COMMISSION OF THE EUROPEAN COMMUNITIES

energy

SUPERCONDUCTING AND OTHER HIGH POWER CABLES FOR ELECTRIC POWER TRANSMISSION STATE OF THE ART AND PERSPECTIVES

1976

EUR 5520 e

COMMISSION OF THE EUROPEAN COMMUNITIES

energy

SUPERCONDUCTING AND OTHER HIGH POWER CABLES FOR ELECTRIC POWER TRANSMISSION STATE OF THE ART AND PERSPECTIVES

H. MARCHANDISE

Directorate General for Research, Science and Education
Brussels (Belgium)

1976

EUR 5520 e

LEGAL NOTICE

Published by the
Commission of the European Communities
Directorate General
"Scientific and Technical Information
and Information Management"

Bâtiment Jean Monnet - Kirchberg

Luxembourg (Grand Duchy)

Summary

This document describes the state of the art of high power cables including those derived from conventional designs (forced cooling by oil or water) polyethylene cables, SF_6-cables and the most advanced ones.

Emphasis is largely placed on superconductung cables and the problems which still require to be solved before an actual commercial cable can be designed.

The paper also summarizes the results of a forecast study of the possible market for high power cables in Europe.

The results of economic comparisons are given with some details.

It is shown that internal cooling with oil or water could make it possible to reach very high power levels. If these cables were successfully developed they would be very serious competitors for the superconducting ones. They could perhaps be more economical up to very high power levels (6000 MVA).

CONTENT

INTRODUCTION

This document summarizes the findings of studies carried out under contract for the Commission of the European Communities on the uses of high power underground cables for electric transmission and the possible needs for developing advanced cables.
It reviews briefly the present state of the art and the performances of various types of cables with particular emphasis on the superconducting ones.

The objective of the work was to form an opinion on the amount of high power cables that could be required in the Community countries up to the year 2000, and on the ways of fulfilling this demand.
It wás also to investigate the amount of R&D which is still necessary before superconducting cables can reach commercial development.

P A R T I

HIGH POWER CABLES

NEEDS, STATE OF THE ART AND PERSPECTIVES.

This review is largely based on studies carried out by Ente Nazionale per l'Energia Elettrica (Rome) and by the Institut für Experimentelle Kernphysik of the Kernforschungszentrum and the University, Karlsruhe.

1. USES OF HIGH POWER CABLES IN ELECTRIC TRANSMISSION

Large amounts of electric power are normally transmitted over large distances by means of overhead lines. Ohmic losses in the lines require the use of suitably high voltages. 380 kV is now common practice in Europe for the high power network. Use of higher voltages (750 kV and 1100 kV) is under study.

Overhead lines offer overwhelming advantages over underground transmission system namely low construction cost, very high transmission capacity, suitability for short and very long distance transmission, reliability and very short repair time.

The cost of underground cables is compared with overhead lines in paragraphe 2.1.
In short, a conventional 220 - 380 kV cable is 10 to 15 times more expensive than an overhead line of the same carrying capacity. In addition high voltage a.c. cables of the current design are not suitable for long distance transmission (charging power).

The share of the transmission network in the capital investment of electric utilities is about 7 %, while 45 % go to the power stations. Substituting only part of the new overhead lines, to be installed, by cables would bring the investments for transmission at higher level than those needed for the generating system. The cost difference between cables and overhead lines is so large that, whatever the demands of ecology and public opinion, it is very difficult to foresee any substantial use of cables in the transmission grids.

There are situations in which overhead lines cannot be installed. Two typical examples are the feeding of electric power into large urban areas and the transmission over wide rivers or across the sea. Undersea long distance transmission usually requires direct current. However if nuclear power stations were to be built off-shore, they would have to be connected to the grid on the continent by a.c. cables over a distance of, say, a dozen kilometers.

In the aforementioned cases there is no alternative to underground cables.

The following table illustrates the relative importance of overhead lines and of cables in the transmission network of the United Kingdom (1974).

Table 1-1. - Existing transmission lines in the U.K. in 1974 [10].

	Overhead lines	Underground cables
400 kV	4.325 km	27 km
275 kV	1.929 km	258 km
132 kV	9.417 km	1.496 km

2. OVERHEAD LINES

2.1. Cost comparison between overhead lines and conventional cables

The cost of high voltage overhead lines is more than ten times smaller than the cost of underground cables of similar voltage and power.

A detailed comparison was published in 1967. Its results are summarized in Table 2-1, where the prices are given in Swiss francs. The cost is in fact the total price of the installed line. It is not a transmission cost anddoes not include operational costs nor the influence of losses.

Table 2.1. - Comparison of overhead lines and underground cables of the same power [9] - (Prices 1967)

U kV	Conductors	Nominal Load MVA	Cost SF/km	Cost ratio Cable/line
150	Line 2 x 3 x 1 x 300 mm^2	240	157.600	6,3
	Cable 6 x 600 mm^2	240	997.000	
220	Line 2 x 3 x 2 x 300 mm^2	600	244.000	7,4
	Cable 12 x 300 mm^2	650	1.796.000	
380	Line 2 x 3 x 2 x 600 mm^2	1200	363.000	10
	Cable 12 x 500 mm^2	1200	3.656.000	

A more recent comparison has been made by the CEGB [10].
It is based on the following assumption. The overhead line is installed along a cross-country route and must be partly undergrounded. It has two circuits and both of them are fully loaded. The cables are designed to carry all the power of the overhead line. Their total cost appearsin the fourth column of table 2.2.

Table 2.2. - Cost comparison of overhead lines with equivalent underground cables in identical situations [10]. (Evaluation of 1974)

Voltage	Conductors of overhead line	Cost of overhead line	Cost of equivalent cable	Cost ratio Cable/line
132 kV	2 x 3 x 175 mm2	13.000 £	131.000 £	10
132 kV	2 x 3 x 400 mm^2	18.000	188.000	10,4
132 kV	2 x 3 x 2 x 175 mm^2	22.000	244.000	11
275 kV	2 x 3 x 2 x 175 mm^2	23.500	369.000	15,5
275 kV	2 x 3 x 2 x 400 mm^2	47.000	556.000	12
400 kV	2 x 3 x 2 x 400 mm^2	66.000	681.000	10,3
400 kV	2 x 3 x 4 x 400 mm^2	77.000	1100.000	14,3

In the first comparison the cables and the lines are independently optimized for a particular load and their overload characteristics are different. In the second one, the cable being in series with the line, it must be able to carry the maximum load of the line which is much higher than the design load at which it is normally operated. The two comparisons relate to different situations. Actually when a cable is inserted in series into a line, additional termination equipment is necessary. If this is included, the cost ratio for 400 kV rises from 14 to 16.

Also in the first comparison the conductor cross sections used for e.g. the 1200 MVA overhead lines is larger than in other designs namely those given in Table 2.2. This makes the line more expensive and reduces the cost ratio.

2.2. Losses in overhead lines

Losses in overhead lines are usually calculated from the ohmic losses ($R I^2$) in the conductors. Other losses are negligeable by dry weather and up to 400 kV. To illustrate this, a few losses are given in Table 2.3. for the three-phase lines.

Table 2.3. - Losses in overhead lines

Conductors	Current Amps	Loss kW/km
3 x 4 x 250 mm^2	1.000	210
3 x 4 x 250 mm^2	800	134
3 x 4 x 400 mm^2	1.000	132
3 x 4 x 400 mm^2	800	84,5

An overhead line is normally operated at a power equal to 50 - 70 % of the maximum thermal load. A few examples are given in the table below for 400 kV.

Table 2.4. - Operating characteristics and losses of overhead lines

Conductors	Maximum thermal load MVA	Natural load MW	Operation 50 % thermal	Loss kW/km
3 x 4 x 265 mm^2	1.900	650	950	185
3 x 4 x 240 mm^2	1.700	580	850	151
3 x 4 x 435 mm^2	2.375	550	1200	121
3 x 4 x 265 mm^2	2.200 (winter)	-	1100	156
3 x 4 x 265 mm^2	1.380 (summer)	-	690	61,5

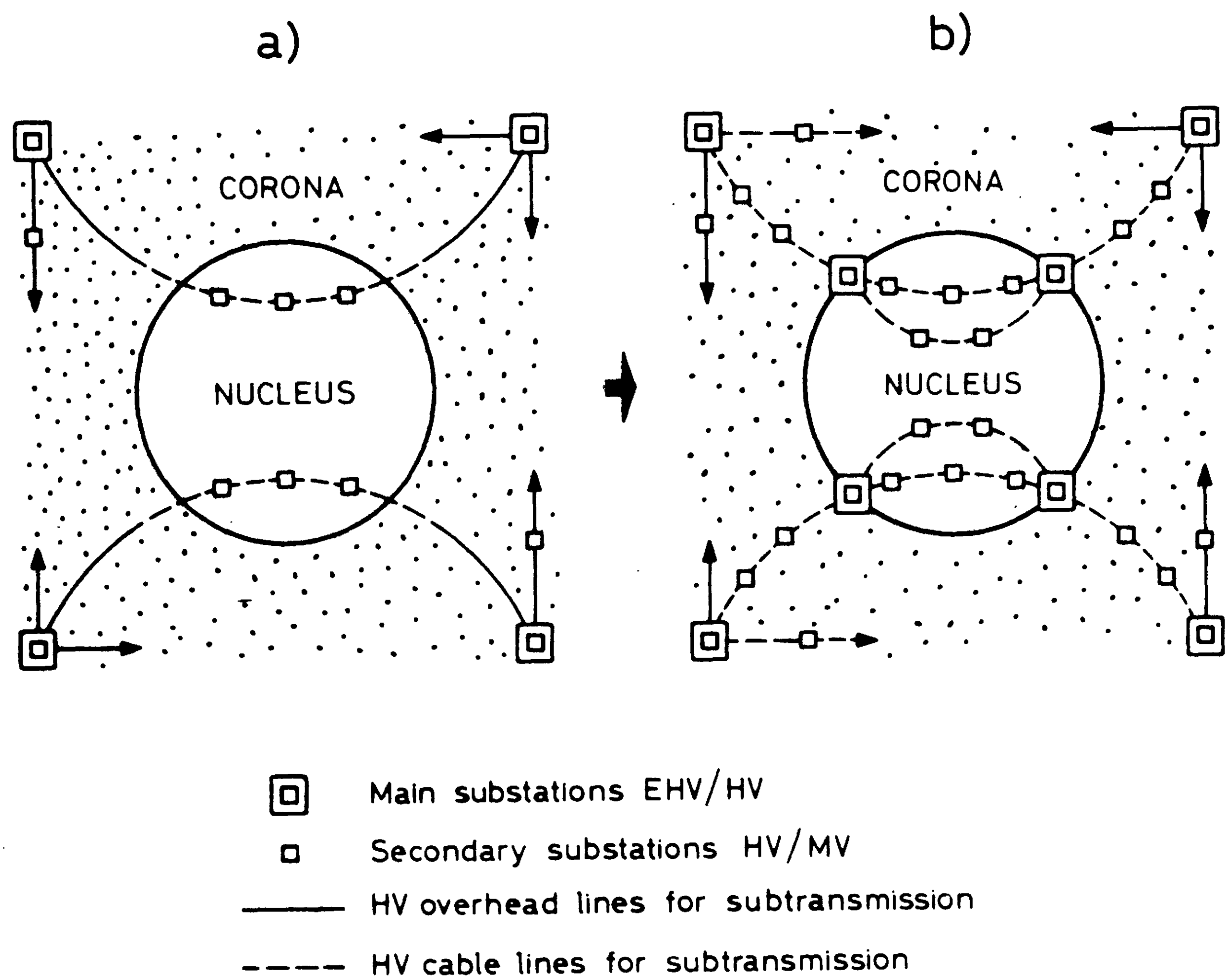


Figure 3-1. - Evolution of the subtransmission network assumed in the calculation.
a) present situation - b) new configuration.
The new EHV/HV substation to be placed around the nucleus will be fed by high power cables as show on figure 3-2.- (from [7]).

3. FUTURE NEEDS OF VERY HIGH POWER CABLES

A forecast study of the possible demand for high power underground cables in Europe was carried out by ENEL under contract for the Commission of the European Communities. The two forseeable uses of such cables were considered, namely

- the penetration into large conurbations
- the connection of off-shore power stations to the main grid.

3.1. Cables for the supply of large conurbations

The forecast considers only those large cities of the E.E.C. which are formed around one dense centre. Large populated areas involving several centres are not considered. They can now be fed more safely and economically by overhead lines. It is assumed that corridors will be reserved for services (gas, water, railways, etc.) and that penetration with overhead lines will continue to be possible.

At present, the "nucleus" of the large conurbations is generally provided with an external ring of overhead lines or cables which penetrate through the urban area (corona) to the primary substations (high voltage/medium voltage)(fig. 3-1).

As the density of power consumption (MW/km^2) increases, the number of these primary substations will have to be increased and the present penetration cables (130 and 220 kV) will not suffice. It will therefore be necessary to install, within the urban area, new transformer stations (EHV/HV e.g. 400kV/130kV) designed to feed the cable network in existence (fig. 3-1). Generally speaking, it will not be possible to reach these new EHV/HV stations with overhead lines crossing the densely-populated corona surrounding the nucleus and recourse will have to be made to very high power cables (1000 - 2000 MVA).

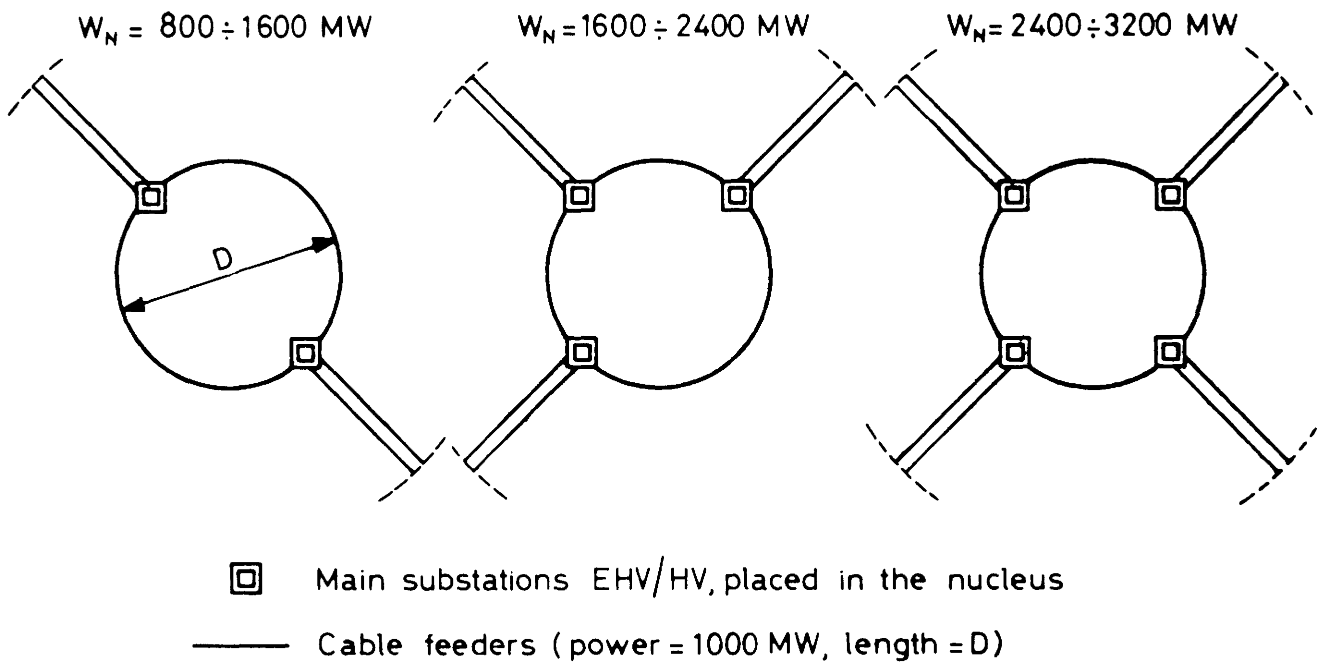


Figure 3-2.- Model a.
Possibles ways of feeding the town nucleus, for different levels of peak power demand W_N (from [7]).

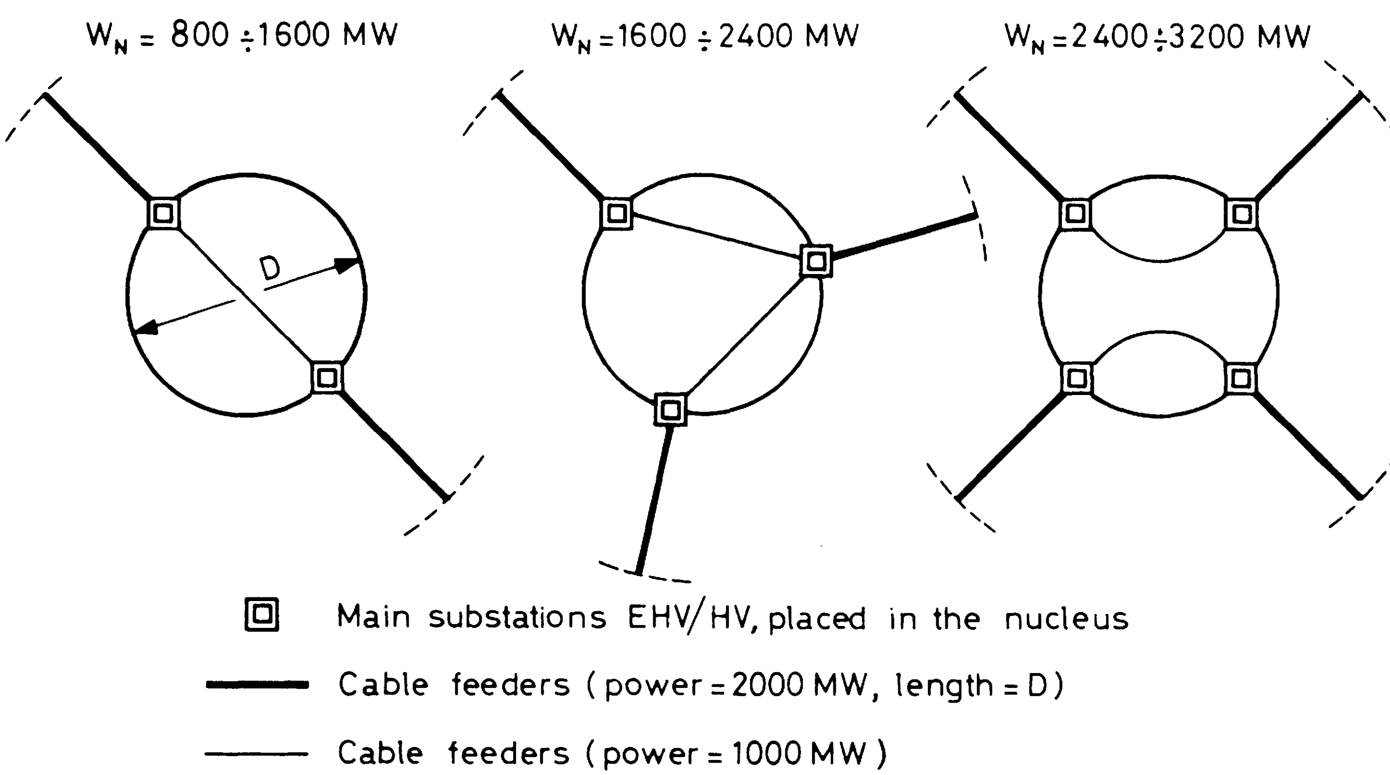


Figure 3-3.- Model b.
Possible ways of feeding the town nucleus for different levels of peak power demand W_N (from [7]).

The power of the EHV/HV stations is supposed to be 1000 MVA. To connect them with a sufficient degree of reliability, two different models are envisaged.

a) The transformer stations are installed at the edge of the nucleus and are connected by means of cables to stations outside the corona of the town. The cable length is assumed to be equal to the diameter of the nucleus. Each transformer station is fed with two cables, each of them being capable of carrying the full load (1000 MVA). This allows for a 100 % reserve (fig. 3-2).

b) The same configuration is adopted for the location of the stations but the EHV/HV stations are fed by one cable of a power equal to double (2000 MVA) the power of the station. In addition, for reasons of security, each station is connected through the nucleus to another EHV/HV station by means of a 1000 MVA cable (figure 3-3).

With these models the length and number of high power cables (rated at 1000 and 2000 MVA) are functions only of the size of the conurbation and of its power demand.

The table 3-1 shows all large towns in the EEC which are expected to have, within the nucleus, a population of about one million inhabitants or more in the year 2000. The surface area of the nucleus is assumed to remain constant between 1980 and 2000. The consumption of electric power per capita is assumed to increase at an average rate of 3 % per annum, or less when the present rate is already very high. To derive the annual peak power demand, the number of hours of utilization per annum is assumed to be 4000.

Table 3.1 shows the lengths of cables required for each town according to the two models a and b . Installation of such cables could in fact start by 1980 - 1985 in the largest towns.

The length of 1000 MVA a.c. cables to be installed from now on to the year 2000 may therefore be equal to or exceed 3.300 km according to model a . If model b is adopted 1.650 km of 2000 MVA cable may be required.

Smaller towns and other conurbations may also call for high power cables. The prediction of table 3.1 can therefore be considered as conservative.

3.2. Cables for the connection of power stations to the main grid

Off-shore nuclear power stations, located a dozen or so kilometers from the coast will have to be connected to the grid by means of cables laid on the sea-bed.
How many such power stations will be built is highly unpredictable.

The highest carrying capacity of these cables would be equal to the power of the individual generating units. In the present state of knowledge, large units of 2400 - 3000 MW may be expected. The date of their appearance will depend upon the technology (classical or superconducting a.c. generators), the total power of the grids, the reserve margins which can be accepted economically. Assuming that 10,20 or 30 % of the new large units installed would required high power underground cables, the total length of 3000 MVA cables required (12 km per unit) in the year 2000 can be predicted as appears in Table 3.2.

Table 3.1. - Electric power requirement of the main EEC town in the year 2000. Length of high power cables needed.

CITY	Population of the center (10^3)	Surface of the center (km^2)	Diameter of the center (km)	Population density of the center (inhabitants/km^2)	Peak power demand (MW)	Peak power density (MW/km^2)	Number of main substations	Length[1)] of high power cables according to the models a and b (km) a	(km) b_1	(km) b_2
Paris	7700	730	30.5	10500	8800	12.1	11	671.0	335.5	91.5
London	6000	670	29.2	9000	9000	13.4	11	642.4	321.2	87.6
Roma	2600	266	18.4	9800	2300	8.6	3	110.4	55.2	27.6
Milano	2300	180	15.2	12800	3100	17.2	4	121.6	60.8	30.4
Hamburg	2200	330	20.5	6700	4000	12.1	5	205.	102.5	51.25
München	1800	245	17.6	7350	2100	8.6	3	105.6	52.8	26.4
Torino	1500	110	11.8	13600	2400	21.8	3	70.8	35.4	17.7
Napoli	1500	110	11.8	13600	1350	12.3	2	47.2	23.6	11.8
Genova	1100	95	11.0	11600	1400	14.7	2	44.0	22.0	11.0
Lyon	850	65	9.0	13100	770	11.8	1	18.0	9.0	9.0
Marseille	1300	240	17.5	5400	1170	4.9	2	70.0	35.0	17.5
Stüttgart	1200	200	16.0	6000	1730	8.6	3	96.0	48.0	24.0
Köln	1400	260	18.2	5400	2500	9.6	3	109.2	54.6	27.3
Frankfurt	960	180	15.2	6000	1400	8.6	2	60.8	30.4	15.2
Düsseldorf	840	156	14.1	5400	1500	9.6	2	56.4	28.2	14.8
Hannover	900	220	16.7	4100	3200	14.5	4	133.6	66.8	33.4
Essen	1000	160	14.3	6250	1100	6.9	2	57.2	28.6	14.3
Bremen	1000	180	15.2	5600	1600	8.9	2	60.8	30.4	15.2
Amsterdam	1350	230	17.1	5900	1800	7.8	3	102.6	51.3	25.6
Rotterdam	1400	400	22.6	3500	3300	8.2	4	180.8	90.4	45.2
Copenhagen	1200	180	15.2	6700	1500	8.3	2	60.8	30.4	15.2
Manchester	900	110	11.8	8200	1500	13.6	2	47.2	23.6	11.8
Birmingham	1300	155	14.0	8400	2300	14.8	3	84.0	42.0	21.0
Glasgow	1100	160	14.3	6900	2400	15.0	3	85.8	42.9	21.4
Leeds	800	160	14.3	5000	1400	8.7	2	57.2	28.6	14.3
TOTAL	44200	5792		7700	63620	11.0	84	~ 3300	~ 1650	~ 680

1) a 1000 MVA cables according to Model a

b_1 2000 MVA cables according to Model b

b_2 1000 MVA cables according to Model b.

Table 3.2 - Maximum length of 3000 MVA cables required in 2000

% power plants requiring a connection by cables	Year of first appearance of large units	
	1980	1990
10 %	210 km	140 km
20 %	430	280
30 %	640	420

Because, as was stressed before, this application is unpredictable, no attempt was made to refine the prediction. The numbers given in Table 3.2 are chosen to be too optimistic. It is clear e.g. that there is little chance for having 3000MW a.c. generators installed off-shore in 1980. The largest generators planned now are still in the 1500 MW range and on the continent. The first undersea connection of that type would probably make use of several cables of smaller unit carrying capacity placed in parallel.

