16 October 1970, Volume 170, Number 3955 SCIENCE

Underground Power Transmission

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The present peak power demand in the United States is 314,000,000 kilowatts (*1*), a quantity which is the result of consumption having doubled each 10 years since 1930 with surprising exactness. This service, already frequently supplied by underground cables (*2*), is provided at modest voltages, often 208 volts, from distribution transformers. These transformers are connected to higher voltages commonly 4,000 to 15,000 volts originating at a substation which derives its power from the transmission system.

The transmission system is the means by which large blocks of power are transported from the generating stations to the area of use. The highest voltage lines are now able to transmit about 2000 megavolt amperes (MVA), which is sufficient to supply the needs of a city with a population of a million people. Transmission lines serve other very important functions. They interconnect neighboring utilities, increasing system reliability in such a way that, except under exceptional circumstances, the existence of supplementary circuits makes it possible to bypass the effects of equipment failure. It also allows standby generation capacity available for peak loads to be shared between utilities or large areas, with the result that less generating capacity is needed and costs are saved.

The type of transmission line for a particular service is selected after a series of exhaustive cost studies have been made. These studies include examination of the various routes available; the cost of the line, its installation, and maintenance; and the cost of the energy lost in transmission. Other factors include a consideration of future loads and further expansion of an area's transmission network. The first choice is to use the line which satisfies these needs best and at the lowest cost. While in the vast majority of cases some form of overhead line is selected, in the large cities underground cables have often been the practical choice because the cost of a right of way for overhead lines makes cables a cheaper alternative. Except in these circumstances, an economic case cannot be made for any underground transmission system when compared with an overhead system. Initially, undergrounding only occurred in very large cities where land cost pressures coupled with legislation made it necessary. By 1966, 1600 miles (2500 kilometers) of underground power transmission cable were installed in urban areas (*3*), a total which must be compared with the 250,000 miles of overhead lines. The public tolerance for industrial pollution, as represented by the towers and swaths cleared for the right of way, is changing markedly and much higher standards of appearance are now demanded by the public than formerly. Consequently it can be expected that pressure from community groups and ultimately from the federal government will force more and more transmission lines to be placed underground near urban and scenic areas. It has been estimated (*3*) that in 1967 about 7 million acres were in use for the rights of way of transmission lines, and this figure may well triple unless extensive undergrounding takes place. Competition for land use because of population growth, the advent of the megapolis, and the increased need to transmit large amounts of power through these regions is such that the trend to underground will receive continued impetus. For these reasons it is likely that the 1900 miles planned in the period 1970–78 will be considerably exceeded (*4*). Because in an increasing number of cases public opinion is overriding purely economic arguments for undergrounding, it is important to understand that providing more electrical power and satisfying higher esthetic standards will be expensive. The need for new lines will have to be recognized well in advance to allow time for resolution of controversial issues or serious delays in construction programs can occur (*4*).

To dramatize the cost of undergrounding a transmission system it is instructive to examine the following figures. Power transmission accounts for about 20 percent of the total money invested in the nation's power system (about $80 billion in the next 10 years). The 1966 report to the Federal Power Commission compares the costs of overhead and underground power transmission and concludes that, on the average, underground transmission is from 9 to 20 times as expensive (*3*), and the result of this increased cost is that this small fraction, less than 1 percent of the total mileage, accounts for a significant fraction of the investment in transmission. The report also concludes that, if by 1980 10 percent of the transmission system is underground (which is most unlikely), the increased cost of electricity to the consumer, because of the extra investment involved, would amount to some 18 percent. When these estimates were made, inflation was not the problem it has since become and this number should be regarded as an underestimate. It is therefore clear that the cost of underground transmission for even a small fraction of the system will require improved systems and entirely new concepts.

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Technical Problems

The amount of power which can be transmitted by a conductor is limited by resistive losses that can be dissipated before the wire becomes hot and loses its strength, or, if it is part of an underground cable, the temperature rise can degrade the cable insulation to the point of failure. If only resistive losses are considered, then the power transmitted by a line increases directly with the voltage, so it is generally advantageous to raise the operating voltage to as high a level as possible. The lowest voltage still in use in transmission lines in the United States is 69,000 volts. The highest voltages are transmitted by extensive overhead systems operating at 765,000 volts, and lines carrying higher voltages are contemplated. The application of very high voltages introduces new problems, such as voltage insulation and charging current. The latter is a problem of special significance in underground cables in that the self-capacity of a cable is many times higher than that of an overhead line, both because of the proximity of the outer conductor and the dielectric constant of the insulating medium. The current that flows to charge this capacitance is 90° out of phase with the voltage and causes no net power drain on the system except for the resistive losses generated by this current. It is also unfortunate that the thermal insulation of the solid dielectric used in cables is much better than that of open air which seriously reduces the heat flow from the central conductor, placing a further restriction of the capacity of the cable. Finally it is the nature of liquid and solid dielectric materials to exhibit loss mechanisms in alternating electric fields. For good dielectrics the dielectric loss in watts per foot (1 foot is 0.3 meter) is

