm{c}} = \frac{1}{\omega\epsilon\epsilon_0}\frac{H}{E}\ \mathrm{m},$$

For a superconducting cable $\bar{Z}_{\mathrm{l}}$ and $\bar{Z}_{\mathrm{c}}$ are thus determined by H, E and ϵ, and are independent of conductor size. H will be higher than in a conventional cable, whereas E is lower. Hence $\bar{Z}_{\mathrm{c}}$, which is approximately equal to the critical length of the cable, will be larger, and the charging power per metre, (rated power)/$\bar{Z}_{\mathrm{c}}$, will be smaller than in conventional cable equivalents. The regulation of the line is largely determined by the per unit surge impedance,

$$\bar{Z}_0 = \surd(\bar{Z}_{\mathrm{l}}\,\bar{Z}_{\mathrm{c}}) = \sqrt{\left(\frac{\mu_0}{\epsilon\epsilon_0}\right)}\,\frac{H}{E},$$

and the natural load is (rated power)/$\bar{Z}_0$.

For the design of figure 10*a*:

$$Z_{\mathrm{l}} = 3.1\times10^{-5}\ \Omega\mathrm{m}^{-1}, \quad Z_{\mathrm{c}} = 0.13\times10^{8}\ \Omega\mathrm{m},$$
$$\bar{Z}_{\mathrm{l}} = 1.7\times10^{-6}\ \mathrm{m}^{-1}, \quad \bar{Z}_{\mathrm{c}} = 0.7\times10^{6}\ \mathrm{m}.$$
$$\bar{Z}_0 = 1.1,$$

and the charging power per metre is 6 kVA. For comparison a 400 kV cable circuit with 2250 mm^2 conductors requires 20 kVA m^{-1}. A superconducting cable will, therefore, require little reactive compensation. The per unit surge impedance is close to unity, so that there is a good match between the thermal and electrical characteristics of the cable, and the regulation is also good, at least with solid insulation (with a helium or vacuum dielectric both E and ϵ are lower, $\bar{Z}_0$ higher, and hence the regulation poorer).

Because H, E and the optimum ϕ do not vary significantly with cable rating, the optimum conductor current rises with the cable voltage, and at a particular power level the voltage is about one third that of the equivalent overhead line.

7. Economics

A variety of cost estimates have been published for superconducting cables. Some promise cost savings at ratings as low as 0.5 GVA, even for a.c. A detailed study of a 33 kV a.c. 0.75 GVA cable with mixed helium and vacuum dielectrics was carried out by C.E.R.L. in conjunction with British Insulated Callenders' Cables Ltd, and gave a capital cost of £244/m (Rogers *et al.* 1971), about 50% higher than that of conventional cable equivalent to one circuit of 275 kV 2×400 mm^2 overhead line. It is unlikely that superconducting cables will ever be competitive at circuit ratings below 1 GVA, even though the use of a solid dielectric permits higher electric stress and reduces the cost: the outer pipe diameter of the present 4GVA a.c. cable is less than that of the 0.75 GVA design.

Although superconducting a.c. cables would probably be competitive at 2 GVA and the first prototype cables on this system would probably be of this rating, a 4 GVA design has been considered here. The satisfactory performance of present 2 GVA cables and the long time required for development and evaluation of superconducting cables make 4 GVA a sensible choice. It is about the lowest rating at which the savings may be substantial enough to encourage acceptance of such a novel design.

Cost estimates for superconducting cables can be moderately accurate in some respects: the costs of refrigeration, helium, pipes, ducts, screens, and civil works are all known. The uncertainties are in the cost of conductor fabrication, which could considerably exceed that of the raw materials, and the cost of constructing and testing the cable in the field. As a guide to the economics, various cables have been costed on approximately the same basis as the 0.75 GVA design quoted above. The results are shown in table 2. Polyethylene has been assumed as the dielectric, and a cheap material, such as aluminium, has been assumed for the radiation screen. Higher manufacturing and installation costs have been allowed, though they are probably still too low: the 0.75 GVA design was carried out in 1968.

Table 2 shows the 4 GVA designs of figure 10, an 8.5 GVA 400 kV a.c. cable, and a 16 GW d.c. cable with 4×4 GVA circuits: this is more compact than a single 16 GVA circuit. It is likely that 400 kV is the limit on voltage for a.c. because of drumming difficulties as the outer conductor diameter of a phase approaches 200 mm. Therefore, above about 10 GVA more than one circuit per phase would be required. With d.c., 90 GW could be transmitted by four circuits with conductors of size similar to the 400 kV a.c. phases. Some diagrams of various cables are shown in figure 11.