4. HIGH VOLTAGE POWER CABLES WITH PAPER INSULATION

4.1. Description and principles

High voltage a.c. cables can be made of three single core cables or of three cores in one single envelope (multicore design).
The major components of a single core cable can be briefly described as follows:

- the conductor which consists of stranded copper or aluminium wires and has normally a circular shape ; it can be made compact around a central wire or annular or as an assembly of four or several shaped conductors (segmental conductor (figure 4-1); there is usually a central duct for oil circulation;
- an electrostatic screen which consists of one or several layers of "semiconducting" paper (carbon black paper);
- the electrical insulation made of many layers of lapped paper tape impregnated with oil;
- an outer electrostatic screen
- a lead sheath
- a plastic sheath
- steel wire armour
- the outer protective sheath.

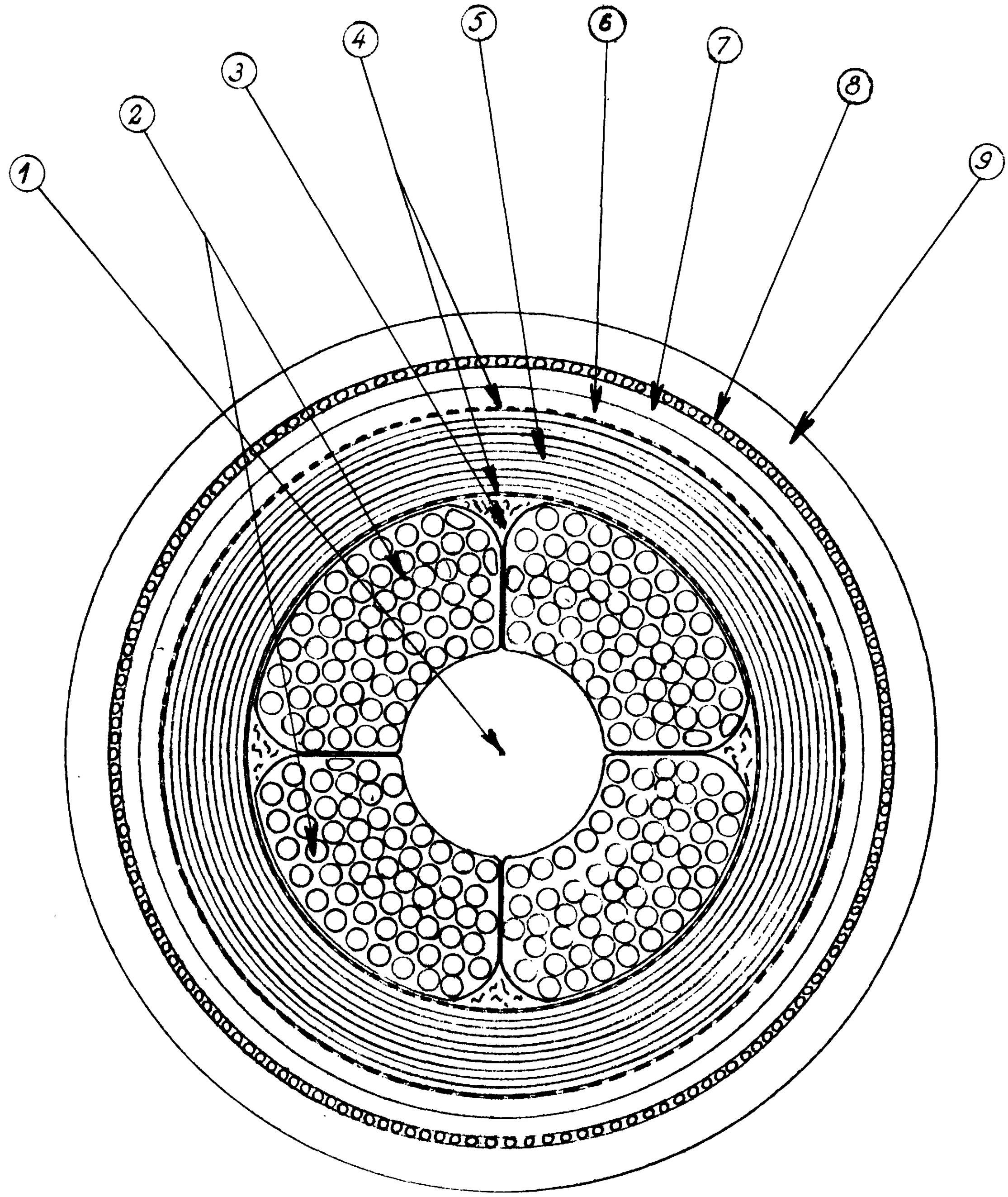


Figure 4-1.- Cross section through a high power low-pressure-oil cable (one phase).

1. central oil channel
2. segmental conductor
3. Paper filling
4. electrostatic screen
5. paper insulation
6. lead sheath
7. plastic sheath
8. steel wire armour
9. outer protective sheath.

Medium voltage cables usually contain all three phases in the same envelope. At very high voltages (more than 225 kV) the insulation thickness required increases the diameter of the cable. There is a limit above which a three-phase cable becomes too rigid to be wound even on the largest usable drums. Above that limit one must use single core cables, or pull three single core conductors in a pipe which is installed and assembled in the field (case of the pressurized cables).

4.2. Cable performance and losses

The power which can be transmitted by a cable at a particular voltage is limited

- by the amount of heat which is produced in the conductor, the screens, the sheath, and in the dielectric;
- by the rate at which heat can be dissipated into the ground;
- by the charging power which is a function of length and capacity.

a) Power losses in the conductor and the metallic components

In an a.c. cable, the ohmic losses are increased by the skin effect and the proximity effect. Both of them increase with increasing conductor cross section (figure 4.2).

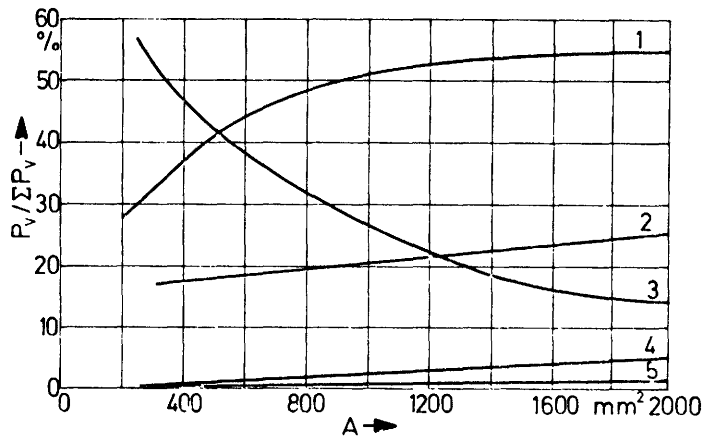


Figure 4-2.- Relative Losses $P_V/\Sigma P_V$ for a 380 kV Cable Line as a Function of Conductor Area A (from [1]).
Conductor Temperature 85° C

1. Sheath Losses
2. Dielectric Losses
3. DC-Losses
4. Skin Effect Losses
5. Proximity Effect Losses.

In high power cables the design of the conductor is governed by the need of reducing the skin and proximity effect.

Stranded conductors are the easiest to make. However power losses are not minimized because the radial distance of each particular wire remains constant along the length of the cable. The losses can be reduced if the conductor is segmented. Each segment is made of a strand of wires which is subsequently shaped and helically twisted to the pitch required for the final assembly into a full conductor.
Litz conductors are more expensive to make but achieve almost complete compensation of the skin and proximity effects.

In addition to the losses in the conductors there are losses by eddy currents induced in screens and sheaths. Screens can be segmented to reduce eddy currents but the sheath ought to be continuous. The losses in it are therefore important. By connecting the sheath of the three single core cables at regular interval (cross-bonding) the intensity of the induced current and therefore the power loss are reduced.

When cables are placed in a steel pipe additional losses occur in it.

b) Power losses in the dielectric

The alternating electric field alters the polarization of the dielectric and produces heat in it. The power dissipated in the dielectric of each phase conductor is given by

$$W = 2\pi f \; C \; U^2 \tan\delta$$

per unit length

where f is the frequence
C is the capacitance
U is the voltage
$\tan\delta = \frac{1}{\omega CR}$ is the loss factor of the dielectric.

At present, the loss factor of oil impregnated paper is about $\tan\delta = 0{,}002$. With this value it was shown that the highest economic voltage of a cable would be practically 750 kV.
At Pirelli, it is felt that oil impregnated papers could still be improved and that its loss factor could be reduced to 0,0015. 1100 kV cables could then be designed for very high power.
Tapes of plastic materials have much smaller loss factor; at present they are very expensive compared to paper and there is little practical experience on them.

c) Evacuation of heat

Temperatures which are permissible in a cable are imposed by two limiting factors.

The highest temperature which can be tolerated without damage by oil impregnated paper is 85°C. Therefore the conductor temperature may not rise beyond that level.

An even more restricting factor for naturally cooled buried cables is the amount of heat which can be evacuated into the ground. Above 40°C the soil dries out and its thermal resistivity rises drastically from 1 to 3 °C m/W.

If the temperature of the soil is to be kept below 40°C, the cable may not be operated at full power and the conductor temperature is less than 85°C. It is possible to install a water pipe above the cable to sprinkle water in the ground and keep it moist. However the prefered method is to put the cable in a special backfill with higher thermal conductivity even when dry. This permits only a rather small increase of the power that can be transmitted by the cable.

4.3. Stabilization of the electrical insulation

The higher the voltage the larger becomes the electric stress which the designer wants the paper insulation to withstand in order to avoid excessively big outer diameters.

The first limitation which has to be faced is due to the low dielectric strength of the voids in the lapped paper insulation. In such a dielectric, thermal expansions and contractions with load variations can produce or enlarge small voids, mainly in the butt gaps between two adjacents tapes in a layer. High electric stresses may give rise the ionization effects in the voids and predischarge currents which cause progressive damage to the electrical insulation. This becomes increasingly severe as the voltage gradient in the dielectric is increased.

The cable must therefore be designed so that the dielectric is compressed and voids cannot develop in it. It can also be filled with oil under pressure: the dielectric strength of oil-filled butt gaps increases with pressure.

The following paragraphs give a brief description of some current types of stabilization for high voltage cables.

4.4. Common types of high voltage cables (natural cooling)

Low pressure oil-filled cables

The cable is connected to oil reservoirs placed at regular intervals a long its length. Oil is maintained at a pressure slightly above atmospheric (1,5 to 2 atm.).

When the power passed through the cable increases, the oil expands and flows through the hollow duct of the conductor into the reservoir. When the cable cools down, the oil is forced back into the cable. Low pressure oil-filled cables can be used up to 225 kV. They can be designed for higher voltages by simply increasing the oil pressure. Pirelli considers it possible to design these cables for 700 kV; oil pressure would then be about 15 bars. It would even be possible to design 1100 kV cables when paper or plastic tapes with very low electric losses will be available.

High pressure oil cables in steel pipes

Three cores made of conductor, electrical insulation, screen and skid wire are installed (pulled in) in a steel pipe which is then filled with oil at a pressure of 15 bars (fig. 4.3). Oil is fed from a vessel where the pressure is maintained by an automatically operated pump. A particular design of this type of cable is called "Oilostatic".
These cables are being used up to 225 kV in Europe and 345 kV in the U.S. (e.g. New York city network).

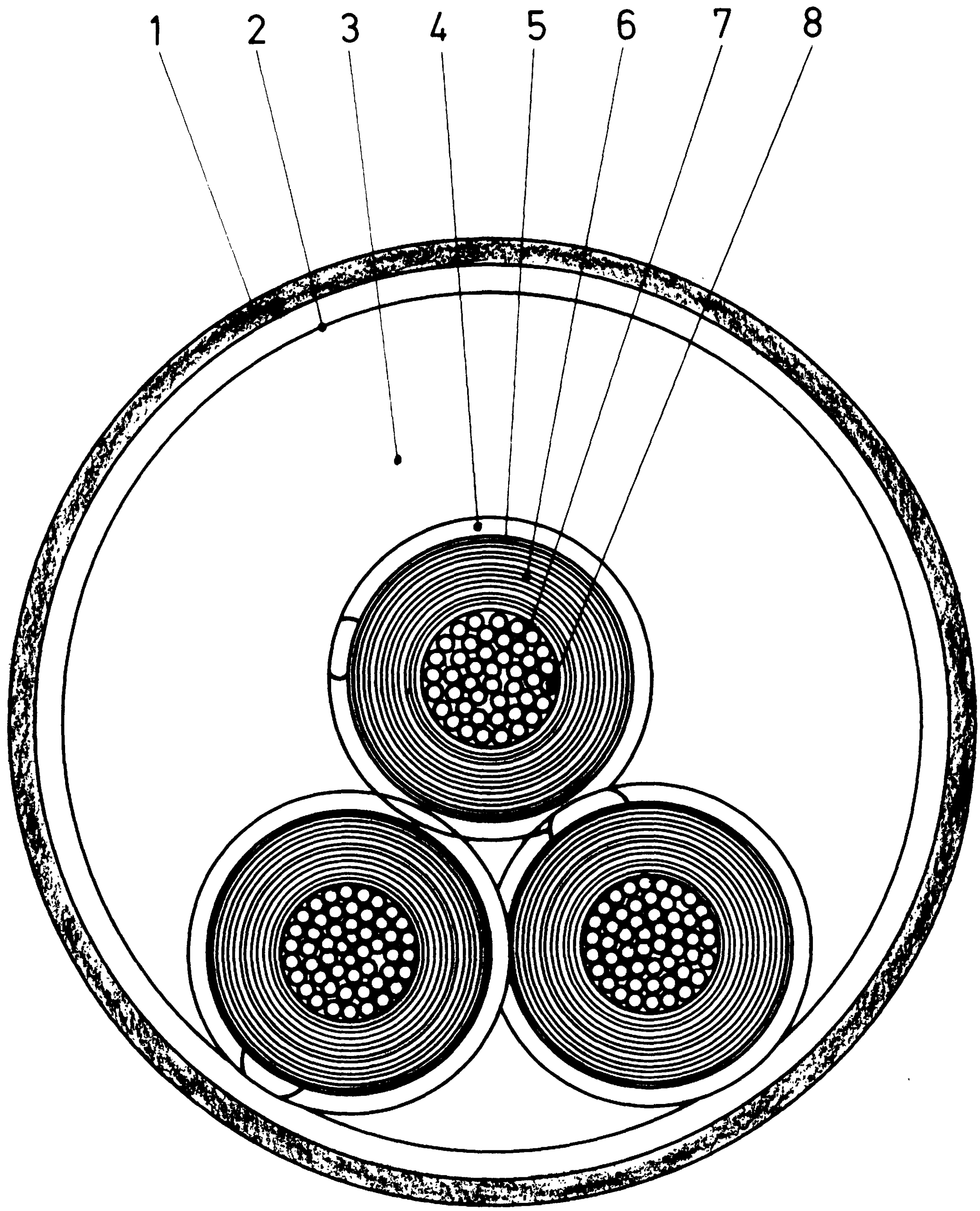


Figure 4-3.- Cross-section of a high pressure oil cable (from [1]).

1 - oversheath	5 - carbon paper and copper foil
2 - steel pipe	6 - paper insulation
3 - oil	7 - carbon paper
4 - copper helix	8 - conductor strands

Externally gas pressurized cable

The stabilization of electrical insulation is achieved not by oil filling but by the pressure applied,on the oil impregnated paper wrapping, by the lead sheath (or PE sheath). The three phase conductors are placed in a common steel pipe filled with nitrogen under a 15 bars pressure. They can be laid individually in the steel pipe or packed together as shown on fig. 4.4.

The deformation of each cable core during heating or cooling must be reversible. The cross section is therefore oval. This design is used for 60 kV and 110 kV [17].

Internal gas pressure cable

The three single core cables without lead sheath are laid in one single steel pipe filled with pressurized nitrogen. Because of the absence of sheath, the gas penetrates the insulation (impregnated paper). At the field strength used in 110 kV cables, ionization does not occur in the voids provided the gas pressure is high enough (15 bars). Higher voltages up to 220 kV are possible when nitrogen is partly replaced by SF_6.

Remark

Gas pressurized cables are very advantageous for installation along undulated routes where large level differences would create excessive hydrostatic pressures in oil-filled cables.

Cables with an outside rigid steel pipe (pressurized cable) are favoured in cities. They offer greater resistance to the most common type of accident i.e. damage by digging machines.

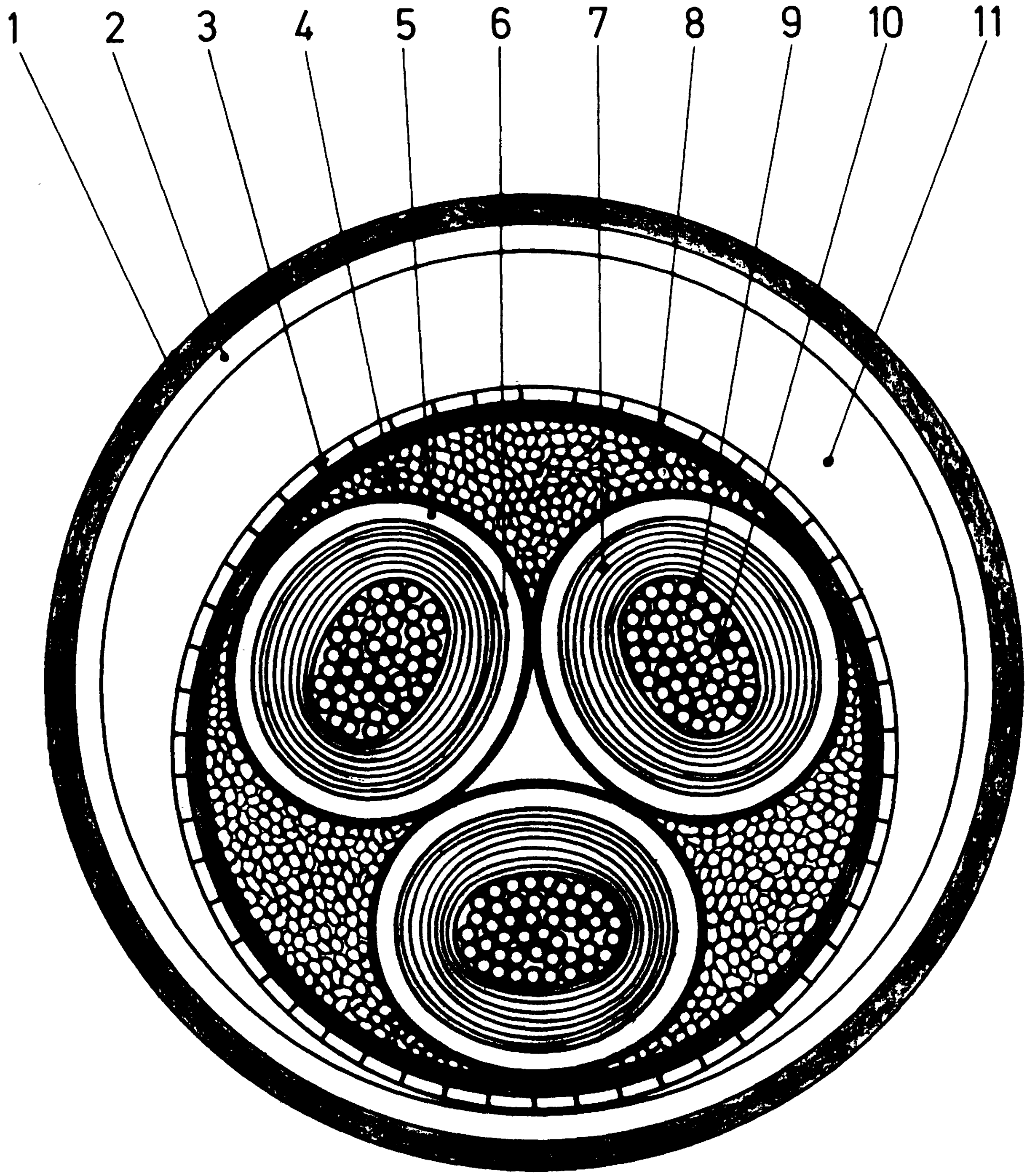


Figure 4-4. Cross section of an externally gas pressurized cable (from [1]).

1 - oversheath
2 - steel pipe
3 - steel tape armour
4 - cooper tape and insulating foil
5 - lead sheath
6 - aluminium tape and carbon paper
7 - paper insulation
8 - wedge filling
9 - carbon paper
10 - copper strands
11 - nitrogen

4.5. Forced Cooling of underground cables

4.5.1. Soil cooling or indirect cooling

The ground in which the cable is buried is cooled by steel water pipes laid parallel to the cables. The cooling is more efficient when a special high conductivity bedding is used. Indirect cooling makes it possible to increase the power of the cable by about 50 %.

4.5.2. Water jacket cooling or external cooling

The cable is placed in a pipe made of reinforced PVC or of asbestos-cement. Both types of pipes are equally suitable. Water is circulated in the pipes and through heat exchangers. This method of cooling increases the maximum power rating of the cable by a factor 3.

Table 4.1 - Estimated ultimate power transmission capability of oil-filled cables [15]

Voltage	Natural Cooling	External Cooling
60 kV	85 MVA	260 MVA
110	200	630
220	350	1000
400	500	1500

Several high power cables with external cooling are in operation already in many parts of the world. Pirelli first showed some years ago that 400 kV cables (3x single-cored, 1935 mm^2 Cu) can transmit at least 3200 A (i.e. 2200 MVA). Now a 4 km section already in commercial use in the United Kingdom has a load carrying capacity of 2600 MVA.

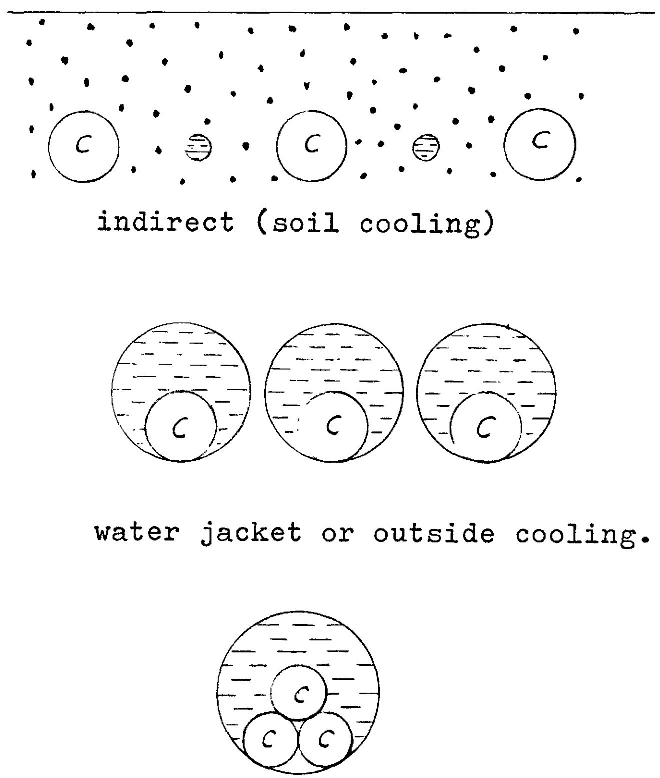


Figure 4-5.-
Some examples of indirect and direct outside cooling.

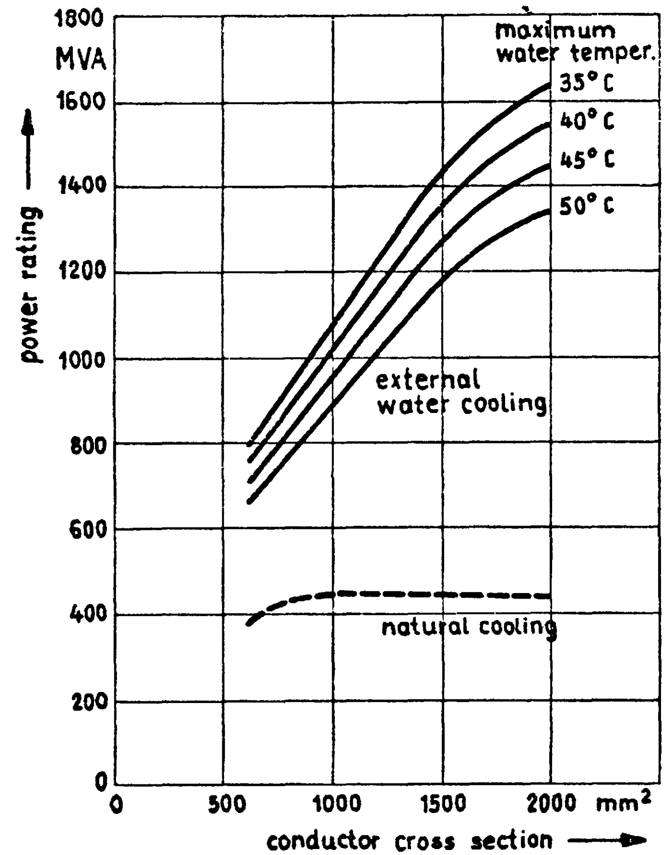


Figure 4-6.-
Rating of 400 kV oil-filled cables under natural cooling and external water-cooling conditions (from [1]).

4.5.3. Internal forced cooling

Cooling a cable internally would take the major part of the heat away from the insulation and therefore improve considerably the current carrying capacity. There is at present no real experience in practice. A trial loop cable made by BICC has been installed and is being tested. Another cable is being manufactured and tested by Felten Guilleaume Kabelwerke in Germany.

4.5.4. Internal cooling with oil

One obvious way of cooling a cable is to circulate oil in the conductor through a central duct similar, but with a larger diameter, than the one which is usually provided for pressurized oil stabilization.

The existing trial 400 kV cable has a copper-cross section of 1.940 mm^2 and an internal duct of 50 mm diameter.

The power rating of the internally oil-cooled cable is a function of the cooling itself and in particular of the inlet and outlet temperatures, duct diameter, distance between cooling stations.