$$2\pi f V^2 C \cos\phi$$

where f is the frequency of the field, V is the voltage, C is the capacity of the cable in farads per foot, and $\cos\phi$ is the power factor. The power factor is an intrinsic property of a dielectric and increases with temperature and may under certain circumstances depend upon the electric field. Table 1 summarizes the performance capabilities of the standard pipe cable and shows the increasing significance of dielectric loss at high voltages.

A direct result of charging current is that cables have a critical length, which is the length where the thermal current

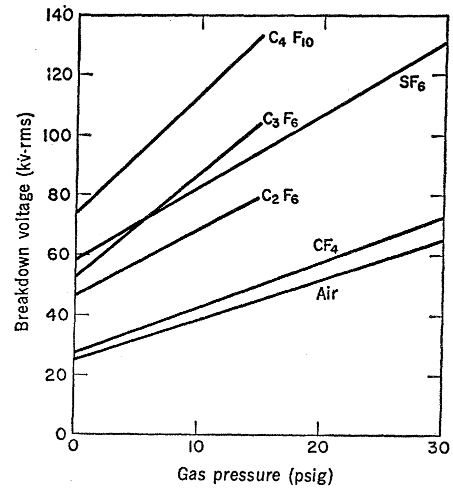

Fig. 1. Breakdown strength of insulating gases plotted against pressure; psig, pounds per square inch gauge; CF_4, carbon tetrafluoride; C_2F_6, hexafluoroethane; C_3F_6, hexafluoropropene; C_4F_{10}, decafluorocyclobutene.

rating of the cable is equal to the charging current flowing. If the cable were made 1 foot longer, the thermal current rating at the input would be exceeded even with no load on the output. The serious limitation introduced by this problem is illustrated in Table 1, where the power carrying capability of the 345-kilovolt cable falls to zero as the length approaches 26 miles. The critical length can be increased by compensating the capacitative currents by supplying inductive reactance at the ends or, if necessary, along the cable; but this results in extra complication and expense.

Until recently, in all but a few instances, an oil-paper dielectric has been the medium used for cable insulation. In these cables, a specially developed paper, impregnated with mineral oil and about 1 inch wide, is lapped vertically on the center conductor, with care being taken that there are no voids. The insulation is held in position by a tightly fitting, flexible conducting sheath. In a modern pipe-type cable, three cables (three phases) are pulled into a steel pipe, ½ mile long, which is filled with oil at high pressure (200 pounds per square inch; 13 atm). Manholes must be placed at half-mile intervals to provide a station for splicing the lengths of cable. In view of the high voltages, the insulation thicknesses (Table 1) are remarkably small and represent the results of continuing development since 1900 (*5*).

The need to avoid clumsy and unmanageable cables and yet to reach higher voltages has forced the cable designer to use higher dielectric stress, and consequently the dielectric loss has increased faster than the square of the voltage. Dielectric loss, which is unimportant at 69,000 volts, amounts to 37 percent of the permissible loss in an oil-paper dielectric at 345 kv and becomes prohibitive at 500 kv. For the next two decades oil-lapped dielectric will continue to hold its dominating position, except that during this period there may be a gradual shift from paper to synthetic materials. These synthetics, such as Mylar, polyethylene paper, and nyon paper (Nomex), have a considerably lower dielectric loss, and because they can be operated at higher electric stress—that is, thinner insulation—provide better heat transfer. Solid dielectric or extruded cables, an alternative to the lapped cable, are being made for voltages as high as 130 kv with some prospects that this voltage may be doubled (*6*). Quite apart from the difficult problems of quality control, this type of cable is difficult both to install and terminate and is therefore unlikely to gain acceptance above 138 or 230 kv.

The first property which must be considered in the evaluation of a dielectric is insulating strength, which must be examined under continuous usage, and the transient conditions that are caused by switching surges or lightning. The newer synthetic materials have considerably enhanced strength, about 10 kv/mil, three or more times that of oil paper and lower losses. A low dielectric constant reduces the charging current, and this must be considered in the evaluation of a material for an alternating-current (a-c) cable. The resistance of a dielectric controls the voltage gradient in direct-current (d-c) cables. Because the temperature dependence of resistivity is marked, the highest field in d-c cables is often in the outer layers. Coupled with these electrical properties is the need for good thermal conductivity and mechanical properties, including flexibility, resistance to stress cracking, and high uniformity or integrity.

