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COMPARISON OF ADVANCED HIGH POWER UNDERGROUND CABLE DESIGNS*)

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Abstract:

In this paper, advanced high power underground cable designs are compared in the light of the available literature, of reports and information supplied by participating industries (AEG, BICC, CGE, Pirelli, Siemens), spontaneous contributions by EdF, France, BBC and Felten & Guilleaume Kabelwerke A.G., Germany, and Hitachi, Furukawa, Fujikura and Sumitomo, Japan, and earlier studies carried out at German public research centres. The study covers cables with forced cooling by oil or water, SF_6-cables, polyethylene cables, cyroresistive and superconducting cables.

Vergleich von fortgeschrittenen Hochleistungskabelkonzeptionen.

Zusammenfassung:

In dieser Studie werden fortgeschrittene Hochleistungskabelkonzeptionen anhand der verfügbaren Literatur, von Berichten und Informationen verglichen, die von den beteiligten Industriefirmen (AEG, BICC, CGE, Pirelli, Siemens) geliefert wurden. Freiwillige Beträge wurden von der EdF, Frankreich, BBC und Felten & Guilleaume Kabelwerke A.G., Deutschland, und Hitachi, Furukawa, Fujikura und Sumitomo, Japan, geliefert. Die Ergebnisse früherer Studien, die von deutschen Forschungszentren angefertigt wurden, werden benutzt. In dieser Studie werden mit Öl und Wasser zwangsgekühlte Kabel, SF_6-Kabel, Polyäthylen Kabel, kryoresistive Kabel und supraleitende Kabel verglichen.

Contents

1. Introduction

The problem of a future underground power transmission has been treated many times. Different conventional and cryogenic cable concepts have been considered in the literature. Many preliminary papers were unable to offer a sufficient background of experimental results because of the small amount of research activities performed at that time. Fortunately, in the past few years the development of advanced conventional cables has been advanced by a remarkable degree and also research on cryogenic cables has progressed. This has made it more and more worthwhile to work on extended surveys of the technical and economic aspects of various cable systems assumed to lend themselves to future power transmission demand. Such a survey is the Arthur D. Little study carried out in the U.S. in 1972. This paper together with the other parts sponsored by the Commission of the European Communities is another study of this type specially emphasizing prospects in Europe.

In this paper, advanced high power underground cable designs are compared in the light of the available literature, of reports and information supplied by participating industries (AEG, BICC, CGE, Pirelli, Siemens), spontaneous contributions by EdF, France, BBC and Felten & Guilleaume Kabelwerke A.G. , Germany, and Hitachi, Furukawa, Fujikura and Sumitomo, Japan, and earlier studies carried out at German public research centres. The study covers cables with forced cooling by oil or water, SF_6-cables, polyethylene cables, cryoresistive and superconducting cables.

Emphasis is put on the present state of the art, possible prospects of development and probable performance and technical characteristics including reliability and availability. An extremely difficult job was the comparison of costs and an estimate of the time by which these cables could be made available commercially. The data published elsewhere are based on different monetary units, different estimates of the development risks and include large uncertainties in terms of the costs of civil engineering etc.. Nevertheless, a common basis has been found.

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eingereicht am 8.8.75

2. Conventional power cables

Within the frame work of this study power cables with paper insulation and natural cooling are called "conventional". Since high power cables are our subject, only voltages of at least 100 kV are considered, though sometimes reference is made to lower voltages.

This section will introduce the principal ideas and problems of cable design and describe the state of the art against which the more advanced concepts outlined in the following sections have to be measured.

2.1 Design principles

The characteristic design element of conventional power cables is the paper insulation of the conductor, the paper being impregnated with a special oil or other synthetic materials. The conductor itself consists of stranded aluminium or copper; the insulation is covered with a screen of metallized paper or carbon paper forcing the electric field lines to coincide with the direction of maximum electric strength, which is perpendicular to the paper tapes of the insulation [2.6,10,13].

Unlike low power and medium power calbes, high power cables require thermal stabilization of the insulation. This is due to the fact that the load carried by the cable in each longitudinal element of the cable is partly converted into thermal energy heating the insulation. Since the load is not constant in time but changes according to the requirements of the consumers [2.16], also the temperature of the cable changes. Due to thermal expansion and contraction, small voids can arise within the insulation, because the conductor, the paper and the impregnation material each have a different thermal expansion coefficient. At moderate field strengths of about 4 kV/mm, as in the case of low power cables, this would not be dangerous, but in high power cables with field strengths ranging between 9 kV/mm (for 110 kV cables) and 13 kV/mm (for 380 kV cables) such voids could give rise to ionization effects causing the insulation to break down. In view of economics and handling of the cable it is not possible to increase the insulation thickness in order to achieve lower field strengths. Therefore, provision must be made to prevent the electric properties of the insulation from changing. This means that voids must be prevented either from being generated or from having a deteriorating influence.