The diagramme of figure 4.7 shows the relationship between power rating, internal diameter and cooling station spacing [3].

The existing 400 kV test cable has a copper cross-section of 1940 mm^2 and an internal duct of 50 mm diameter.

On the basis of the present experience it is estimated that a cable with an internal duct of 85 mm in diameter could be rated at 2,6 to 2,9 GVA depending upon the oil inlet temperature and assuming that the spacing between the cooling stations is 4 km. The cost of such a cable including ancillary equipment is believed to be 70 - 75 % of that for naturally cooled cables [3]. Refrigerating the oil would further increase the power rating of the same cable, as indicated in Table 4.3.

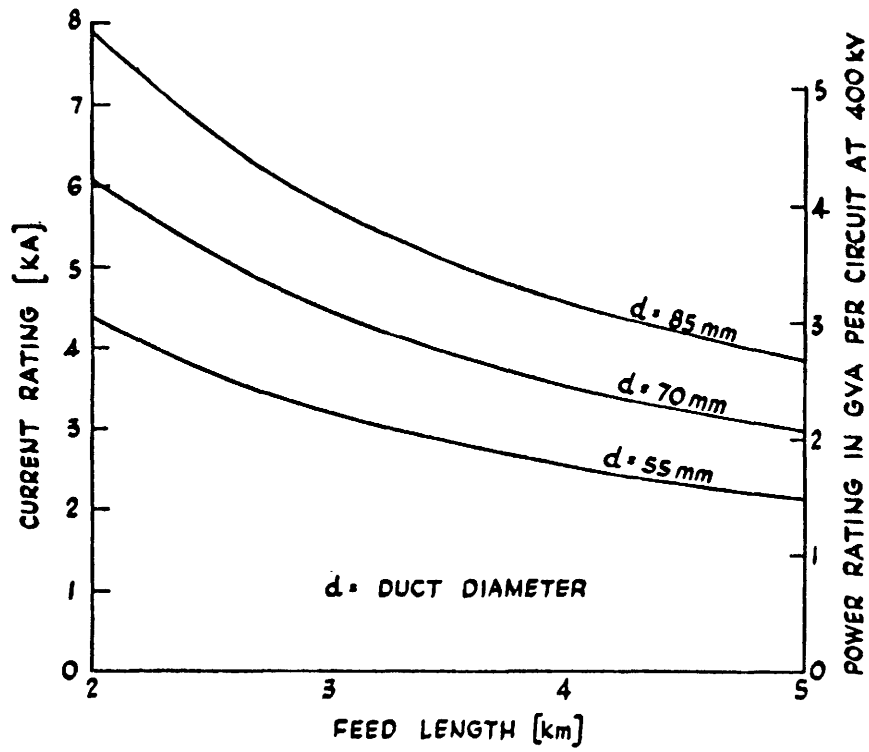


Figure 4-7.- Ratings of internally oil-cooled cables with 2600 mm^2 copper conductors and their relationship with duct diameter and cable length between cooling stations (from [3]).
Oil temperature at the inlet + 20° C, outlet + 85° C.
Pressure : 0,69 MPa (100 psi).

Table 4.3. - Ratings of internally oil-cooled cables at 400 kV with refrigerated oil [3].

100 % Duty	Natural cooling only	Forced cooling			
		Oil inlet temperatures °C			
		+ 20	0	- 20	- 40
Current kA	1,8	3,87	4,28	4,68	5,0
Power MVA	1.250	2.680	2.970	3.250	3.460

4.5.5. Internal water cooling

It is tempting to use water instead of oil to cool the cable internally. Water has indeed a higher heat capacity and has therefore better cooling performance. However it cannot be circulated in a high voltage electric cable unless it is contained in a leakproof tube.

An experimental cable is being manufactured by Felten-Guilleaume Kabelwerke AG. and will undergo testing in the course of 1975.

A cross-section of the cable is shown on figure 4.8. The paper insulation is immersed in oil at a moderate pressure (2 bars maximum). Water is circulated in the inside tube with an inlet pressure of 31 bars and a temperature of 30 °C. Outlet conditions are 80 °C and 1 bar.

At 110 kV, a water-cooled cable with an internal cooling channel of 70 mm and an outer conductor diameter of 100 mm, should be able to carry 600 MVA on a 10 km distance with no intermediate cooling station. For a transmitted power of 900 MVA, the spacing between water cooling stations can still be 6 km.

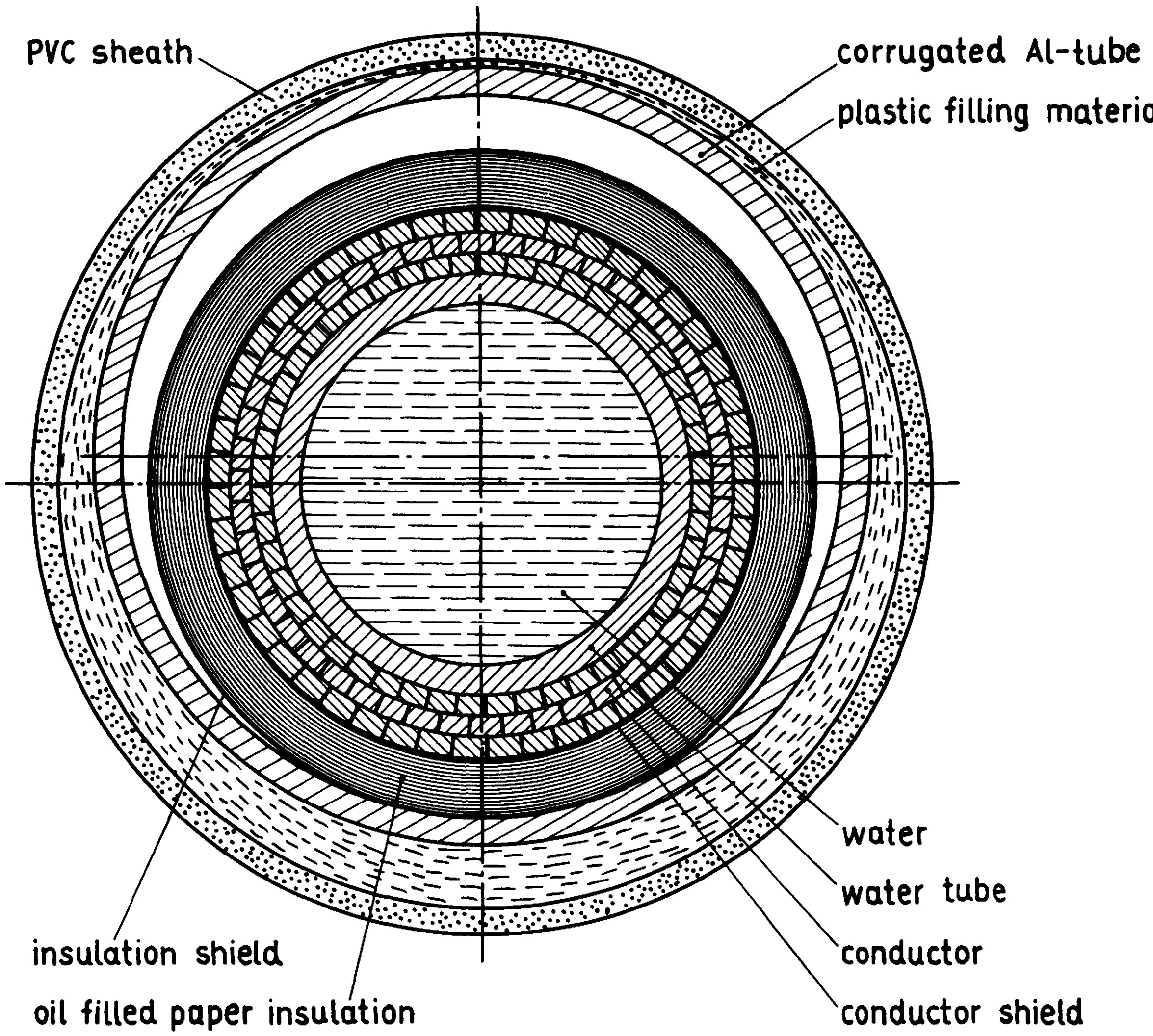


Figure 4-8.- Crosssection of a 110 kV cable with internal water cooling (from [1]).

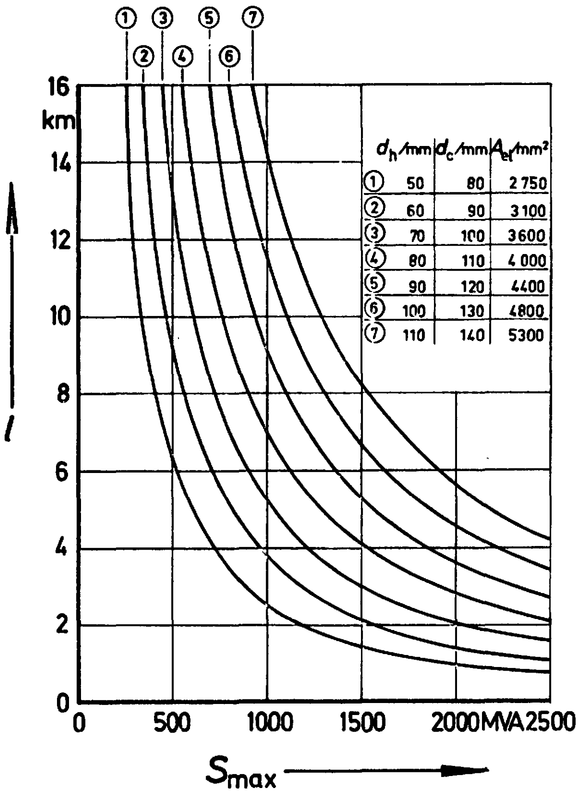


Figure 4-9.-

Distance between two consecutive cooling stations as a function of the maximum power Smax transmissible in 110 kV cables with internal water cooling.

d_h diameter of water channel

d_c conductor outside diameter

A_{el} conductor cross section.

(from [16]).

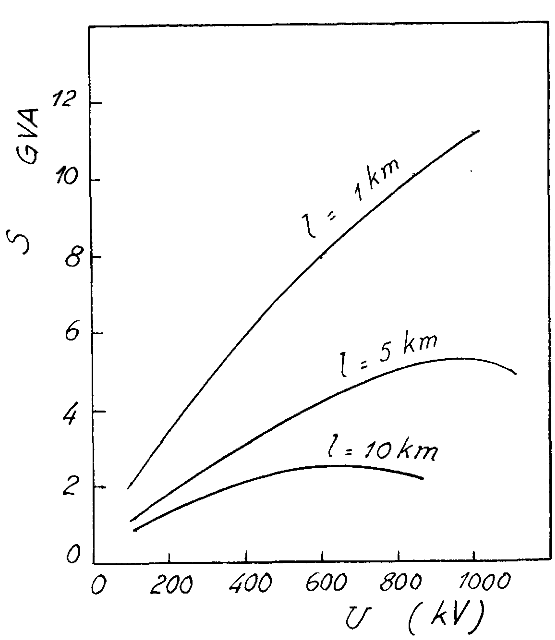


Figure 4-10.- Maximum transmissible power as a function of rated voltage. The cable is internally cooled and has following dimensions: d_h = 58 mm

d_c = 90 mm

(from [18]).

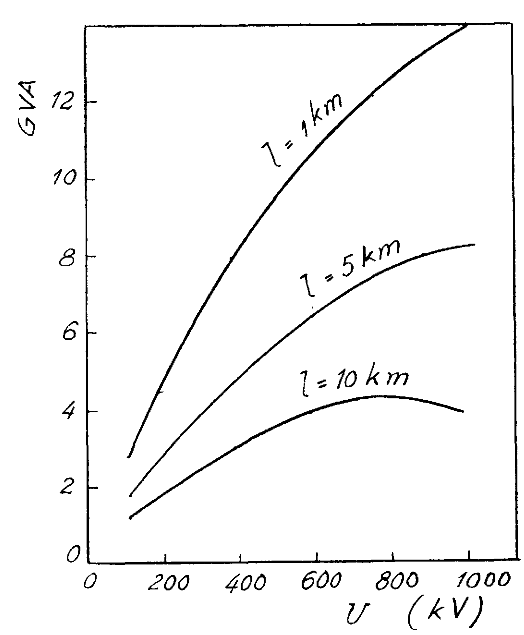


Figure 4-11.- Maximum transmissible power as a function of rated voltage. The cable is internally cooled and has following dimensions: d_h = 76 mm

d_c =110 mm.

(from [18]).

For fixed inlet and outlet temperatures of the cooling water, the power which can be transported by a given conductor is a function of the spacing between cooling stations. For high power cables used to feed power into a large town a cooling-station spacing of 5 km may be acceptable. When this spacing is imposed, it is still possible to increase the conductor cross-section by increasing simultaneously the outside and inside diameter (influence of the skin effect).

It is thus possible to design cables with very large power transmission capacity (fig. 4.9). It is not known at present what the limits imposed by the rigidity of the cable may be. However the first experiments are encouraging.

Instead of increasing the conductor diameter one can increase the cable voltage. Figures 4.10 and 4.11 give a few examples.
A cable with rather small dimensions D_i = 58 mm and D_e = 90 mm connot transmit more than 2 GVA when the spacing of cooling stations is 10 km.
Increasing the diameters to

$$D_i = 76 \text{ mm and } D_e = 110 \text{ mm}$$

gives the following possibilities:

	10 km	5 km
400 kV	3 GVA	4,5 GVA
765 kV	4 GVA	7,5 GVA
1100 kV	3,5 GVA	8,5 GVA

Table 4.4. - Examples of a few high power cables with oil-impregnated paper insulation.

		(AEG) Natural cooling	(Pirelli) Indirect cooling	(AEG) External cooling		(BICC) Natural cooling	(BICC) Internal oil-cooling
Rated voltage	kV	400	400	400	400	400	400
Copper cross section	mm^2	2.000	3.000	1.000	2.000	2.600	2.600
Continuous load	MVA	560	2.300	1.025	1.500	1.300	2.600
Losses	kW/km	67,1	350	212	225	169	484
Length between cooling stations	km	-	-	-	-	-	5

4.6 Conclusions

Oil impregnated paper cables are presently operated in Europe at a maximum power of about 1300 MVA under 400 kV. To reach that power they are cooled by a water jacket.
Internal cooling with oil would make it possible to carry twice as much power with the same amount of copper conductors and when the spacing between cooling stations is 4 km. Undercooling the refrigerant to -40 °C would raise again the cable ampacity to 3,5 GVA.
Water cooling is being developed and appears quite promising. With normal water cooling and an inlet temperature of 30°C, a 400 kV cable could carry 4,5 GVA when the distance between cooling stations is 5 km.

These cables appear to be competitive with all other novel designs. They require only narrow trench and lend themselves to stepwise developments based on traditional and proved technology.

5. CABLES WITH SOLID POLYETHYLENE INSULATION

The dielectric is extruded around the conductor and forms a continuous solid sheath around it.

Two major varieties of materials are used: normal polyethylene and cross-linked polyethylene.

Normal polyethylene can be used as outer protection cable sheath or as substitute for the lead sheath for the cables stabilized by an outside pressure.

The application considered here,namely the electrical insulation of the conductor itself, requires special care in the fabrication and in controlling the purity. Additives are introduced into it as voltage stabilizers. It is already widely used for power cables up to 110 kV since many years. More than 30 km of 225 kV PE cables are operating in France satisfactorily. Tests are being made on 400 kV cables.

Besides the ease of continuous fabrication, polyethylene offers several avantages over oil impregnated paper. Its dielectric loss factor is considerably lower (more than ten times). Its thermal conductivity is double that of impregnated paper. This makes it possible to cool the cable more efficiently.
Polyethylene melts between 105°C and 155°C. The maximum rated temperature is 70°C.

Cross-linked polyethylene is obtained by mixing with small additions of a peroxyde and vulcanizing by a brief heating at 170°C (1 minute). XLPE for dielectric insulation also contains voltage stabilizers. Its dielectric properties are similar to those of straight PE, the permissible temperature is ten degrees higher. However it has not been used successfully at voltages higher than 63 kV. This is attributed to the decomposition products of the peroxyde additives during cross-linking. The electric gradient in PE is now limited to 9 kV/mm. Studies are underway to increase this value.

Table 5.1 - Comparison of a few dielectrics [17]

	Impregnated paper	PE	XLPE
Maximum temperature °C	65	70	90
Permittivity	4	2,3	2,3
Loss factor (tan δ)	$3\text{-}10\times10^{-3}$	$2\text{-}3\times10^{4}$	$2\text{-}5\times10^{-5}$
Thermal resistivity °C cm/W	600	350	350
Maximum electric gradient			
at 60 kV kV/mm	3,5 à 4,5	3,2 à 4,5	3,2 à 4,5
130/225 kV kV/mm	13 à 15	8 à 9	-

Polyethylene cable can be cooled from the outside. In this case the PE dielectric must be sealed by a lead sheath to avoid any direct contact with water.

At the present time polyethylene cables find increasing applications up to voltages of 220 kV. No prediction can be made as to their future development for higher voltages or high power.

6. CABLES WITH GASEOUS DIELECTRIC (SF_6)

An SF_6 cable is usually made of three single core conductors. Each conductor is placed in a metal pipe and is supported by insulators (figure 6-1). The space between the central conductor and the outer tube is filled with SF_6 gas under a pressure of 2,5 to 4 bars.

This inner conductor itself is tubular because of the skin effect. It could also be made of stranded wires but such solution is quite speculative.
SF_6 cables offer the following advantages:

a) the dielectric losses are negligible
b) the dielectric has relatively good thermal conductivity and provides good heat transfer between the inner conductor and the outer sheath; the maximum temperature is however limited by the stability of the epoxy insulators
c) because of the comparatively large distance between conductor and outer sheath and the low dielectric constant of the insulating gas ($\varepsilon_r \simeq 1$), the capacitance is small (about 5 times smaller than a cable and 5 times greater than an overhead line). The capacitive charging power is consequently much smaller than in a paper insulated cable.

If there is no limitation on the size of the cable, the design can be considered rather flexible. Conductor cross-section is never a problem. For mechanical strength the inner conductor must at least have a 5 mm wall thickness. Higher voltages can be achieved simply by increasing the diameter of the outer pipe.

The dielectric strength is smaller than that of the oil and paper dielectric. This is why rather large diameters are required.
For 400 kV, the outer sheath diameter is typically of 500-520 mm.

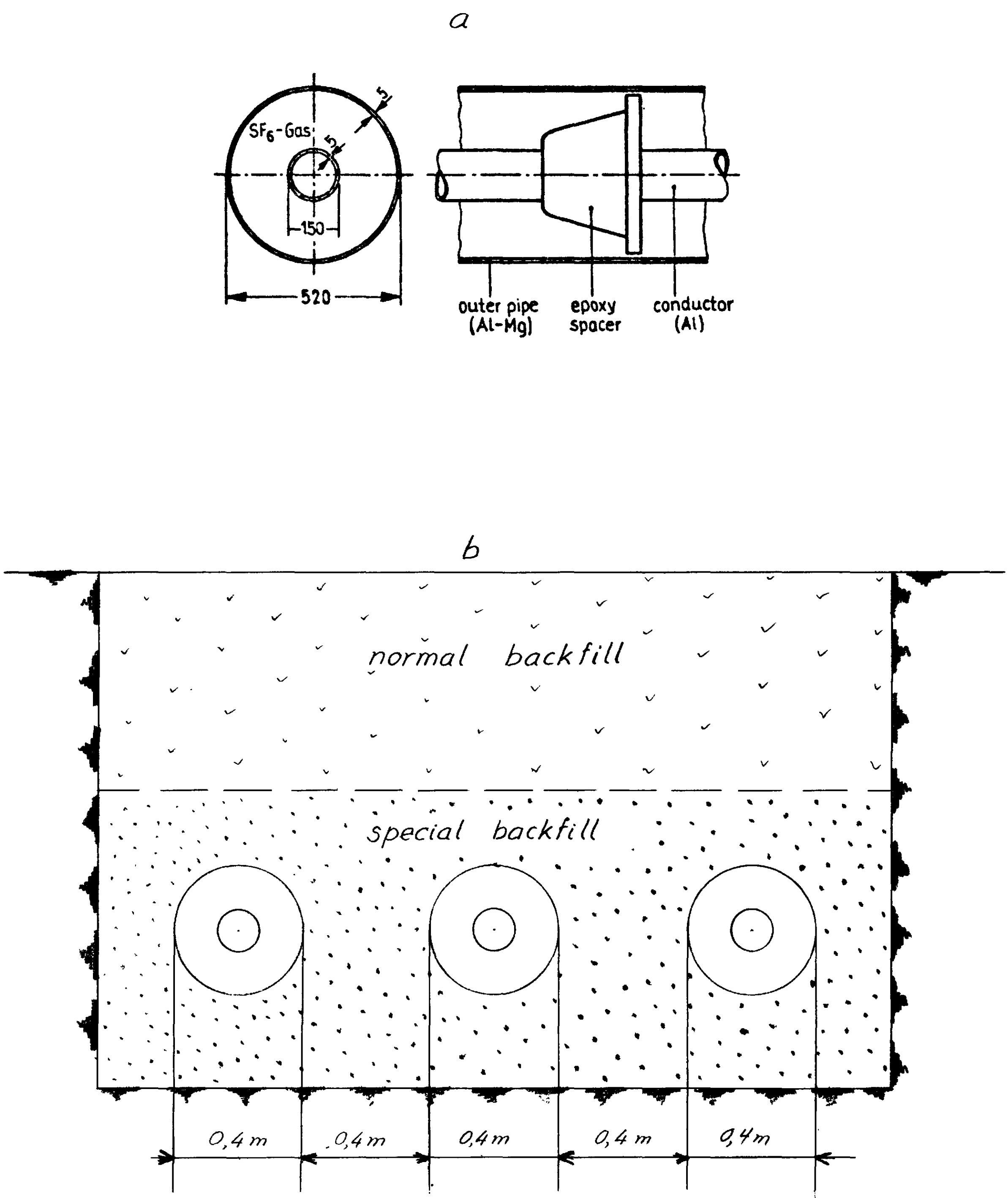


Figure 6-1.- SF_6 cable.

a) cross section view

b) buried threephase 220 kV cable.

Up to now, in most designs the inner conductor and the outer sheath are made of rigid aluminium pipes (maximum length = 20 m) assembled in the field. This poses difficulties namely to achieve high degree of cleanness which is mandatory.

If use could be made of corrugated tubes it would be possible to envisage flexible cable up to 220 kV. This would enable to manufacture cable lengths of about 250 m and wind them on drums.

The ampacity of SF_6 cable is essentially governed by the rate of heat removal. Buried cables are limited by the 40°C limit imposed by soil dry-out. Cables installed in the open air have much higher ampacity (Table 6.1). Water cooling of the outer sheath makes it possible for the cable to carry power up to 10.000 MVA.

There is a considerable amount of experience of SF_6 technology in switchgear and sub-station equipment. There is very little operating experience on SF_6 cables. In the U.S.A. a 180 m line was installed for the first time in 1969. Its ampacity was 2000 MW under 345 kV. Several other lines were installed since then.
In Europe, the first installation of this type has recently been built in southern Germany (400 kV, 900 A nominal, length 700 m).

SF_6 cables can be used successfully, without problems of hydrostatic pressure, to connect points located at considerably different levels.

Several technical problems should be solved before large scale commercial applications are envisaged:

- design and material stability of insulators
- detailed study of mechanical stresses on the sheath (fatigue, effect of fault currents, expansion bellows, stresses and fatigue at the contact with insulators)
- corrosion protection
- fault detection and repair

Table 6.1 - SF_6 filled cables. Three single core phases laid in flat formation (+) [13].

	Buried			Open air	Water cooled
Rated Voltage kV	225	400	750	400	400
Outside diameter mm	418	504	644	504	504
Conductor diameter/thickness	200/13	240/13	260/12	240/13	240/13
Continuous Load MVA	1000	2000	4000	4000	4000
Losses kW/km	188	199	215		
Critical length km	300	400	600		

+) Maximum sheath temperature 60°C.

Although there is no great homogeneity in the data available on the trench width requested for each type of cable, it appears that the SF_6 cables will require the largest space. This will not be favourable for feeding power into large cities. In addition the present rigid design would make them preferable for straight line connections across the country.

They could therefore find different types of applications than compact and flexible high power cables.

7. CRYORESISTIVE CABLES

Very pure metals like copper, aluminium or beryllium at low temperature have an electrical resistivity which is several orders of magnitude smaller than at room temperature.
Aluminium is preferable because of the high magnetoresistivity of copper.

The conductors are made of braided wires on a cylindrical support. The conductor is surrounded by the dielectric which is made of lapped plastic tape. To avoid overheating of cable components by the alternating magnetic field, the dielectric is surrounded by a magnetic shield. The conductor is cooled with pressurized liquid nitrogen at 80°K which circulates along the core and impregnates the dielectric. The three phase conductors are enclosed in a double wall cryogenic envelope.

The design of those cables shows great similarities with superconducting cable. It has greater flexibility. Detailed cost estimates made in France, in Great Britain [3] and in Germany [21] showed that these cables would have no advantage over superconducting cables nor over more conventional cables.

8. SUPERCONDUCTING CABLES

Superconducting materials can carry very heavy currents with no ohmic lossed, if however, the current is constant (d.c.) - A.C. currents induce losses which may be prohibitive. They restrict the choice of possible materials and pose serious difficulties in the cable design.

The superconducting material is used as thin layers on a support made of high conductivity metal (copper or aluminium). It must be permanently maintained at a temperature in the neighbourghood of 5 K by supercritical helium which is circulated through the cable. A rigid d.c. cable could be made simply with tubular copper conductors plated with niobium. However, in order to be flexible the conductor must be made of stranded wires (copper or aluminium plated with niobium) or lapped metal tapes (copper or aluminium coated with a Nb_3Sn deposit). They are supported by an inner teflon core-former.
The composite conductor is surrounded by an electrostatic screen and by an adequate thickness of dielectric made of lapped plastic tape. The dielectric is in direct contact with helium which permeates through it.