For practical reasons high voltage cables are made in short lengths, and many splices are necessary. Making a dependable splice is costly and time-consuming. A splice on a 345-kv cable can take 8 or more 24-hour workdays and must be performed in a specially constructed air-conditioned room. Joints are therefore an important component of the installed costs of an underground cable and are reflected in the cost of repairs. Thus when an outage occurs in a line, part of which is a cable, power is not restored until the cable has been checked.

Cables Insulated with Compressed Gas

At 345 kv and above long lengths of oil-paper cables require expensive reactive compensation, and even with the newer materials dielectric loss significantly reduces the power handling capacity. It is therefore attractive to consider other dielectrics for voltage insulation. A cable in which a compressed gas is used as an insulating medium appears to offer a practical and immediate alternative at high voltages and power levels (*7*). Some of the more common electronegative insulating gases employed for this purpose are SF_6 (sulfur hexafluoride) and C_2F_6 (hexafluoroethane), the molecular structure of these gases being tailor-made to provide a high level of dielectric strength, as can be seen from the comparison with other gases shown in Fig. 1.

A view of a gas-insulated cable is shown in Fig. 2. The inner and outer conductor for each phase are rigid aluminum tubes, the inner tube spaced from the outer by carefully designed concentric epoxy insulators. The cable is of considerably larger diameter than that of the equivalent pipe cable. Advantages resulting from gaseous insulation include negligible dielectric losses, convective heat transfer from the center conductor, and, as a result of the large surface area of the outer cylinder, good heat transfer from the cable to the surrounding soil. A very important benefit is that the critical length is much greater than that obtainable with solid dielectric cables; at 500 kv the critical length is 550 miles as compared to 17 miles for a pipe cable of the same voltage rating. On the other hand the large-diameter tubes, made necessary by the lower dielectric strength of gases, require wider and more expensive trenches (*8*).

The lines are prefabricated in sections, and a reasonable length for these sections is in the neighborhood of 40 feet with the result that a very large number of welded gastight joints must be made when laying the line. This process can be automated but represents an additional cost which should be compared with cable splicing. Provision for thermal expansion which can amount to ½ inch in 40 feet must be provided by specially constructed sections.

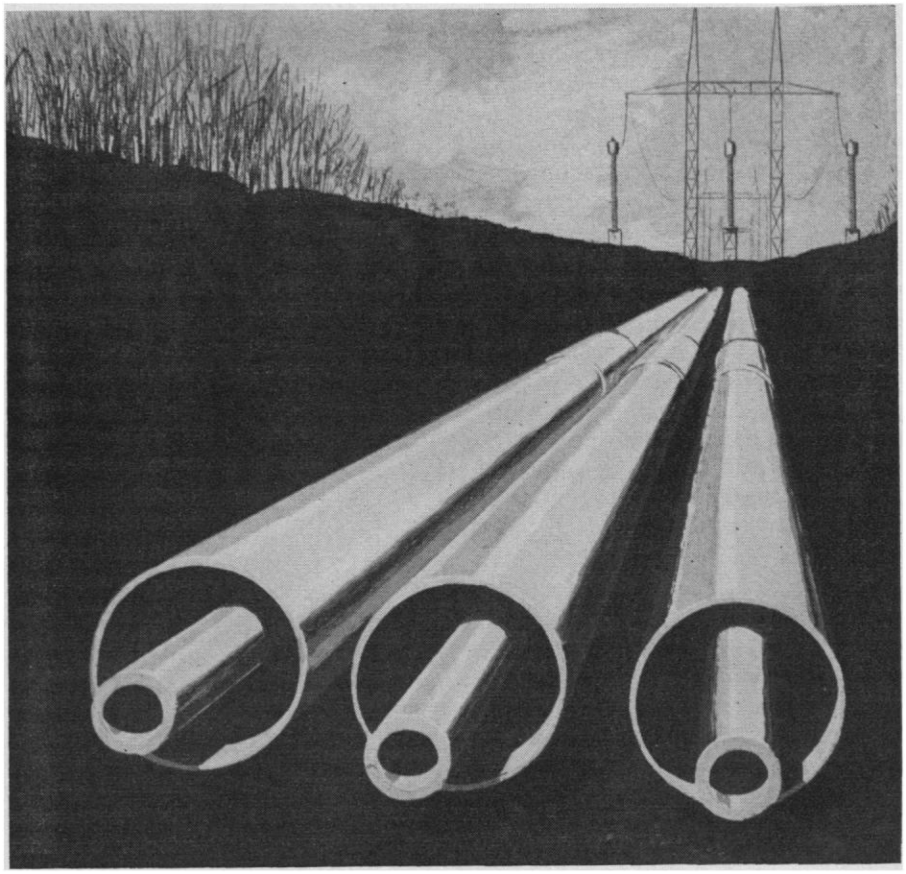

Fig. 2. Views of a compressed gas-insulated cable.