Thermal stabilization is possible in many ways each approach corresponding to a specific type of power cable. These are the most important methods:

a) low pressure oil cable,
b) high pressure oil cable,
c) externally gas pressurized cable,
d) internally gas pressurized cable.

They will now be described in brief.

2.1.1 Low pressure oil cables

Low pressure oil cables were first used in underground high power transmission. They were invented in the twenties [2.10]. The impregnating material of the paper insulation is mineral oil of low viscosity. It is kept under a pressure of at least 1 - 2 bar at the highest point of each section into which the cable is subdivided. Channels parallel to the conductor - often a central hollow duct - allow the oil to flow into reservoirs at the ends of the sections when the temperature rises; it is forced back by air filled devices when temperature decreases. In this way, the generation of voids by thermal effects is suppressed.

Normally the cable has only one conductor, which is surrounded by a screen of carbon paper, a sheath of lead or aluminum, reinforced if necessary, and an oversheath of plastic material for corrosion protection (see Fig. 2.1). Thus the cross section is not too large and the cable can be drummed to facilitate transport and laying. For a three phase line, three cables are

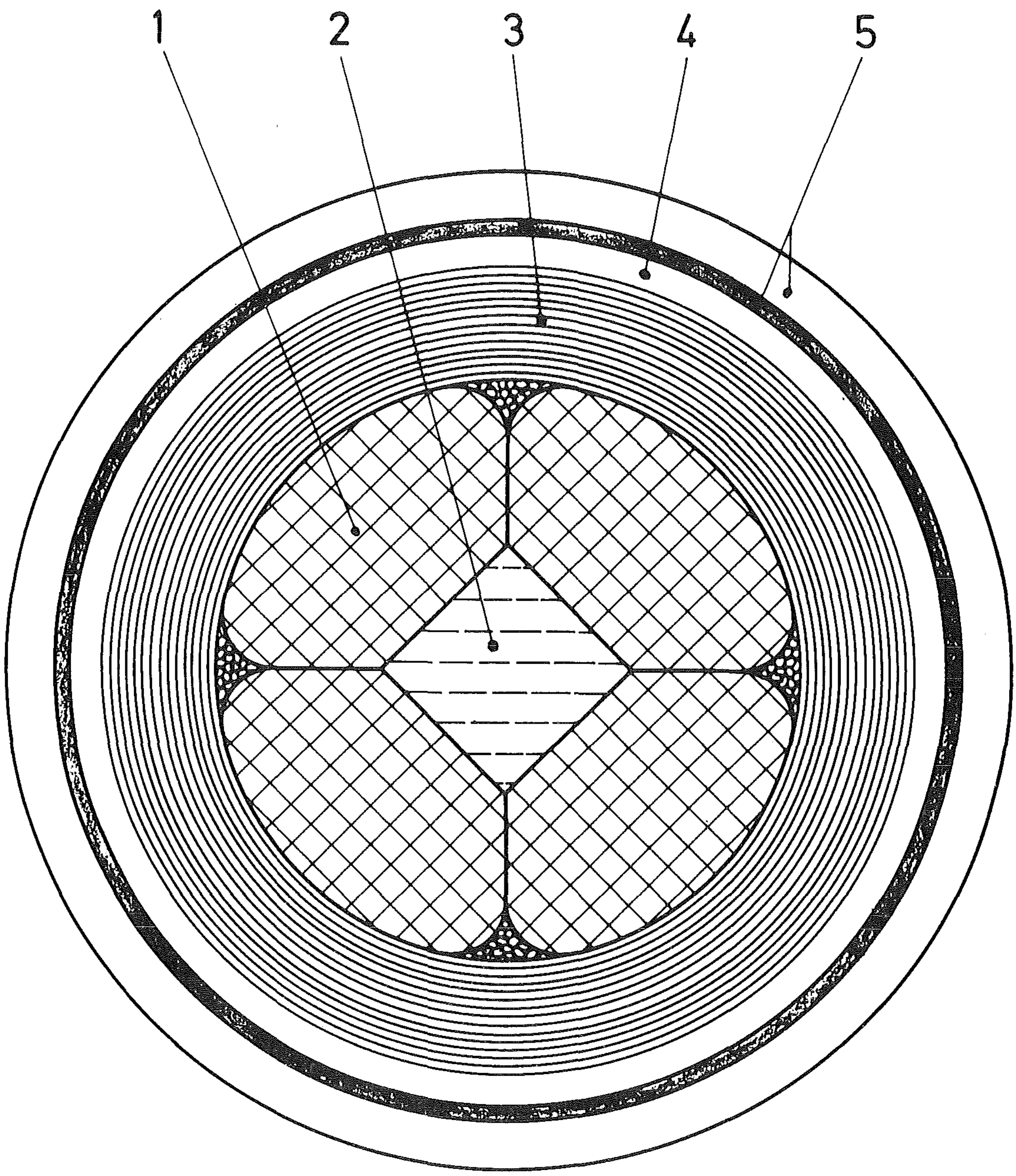

Fig. 2.1: Cross section of a low pressure oil cable [2.3]

1 - segmental conductor

2 - central oil channel

3 - paper insulation

4 - lead sheath

5 - oversheath

layed parallel in the same trench [2.3].

The voltage in conventional single conductor cables ranges up to 400 kV; the maximum load transmitted in a three phase current line with natural cooling is about 600 MVA.