In an a.c. cable each phase conductor must also be surrounded by a magnetic shield in order to avoid overheating of all surrounding metal parts by the alternating magnetic field. The shield is a tubular conductor made of stranded wires around the dielectric. These wires are similar to those of the conductor core (copper or aluminium plated with niobium). The complete phase conductor must be designed and manufactured to accomodate thermal contraction and expansion. The outer conductor wires must maintain the dielectric pressed on the inner conductor.

Each core is normally placed in a tube in which helium is circulated. These tubes are placed in a cryostat which is under vacuum to reduce heat in-leakage. The outside wall of the cryostat is cooled with liquid nitrogen and is surrounded by superinsulation which is also under vacuum. It must reduce the leakage of heat from the outside to the outer cryostat wall.

The design figures used in a.c. cable projects for the heat generation in the conductors and dielectric, and heat leakage from the shield are as follows:

Superconductor a.c. loss	0,05 W/m
Dielectric loss	0,05 W/m
Heat inleak	0,1 W/m
Viscous drag	0,03 W/m

This heat must be taken away by supercritical helium. For very large refrigeration units (> 1 MW) the Carnot efficiency could reach a value of 0,2 and the power needed to eliminate 1 W of heat at 4,2 °K could be as low as 350 W. It would be larger for smaller units.

In a d.c. cable of similar power the total amount of heat to evacuate is only about 0,1 W/m. There is no loss in the superconductor nor in the dielectric and the heat inleak may even be smaller than in an a.c. cable because the diameter can be smaller.

The requirement for the superconducting cables to be contained in a sealed cryogenic envelope increases the outside diameter. To wind a cable on the largest drum which can still be handled and transported, the outside diameter should not be larger than 250 mm. The length of the cable section which the drum can carry is then about 250 m.

AEG was able to design a fully flexible d.c. cable with a 250 mm diameter. The cable consists in fact of two unipolar such cables. It can carry 5 GW under 200 kV.

Fully flexible a.c. cables do not appear to be feasible at the power required for the cable to be economically attractive. Rigid cable designs are not practical because too much assembly work would have to be done in the field (the maximum possible length of rigid section is 20 m). The semi-flexible concept has therefore

been given the greatest attention in Europe.
The cryogenic envelope is rigid and assembled in the field. The conductors are manufactured in lengths of about two hundred meters and then can be pulled into their channels in the finished cryostat.

Helium pipes and components of the cryogenic envelope have to be designed to accomodate thermal expansions and contractions. This is taken care of in flexible designs by the corrugated tubes. In semi-rigid designs bellows must be provided at regular intervals in the pipes. Helium tubes and heat shield could also be made of Invar.

Superconducting cables are being studied in several places in the world (Germany, France, United Kingdom, Austria, Unites States and Japan). In Germany (Siemens) a prototype a.c. cable 30 metres long is being built and tested.

The technological development of superconducting cables is described in the details in publications and was reviewed critically for the Commission by Dr Baylis and his Colleagues at the CEGB. The state of the art is summarized in the second part of this document which also gives special emphasis on the problems which are still to be solved and outlines those areas of basic research which may have to be covered before a final cable design can be made.

Actual values of heat losses in an a.c. superconducting cable are not really known with accuracy. Other major problems are heat transfer to supercritical helium and transient behaviour namely in case of fault current. It is expected that the superconductor will revert to the normal resistive state for a brief period during which the current will have to flow in the high conductivity back-up metal (copper or aluminium). Large amounts of heat may thus be generated during that period unless the transient is very short. Post fault conditions in the cable cannot be calculated at present and one would have to rely on large scale testing, unless further data are generated on superconductor behaviour and helium heat transfer under transient conditions.

It is anticipated that the cable would not be available for normal operation immediately after a fault current transient.

The greater complexity of superconducting cables makes them more liable than other cables to incidents and breakdown.

The total repair time would be considerably longer namely because of the several weeks periods needed for heat up and cooldown. They will therefore have to be designed and built with a very high degree of safety and reliability.

Superconducting cables can only take the full advantage of superconductivity in the case of d.c. power transmission. They are very attractive economically and can carry enormous power 5 - 10 GW without major difficulty. They must necessarily be used in conjunction with converter stations at both ends. The additional cost and power losses which occur in the end stationsare such that superconducting d.c. cable are more expensive than a.c. cable transmission for medium distance transmission. The break-even point is said to be in the range of 100 to 200 km. Then they are still more expensive of course than overhead lines both a.c. and d.c. They could offer alternative solutions where long stretches of transmission lines would have to be undergrounded.

Obviously superconducting d.c. cable can also be used for short links like e.g. asynchronous coupling of separate networks.
New incentives for using d.c. superconducting cable in the power grid may appear in the future. Direct association of a.c. generators with converters to feed directly powerful d.c. cables at voltage below 100 kV would eliminate HV.EHV transformers and reduce to cost of AC/DC conversion.

The design of superconducting cables for a.c. power transmission is rather more complex because of a.c. losses which occur in the superconductor itself and because of the effects of the alternating magnetic field (eddy currents, etc). The cooling power required for an a.c. cable is much higher than for a d.c. cable.

The heat losses at the cable terminations (transition between liquid helium temperature and room temperature) are substantial. Because of the cost of these losses and of the cooling stations, the minimum economical transmission length is considered therefore to be about 10 km.
The cost of the superconducting cables is compared with those of conventional and advanced cables in chap. 9.

9. COST COMPARISON

The cost comparison given in this chapter are based on two different evaluations. The main comparison is shown on the investment expenditure. The investment cost is calculated in DM/MVA km and includes

- the price of the cable
- the price of accessories, terminals and cooling stations if any,
- the capitalized value of the power losses (taken as 900 DM/kW)
- the civil engineering and installation cost.

The second one is taken from a study made in the United States by A.D. Little Inc. [22], [23]; it uses the capital costs per year, MVA and km.

Oil-filled cables are compared among themselves in figure 9.1. Here the costs do not include installation (earth digging, street repair, etc.). The prices quoted by different authors for civil engineering work vary considerably. The installation cost of a 440 kV cable in Berlin was recently estimated [1] to be 1800 DM/m for a forced-cooled oil cable and 3800 DM/m for a SF_6 cable (2000 MVA).
The estimates given by EDF is less than 1200 DM/m for SF_6 cable of the same voltage and power.

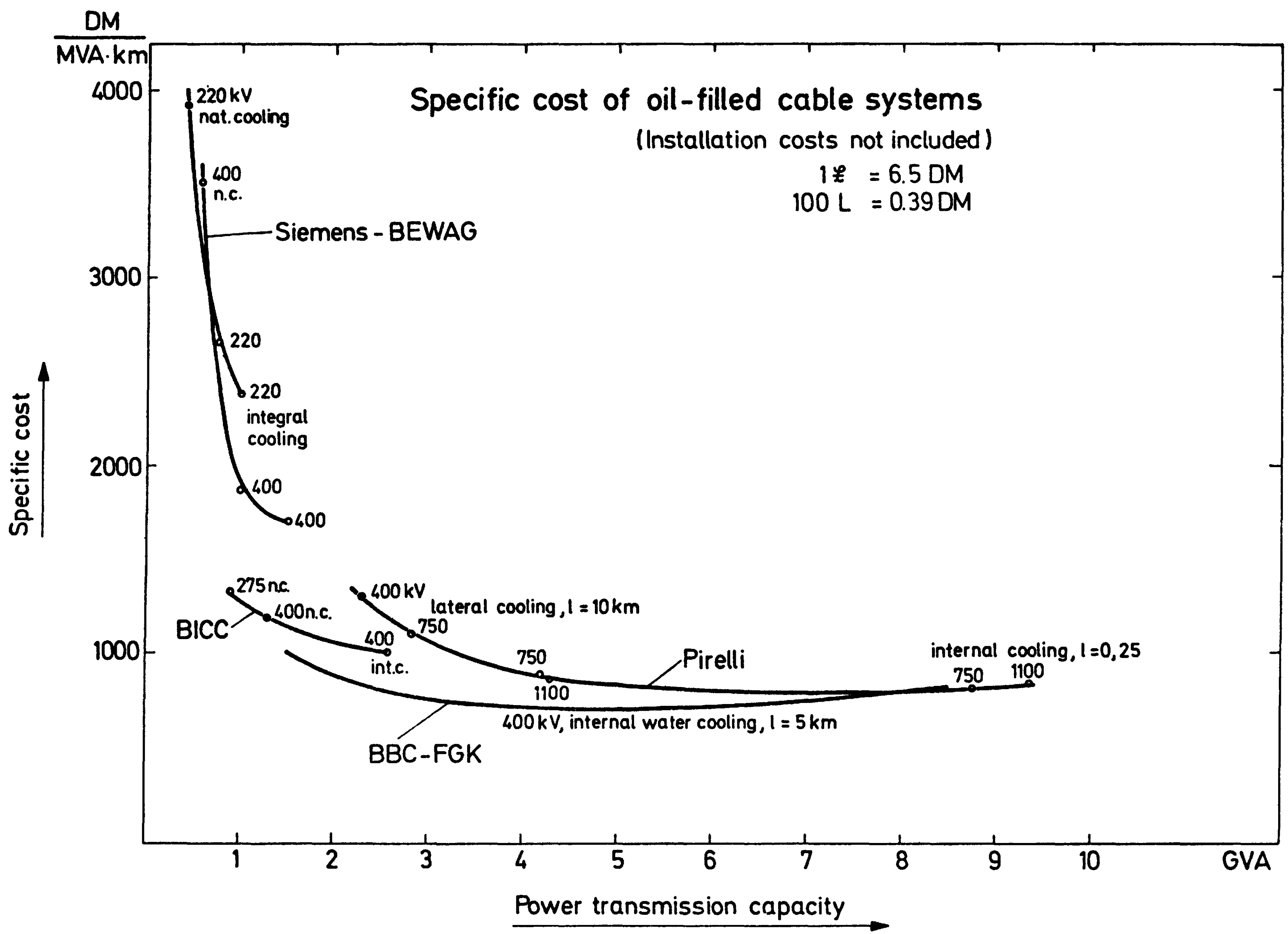


Figure 9-1.- Specific cost of HV cables with paper insulation (from [1]).

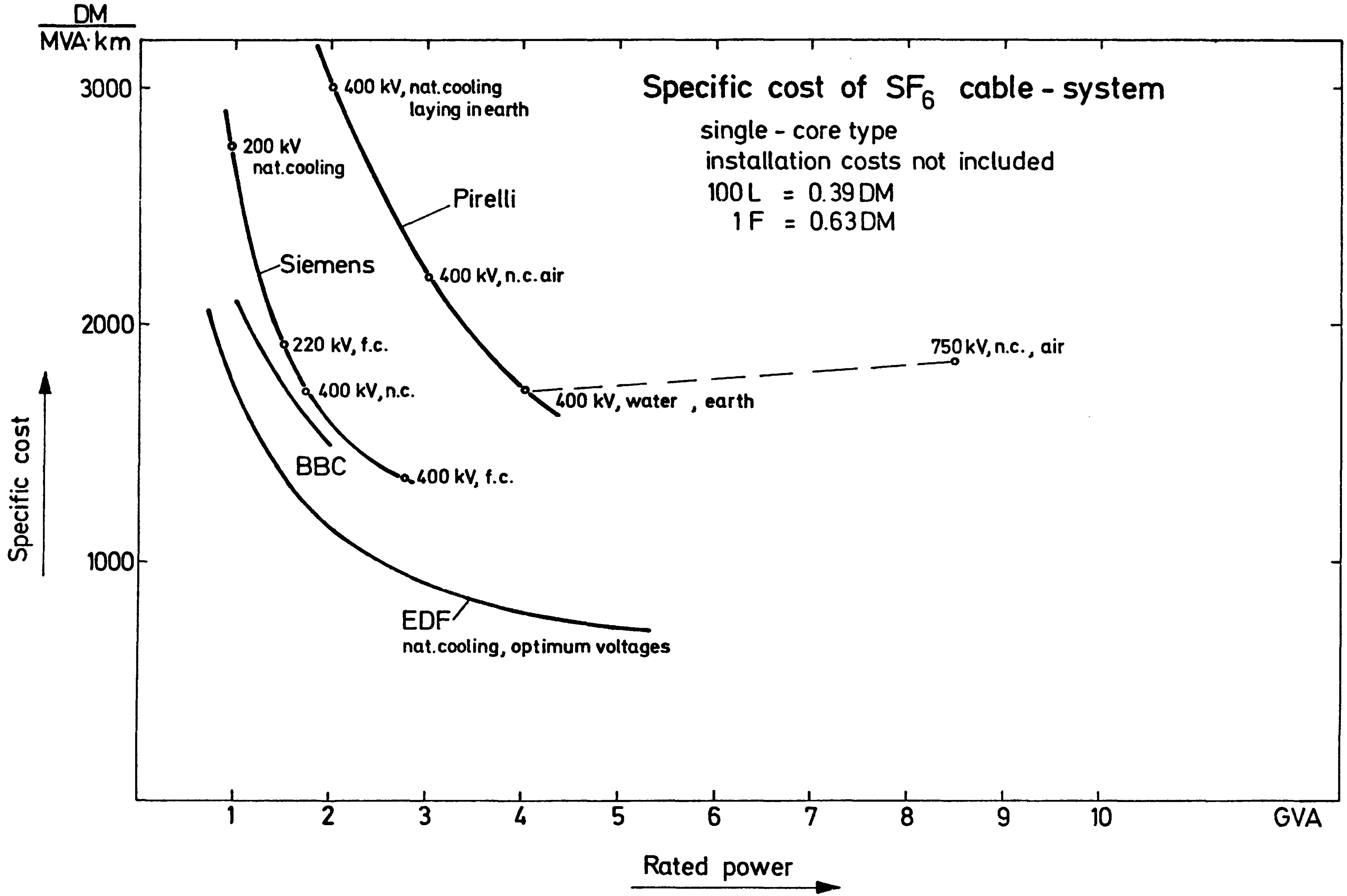


Figure 9-2.- Specific cost of HV cables with gaseous insulation (from [1]).

The curves shown on figure 9-1 for a particular type of cable are drawn continuous although the cost data are for voltages which increase with power. If the voltage was fixed then the curve would progressively become horizontal at higher powers. It would have no real meaning because the carrying capacity is restricted by the surface temperature of the cable.

The data available to us on SF_6 cables exhibit considerable scatter. This reflects the difficulty of evaluating the cost of equipment for which there is little industrial experience available. While the upper curve of figure 9.2 is perhaps overestimated, the lower one is perhaps too optimistic. It is however clear that the potential economic prospects of a cable cannot be discussed on the basis of the cost of a prototype.
It must also be born in mind that SF_6 cables will be assembled in the field and that the cost without installation cannot be directly compared with those of figure 9.1. The lowest and the middle evaluations are reproduced on figure 9.5 where the installation costs are included.

The cost evaluations made in the USA in 1972 are reproduced in figure 9.3. Here they are expressed as investment cost per year i.e. in DM/MVA .y.km.
On the same diagramme the cost of European cables with internal water cooling are added.

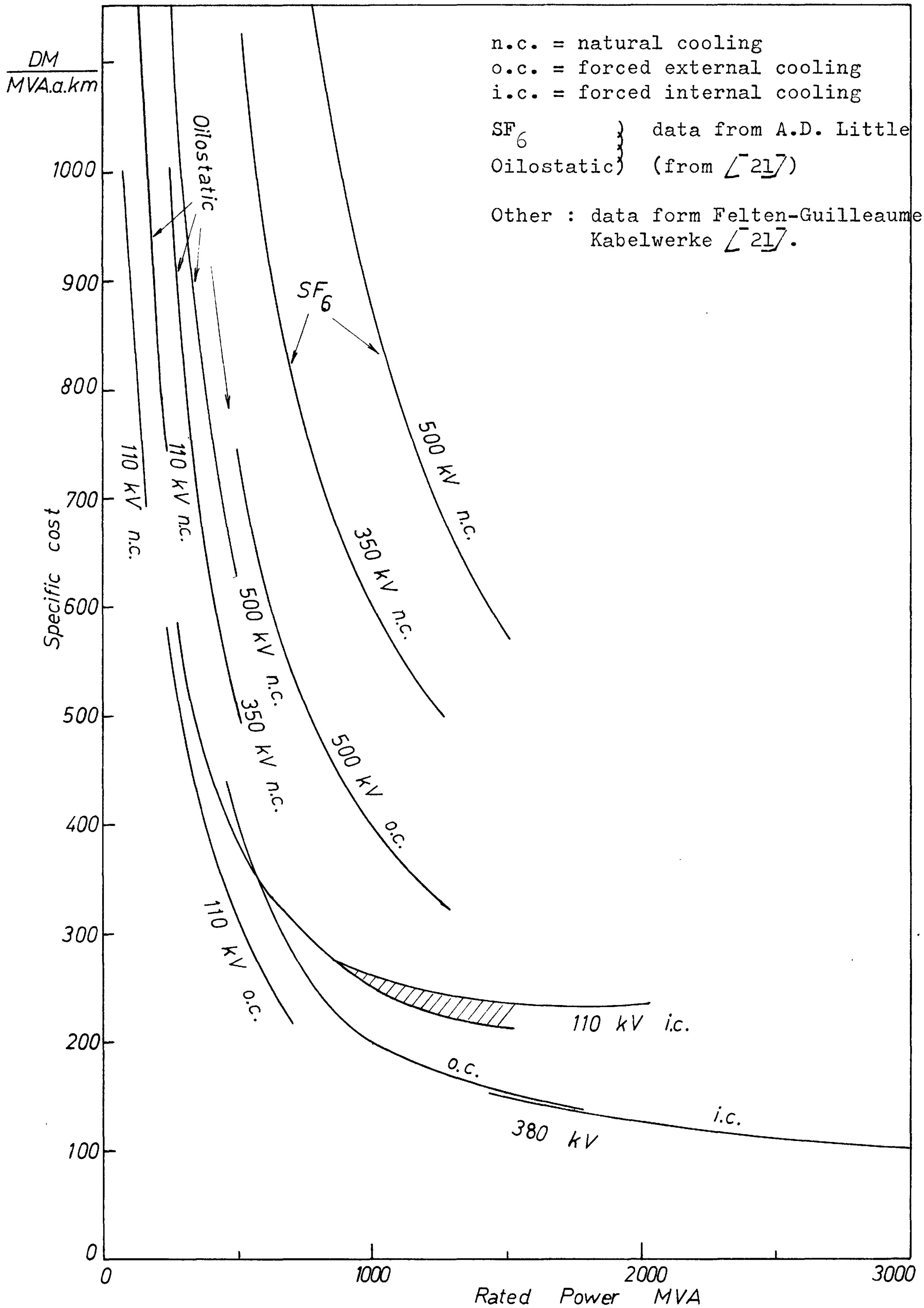


Figure 9-3.- Specific cost of advanced cables.

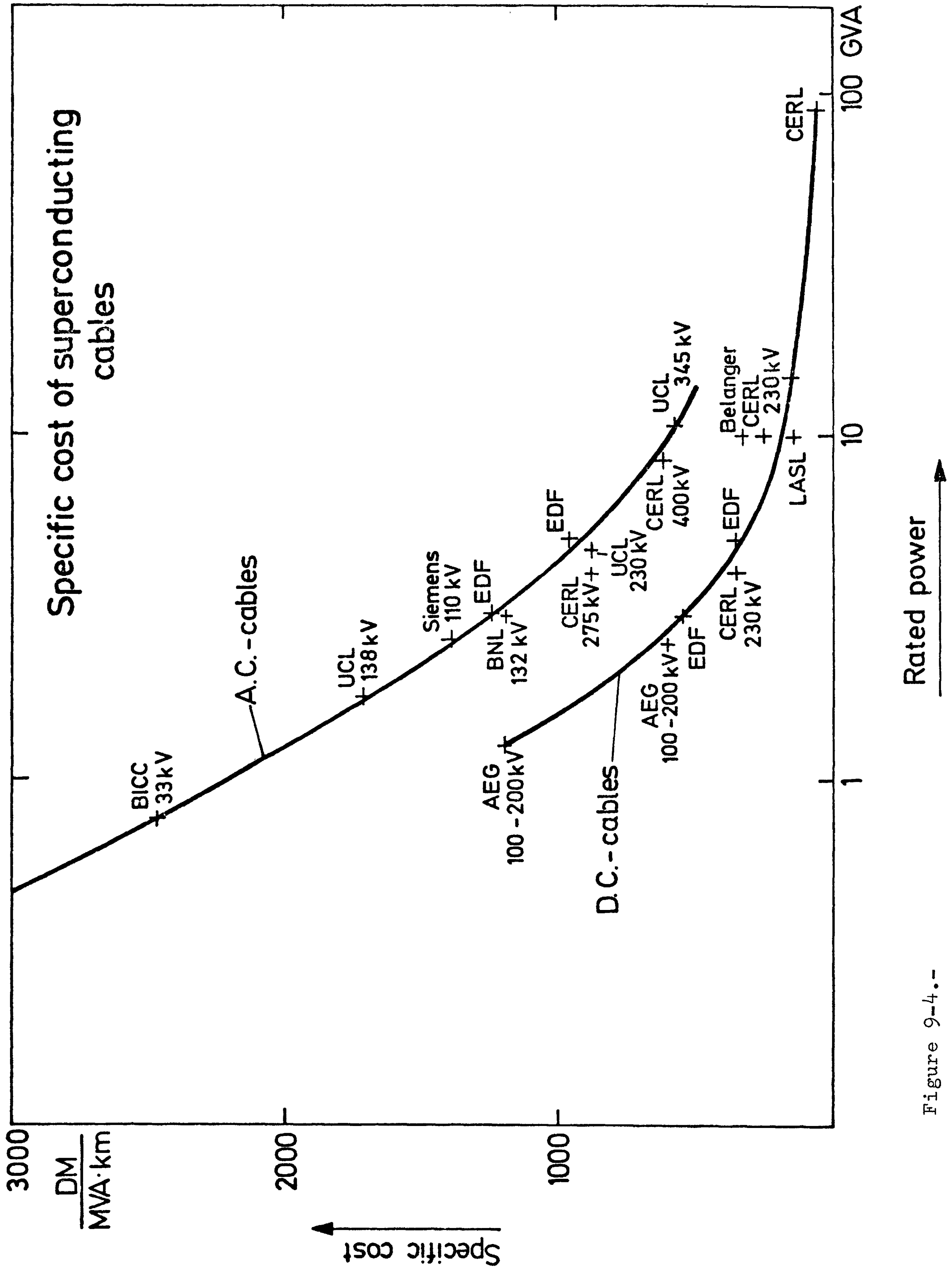
Superconducting cables

Many cost estimates of a.c. superconducting cables have been published in the literature.

For the comparison, they were converted in DM at the currency rate of the reference years and were corrected by the average increase in price of industrial products in Germany.

It is obvious that these estimates include a large uncertainty as the performance of the materials and the cable itself are not known with accuracy. Despite of that, the scatter of the data is remarkably small (figure 9.4).

The cost of d.c. superconducting cable is remarkably smaller than that of a.c. superconducting cables. In fact it is cheaper than any other type of cable.



Specific cost of superconducting cables
A.C.-cables
D.C.-cables
BICC 33 kV
UCL 138 kV
Siemens 110 kV
EDF
BNL 132 kV
EDF
CERL 275 kV
UCL 230 kV
CERL 400 kV
UCL 345 kV
AEG 100-200 kV
AEG 100-200 kV
EDF
CERL 230 kV
EDF
Belanger
CERL 230 kV
LASL
CERL
3000
2000
1000
DM/MVA·km
Specific cost
1
10
100 GVA
Rated power

Figure 9-4.-

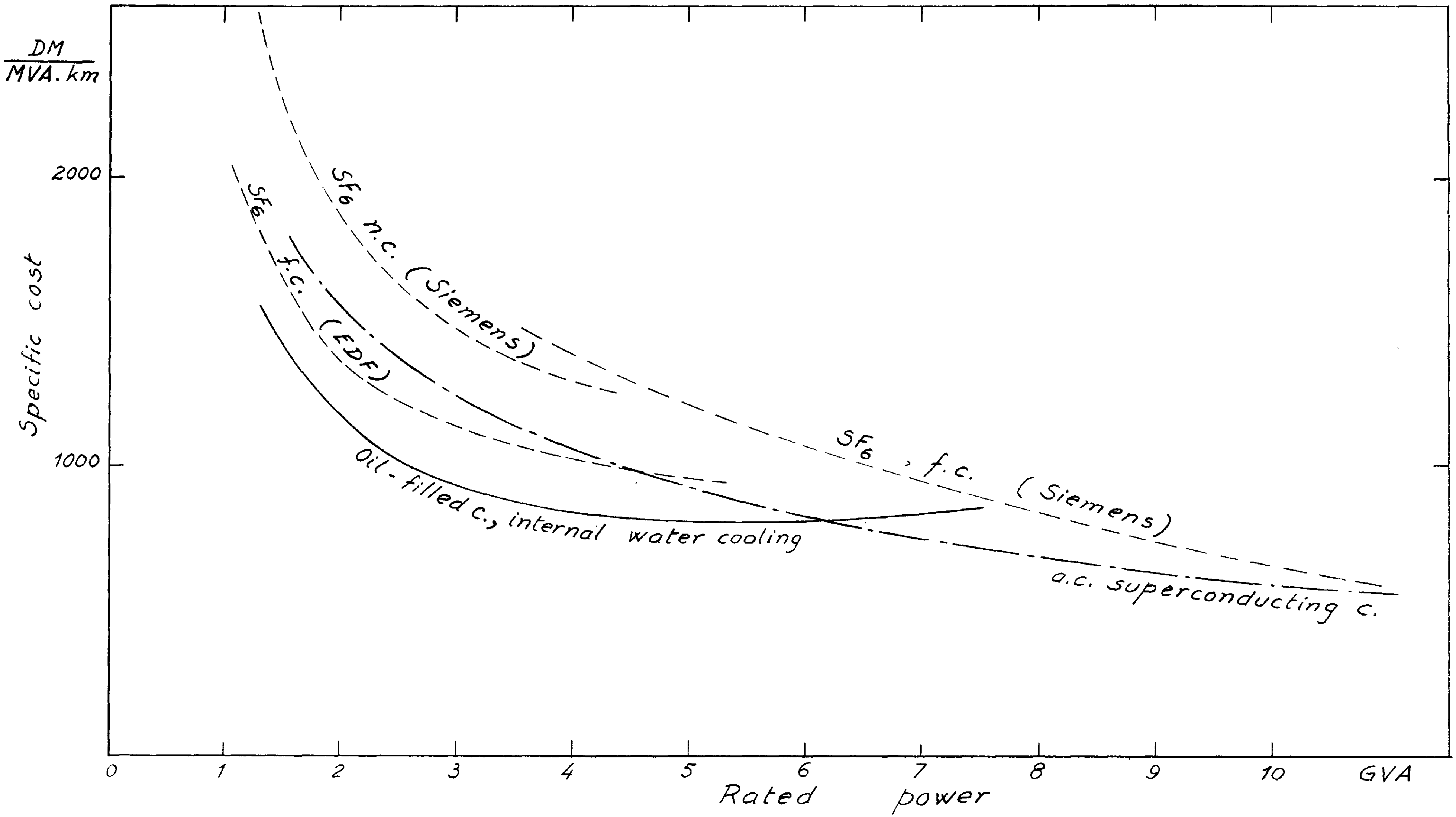


Figure 9-5.- Cost comparison of advanced cables (installation costs included) (from [1]).