The cable insulated with compressed gas becomes less expensive than the conventional cable at power ratings in excess of about 1000 MVA. In addition, it is the only cable now available which can match overhead lines in capacity and voltage handling capability—a significant advantage. The survey of 1966 (*3*) recommended careful economic evaluation of gas-insulated systems, and the system seems to be gaining acceptance by the utilities in special circumstances. For example, Consolidated Edison Co. is installing a 600-foot section of 345-kv, three-phase system to avoid a difficult overhead crossing (*9*). Gas lines are very compatible with the trend to all enclosed substations. The components in these stations are usually gas pressurized and therefore much more compact and can be installed in the basement of buildings and other downtown areas. Rising voltages and power levels indicate that, provided no serious maintenance or reliability problems are encountered, the 1970's will see considerable lengths of compressed gas-insulated cables in service.

Cryogenic Cables

The subject of superconducting or supercooled cables has recently become the subject of intensive study. The advantages of very low or zero conductive losses are technically obvious, being primarily a very large increase in the

Table 1. Summary of the performance characteristics of oil-paper dielectric pipe cables. The thermal capacity of a cable depends on the conductivity of the surrounding soil, which can show considerable variations; a typical value was assumed to arrive at the figures given in this table (1 inch is 2.54 cm; 1 foot is 0.3 m; 1 mile is 1.6 km).

Nominal voltage rating (kv)	69	138	230	345
Permissible average loss (watt/ft)	6.66	6.96	6.99	7.30
Dielectric loss (watt/ft)	0.54	1.36	1.40	2.68
Power factor (percent)	0.45	0.45	0.25	0.25
Insulation thickness (inches)	0.285	0.505	0.835	1.025
Thermal rated capability (MVA)	105	200	330	440
Critical length (miles)	55	41	38	26

thermal limit to the power-carrying capacity of the cable. In exchange for this very substantial advantage, a host of new problems is encountered which at this early stage of development are not proved to have practical solutions that satisfy the standards required by the utilities. Lacking these, economic evaluations tend to be superficial, but it certainly appears that, if the amounts of power to be handled approach 1000 megawatts, there are distinct economic advantages to cryogenic techniques.

The change of conductivity of pure aluminum as it is cooled to cryogenic temperatures is shown in Fig. 3. The figure shows that at the temperature of liquid nitrogen (77°K) the resistance has decreased to one-tenth of its value at 300°K, at the temperature of liquid hydrogen (20°K) by one-thousandth. Very pure aluminum at liquid helium temperature (4.2°K) shows a decrease of one ten-thousandth (*10*). At standard power frequencies it is not possible to take full advantage of this decrease in resistivity because of the skin effect which restricts most of the current to a layer of depth

$$(2\rho/2\pi f\mu)^{1/2} \text{ cm}$$

where ρ is the d-c resistivity, μ is the permeability of the conductor, and f is the frequency. The resistance of the current-carrying surface layer is therefore proportional to $\rho^{\frac{1}{2}}$, so that a change in resistivity of 100 produces an effective change in the cable resistance of only a factor of 10. At low temperatures another effect should be considered. The mean free path of the conduction electrons becomes larger than the skin depth, and the effective electric field must be averaged over the mean free path, producing a small increase of surface resistivity significant at standard power frequencies.

Cooled to 4.2°K, resistive cables do not appear to offer advantages over those made with superconductive materials, but a good case can be made for cables cooled by liquid hydrogen and liquid nitrogen. For example, Neal (*11*) describes a three-phase 3000-MVA, 500-kv cable, 10 miles long, cooled by liquid hydrogen. The conductors are aluminum tubes 3 inches in diameter with a 50-mil wall, held by high voltage insulation inside a 6-inch-diameter tube of the same thickness. He calculates that the losses are 34 kw/mile for the conductor and shield, 4 kw/mile for dielectric and 4 kw/mile for thermal losses. The resistive losses alone at