2.1.2 High pressure oil cables

The high pressure oil cable or "oilostatic" cable was developed in the forties and has achieved a dominating position in the USA [2.10]. It is always a three phase current cable. Each of the three conductors is surrounded by a paper tape insulation impregnated with special oil and a screen of carbon paper or metallized foil. The strands are armored with metal tapes to give protection during the transport and laying processes [2.4,5]. They are pulled together into a steel pipe which is finally filled with oil of low viscosity (see Fig. 2.2). As in the case of single conductor cables, the oil can flow to expansion reservoirs when the temperature rises, but pumps pressurize it to 15 - 17 bar. It acts on the insulation, since the screen is elastic and also permeable. Because the "external" oil has similar physical and chemical properties as the impregnating oil, it is guaranteed that no voids can be formed by thermal effects.

The electric properties of the oilostatic cables are as good as those of low pressure oil cables, even better in some respects; applicable voltages and transmissible loads are roughly identical.

The steel pipe may be an advantage of the oilostatic cable, because it gives better protection against external forces and allows only short sections of the cable trench to be dug at a time, which can be of importance in cities. Furthermore, there is no need to have the complete cable ready when the trench is open, which makes planning easier. On the other hand, the steel pipe is costly in fabricating and in laying, and in the case of leakage the danger of polluting the ground water is high because of the relatively large amount of oil in the