Remarks on the cost comparison of a.c. cables

The data available on the costs of future high power cables had previously indicated that the superconducting cable would become competitive with externally cooled conventional cables at about 2,5 GVA. Recent development of internal cooling especially internal cooling with water may repell the break-even point to much higher powers. The diagram shown on figure 9.5 suggests 6 GVA.

Some authors predicted that SF_6 cable could be cheaper than superconducting cables up to 4 GVA [13] but most estimates do not foresee any cost advantage.

Although nobody knows exactly what the real costs will be, it must be borne in mind that water cooled cables are based on very simple technology. They can still be improved and optimized, and no great increase in cost as compared to those shown here is to be expected.

Superconducting cables however call for a complex and difficult technology. Real cost could escalate when actual design and fabrication starts.

10. LOSSES IN HIGH POWER CABLES

Table 10.1 surveys a few data on the losses in power cables. The data available are not sufficient to draw clear conclusions. It may however be observed that the losses in high power cables at voltages higher than 110 kV are usually smaller than 0,2 %. They get closer to 0,1 % as the voltage increases. Superconducting a.c. cables are shown to be less than 0,1 % and down to 0,03 %. It would be rather difficult to say now that they have significantly lower losses than other types of cables. In addition the figures for superconducting a.c. cables are not yet substantiated by experience.

Superconducting d.c. cables have definitely the lowest losses.

Table 10-1.- Transmission losses in various types of cables (reproduced from /1/).

Source of information		rated voltage kV	rated power MVA	Losses per metre W/m	Losses per 10 km rated power %
	Overhead line, for comparison				
	1 system, 2x435/55 mm² Al	110	350	366	1.05
	4 systems, 4x265/35 mm² Al	400	7600	2750	0.36
	1 system	725	5800	705	0.13
	Oil cables				
AEG	1000 mm² Cu, single core, nat.cool.	110	131	52.5	0.4
AEG	" " " , ext.cool.	110	398	324+16 1)	0.86
AEG	2000 mm² Cu, " " , " "	110	631	418+20 1)	0.7
Siemens-bewag	2000 mm² Cu, " " ,forc.cool.	220	1000	420	0.42 2)
"	2000 mm² Cu, " " ," "	400	1500	300	0.2 2)
AEG	2000 mm² Cu, single core, nat.cool.	380	560	67.1	0.12
AEG	2000 mm² Cu, " " ,forc.cool.	380	1500	225+12 1)	0.16
Pirelli	2000 mm² Cu, lateral cool.	750	2850	297	0.13 2)
Pirelli	2300 mm² Cu, " "	1100	4280	362	0.1 2)
F & G	internal water cooling, diameter of internal duct = 100 mm	110	1000	500	0.5
	PE cables				
AEG	1000 mm² Cu, single core, nat.cool.	110	145	58.2	0.4
AEG	1000 mm² Cu, " " ,forc.cool.	110	448	386+18 1)	0.09
	SF_6 cables				
Siemens	13000mm² Al, three core	110	1800	480	0.27
Pirelli	8000 mm² Al, single core, nat.cool. air laying	400	3000	450	0.15
Pirelli	8000 mm² Al, " " ,earth laying	400	2000	200	0.1
Pirelli	8000 mm² Al, " " , ext.water cool.	400	4000	800	0.24 3)
Siemens	9000 mm² Al, single core	400	4800	270	0.056
Siemens	9000 mm² Al, " " ,forc.cool.	400	7800	1260	0.162 3)
Pirelli	8000 mm² Al, " " , nat.cool. air laying	750	8500	675	0.08
AEG	9000 mm², single core	380	527	75.6	0.143
AEG	13000mm², " "	380	1265	80.1	0.064
AEG	28700mm², " "	380	2050	93.0	0.046
AEG	9000 mm², " "	525	727	75.6	0.104
AEG	13000mm², " "	525	1750	80.1	0.046
AEG	28700mm², " "	525	2830	93.0	0.033
	Cryoresistive cables				
Pirelli	1700 mm² Cu, 90 K	400	4000	2240 (CPC=8W/W)	0.56
	Superconducting cables			4)	
Siemens	AC	120	2500	130	0.052
BNL	AC	132	3000	240	0.08
CGE/EdF	AC	140	3000	268	0.1
CGE/EdF	AC	180	5000	368	0.0735
CERL	AC	275	4000	112	0.028
CGE/EdF	DC	±110	3000	54	0.028
CGE/EdF	DC	±140	5000	63.2	0.019
AEG	DC	±200	5000	81	0.016
CERL	DC	230	4000	32.6	0.0082

Comments:
1) for recooling
2) The losses per metre are multiplied by a factor of 1.2 taking into account the power needed for recooling the coolant
3) recooling included
4) including 150 kW per terminal, if no values are reported

11. COMMERCIAL AVAILABILITY

(reproduced from [1]).

Type of cable	Type of cooling Voltage, power	Available	Available soon	Available in the future
	UHV - natural cooling			
Oil-paper	550 kV 1.400 MVA	x		
dielectric	750 kV 1.600 MVA		x	
	HV and UHV - external forced cooling			
	220 kV 1.000 MVA	x		
	380 kV 1.600 MVA	x		
	380 kV 2.000 MVA	x	x	
	550 kV 2.000 MVA		x	
	750 kV 4.000 MVA		x	
	Internal cooling			
	Oil cooling			
	225 kV 1.200 MVA	x	x	
	380 kV 2.500 MVA	x	x	
	500 kV 3.000 MVA		x	
	Water cooling (L = 5km)			
	110 kV 2.000 MVA		x	
	380 kV 8.000 MVA			x
Lapped synthetic insulation	Natural cooling			
	750 kV 1.500 MVA		x	x
	1000 kV 1.500 MVA			x
	External cooling			
	380 kV 4.500 MVA		x	x
	750 kV 4.500 MVA			x
Extruded synthetic insulation	Natural cooling			
	110 kV 325 MVA	x		
	225 kV 650 MVA		x	

	External water cooling 110 kv 660 MVA 225 kV	x	x	
Gaseous dielectric SF_6	Natural cooling 380 kV 2.500 MVA 500 kV 3.500 MVA	x x	 x	
	Air or water cooling 500 kV 7.000 MVA 500 kV 10.000 MVA		x x	x x
Supercon-ducting cables.	a.c. and d.c. cables			1990

PART II

SUPERCONDUCTING CABLES

STATE OF THE ART AND FURTHER RESEARCH NEEDS

This review is essentially based on a study carried out at the Central Electricity Generating Board (CERL) by Dr J.A. Baylis and Co-workers.

1. GENERAL DESCRIPTION

In a superconducting cable current flows through a superconductor supported by a normal conducting metal (copper or aluminium). The superconductor is in direct contact with the coolant (supercritical helium at a temperature of about 5 K).

The composite conductor is surrounded by an electrostatic screen and the dielectric made of lapped plastic tape. The dielectric is also in direct contact with flowing helium. In an a.c. superconducting cable each phase conductor must be surrounded by a coaxial electromagnetic shield normally at ground potential.

The conductors may be coaxial or parallel. The parallel arrangement seems to be preferred for both d.c. and a.c. three phase cables. The three conductors are enclosed in seperate metal tubes or in one single metal tube. This metal tube is in fact the inner wall of the cryostat whose function is to protect the conductors and helium against in-leakage of heat.

The cryogenic envelope contains a heat shield cooled by liquid nitrogen and surrounded by superinsulation. It is maintained under vacuum.

A completely rigid design is not very practical because the cable can only be manufactured in 20 m sections which have to be assembled in the field. A completely flexible design using corrugated tubes for all envelopes, can be made. However because the cable has to be wound on drums whose sizes are restricted for reasons of transport and handling, the largest possible outside cable diameter appears to be 250 mm. The cable length which could then be wound on the drum would be about 250 m.

The semi-flexible design has up to now been given the most attention in Europe for a.c. cables. The cryogenic envelope is rigid and is manufactured in 20 m sections assembled in the field. The conductors are made flexible and are pulled into the cryostat when it is assembled in the field.

In Austria, work is being pursued on the fully flexible design.

AEG also chose the fully flexible design for its d.c. cable project. The cable designed for 200 kV can carry 5 GW. Its overall diameter is 250 mm.

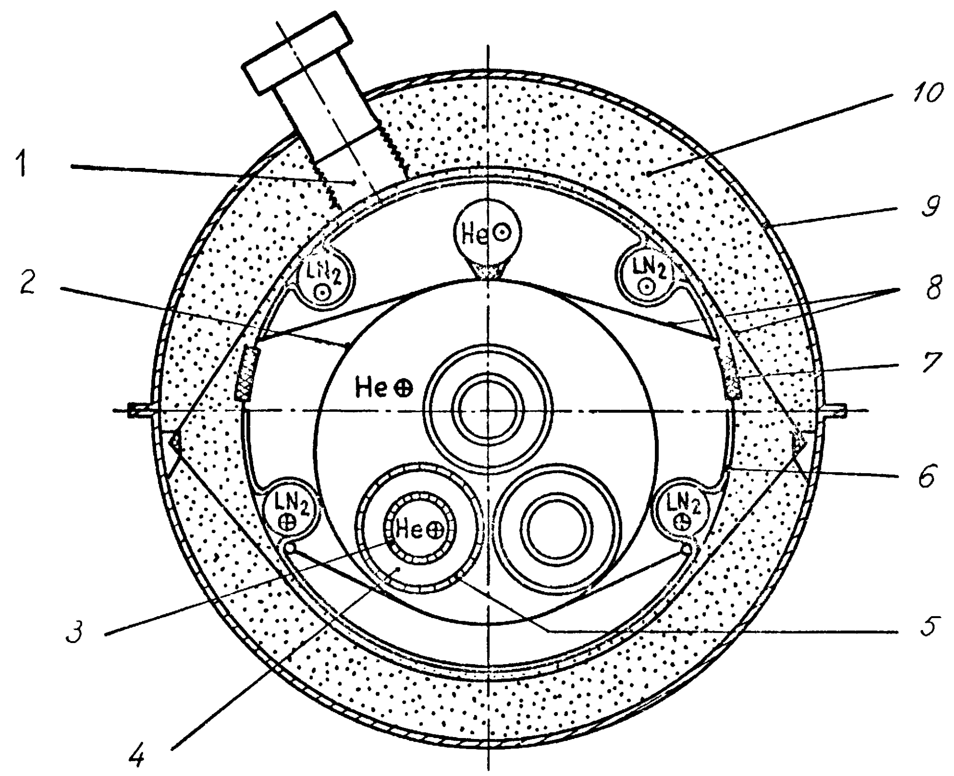


Figure 1.- Cross section view of the CGE/Air Liquide design of an a.c. superconducting cable (from [1] [14]).

1 - Connection to vacuum pump
2 - Helium pipe (Invar)
3 - Inner conductor
4 - Lapped polyethylene tape
5 - Outer conductor
6 - Thermal Shield (Invar)
7 - Spacer
8 - Suspension wires
9 - Outer steel pipe
10 - Thermal insulation (vacuum and alumina powder).

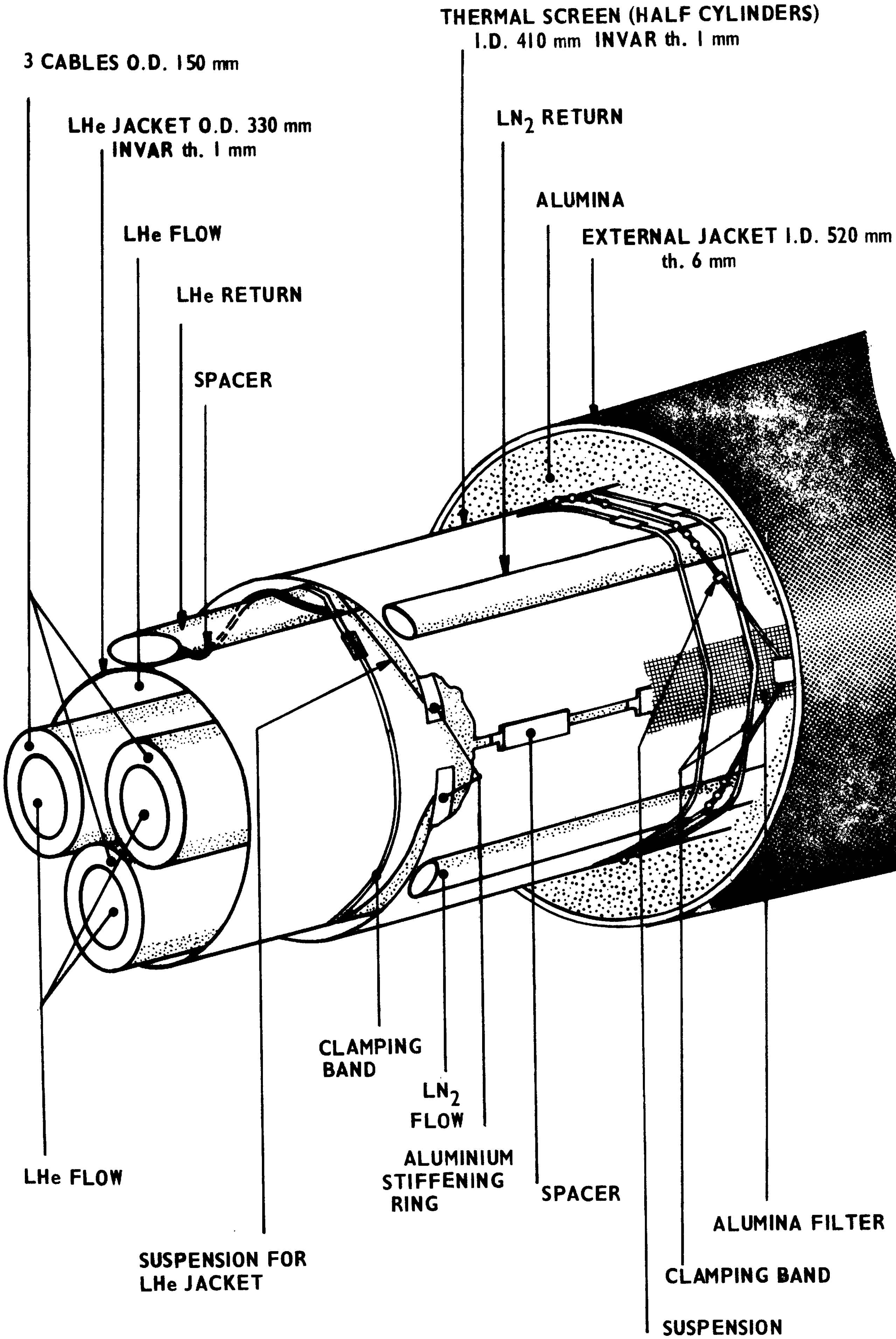


Figure 2.- CGE/Air Liquide design for a cryogenic envelope with alumina powder between the Invar thermal screen and the outer pipe /8/

2. THERMAL INSULATION AND THE CRYOGENIC ENVELOPE

The cryogenic envelope has to protect the helium duct against in-leakage of heat. As in any other applications, the basic design features of the envelope are a vacuum space to eliminate gas convection and slender supports to limit conduction. Additional features have to cope with radiation. A black surface at 300 K would radiate 460 W/m^2 to a surface at 5 K. This has to be reduced drastically. Most designs therefore insert a heat shield cooled with liquid nitrogen between the helium duct and the outside envelope.

Assuming that the surfaces have low thermal emissivity, the 80 K surface would only radiate 0,1 W/m^{-2} to the 5 K surface. The heat flux from the outer envelope and the thermal shield can be reduced to 2 W/m^2 by means of a 10 mm superinsulation. This consits of many layers of aluminised mylar sheet. Alumina powder has also been proposed (CGE design) [6] but seems to have poorer insulation properties than metallized mylar foil [5].

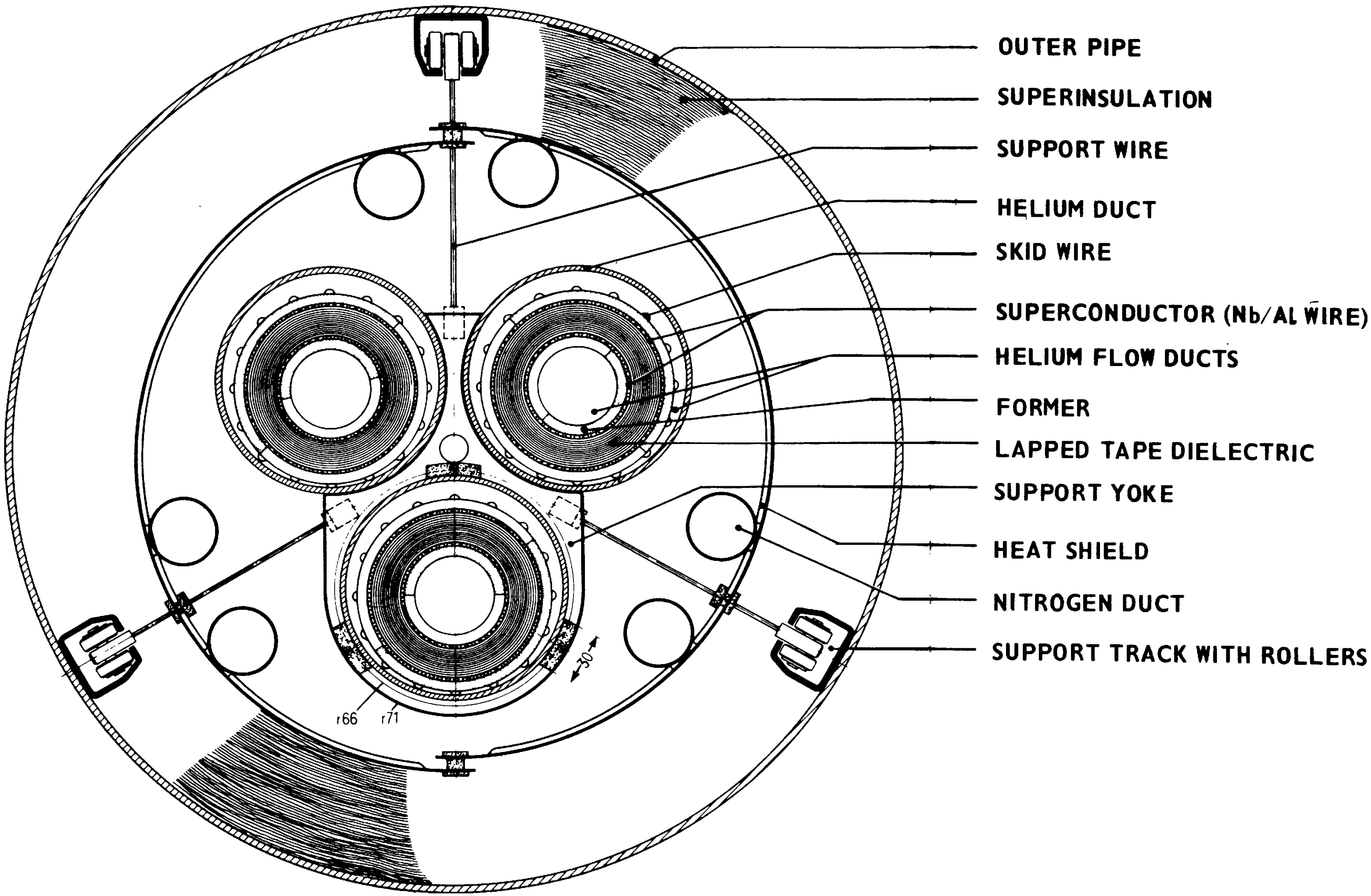


Figure 3a.- Siemens design of a superconducting a.c. cable 2,5 GVA, 110 kV (from [8]).

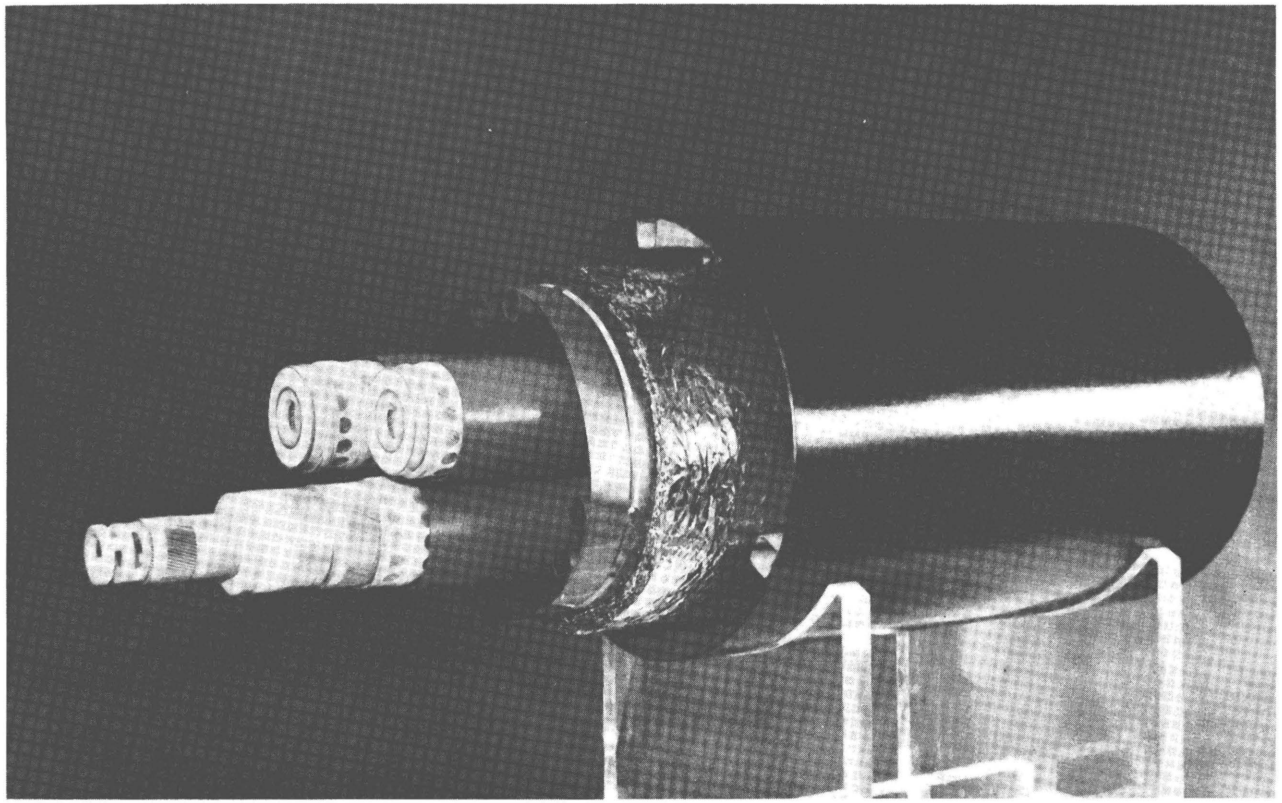


Figure 3b.- Mockup of the cable designed by Siemens (Nb/Al wire conductors and lapped tape dielectric) from [8].