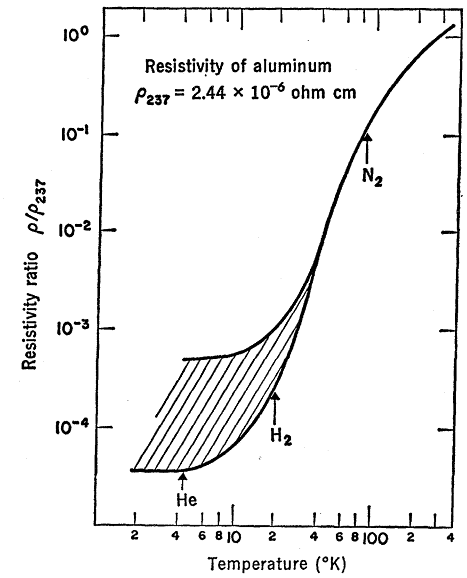

Fig. 3. The change of conductivity of pure aluminum as a function of temperature. The resistivity at liquid helium temperatures (ρ_{237}) is almost solely a function of the impurity concentration (shaded region).

ambient temperatures in an equivalent cable would exceed 360 kw/mile. This low loss cannot be matched at liquid nitrogen temperatures, but Graneau (*12*) has pointed out certain important advantages of cryogenically cooled systems which are particularly applicable at liquid nitrogen temperatures. He holds that the main incentive for developing a low-temperature cable is the removal of many constructional and material constraints which ambient temperature imposes on conventional underground transmission lines. Reduced capital investment should be an overriding objective even at the expense of increased power losses. Figure 4,

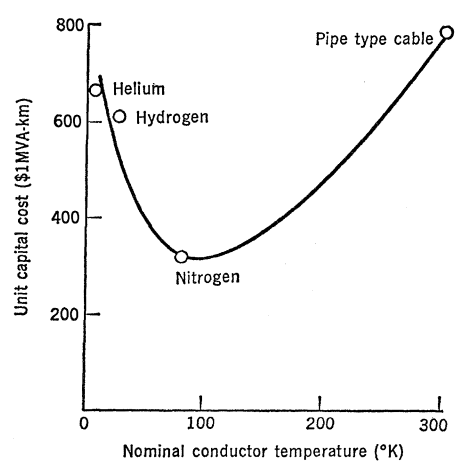

Fig. 4. A comparison of the capital cost of different types of cable as a function of conductor temperature (*12*).

which is taken from his article, shows a minimum in capital cost at a temperature of about 100°K.

The electrons responsible for superconductivity do not obey Ohm's law, the current flow being associated with a very thin layer, 500 Å in thickness, on the surface of the conductor. In a type I or elementary superconducting material, such as Sn or Pb, there is no measurable resistance or loss to d-c currents up to a critical current or magnetic field. The critical field of Pb at 4.2°K is 500 gauss, a value which would severely limit the maximum current flow in a superconductor of practical size. The discovery of type II superconductors, such as Nb_3Sn, has essentially removed this problem, the critical field at liquid helium temperature of Nb_3Sn being $\approx$ 100 kgauss.

Although direct current flow is without loss, an alternating current produces an electric field in the superconducting layer which, acting on the ordinary conduction electrons also present, is responsible for ohmic loss. The magnitude of this loss for a given material depends on the roughness of the surface, the presence of work hardening, and on impurity concentrations. At standard power frequencies these losses are very small compared to the losses in the best of the normal materials, such as high purity copper or aluminum (Fig. 5). In type II superconductors some field penetration occurs above the first critical field, with considerable increase in the a-c losses resulting. For this reason and because there are no cryogenic liquids with a boiling point between 4.2° and 20°K, superconducting cables have always been considered as operating at liquid helium temperature. The recent advent of superconductors with a critical temperature above 20°K is promising in that new materials operating at liquid hydrogen temperature will become available. Considerable investigation is required to establish that the losses measured in small samples can be related to long lengths of line produced under industrial conditions.

The essential features of a superconducting cable are shown in the cross section of Fig. 6. A thin superconducting cable skin of niobium is plated onto a very pure (99.999 percent) aluminum conductor. The normal conducting material is provided as a backing to the superconductor to obtain thermal stability and to provide an alternative path for the current if, under short conditions, parts of the cable lose their super-

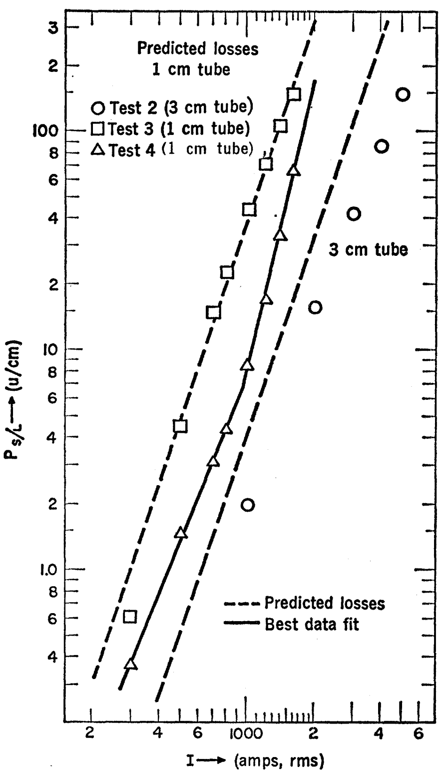

Fig. 5. Alternating-current power loss ($P_{S/L}$) in a niobium superconducting cable. The loss is given in microwatts per unit conductor length (*17*).

conducting property. The conductor is contained in a shield from which it is electrically insulated by a vacuum. The voltage insulation can be provided by liquid helium, but it is not as effective an insulator as the other cryogenic fluids (~ 0.5 kv/mil compared to more than 1.0 kv/mil for liquid nitrogen).