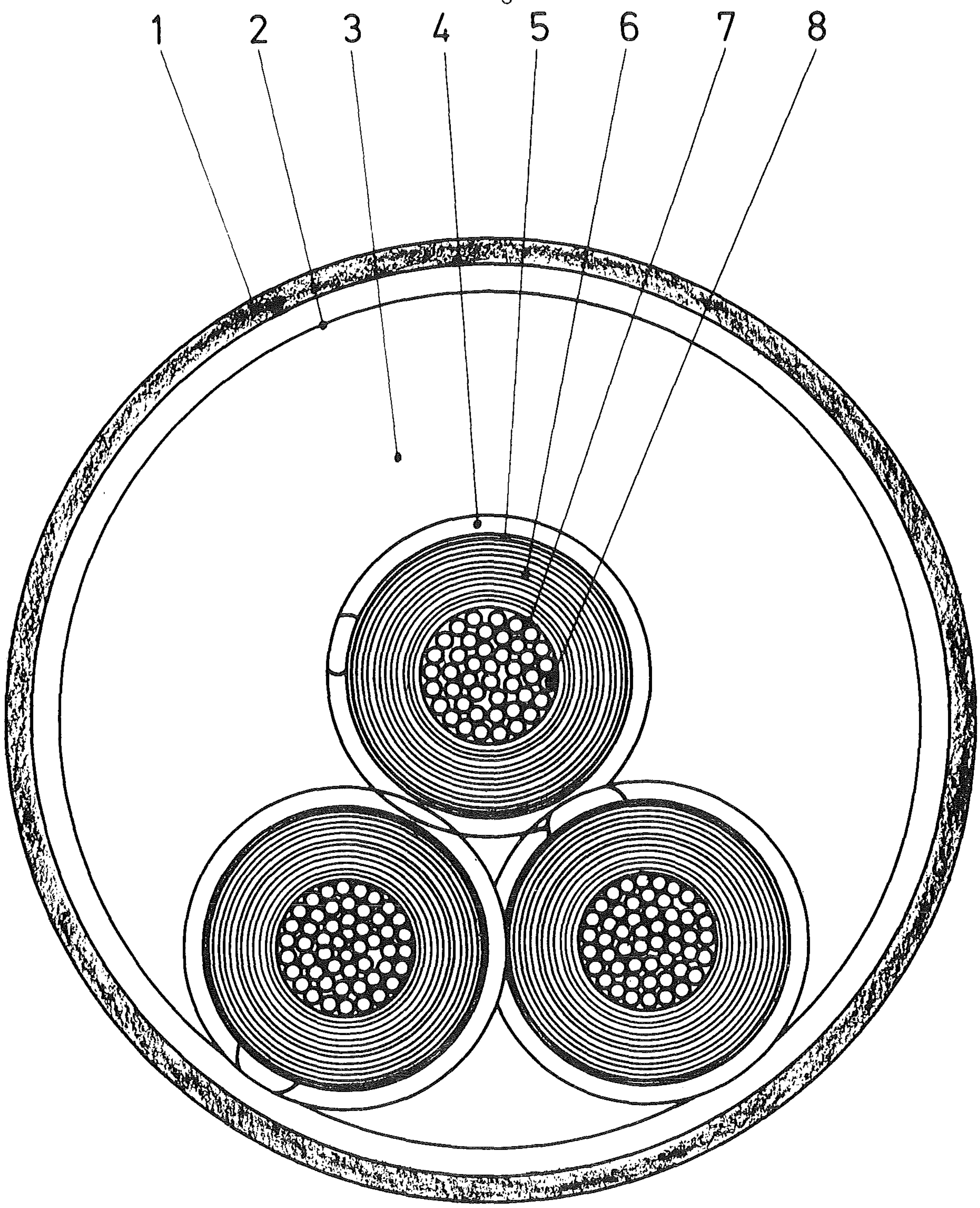

Fig. 2.2: Cross section of a high pressure oil cable [2.4]

1 - oversheath

2 - steel pipe

3 - oil

4 - copper helix

5 - carbon paper and copper foil

6 - paper insulation

7 - carbon paper

8 - conductor strands

pipe and the reservoirs [2.13].

2.1.3 Externally gas pressurized cables

Externally gas pressurized cables have been developed from 60 kV mass cables [2.9,10]. The principal structure is similar to the high pressure oil cable: three phases in a common steel pipe, but the insulation of each conductor is mantled with lead, the oil replaced by compressed gas (see Fig. 2.3). The gas pressure of about 15 bar acts on the lead sheath, which has not a circular but a nearly elliptic or triangular cross section for easier deformation. The lead is pressed onto the insulation, thus preventing it from mass migration and void formation. The voltages at which those cables are operated range between 60 kV and 150 kV, the 110 kV level being preferred.

2.1.4 Internally gas pressurized cables

Internally gas pressurized cables are even more closely related to oilostatic cables: the only difference is the substitution of the high pressure oil by compressed nitrogen. Since there is no lead sheath around the insulation, the gas can invade the insulation and fill the voids eventually formed. The breakdown field strength of compressed gas grows in proportion to the pressure, according to Paschens law. At the field strengths given ionization is no longer possible at pressures of about 15 bar [2.8,10].

Cables of this type have been built for voltages up to 110 kV. If the nitrogen is partly replaced by SF_6-gas, voltages of 220 kV are possible.

Especially for cable lines which have to overcome large differences in altitude, gas-filled cables are advantageous because hydrostatic pressure plays no role in these designs. In case of leakage, pollution of the environment is impossible, which is another advantage. On the other hand, voltages and hence load are not as high as they can be in oil-filled cables (see Fig. 2.4).