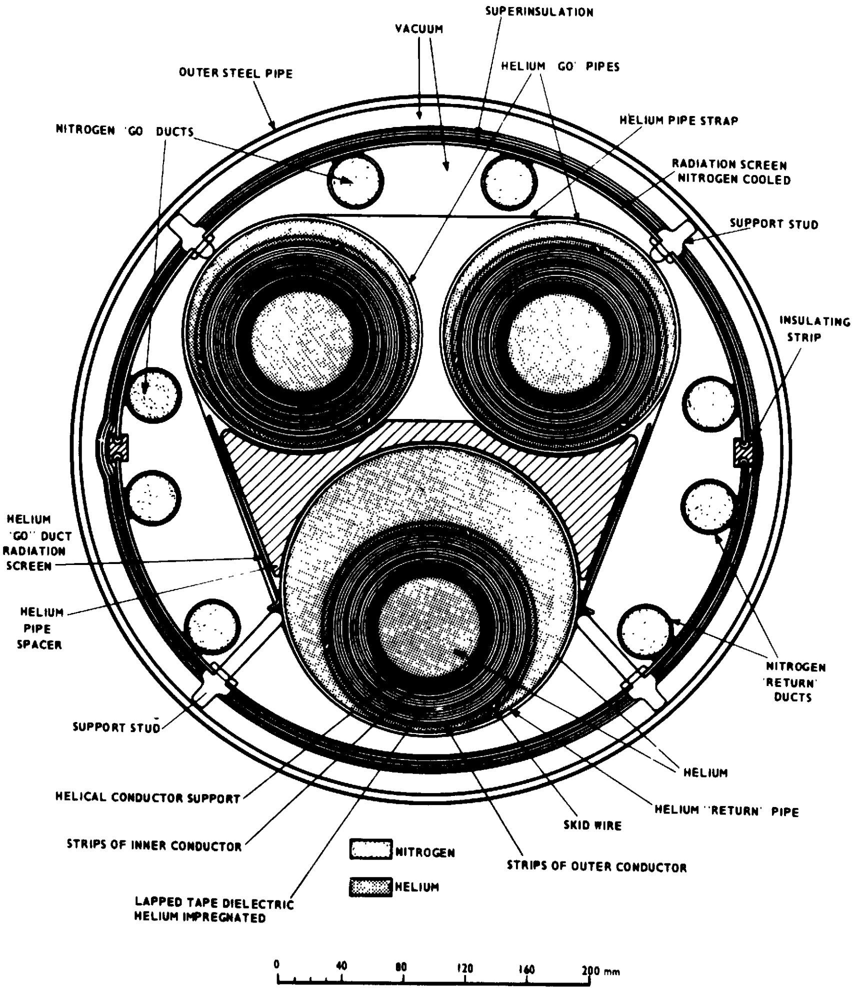


Figure 4.- CERL design of a 4 GVA superconducting a.c. cable (from [1] [20]).

3. DESIGN OF COMPOSITE CONDUCTORS

Conductors

In a rigid cable design the conductor can be made as a solid metal tube. Provisions are to be made to accomodate the axial contraction on cooldown. This can be achieved by inserting expansion joints (e.g. bellows) along the tube, by making the tube itself of Invar or even by using a corrugated tube.

In a flexible conductor design, the conductor must be either made as a flexible corrugated tube or consist of stranded wires on a cylindrical support (figure 5).

The respective merits and disadvantages of the different designs are discussed at length in the litterature and in a review made by Baylis at al. [8].

In the case of an a.c. cable the variable magnetic field produced by each conductor must be contained inside a shield in order to prevent heating of the metal components around the cable. This is done very simply by circulating an equal and opposite current in the coaxial cylindrical conductor placed around each phase conductor. The outer conductor is made of stranded wires as the inner conductor. It must be designed so as to keep the lapped dielectric pressed on to the inner conductor even after cooldown. To achieve this, the pitch adopted to wind the outside conductor wires is different from the one of the inner conductor.

If the individual wires of the inner and outer conductor were laid parallel to the cable axis, there would no axial component to the magnetic field. Because they are laid helically and that their pitches are different, their axial component do not compensate. There is therefore a net axial magnetic field and a circumferential current flowing on the under surface of the inner conductor and on the edges of the individual wires (fig. 6). The circumferential current is typically 15 % of the rated current [8].
The outer conductor need superconductor only on its inside face, while the inner conductor must be completely clad with superconductor [8].

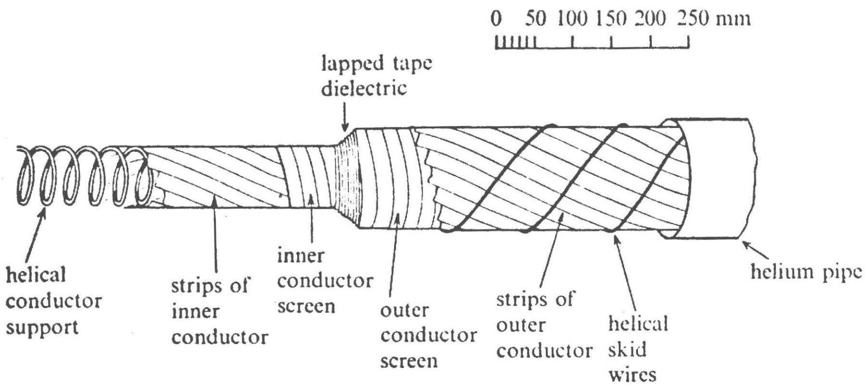


Figure 5a.- Details of flexible conductor construction with a lapped tape dielectric (from [20]).

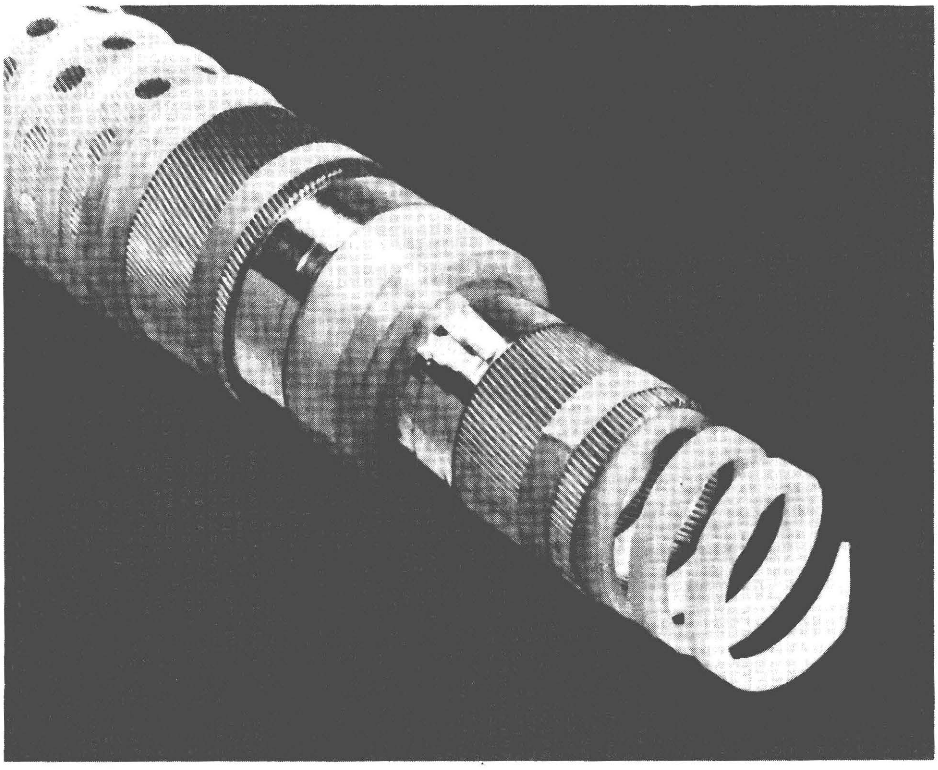


Figure 5b.- Siemens design of a flexible conductor for a.c. cable (from [8]).

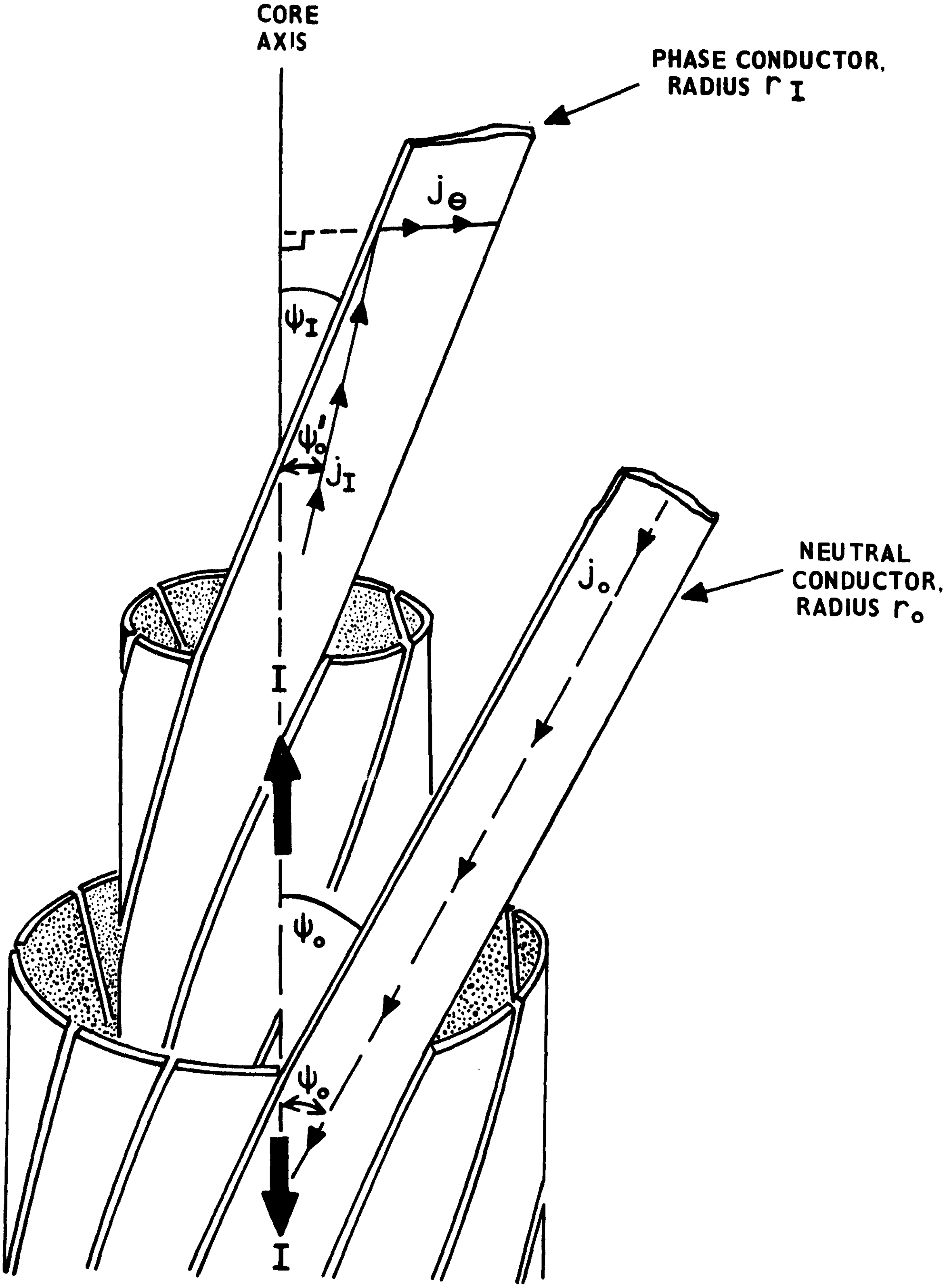


Figure 6.- Current flow in the stranded conductors of a flexible superconducting a.c. cable (from [87]).

4. SUPERCONDUCTORS - PERFORMANCES, A.C. LOSSES

For a.c. current applications, the superconductor is requested to have very low a.c. losses in addition to having high critical temperature and high critical field.

All hard type-II superconductors have low critical field, and would therefore have to be operated in the mixed (Shubnikov) state. They are then penetrated by the magnetic flux in the form of magnetic filaments or vortex lines. The changing pattern of magnetic field with alternating current gives a hysteresis loss which, to the first approximation varies with B_s^3/J_c where B_s is the self-field and J_c is the critical current density.

Niobium

Until recently, the only possible choice appeared to be pure niobium. This is the only metal which is a type-II superconductor and has the highest critical field B_{c1} of all materials of that family. Its high B_{c1} value makes it possible to operate it in the Meissner state even at a reasonably high current density. In the Meissner state, there is no hysteresis and therefore no a.c. losses except where field enhancement is produced by surface irregularities or sharp edges.

Properties of some superconductors [20]

	T_c	B_{c1} At 5K	B_{c2} At 5K	J_c At 5K and 0,5 T
Nb	9,2 K	0,126 T	0,23 T	normal
Nb - 25 % Zr	10,9 K	0,02 T	7 T	2×10^{10}
Nb - 44 % Ti	9,3 K	0,02 T	9 T	$3,5 \times 10^{9}$
Nb_3Sn	18,0 K	0,02 T	20 T	2×10^{10}

Losses in pure niobium increase with decreasing quality of surface finish, increasing lattice defect density, etc. They vary approximately with the 4th power of the magnetic field.

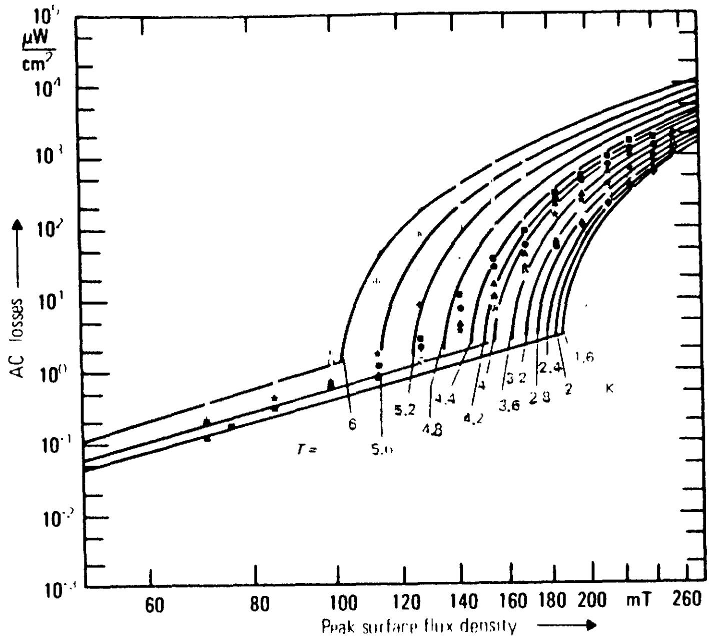


Figure 7.- A.C. Losses in niobium as a function of temperature and magnetic field. (frequency = 50 Hz), (from [5]).

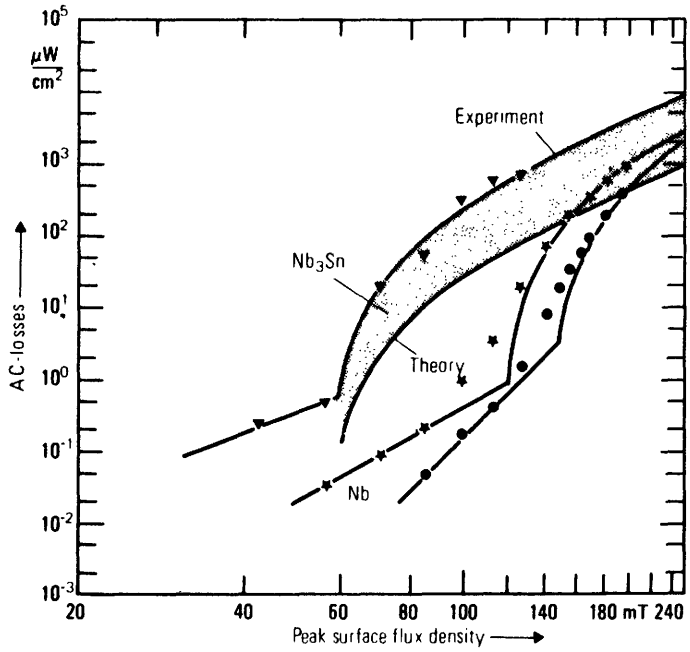


Figure 8.- A.C. Losses in niobium and Nb_3Sn at 4,2 K (frequency 50 Hz), (from [5]).

Measurements of a.c. Losses on Nb superconductor specimens were made at Siemens [5] (figure 7). They show that the losses can be kept in the linear range of variations even at 6 K (the outlet helium temperature) if the peak surface flux density is kept below 0,100 T.

It is still a practical fact that losses in commercially fabricated Nb are expected to be much greater than observed on laboratory specimens. Instead of 0,01 W/m^2, actual losses are predicted to range from 0,05 W/m^2 (Bogner) to 0,1 W/m^2 (Baylis) at the peak surface flux density 0,1 T which corresponds roughly to a r.m.s. current density of 600 A/cm. Because some reserve margin has to be provided for overload and fault current the rated current density now adopted is 400 A/cm (r.m.s.). To carry such current a 20 μm Nb layer is sufficient.

Nb_3Sn

Because of its very low critical field B_{c1}, Nb_3Sn alloy is in the mixed state at surface fields as low as 60 mT. Above this value, the a.c. losses increase very quickly with increasing field and current (figure 8)[5]. At 100 mT losses in Nb_3Sn are two orders of magnitude larger than in niobium.

The preparation process has considerable influence on Nb_3Sn performance and in 1974, loss values as low as 0,04 W/m^2 were reported (figure 9) [8]. If these values are reproducible, Nb_3Sn would become very much attractive for a.c. cables. The required layer thickness for rated and overload currents is not well established but probably lies in the range of 1-10 μm.

Type II superconductors can carry much larger current than niobium. They can therefore operate under overload conditions without being driven normal and therefore with much smaller power dissipation than in a Nb/Cu or Nb/Al conductors.

In the case of the most severe fault current with d.c. offset, as shown in figure 10, the amount of heat generated under nearly

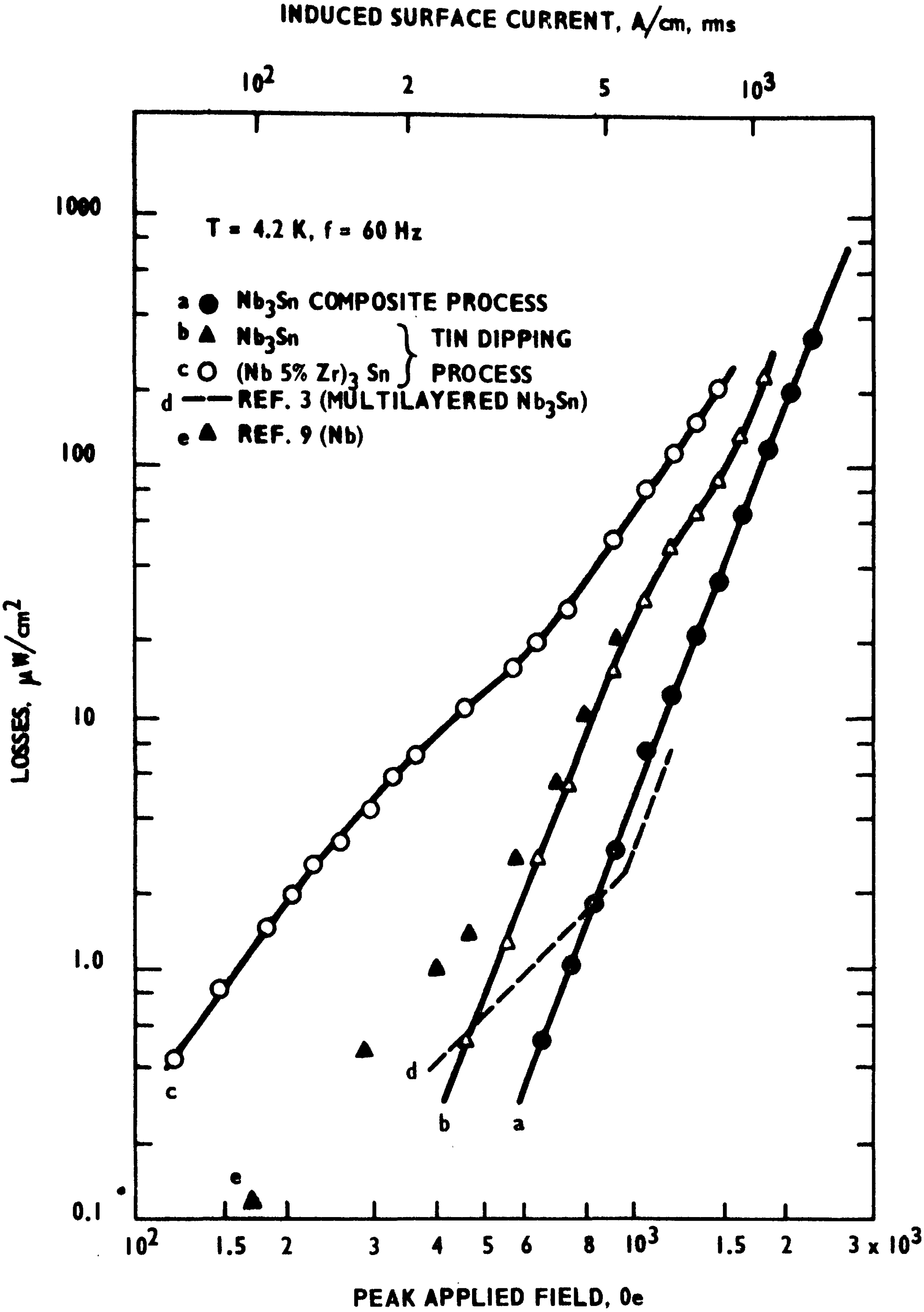


Figure 9.- A.C. Losses in various Nb_3SN samples at 4,2 K (frequency 60 Hz). (from [8], [19]).

adiabatic conditions, is so large that the superconductor would probably be driven normal. In addition, designing for fault current would require thicker Nb_3Sn layer.

Because of flux jumps at large current density the type II superconductors cannot be expected to operate to their full theoretical critical current.

Possible performance of type II superconductors under fault current with d.c. offset is therefore dubious.

However Nb_3Sn could be envisaged as a intermediate back-up to improve the overload capability of Nb conductors. It would in fact considerably reduce the heat dissipation under fault current conditions; its a.c. losses are several orders of magnitude smaller than the Joule effect in copper or aluminum. Brittleness of the alloy introduces design and fabrication problems which are not solved yet. They are much more difficult for the back-up configuration than for d.c. uses where Nb_3Sn can be placed in the neutral plane of the composite tape.

5. NORMAL METAL BACKING

The normal metal backing must have very low resistivity at liquid helium temperature. Therefore a choice has to be made between copper and aluminium.

Copper is preferred by some designers because it has high heat capacity. It also has large magnetoresistivity, a result of which is that there is no benefit in using a very high conductivity copper. A residual resistivity ratio of 200 would be sufficient. Oxygen-annealed copper might be satisfactory.

Aluminium could reach a very low resistivity and is preferred in many cases. There is every incentive to use very high purity metal with a residual resistivity ratic up to 10.000.

6. STABILISATION AND FAULT CURRENT BEHAVIOUR

In magnet applications, superconductors are provided with some degree of cryogenic stabilisation. They are thus embedded in or backed with a normal very high conductivity metal (copper or aluminium). In cable applications, the stabilisation has to be calculated to minimize the heat generation during fault current transient. The peak current surge resulting from failure of some part of the system is typically 25 times greater than the rated current and the d.c. offset is ten times the rated current (fig. 10). The primary breaker operating time is between 60 and 150 ms.

At these very high current levels, niobium will be driven "normal" immediately. The current has therefore to be carried by a low resistivity conductor (Copper or aluminium). When the conductor thickness is greater than the skin depth, the power dissipation is about 22 kW/mm^2 for a current density of 500 A/mm r.m.s. If the temperature of copper is thereby increased above 15 K, the heat generated in it increases very rapidly and could reach values higher than 60 kW/m^2. (This must be compared with 0,05 W/m^2 under normal conditions).

Insufficient data are available to calculate the temperature rise and the heat transfer rates during a fault pulse. According to Bogner [5] the average (or equilibium) temperature increase of helium by a pulse of 100 kA (at the beginning of the fault) in a cable made of Nb on aluminium support would be 1 K after 4 cycles (80 ms). Therefore after interruption of the current, the cable would be able to carry again the full rated load. It is to expect that this will not occur during a transient and that the conductor temperature will rise to very high values (20 to 40 K).