The conductors for the three phases are included inside an outer cylinder at liquid nitrogen temperature insulated from the surroundings by vacuum and many layers of aluminized plastic ("superinsulation"). The conductors and shields are cooled by liquid helium flowing in contact with them. The price paid for superconductivity is considerable. The conductor and shield must be coated with a thin layer of superconducting material, and an extra cryogenic fluid is needed to reduce the radiant heat transfer between conductors at the temperature of liquid helium to the surroundings. The heat transfer across a vacuum from a wall cooled to liquid nitrogen temperatures is about 10 μw/cm², which, in the case of a d-c cable, would be the only loss.

Garwin and Matisso (*13*) have proposed a superconducting cable design of very high capacity, which requires liquid helium and nitrogen refrigeration stations every 20 km. The capacity of this d-c cable is estimated to be 100 Gw (10^{11} watts). Rogers and Edwards (*14*) have designed a more modest 750-MVA cable in which concentric conductors are cooled internally by liquid helium and insulated by vacuum. The spacers between the conductors are of fluorinated ethylene propylene which has a power factor of 10^{-5} or better at these temperatures. The total load on the liquid helium in a 10-km length of this cable is about 1 kw and can be accommodated by a liquid helium flow rate of 1.8 liter/sec. Other designs by Gauster *et al.* (*15*), Klaudy (*16*), Eigenbrod *et al.* (*17*), and Walker and Symonds (*18*) serve to bring out different aspects of the problem, and by their very diversity serve to emphasize that a practical solution is far from available. The current-carrying capacity of superconducting cables is so high that high voltages are not necessary to achieve high power ratings. Advantage can be taken of this to reduce the voltage insulation problem and also to connect directly to the generators without the need for large step-up transformers.

Flux jumps and instability occurring at high current densities resulting in reversion to normal conductivity represent a serious problem. It appears that such instabilities can be avoided if the diameter d of the superconductor is very small, less than

$$10^9 S T_0 \alpha^{1/2}/Jc$$

where S is the heat capacity (joule/cm³ °K), T_0 is approximately half the critical temperature T_c, J_c is the critical current density (amp/sec), and α is a numerical factor between 0.6 and 0.9. The multiple-filament wire developed by Smith *et al.* (*19*), in which many filaments of NbSn 0.002 mm in diameter are embedded in a matrix of ordinary conductor, offers one practical solution to this difficulty.

Cryogenic cables may be insulated either by vacuum or cryogenic liquid, for both of which spacers are needed, or by cryogenic liquid impregnated dielectric supporting the center conductor directly. The advantages of low temperature are negated if dielectric losses become significant. From this point of view vacuum insulation has a distinct advantage. However, achievement of high breakdown strengths across a vacuum gap requires very careful techniques. In d-c systems metallic surfaces must be carefully polished, conditioned to voltage, and operated at approximately 10^{-6} torr, free from contaminants such as oil vapor, which rapidly reduce insulating strength. Trump (*20*) has pointed out that the voltage capability in a vacuum soon reaches an equilibrium value when the interelectrode spacing is increased and that it is still difficult to insulate more than 500 kv d-c between electrodes of 100-cm² area spaced 2.5 cm apart. A further problem inherent in vacuum insulation is that dark currents occur at high stresses, which may be as high as microamperes per square centimeter at useful field gradients. This current amounts to a very large loss between 0.1 and 1.0 watt/cm², depending on the voltage. This loss would be prohibitively high for any cryogenic system. Much more encouraging results for a-c vacuum insulation are claimed, a difference worth intensive study (*21*).

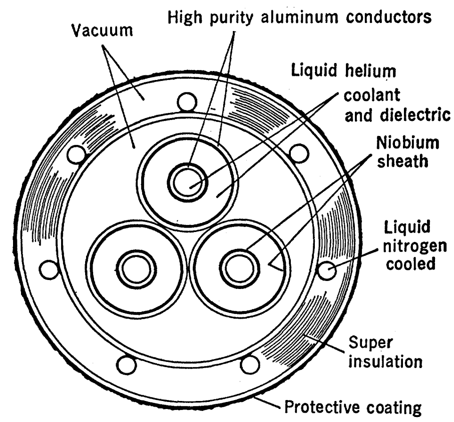

Fig. 6. A cross section of a superconducting cable.