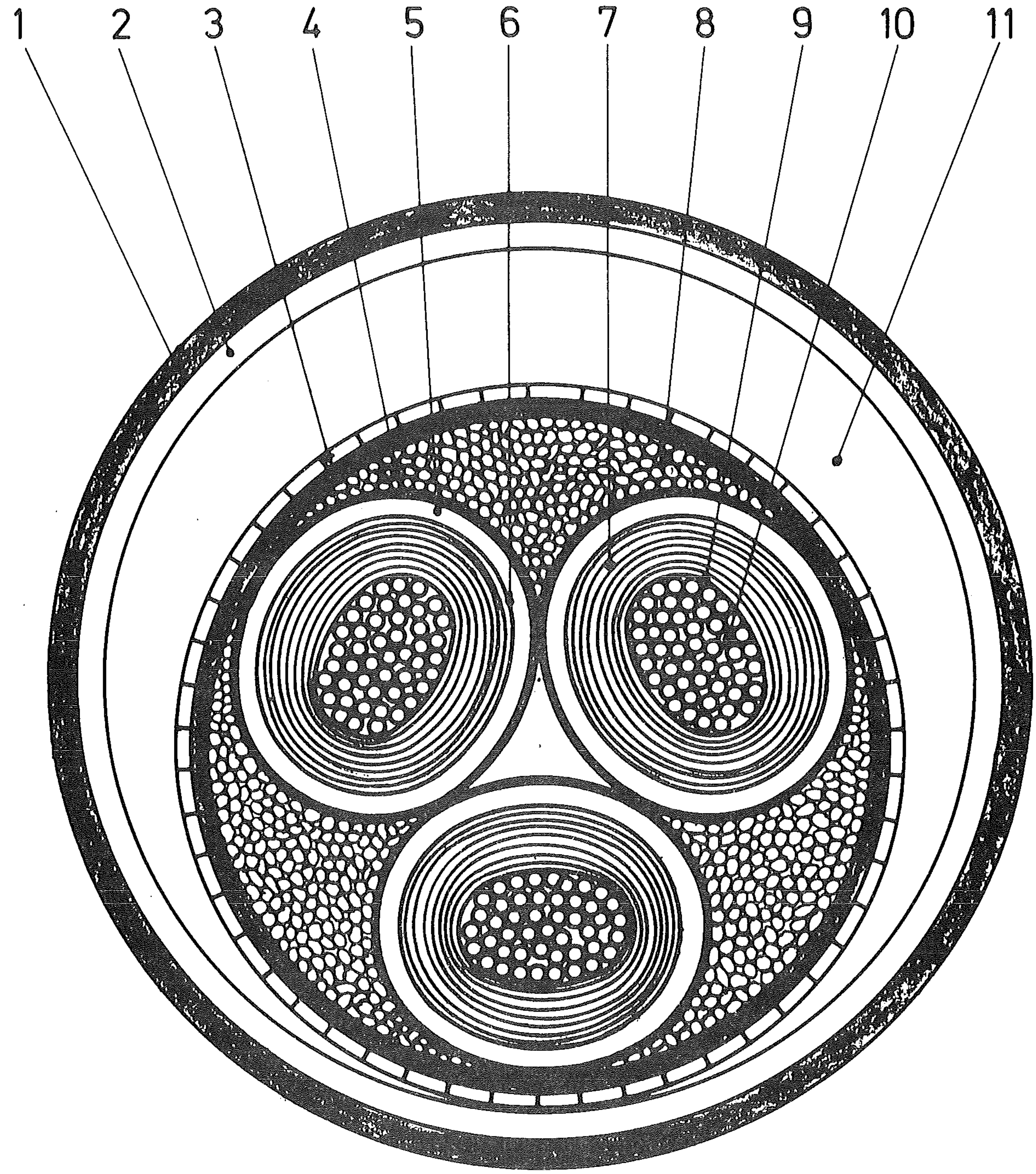

Fig. 2.3 Cross section of an externally gas pressurized cable [2.4]