If Nb_3Sn was used instead of Nb, then it could carry the fault current without reverting to the normal state. It would have high a.c. losses but these would nevertheless be smaller than Joule

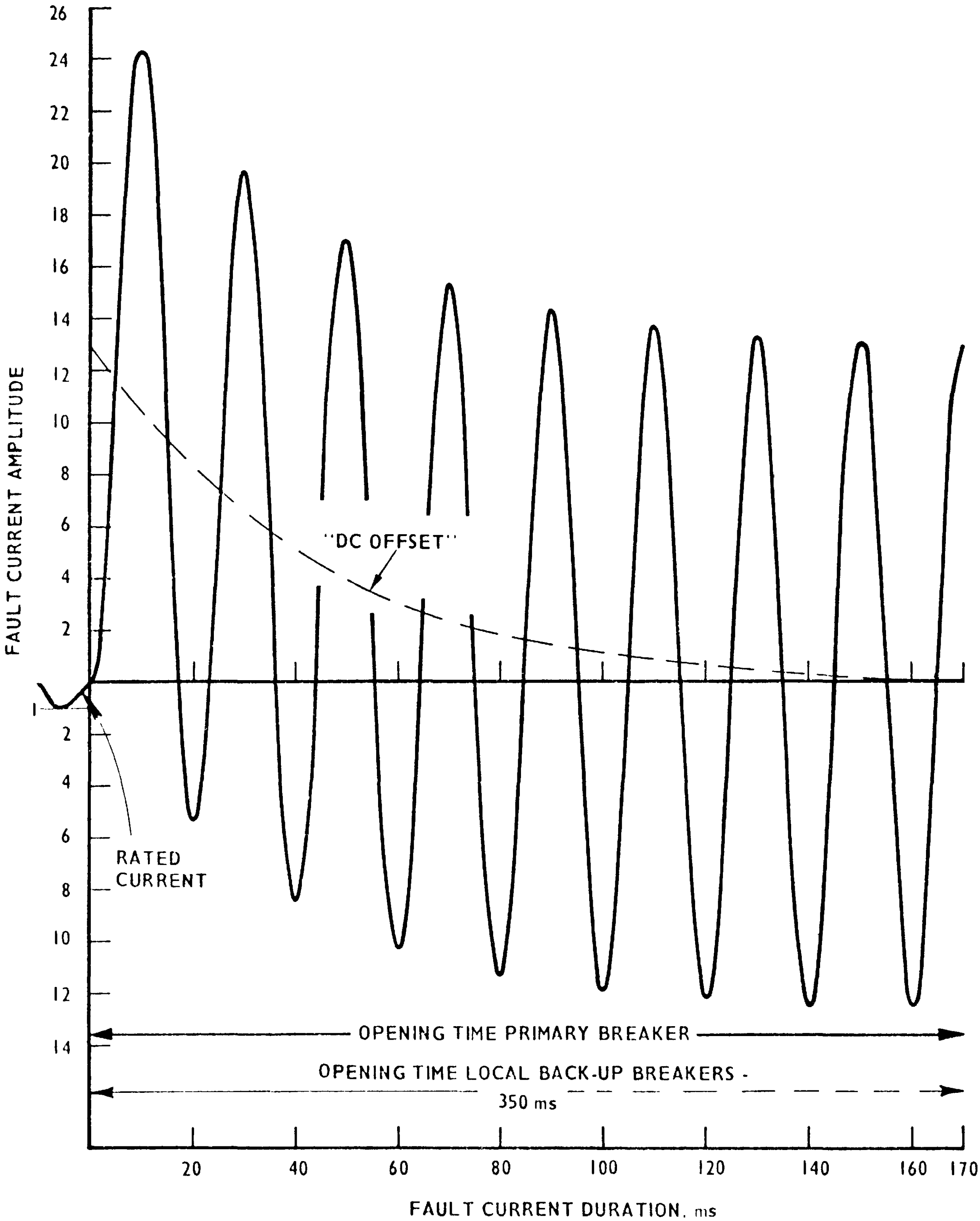


Figure 10.- "Worst case" fault current waveform in CEG B network (from [8]).

effect in resistive copper or aluminium. The cable could therefore be ready to operate again almost normally immediately after the fault disappears. The assumption is made, of course, that the fault is only of very short duration.

Several possibilities can be envisaged to improve the fault current characteristics of the cable [8].

a) Niobium could be backed by a type II superconductor with high critical current. Nb-Zr alloy (100μ thick) could be used for that purpose.

b) The temperature rise of the normal conductor backing could be reduced if its specific heat was higher. Use of lead in addition to copper is envisaged by some designers.

c) Nb_3Sn would probably be able to carry the full fault currents but this is not absolutely sure because of flux jump instabilities. However, its brittleness offers many diffcult problems. Nb_3Sn is normally manufactured as thin films (10μm) on metal ribbon 50 μm thick. Because it cannot withstand any tensile stress it must be very thin and when it is included in a composite structure it must be located at the neutral plane. There is as yet no obvious design for using Nb_3Sn in a superconducting a.c. cable.

The current state of the art makes it possible to design an experimental superconducting cable with Nb superconductor and to hope that its a.c. losses will be reasonably small. There is however no means of predicting its fault current performance and one has to rely entirely upon full scale testing. It will however soon or later be necessary to develop methods of computing rates of superconductor and conductor heating and rates of heat transfer to liquid helium in fault current conditions.

Continued investigations are necessary on the laboratory scale to develop higher performance composites, in particular with respect to fault current. Decreasing the a.c. losses of Nb_3Sn in a consistent and reproducible manner is necessary. Optimisation Nb layer superconductor has not yet been fully achieved.

While designing new types of composite conductors continued attention should be paid to joining.Techniques for Nb conductors are said to be available, they still have to be improved.

7. ELECTRICAL INSULATION

The dielectric material used in superconducting a.c. cable must have high dielectric strength and low losses. On the basis of the overall thermal balance of the cable, the dielectric losses are required not to exceed 0,05 W/m. To achieve this, the dielectric must have a $\tan\delta < 2 \times 10^{-5}$ at 5K. Non-polar polyethylene, polypropylene and teflon PTFE can be satisfactory in this respect.

Several dielectric systems can be envisaged

- vacuum + solid dielectric spacers
- helium + solid dielectric spacers
- lapped dielectric film immersed in helium.

The last one is favoured the most and is the only practical solution for semi-flexible cables.

Dielectric strength of lapped plastic tape decreases with tape thickness because helium has lower dielectric constant. For thickness common in cables, effective breackdown strength of 10 kV/mm can be expected [5]. Under d.c. voltage it is 20 kV/mm. Bu t gaps between adjacent tapes in a layer are week points in the insulation, because partial discharges may occur through the helium and cause progressive damage to the dielectric foil. Dielectric strength of lapped plastic film and partial discharge phenomena need further investigation.

The dielectric system must be surrounded by electrostatic screens whose function is to smoothen the field enhancement at the butt gaps between wires of stranded conductors.

The lapping parameters must be chosen to ensure adequate flexibility and to cope with the thermal contraction which is much greater for plastic film (2-3 %) than for metals (0,3 - 0,4 %). Any stress greater than the elastic limit at 4 K must be avoided. This is still possible for dielectrics like polyethylene whose elongation at the elastic limit exceeds the thermal contraction.

The dielectric has to remain compressed on the inner conductor and should not develop slackness during 30 - 40 yrs operation. It should keep its full integrity even after the severe stresses produced by fault current. These tend to collapse the inner conductor and burst the outer one and major stresses on the dielectric occur on recoil of the conductors.

8. PERFORMANCE OF SUPERCONDUCTING A.C. CABLES

To minimise cable cost, the core has to be compact (smallest possible outside diameter). The amount of superconductor is given by the maximum allowable critical current density (400 A/ cm for niobium) and by the overload safety margin. The amount of normal metal backing (copper of aluminum) is given by the requested fault current safety.

If V is the phase-to-neutral voltage, the electric field at the inner conductor surface $E_i = 2\ V/[a \ln (b/a)]$ where a and b are the diameters of the inner and outer conductors respectively.

For given values of E_i, determined by the dielectric, and H_i, determined by the conductor, and b, the transmitted power is a maximum when $b/a = \sqrt{e}$. The value of the maximum power is therefore

$$\frac{1}{4} \pi a^2 E_i H_i .$$

The voltage can also be expressed as a function of power, E_i and H_i

$$V = \left(\frac{PE}{4\pi H_i} \right)^{0,5} \text{Volts}$$

Figure 11 shows the optimum curve for V as a function of P calculated by CERL [8].

The dotted curves correspond to b values 10 % greater than the optimum diameter. As a substantial part of the cable cost varies as b, variations within that range do not impose too severe penalty.

For niobium, the current density can be 400 A/cm (rms). The electric stress on the dielectric can be 10 kV/mm (rms). Heat losses considered as typical design paramaters for a 2,5 GVA cable are [8]:

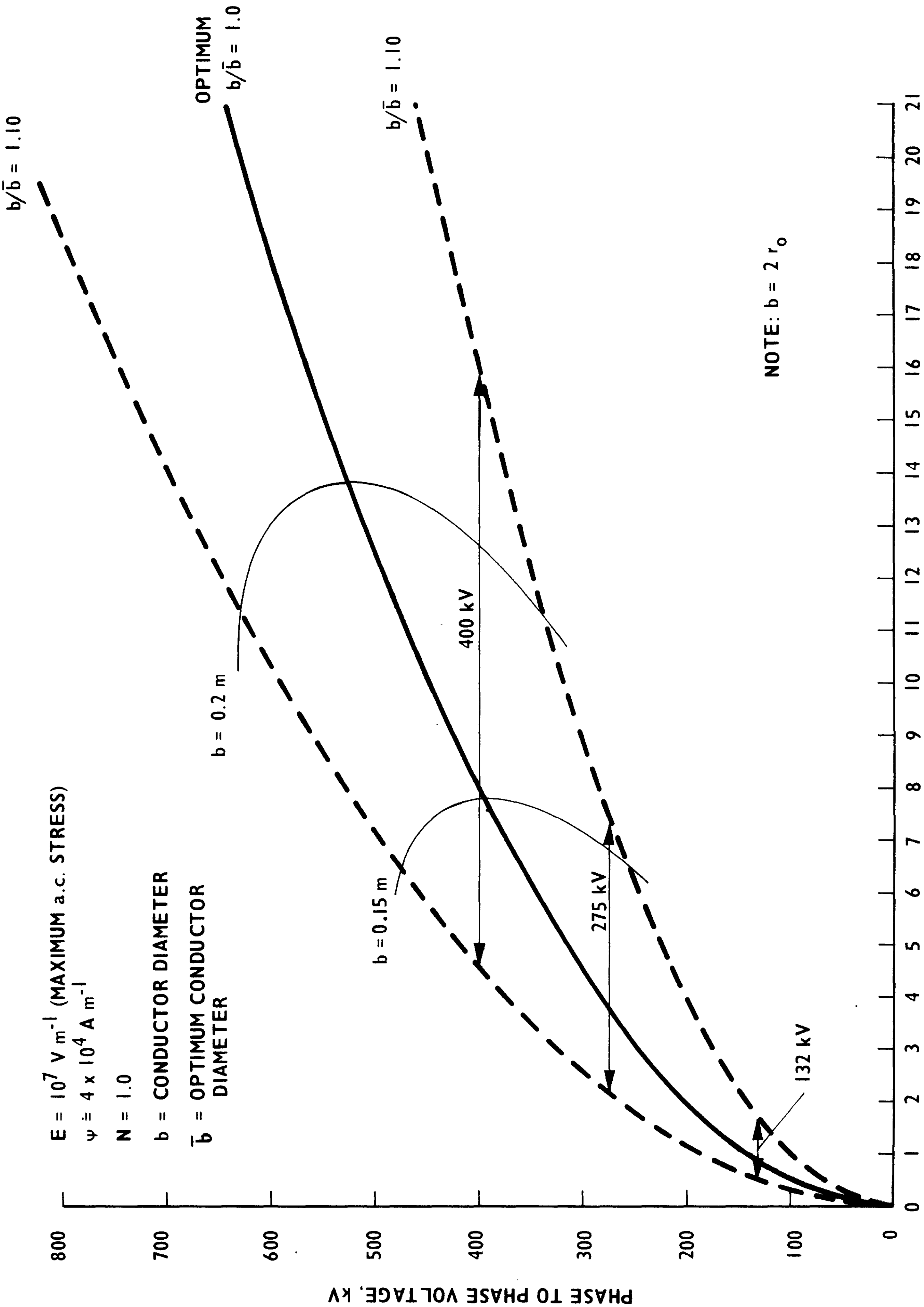


Figure 11.- Variation of power throughput with voltage (from [8]).

superconductor a.c. loss	0,05 W/m
dielectric loss	0,05 W/m
heat inleak	0,1 W/m
viscous drag	0,03 W/m.

The cost and losses associated with terminations (cooling station) require a minimum length of cable which is now considered to be about 10 km.

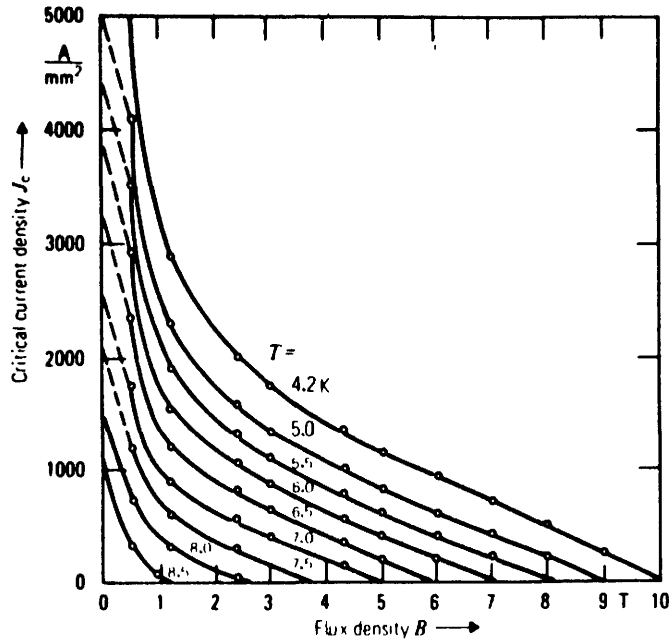


Figure 12.- Variation of critical current density of Nb - 44w % Ti with magnetic field. (from [87]).

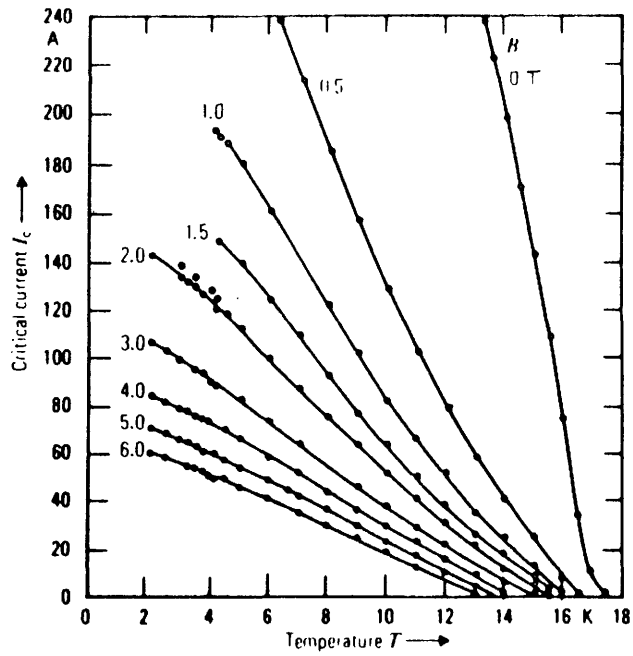


Figure 13.- Variation of critical current density of Nb_3Sn with temperature. (from [87]).

9. SUPERCONDUCTING D.C. CABLES

Superconductors are ideally suited for d.c. power transmission since there is no power dissipation. The choice of possible superconductors is not restricted by a.c. loss considerations. Materials with high critical field and high critical current density are therefore preferred (NbTi, Nb_3Sn).

Higher current densities can be tolerated than with a.c. However type II superconductors in the mixed state carry current in the bulk and the thickness has to be increased with the desired intensity.

It is important to note that the critical current density J_c decrease sharply with increasing magnetic field between 0 and 1 T (figure 12). It also decreases linearly with increasing temperature (figure 13).

If a ductile superconductor was used, the ideal conductor shape would be tubular with circular cross section. Typical current densities would be 1000 - 2000 A/cm and magnetic field 0,125 - 0,250 T. If the tube radius decreases, superconductor thickness must increase.

There are however reasons to prefer Nb_3 Sn which has even greater capability. Tubular conductor cannot be used because Nb_3 Sn can only be manufactured on tapes.

Ribbon-shaped conductors developed by AEG consist of two Nb_3 Sn layers, 12 mm wide, soldered together between two thin strips of high conductivity copper (thickness 0,250 mm) so that the brittle superconductor is close to the neutral plane and can be flexed without damage.

Copper is necessary for cryostatic stabilization to avoid propagation of local flux jumps which occur at high current densities. In a d.c. cable,the copper backing provided for stabilization is normally not necessary as fault current are not larger than twice the rated current.

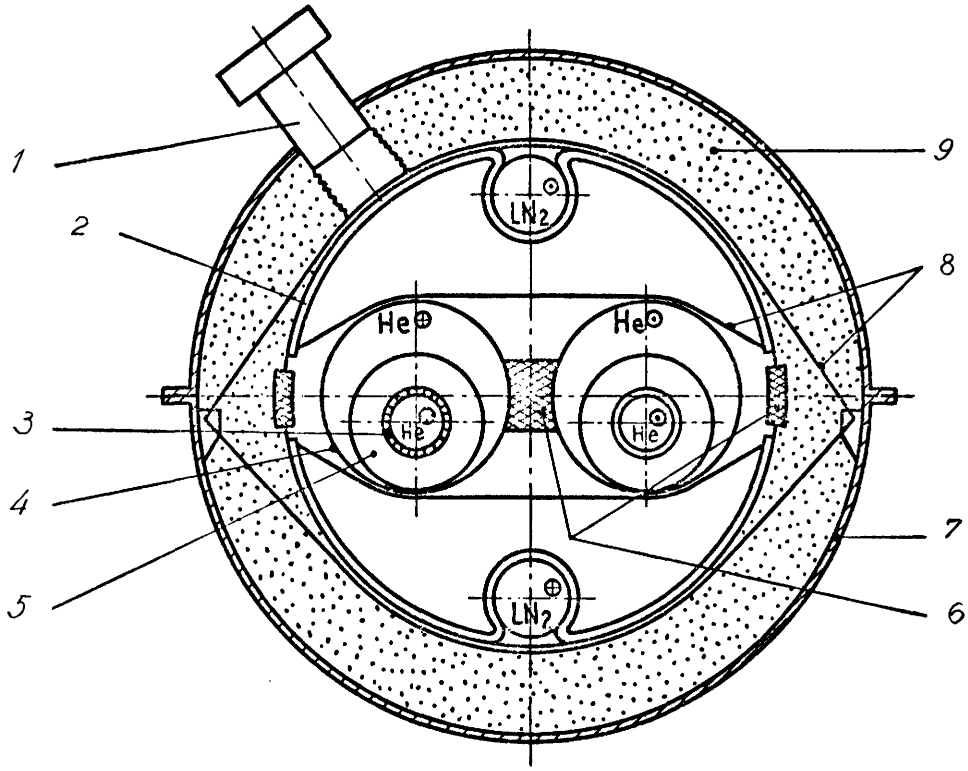


Figure 14.- CGE/Air Liquide design of a superconducting d.c. cable. (from [14]).

1 - Connection to vacuum pump
2 - Thermal shield (Invar)
3 - Conductor
4 - Helium pipe
5 - Lapped Mylar tape
6 - Spacers
7 - Outer steel pipe
8 - Suspension wires
9 - Thermal insulation (vacuum and alumina powder).

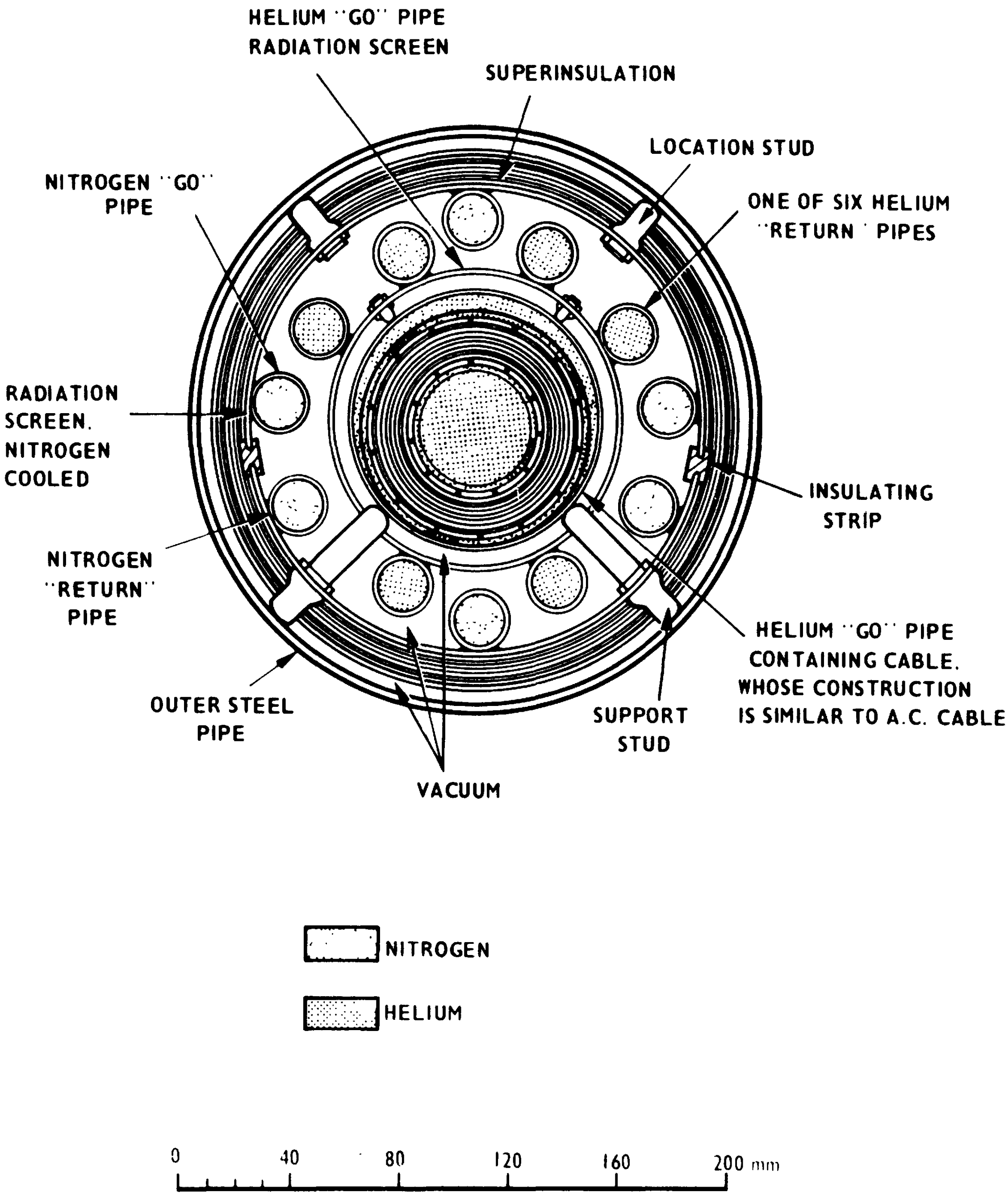


Figure 15.- CEGB design for a 4 GW, 230 kV d.c. superconducting cable (from [87]).

The second important feature of a d.c. cable is the absence of losses in the dielectric and the higher admissible electric stress (20 kV/mm). The AEG design uses conventional cable paper in helium (10 mm thickness) and carbon paper screens.

The d.c. cable can be designed as an assembly of two coaxial or two parallel conductors. The latter design seems to be preferred.

It leaves however a high intensity unshielded magnetic field that may cause amenity.
In addition the residual a.c. ripple from the rectifier, could be the cause of losses (eddy currents) in the outside metallic cable structure.

The AEG design consists of two unipolar (single conductor) flexible cables. Each one has an outside diameter of 250 mm (figure 16, 17).

In a superconducting d.c. cable there are virtually no power losses. The heat to be evacuated is the inleakage through the thermal insulation. The cooling power required to compensate it in the AEG design is estimated to 230 kW/km.

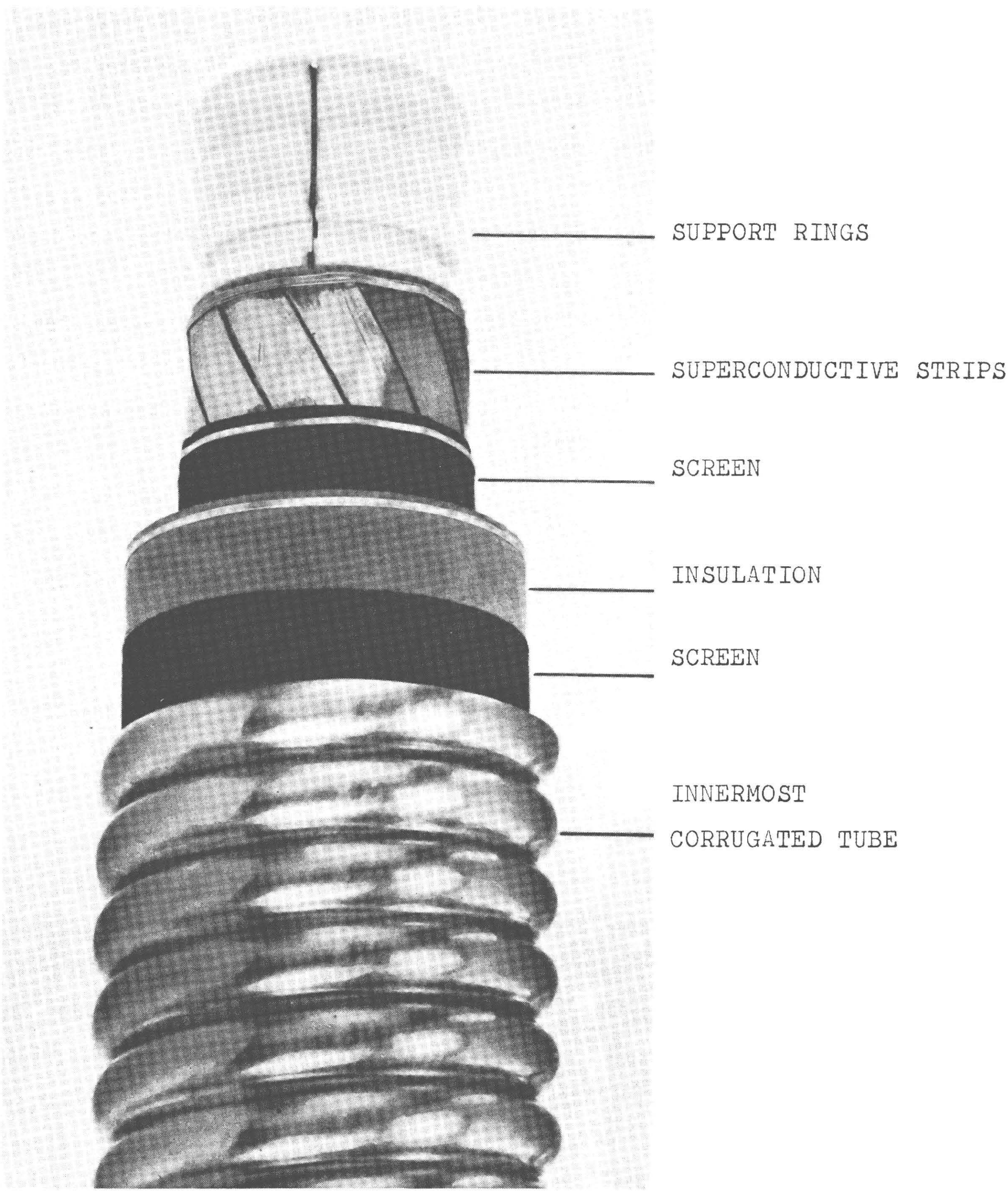


Figure 16.- Conductor of the superconducting d.c. cable designed by AEG for 200 kV and 12,5 kA - Nb_3Sn ribbon conductors and lapped paper tape dielectric. (from [8]).