Direct-Current Cables

The history of power transmission shows that d-c cables have seldom found practical application except under circumstances making reactive compensation of a-c cables a practical impossibility, as is the case in long underwater cables (*22*). There are, for example, d-c power links under the English Channel, between the north and south islands of New Zealand, and between the island of Gotland and Sweden. Because of the impedance characteristics of a d-c line, it is easy to reverse the power flow which can be very desirable. For example, the reason for the cross-channel link is that the peak power loads in France and southern England occur at different times; therefore, by reversing the power flow the generating capacity can be shared, a saving in power plant

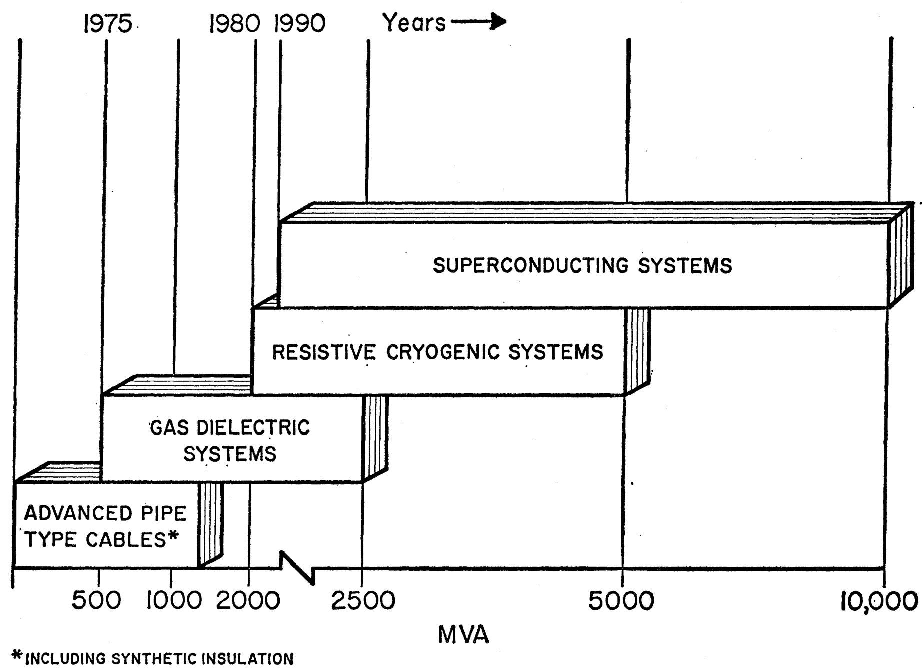

Fig. 7. Estimated ranges of capabilities of new underground transmission systems. [Courtesy of P. Cory, Boston Edison Co.]

more than offsetting the cost of the cable and the conversion equipment. When power flow is reversed, it is necessary to reverse the inverter voltage. A sudden reversal of the voltage on a cable with the dielectric previously polarized in the other direction has the effect of putting a "double voltage" on the cable, sometimes with bad effects. The cross-channel cable failed in this manner. The increased coupling of local systems by the national grid and ultimately perhaps by an international one raises serious stability problems. A d-c link can have an important isolating or stabilizing influence. It can be used to connect systems of different phase or frequency.

The current capacity of a d-c cable is almost solely determined by the resistive loss in the conductor since there is no charging current or dielectric heating; and because there is no skin effect, this resistive loss is less. In addition, the insulating strength of dielectrics is considerably greater for d-c than for a-c by two to ten times, which means that thinner dielectric walls can be used, a combination of factors resulting in an increase in the thermal capacity of a d-c cable over its a-c counterpart. Another advantage of d-c over a-c which may be exploited in the long term is that direct current can be transmitted with no loss in a superconducting system and with reduced loss in a cryogenically cooled cable because of the absence of skin effect. These advantages have not proved exploitable because of the cost of a-c to d-c conversion equipment, now about $25 per kilowatt. However, improvements in solid state converter devices may ultimately bring conversion costs down to $16 per kilowatt or even less (*23*). If this occurs a good case can be made for a much wider use for direct current. Quite apart from the installation of new cables, it would appear that existing oil-paper dielectric cables could be substantially upgraded, by a factor of 2 or more, if they could be converted to direct current.