The 4 GVA a.c. cable would have a capital cost about half that of two conventional 400 kV cable circuits carrying the same power: the saving comes largely from the reduced size and

TABLE 2. COST BREAKDOWN OF A.C. AND D.C. SUPERCONDUCTING CABLES: 1968 PRICES (£ m^{-1})

(*Note*: Electrical termination and terminal equipment costs are not included.)

	4 GVA a.c. (figure 10*a*)	4 GVA d.c. (figure 10*b*)	8.5 GVA a.c. (figure 11*c*)	16 GVA d.c. (figure 11*e*)
cable: conductor, dielectric, etc.	55	14	88	55
helium pipes and joints	39	9	53	21
cryogenic envelope	43	21	61	27
helium refrigerators	67	33	85	41
helium filling	29	3.5	53	10
nitrogen refrigerators and filling	4	1.5	5	2
field installation	44	27	53	26
capitalized fridge running costs	36	16	48	21
total cost	317	125	471	213
£ per GVA m (or MVA km)	78	31	53	13

quantity of conductor. The running cost plus cost of reactive compensation would be approximately divided by three. The comparison is not fair in that superconducting cables would probably be used in multiple circuits, and hence the present 4 GVA design should be compared with a cable of conventional type with 4 GVA rating. It has been estimated that directly cooled 750 kV conventional cable would transmit 4 GVA per circuit at about 75 % the cost of present 400 kV cables. Such cable would border upon the limits of an already very highly developed technology, while its superconducting alternative represents a first step in a new technology, and improvements in the design parameters assumed here can be hoped for as development proceeds. On the other hand, the costings of the superconducting cable are less precise and might escalate as the cable approaches reality.

The costs of d.c. superconducting cables are dwarfed by the costs of terminal equipment, at least £7 M per GVA for each termination with present equipment. The break-even length at 4 GVA for a.c. and d.c. superconducting cables is, therefore, at least 300 km. Increases in rating have brought great savings in £/GVA m for cables conventional or unconventional, while similar reductions have not been made in inversion and rectification costs. At present, the higher the rating, the less attractive is d.c. One can only hope that future research effort will change this situation.

8. DISCUSSION

Research into the technical difficulties inherent in superconducting cables is being carried out in several laboratories, interest being mostly in a.c. Simple Nb/Cu tubes have already been made and tested by the Union Carbide Corporation (Eigenbrod, Long & Notaro 1970), by Siemens (Bogner & Schmidt 1971), by C.E.R.L. (in conjunction with Imperial Metal Industries) (Graeme-Barber & Maddock 1972) and by Furukawa in Japan. Further tests are reported to have been carried out in Austria and Russia, and much work on dielectrics and cable assessment has been undertaken in France. Large research programmes are now in progress at Union Carbide (Meyerhoff 1972), at the Brookhaven National Laboratory where Nb_3Sn is the chosen superconductor (Forsyth *et al.* 1972), and at Siemens and AEG-Telefunken in Germany. At C.E.R.L. it is intended to complete a detailed reassessment during the next two and a half years, using data from the test facility shown in figure 12. Despite all these efforts, it is not likely that a superconducting cable will be ready for evaluation on the system before 1980, and as shown