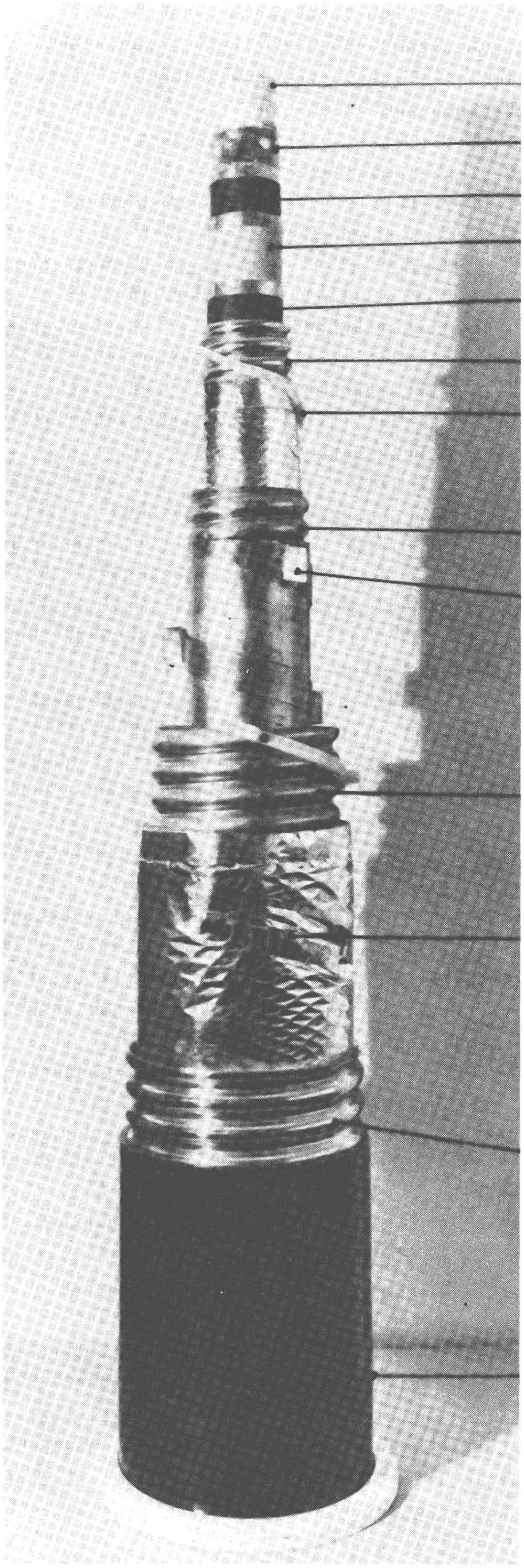


Figure 17.- Complete one-pole superconductor d.c. cable designed by AEG (from [8]).

10. REFRIGERATION AND HELIUM COOLING [8]

Helium conditions

Superconducting cables will be cooled by single phase helium above its critical pressure of 2,2 bars. The exact conditions of the helium will be determined by optimization of a particular cable design and the conductor material.

In an a.c. cable with niobium conductors the temperature will range from 4,4 K to 5,6 K and therefore the pressure will be 4-10 bars.

The flow rate will have to be adequate to carry away the heat losses and leaks without too high a temperature rise (maximum outlet helium temperature for a Nb cable 6 K). The velocity of helium is expected to be about 0,2 m/s. Transit time for a 10 km cable is about one day. The Reynolds number will be of the order of 10^5, the flow will be fully turbulent. Pressure drop is less than 0,5 bar.

Helium flow and heat transfer

Supercritical helium cannot be treated either as a liquid or as a gas and calculations cannot be handled in any classical way. The full treatment requires the integration of differential equations along the duct by making use of the equation of state. This can be done by means of a computer code but cannot be used practically for engineering and optimising calculation.

Experiments are needed to study helium flow in smooth tubes and in ducts of various configurations.

Permeation of helium through the dielectric which must be efficiently cooled needs to be studied carefully.

Accurate heat transfer calculation are impossible at the present time because the properties of helium do vary with temperature in the neighbourhood of the critical composition and because of the complex geometries.

Calculations are even more difficult in the case of transient conditions. Only experimental approach is likely to give useful results. However no work has been done to date.

Transient heat transfer need to be studied carefully not only for safety reasons but because it has to be taken into account for the ultimate selection of the superconductor.

Cable cooldown

The cable will probably have to be cooled down in at least two stages; first with nitrogen, then with helium. Because of the large volume of the cable, cooldown will be very slow. The rate of cooldown will be limited namely by the fact that, initially liquid nitrogen fed at one end of the cable will come out at the other end at nearly room temperature. The exit flow velocity cannot be greater than the speed of sound and therefore feed rate has to be kept low.

Cooldown time of a 10 km 2,5 GVA cable is expected to be at least 2-3 weeks; other estimates put this time up to 4-5 weeks.

Refrigerators

Large helium refrigerators (compressors and expanders) need to be improved in order to reach the reliability standards of electric utilities. Helium contamination with lubricating oil is also an important problem. Efficiency and economic considerations make it preferable to have large refrigeration stations with a cold power greater than 1 kW.

Refrigeration efficiency

The ratio between the available cooling power at temperature T and the amount of power required by the refrigeration unit at temperature T_o is given by

$$\frac{Q\,(T)}{W(T_o)} = \frac{T}{T_o - T} \cdot \eta$$

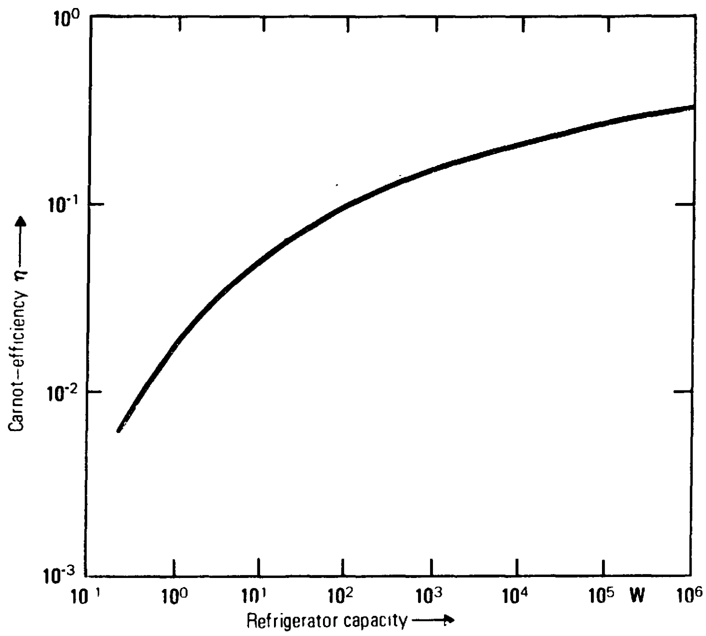


Figure 18.- Efficiency of low temperature refrigerators as a function of refrigeration capacity (from [5]).

η is the Carnot efficiency; it indicates the fraction of the ideal efficiency which is actually matched by the refrigeration unit.

The Carnot efficiency is a function of the size and the power of unit. It is shown in figure 18.

For the plant required to cool a 10 km cable, η will be close to 0,2. For helium cooled at 4,2 K, the ratio Q/W would be 1/350. The nitrogen refrigeration unit operating at 80 K, would have a ratio of 1/10.

Post fault operation

Refrigerators must have appreciable overload capacity depending upon the cable design. Fault energy dissipated in the helium may range from 6×10^3 J to $4,5 \times 10^5$ J/m^3 in a niobium cable. The higher value corresponds to a major fault dissipating heat in the backing metal. The temperature and pressure rise could be 1,3 K and 4 bars.

In Nb_3Sn a.c. cables, the steady state heat removal from the helium would be of the order of 0,3 to $1,5 \times 10^6$ J/m^3. Additional heat due to fault current could be of little significance in the optimistic hypothesis but,as was said before (§ 6), high transient current behaviour of Nb_3Sn is still unknown.

Helium circulation and storage

It is generally accepted that helium should be circulated in the cable not directly through the refrigerator but by means of a pump. Circulators for liquid helium are not considered satisfactory at the present time.

Considerable capacity is needed to store helium in case of cable failure. A 10 km cable may need up to 150-200 m^3 liquid, or 150.000 m^3 of gas at atmospheric pressure.

11. TERMINATIONS [8]

Cable terminations are very critical items. A few designs have been made but not completely tested.

The function of the termination is to

- establish electrical connection between superconductor at liquid helium and normal conductor at room temperature;
- ensure continuity of electrical insulation with due regard to temperature gradient and change in direction of the electric gradient.

In addition, the conductor must be cooled without to much heat losses in order to avoid any instability originating in the superconductor at the junction. If this cooling is ensured by boiling helium, the gas at high voltage has to be returned to the refrigerator at the earth potential with appropriate precautions.

For a continously cooled lead the heat load at 4,2 K is about 1 m W/A at no current and about 3 m W/A at full working current.

The total heat loss per terminal for a 2,5 GVA a.c. cable is roughly 150 kW (calculated with the refrigerating power).

12. RELIABILITY [8]

The allowable outage rate (equal to failure rate x repair time) is estimated by comparison with overhead lines or conventional cables. A desirable goal would be 0,3 hrs/km yr. For a repair time of 2.000 hrs the failure rate should be smaller than $1{,}5 \times 10^{-4}$/km yr.

The repair time of a conventional high power cable is usually 6 weeks. Warmup and cooldown of the superconducting cable take 2-3 weeks each. This brings the total estimated time to 10-12 weeks. Other estimates call for several months.

The number of vacuum joints for a three phase cable depends upon the envelope and cable designs but is in the range of 70 to 400 per kilometre and some of these may be longitudinal welds several km long. In order for the cryogenic envelope to comply with the above reliability requirement, individual welds and joints must have extremely low failure rates. Very special care has to be taken not only during shop fabrication, field assembly but also in the installation to avoid e.g. undesirable earth subsidence.

Since the majority of cable faults which occur to conventional cables in urban environment are caused by dig-in accidents, extra protection, ideally a special tunnel, is to be recommended.

The outage rate due to refrigerators should be less than 0,1 to 0,5 hrs/km yrs and the number of outages of any duration should be less than $5 \cdot 10^{-3}$/km yr. The heat capacity is sufficient to keep it at a low enough temperature to switch it back on the full load after a few hours. The fault current capability is then significantly reduced. With the present state of technology it may be considered that these reliability standards require duplication of the refrigeration plant.

13. REDUNDANCY [8]

Most high power transmission systems are designed for double contingency cover. With double contingency, if two circuits are inoperative between two nodal points of the system, the remaining parallel paths must carry a high proportion of the maximum power transferred between the two nodes. It seems very likely that double contingency will be required also when superconducting cables are used.

To connect e.g. a 6 GVA generating complex to the main transmission system, one would therefore require 3 x 6 GVA cables or 4 x 3 GVA cables if only superconducting cables are used. Alternatively there might be 2 x 3 GVA cables and a double circuit 400 kV overhead line. The cables and lines would have to follow different routes with no more than two circuits in close proximity [8].

14. SAFETY [8]

The degree of protection which may be needed for an a.c. cable will essentially be commanded by its fault current behaviour. It may be necessary to connect superconducting cable to the grid by means of transformers in order to limit the d.c. offset of major faults. It may also be necessary to protect the cable by special fast acting circuit breakers.

Continuous supply of electric power must be guaranteed to all critical components of the cable (vacuum pumps, N_2 refrigerators, He-refrigerators).

Safety valves must be provided along the cable to release pressure in case of local or general increase in temperature or pressure.

Cable operation will have to be monitored in order to detect any dangerous propagation of flux jumps.

Similarly any damage to the dielectric may have to be detected because an internal arc may cause the cable to explode.

15. RESEARCH NEEDS

Materials

Material selection will be influenced by their capability of carrying fault current. Operation conditions under fault current must be carefully investigated in particular with respect to heat transfer.

Should niobium be finally chosen, parameters affecting its a.c. losses should be carefully investigated to improve the quality of commercially produced conductors. Fault current capability should be studied in order to provide data for the design of conductors with optimum overload current ratings.

Studies on Nb-Zr alloys should continue because of the possible use of this material as back-up layer for niobium. Optimization of composition and metallurgical condition with regard to a.c. losses, flux jump instabilities would be useful.

Nb_3Sn appears to be an attractive candidate material. Adequate quality (a.c. losses) must be reproducible in commercial production. Fault current behaviour must be extensively studied. Because of intrinsic brittleness, adequate tape designs have to be produced to ensure the ruggedness required for safe handling and lapping.

Solutions available for d.c. current are not acceptable for a.c. because of eddy currents developing in the "normal" metal cladding.

Flux jump instabilities and rate of propagation of local normal regions must be very carefully studied in order to know if special detection and protection devices are necessary.

Power losses in joints between conductor segments should be measured accurately.

Conductor design

Significant improvement of the conductor design would result from a method of maintaining radial tightness on cooldown which would not rely on unequal conductor pitches.

Dielectric

A considerable amount of work is necessary to study the electrical strength, dielectric loss and mechanical properties of lapped tapes.

The radial and longitudinal electrical strength should be studied with the following factors: tape material and properties (porosity and fabrication method), lapping parameters, impregnant conditions (He temperature and pressure). Influence of discharges should be looked at carefully.

The dielectric losses should be studied to identify the most promising materials, effect of electric stress, helium purity, temperature and pressure.

Mechanical and thermal properties of the promising materials should be studied in the details to check

- their ability to sustain winding and unwinding without damage during cable fabrication;
- their long-time stability at low temperature under mechanical stress, including thermal cycling effect.

Larger scale experiments carried out on the best materials should then determine accurate design values (total dielectric loss, breakdown strength, etc.). Effect of temperature and pressure rise under fault current conditions should also be determined.

Cable core

When data on materials performance are well established, cable core segments will have to be fabricated and their capabilities fully tested (handling suitability, fault current behaviour, dielectric behaviour, cooldown, skid wire performance, etc.).

Hydraulic characteristics of cable core will have to be studied and optimised.

Straight Joints

Methods of jointing conductors and reconstructing the dielectric around each individual joint have to be developed and proved. Electric losses and thermal losses have to be measured.

Helium stop-joint

Joints design have to be optimized and tested.

Cryogenic envelope

A large amount of engineering and development work is still necessary to optimize envelope design and to ensure high reliability of the helium tubes and vacuum containment.

Work related to reliability and safety will have to include instrumention for monitoring and detection. Bursting disc venting arrangements will have to be designed.

Refrigeration and helium

General hydrodynamics of supercritical helium is to be studied experimentally to produce data needed for the design and optimization of cooling channels in the cable, heat exchangers, etc.

Heat transfer studies are even more important as the present state of knowledge is considered as totally inadequate. In particular, transient heat transfer during fault current surge must be studied on the basis of experimental data.
Refrigerators and circulators have to be improved. They require development work and testing.

Terminations

Essentially development work and testing.

CONCLUSIONS

In the next 25 years there will be a growing demand for high power cables. Their major forseeable use will be to feed electric power to the centre of large towns. Power carrying capacities much larger than about 2000 MVA do not appear to be necessary according to the growth predictions which can be made now.
Power carrying capacities much in excess of this figure may be required locally. A link of 2600 MVA e.g. already exists in the United Kingdom. Such applications will require advanced solutions but no large market can be predicted for them.

Classical cables have been improved to power levels much higher than 1000 MVA. With external forced cooling they can reach 2000 MVA or more at 400 kV. Development of internal forced cooling is in progress and power ratings much higher than 2000 MVA are predicted to be feasible and economical.

Considerable progress has been made in Europe, particularly in Germany, in the field of superconducting cables. However important questions concerning the behaviour for a.c. power transmission have not yet received satisfactory answers. It is estimated that research and development work over ten to fifteen years is still necessary before these cables are commercially available.

Superconducting d.c. cables offer much less difficult problems to solve at least from the electrical point of view. They should have very low losses. This advantage is however overshadowed by the costs and power losses of conversion equipment at both ends. They could find special applications but no large market can be anticipated on the basis of the information available now.

Superconducting a.c. cables do not show any clear economic advantage over its contenders, up to very high power levels. Internally cooled cables based on simple technology might become even more economical when they are further developed and could be in a better position based on longer experience and proved reliability.

There is at present no economic justification to press for large scale development programmes of superconducting cables. It is however wise to keep in Europe a rather basic research effort of an adequate level, concentrated on some of the major problems (dielectric, losses in superconductors, fault current behaviour, etc.). In case the forced oil - and water - cooled (internally) cables do not hold their promise, the development of superconducting cables would be a necessity. Several European firms and organizations have now a leading position in superconducting cable technology. Collaboration among them on basic research should be encouraged in order to share the cost of it and ensure efficient progress.

High power cables with external forced cooling are able to solve all problems of the immediate future.Industry should carry on improving their performances steadily.

High performance cables with internal cooling by oil or water deserve immediate attention too. They are still not favoured by all manufacturers because of some additional complexity due to the internal coolant flow. Actual operation of such prototype cables will soon make it possible to evaluate their merits. From the present state of technology, developments could be expected to be rather fast and lead soon to commercial applications in Europe and elsewhere.
Here also European industry may soon have a world leading position which is worth encouraging.

REFERENCES

[1] - Comparison of Advanced High Power Underground Cables.
J. Erb, W. Heinz, I. Heller, A. Hofmann, H.J. Köfler,
P. Komarek, W. Maurer, A. Nahar.
Institut für Experimentelle Kernphysik of the Kernforschungszentrum and the University of Karlsruhe (1974)
EEC Contract N° 80-73-12 ECID

[2] - Extra High Voltage Cables for High Power Transmission.
Industrie Pirelli, Spa, Milano (1974)
EEC Contract N°081-73-12 ECI

[3] - Advanced Types of High Power Underground Cables.
E.C. Rogers
British Insulated Callender's Cables Limited (1974)
EEC Contract N° 074-73-12 ECI UK

[4] - Technical and Economical Aspects for the Application of
New Typs of Advanced High Power Cables
H. Becker, K. Werner
AEG-Telefunken (1974)
EEC Contract N° 079-73-12 ECI D

[5] - Transmission of electrical energy by superconducting cables.
G. Bogner
Superconducting Machines and devices
Plenum Publ. Corp. 1974

[6] - Technologie et perspectives techniques et économiques des
nouveaux types de câbles souterrains à l'étude en France.
Laboratoires de Marcoussis. Centre de Recherches de la
Compagnie Générale d'Electricité. (1974)
EEC Contract N° 075-73-12 ECI F

[7] - Study on the Future Need for Large Generating Units and
High-power Underground Cables in the European Community
(1980 - 2000)
Ente Nazionale per l'Energia Elettrica - Rome (1974)
EEC Contract N° 082-73-12 ECI I

[8] - Research Needs for Superconducting Cables.
J.A. Baylis, D.J. Brassington, D.N.H. Cairns, J. Sutton,
B.J. Maddock, D.A. Swift.
Central Electricity Research Laboratories (CEGB) - (1974).
EEC Contract N° 072-73-12 ECI UK

[9] - Kabel oder Freileitung. Stellungnahme der Eidg. Kommission für elektrische Anlagen.
Bulletin des Verbands Schweizerischer Elektrizitätswerke 61 (1970) 15. p 197 - 209

[10] - CEGB Statistical Yearbook 1973-1974.

[11] - Les possibilités des lignes aériennes pour le transport de l'énergie électrique.
J. Claude et Y. Porcheron.
Congrès de la Société Française des Electriciens - 1971.

[12] - Gestaltung künftiger Erzeugungs- und Übertragungsanlagen für elektrische Energie in der Bundesrepublik Deutschland bis 1985.
A. Hofman, B. Lezenik, G. Lottes.
Elektrizitätswirtschaft - Vol. 71, 1972, N° 25, p 727-737.

[13] - Transport d'énergie électrique par câbles à isolation gazeuse.
L. Deschamps, A.M. Schwab, Y. Jegon.
E.D.F. Bulletin de la Direction des Etudes et Recherches - Série B - 1973 - p 93-130.

[14] - Transport d'énergie électrique par cryocâbles.
L. Deschamps, A.M. Schwab, Y. Jégon.
E.D.F. Bulletin de la Direction des Etudes et Recherches.
Série B - 1973, N° 1, p 49-97.

[15] - Grenzleistungen von Höchstspannungskabeln mit innerer Wasserkühlung.- W. Rasquin
ETZ-A.- Vol. 95, N° 2, 1974, p 65-68

[16] - High-Power Cables with Internal or External Water Cooling.
H. Birnbreier, W. Fischer, W. Rasquin, G. Grosse, Plankermann, W.D. Schuppe.
Internation. Conference on Large High Voltage Electric Systems (CIGRE) 1974.

[17] - Câbles Isolés.
Techniques de l'Ingénieur - 1974.

[18] - Hochleistungskabel mit Ölpapier-Isolierungen für 765 kV und 1100 kV.
W. Rasquin
Elektrizitätswirtschaft - Vol 73, N° 26, 1974, p 780-785.

[19] - Power Transmission Project.- Cable Design.-
E.B. Forsyth.
Brookhaven National Laboratory - 1974.

[20] - Superconducting cables for a.c. and d.c. power transmission.
J.A. Baylis
Phil. Trans. R. Soc. Lond. A.- Vol 275, 1973, p 205-224.

[21] - Energieübertragung mit Kryokabeln.-
H. Birnbreier, K. Düring, W. Fischer, I. Heller, A. Hofmann, P. Komarek, E. Kuhn, H.W. Lücking, W. Rasquin, E. Zimmermann.
Jül - 938-TP.- 1973

[22] - Underground Power Transmission.-
A.D. Little Study., Inc. - 1971

[23] - The Place of Cryogenic Systems in more economical underground power transmission.
James Nicol (A.D. Little, Inc.)
Applied Superconductivity Conference - 1972.

BUREAUX DE VENTE

Les documents publiés par la Commission des Communautés européennes sont vendus par l'Office des publications officielles aux adresses et au prix indiqués ci-après. Lors de la commande, bien indiquer la référence exacte et le titre du document.

FRANCE

Service de vente en France des publications des Communautés européennes — Journal officiel
26, rue Desaix — 75 732 Paris - Cédex 15e
Tél. (1) 306 51 00 — CCP Paris 23-96

ALLEMAGNE (RF)

Verlag Bundesanzeiger
5 Köln 1 — Postfach 108 006
Tél. (0221) 21 03 48
Télex : Anzeiger Bonn 08 882 595
Postcheckkonto 834 00 Köln

BELGIQUE — BELGIË

Moniteur belge — Belgisch Staatsblad
Rue de Louvain 40-42 — Leuvenseweg 40-42
1000 Bruxelles — 1000 Brussel — Tél. 12 00 26
CCP 50-80 — Postgiro 50-80

Sous-dépôt :
Librairie européenne — Europese Boekhandel
Rue de la Loi 244 — Wetstraat 244
1040 Bruxelles — 1040 Brussel

DANEMARK

J.H. Schultz — Boghandel
Møntergade 19
DK 1116 København K — Tél. 14 11 95

GRAND-DUCHÉ DE LUXEMBOURG

Office des publications officielles des Communautés européennes
Case postale 1003 — Luxembourg
Tél. 4 79 41 — CCP 191-90
Compte courant bancaire : BIL 8-109/6003/200

IRLANDE

Stationery Office — The Controller
Beggar's Bush
Dublin 4 — Tél. 6 54 01

ITALIE

Libreria dello Stato
Piazza G. Verdi 10
00198 Roma — Tél. (6) 85 08
CCP 1/2640

PAYS-BAS

Staatsdrukkerij- en uitgeverijbedrijf
Christoffel Plantijnstraat
's-Gravenhage — Tél. (070) 81 45 11
Postgiro 42 53 00

ROYAUME-UNI

H.M. Stationery Office
P.O. Box 569
London S.E. 1 — Tél. 01-928 69 77, ext. 365

ÉTATS-UNIS D'AMÉRIQUE

European Community Information Service
2100 M Street, N.W.
Suite 707
Washington, D.C., 20 037 — Tél. 296 51 31

SUISSE

Librairie Payot
6, rue Grenus
1211 Genève — Tél. 31 89 50
CCP 12-236 Genève

SUÈDE

Librairie C.E. Fritze
2, Fredsgatan
Stockholm 16
Post Giro 193, Bank Giro 73/4015

ESPAGNE

Libreria Mundi-Prensa
Castello 37
Madrid 1 — Tél. 275 51 31

AUTRES PAYS

Office des publications officielles des Communautés européennes
Case postale 1003 — Luxembourg
Tél. 4 79 41 — CCP 191-90
Compte courant bancaire : BIL 8-109/6003/200

Prix : FB 50,—

OFFICE DES PUBLICATIONS OFFICIELLES DES COMMUNAUTÉS EUROPÉENNES
Case postale 1003 — Luxembourg 5983