Microwaves

It has been suggested (*24*) that economic power transmission could be obtained by exploiting the very low attenuation that occurs in circular waveguides propagating the TE_{01} mode wavelength. In principle, a waveguide with a radius of 1.15 m operated at a frequency of 3 Ghz has a power-carrying capability of 10.6 Gw. Even if the difficulties of generating and converting such vast amounts of microwave can be solved, the mechanical tolerances on the waveguide are severe. Departures from exact cylindrical geometry and other nonuniformities, such as tilts in the butting flanges, cause a small fraction of the power to be converted into other modes (TM_{11}, TE_{11}, and so on) which are highly attenuated.

Summary

Much of the generating capacity to meet the needs of the future may be from generating stations in groups of two or three, each of 1000 Mw, located away from the growing urban areas. Transmission systems will become longer and be of higher duty; and a combination of popular demand and land cost will force the system underground at increasing distances from cities. The need for higher capacity cables to match the new overhead systems and for reduced capital and installation costs is forcing the search for better materials and new techniques. The vast size of the power industry implies that a breakthrough in technology would have dramatic consequences and even a small improvement in materials or techniques can be of significant economic importance.

Automation or other improvements in the techniques of trenching and cable laying must be considered along with improved cable designs. In congested areas trenching is often no longer convenient, and deep service tunnels may provide an answer. New techniques for boring and lining tunnels can therefore have a direct bearing on the costs of transmitting power. Cryogenic lines cooled with hydrogen are being investigated; but can they be made safe for installation in cities? Is it safe to use the earth as a return for d-c cables? The answers are certainly not obvious. A host of similar problems must be considered, some mundane, but many requiring the utmost in sophistication if economic solutions to them are to be found.

New materials such as superconductors operable at higher temperatures, or better insulating materials with low power factors, are under intensive development, but, even if nothing startling is found, new types of cables will come into use at a time and a rating, much as shown in Fig. 7. Short lengths of gas-insulated cable are already going into the transmission system, and cryogenic cables have reached an early test phase. The situation is dynamic, and a vigorous example of the application of basic and applied research to a problem of the greatest importance to our industrial civilization.

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Measurement of Fast Biochemical Reactions

Flow and relaxation methods are being used to study chemical processes in biological macromolecules.

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Biochemists are now attempting to describe the flow of energy and information in the cell in terms of more primary chemical processes in biological molecules (*1*). For macromolecules these processes include conformational isomerizations; helix-coil transitions; the formation of secondary, tertiary, and quaternary structure; and interactions with ligands. These processes, in turn, can be described by the processes of formation and disruption of electrostatic, hydrophobic, and hydrogen bonds and of the transfers of electrons and protons mediating changes in covalent structure.

These chemical processes, in general, occur with half-times of considerably less than 1 second and may be classified as "fast" (*2*). Most methods for studying such reactions are relatively new (*3*), and only in the last decade have these methods been extensively applied to biological molecules (*1, 4*). It is interesting, however, that much of the pioneering work in making fast reactions accessible to measurement came from biochemists. The continuous flow apparatus of Hartridge and Roughton (*5*) for study of reactions of hemoglobin with its ligands, and the accelerated and stopped flow instruments of Chance (*6*) for study of enzyme-substrate interactions first made it generally possible to measure chemical reactions with half-times in the millisecond range. Extension into the microsecond and nanosecond ranges did not occur until the work of Eigen and his collaborators (*7*) with chemical relaxation techniques in the 1950's. These relaxation methods were originally applied to the kinetics of chemical bond formation and disruption and resulted in the first accurate estimates of the rates of these processes. Table 1 lists these values for a number of chemical processes as a reference scale for considering reactions of biological macromolecules. Application of relaxation methods to biopolymers originated in Eigen's and Alberty's laboratories, but they are now employed by many other investigators. In addition, there have been continuous improvements in the performance and versatility of flow instruments so that these too are now being applied to a wider range of problems.

In this article it is my purpose to provide a general review of some of the recent applications of flow and relaxation techniques to fast biochemical reactions. Several of the methods, especially stopped flow and temperature jump, are of such general relevance that they are becoming part of the basic equipment of many groups studying proteins and nucleic acids. This change has been facilitated by the availability of several commercial flow and relaxation instruments (*8*) and of improved electronic and hydraulic components from which instruments can be constructed or from which existing equipment can be modified. Several articles and books devoted to the design and principles of these instruments have appeared (*7, 9*).

Flow Techniques

Continuous flow instruments are based on observation of a reaction along the length of a tube through which the mixed reagents are propelled. The elapsed time after the initiation of the reaction is a function of distance along the tube. This method still has certain advantages (*10*), but the frequent need in biochemistry for strict economy with reagents has made the stopped flow technique more generally useful. In stopped flow instruments, small volumes (usually about 0.1 ml of each) of two solutions are mixed together just before they enter a cell, which has observation ports or other sensors. Flow is mechanically

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