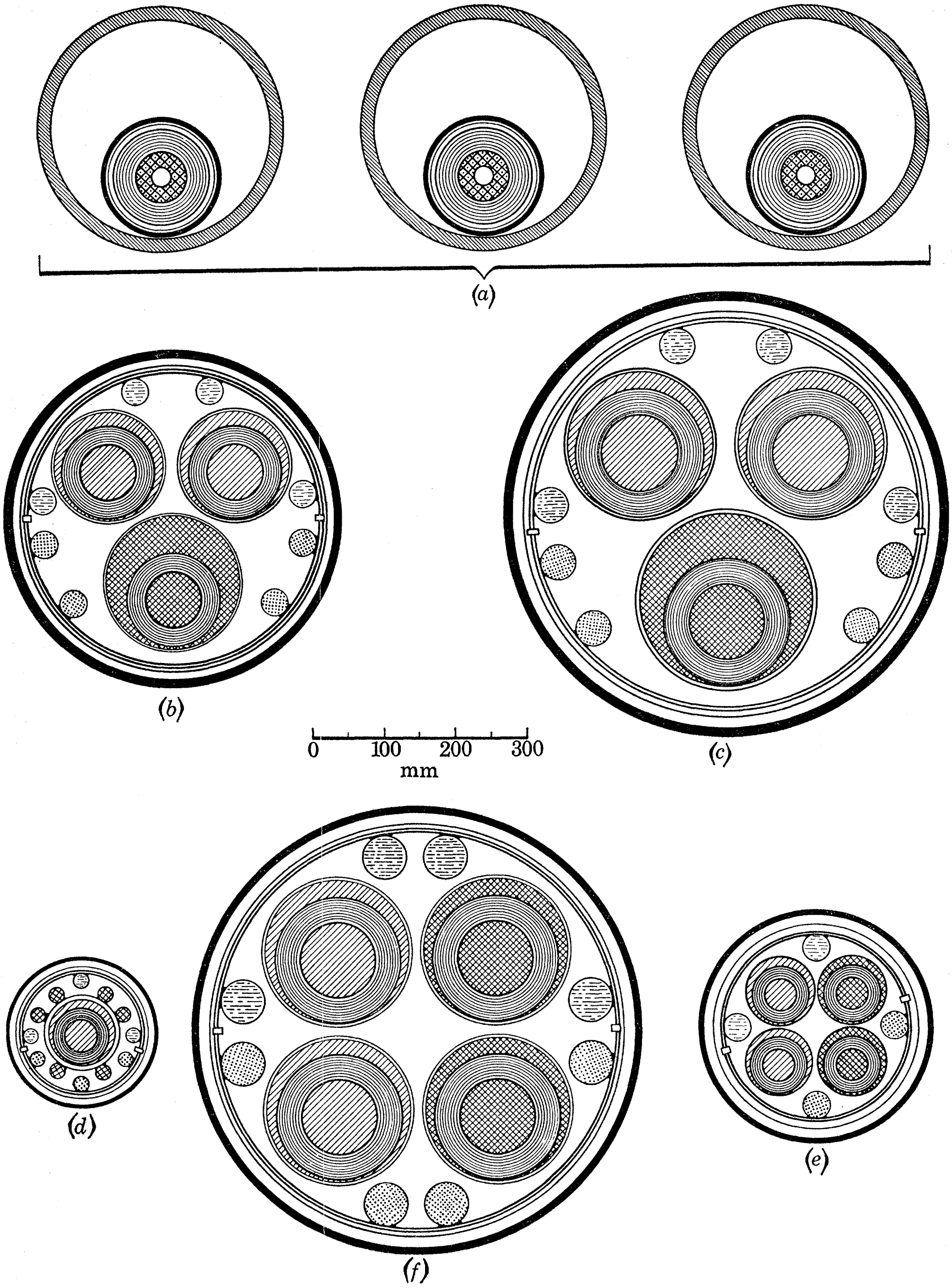

FIGURE 11. Cross-sections of various cables. Nitrogen and helium flows indicated as in figure 8. (*a*) Conceptual design for a conventional oil-filled 750 kV a.c. cable, directly cooled by water in rigid PVC pipes; $E = 20\ \mathrm{MV\,m^{-1}}$; power rating 4 GVA at sheath and conductor temperatures of 25 and 95° C. (*b*) 275 kV 4 GVA a.c. superconducting cable of figure 10*a*. (*c*) 400 kV 8.5 GVA a.c. superconducting cable; $E = 8.6\ \mathrm{MV\,m^{-1}}$; $H = 37\ \mathrm{A\,mm^{-1}}$. (*d*) 230 kV 4 GW d.c. superconducting cable of figure 10*a*. (*e*) 230 kV 16 GW d.c. superconducting cable; four circuits as in (*d*). (*f*) 534 kV 90 GW d.c. superconduting cable with four circuits with dimensions as in (*c*); $E = 20\ \mathrm{MV\,m^{-1}}$; $H = 125\ \mathrm{A\,mm^{-1}}$; total cost ≈ £5.4/MVA km.

in §1 requirements for circuits with lengths of 15 km or more and power ratings of 4 GVA and above may not arise before 1990.

Designs for 4 GVA cables operating at 275 kV (a.c.) and 230 kV (d.c.) have been described in some detail to bring the technical and economic factors of superconducting cables into focus. The designs are based on a lapped tape dielectric, and this is shown to have advantages over the alternatives, helium or vacuum. The dielectric is not yet proven, particularly with regard to a satisfactory conductor screen and the electric strength of thick tape structures impregnated with helium; however, fairly conservative stress levels have been assumed. The conductor for a.c. is formed from strips of aluminium covered with niobium superconductor. The strips are simple, but give a limited fault current capability and a complicated thermal design. A more sophisticated conductor, with a layer of hard type II niobium alloy between the niobium and the base metal, could remove these difficulties and allow some increase in current rating, provided satisfactory behaviour of the hard type II superconductor can be assured. The niobium layer can be dispensed with in d.c. and, because of the lower fault current rating, satisfactory performance is almost certain. It may also be possible to dispense with the niobium layer in a.c., especially if a high T_c superconductor such as Nb_3Sn is used. Current densities would then be about the same as with Nb/Al, but refrigeration costs would be reduced by operation at 8 to 10 K and the fault current capability should be improved. Prospects for Nb_3Sn depend much on its fabrication cost and on the great problem of its brittleness.

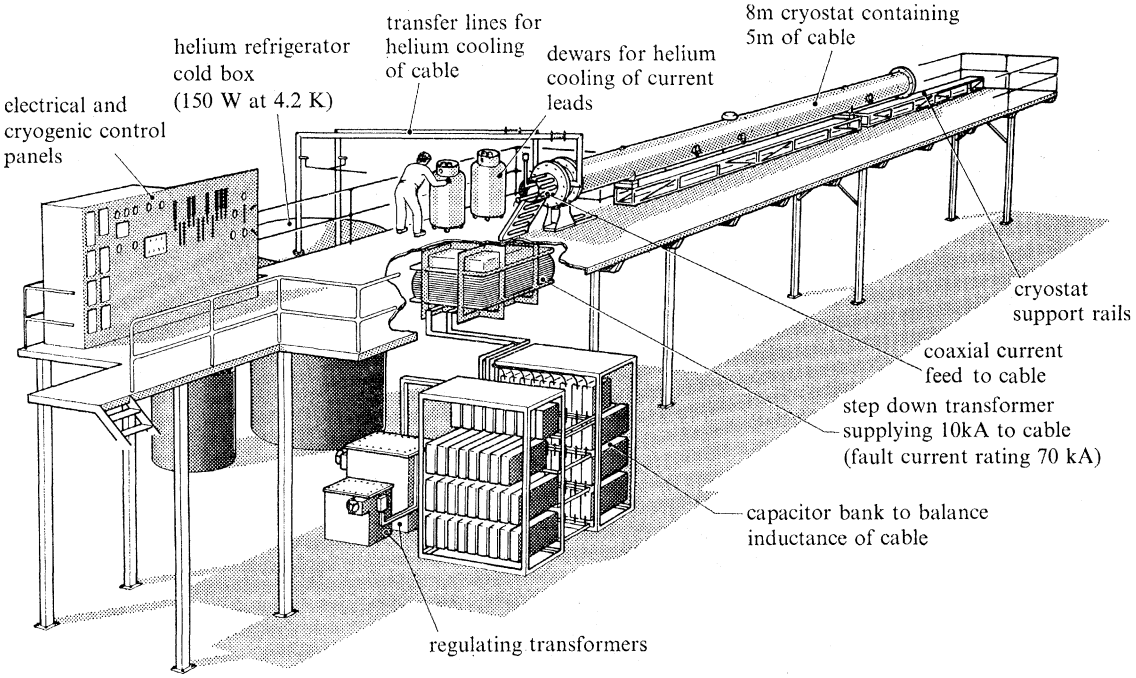

FIGURE 12. C.E.R.L. superconducting cable test facility (arrangement for high current experiments on a shorted length of single phase coaxial cable).

A.c. superconducting cables are shown to have a low charging current, and hence a long critical length and little need for reactive compensation. Their per unit surge impedance can be close to unity giving good regulation. They are also light and compact. Preliminary calculations indicate useful savings at ratings of 4 GVA, but accurate costs cannot yet be determined.

Even for a.c. superconducting cables, whose range of application is likely to be 4 to 10 GVA per circuit, the time scales are long. For d.c., whose useful range may be 4 to 100 GW, they seem longer still, and massive reductions are required in the costs of terminal rectification and inversion equipment before the great economies of the cable itself can be exploited.

The prospects for both a.c. and d.c. also depend on relative advances in other new designs of underground cable, on the way transmission systems develop and the requirements for large power transfers, and on successful demonstration that vacuum integrity can be preserved in the long and complicated structure which houses the superconductor and keeps it at liquid helium temperature.

9. Conclusions

1. Steady progress is being made in laboratories towards the development of superconducting cables. However, many years' work remain, and it may be twenty years before substantial requirements for such cable will arise.

2. A.c. superconducting cables are suitable for bulk ($\geqslant$ 4 GVA) transmission to and around large cities, perhaps from central power stations on their outskirts, as integral parts of a.c. networks operating at transmission voltages of a few hundred kV.

3. D.c. superconducting cables may be suitable for high-capacity asynchronous interconnexions between a.c. networks or for very long underground circuits. The cables are cheap and their prospects depend on what reductions can be made in the cost of inversion and rectification equipment.

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