1 - oversheath

2 - steel pipe

3 - steel tape armour

4 - copper 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

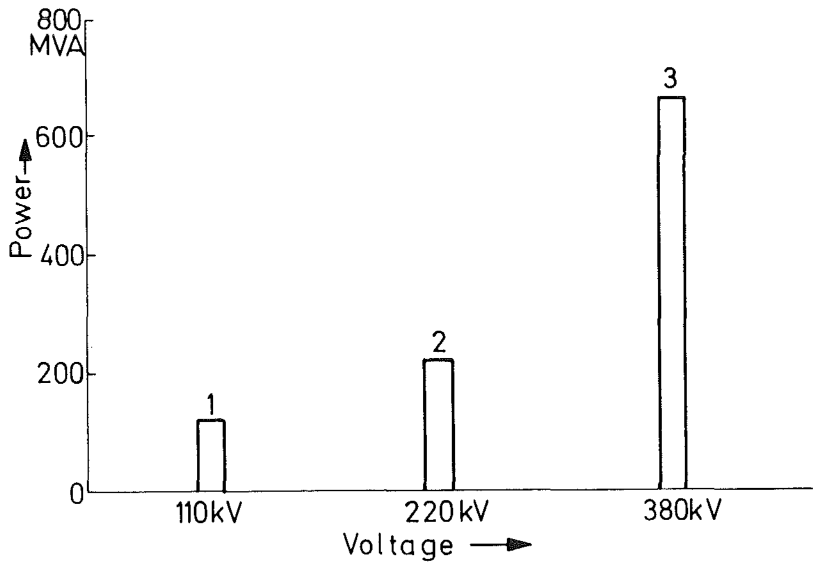

Fig. 2.4 Limits of transmission capacity of conventional power cables [2.2]

1 - internally gas pressurized cables

2 - externally gas pressurized cables

3 - oil-filled cables

2.2 Power limitations

The load which can be carried by conventional power cables is limited by internal and external parameters. One important internal parameter is the loss per unit length of the cable line, other internal parameters are the temperatures permissible within the different components and their thermal conductivity. External parameters are, e.g., the thermal resistivity of the surrounding soil and the length of the cable line.

2.2.1 Losses

Losses are caused either by current or by voltage. The current can induce losses in the conducting material within the cable, whilst the voltage induces losses in the dielectric.

2.2.1.1 Current induced losses

Besides the normal ohmic loss in the conductors there are additional losses in the case of ac cables which are due to the eddy currents induced by the alternating magnetic field associated with the current. In the conductor itself the eddy currents give rise to the well known skin effect which lowers the useful conductor area, thus raising the resistivity. If there are other conductors nearby, the eddy currents induce losses in those as well. This phenomenon is called proximity effect. Both effects grow in proportion to the conductor area [2.2].
In order to reduce the skin effect, the conductor is made hollow or even segmented. Fig. 2.5 shows to what extent this decreases the skin effect.

Eddy currents also induce losses in the screens and sheaths of the conductors. In a three phase single conductor cable system the longitudinal component of the currents induced plays the main role. Fig. 2.6 shows the relative magnitudes of the different effects in this case. Obviously, sheath losses must be taken care of. They can be reduced by the methods of bonding, e.g., single point bonding or cross bonding, the effect of which is shown in Fig. 2.7.

In pipe-type cables, losses occuring in conductors, screens and sheaths are higher than in comparable self-contained cables, due to the proximity of the three conductors. Within the steel pipe there are also losses because of eddy currents and, additionally, magnetic hysteresis, which do not exist in the other case. These are some of the reasons why, e.g., oilostatic cables have a lower ampacity than low pressure oil cable lines of the same conductor area.

2.2.1.2 Voltage induced losses

The alternating electric field penetrating the insulation of the conductors alters the polarization of the dielectric, giving rise to thermal losses in that material. The loss L per unit

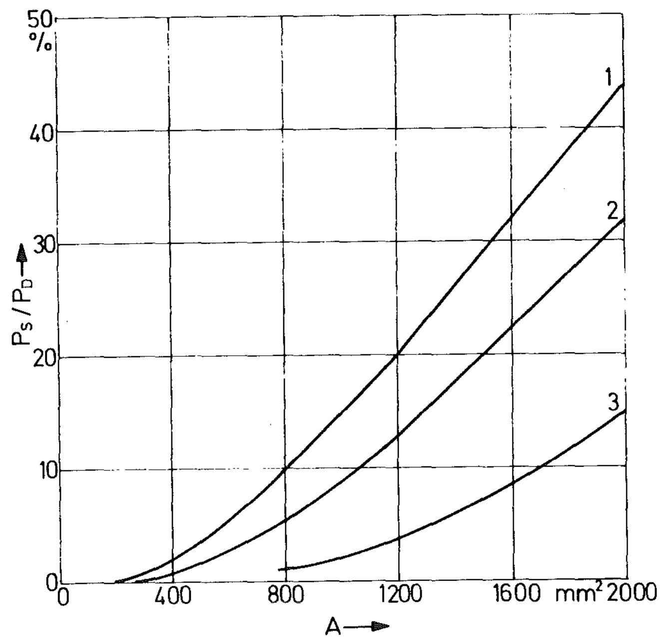

Fig. 2.5: Relative Size P_S/P_D of Skin Effect Losses P_S to DC-Losses P_D as a Function of Conductor Area A [2.2]. Conductor Temperature 85° C.

1. Round Conductor
2. Hollow Conductor
3. Segmental Conductor

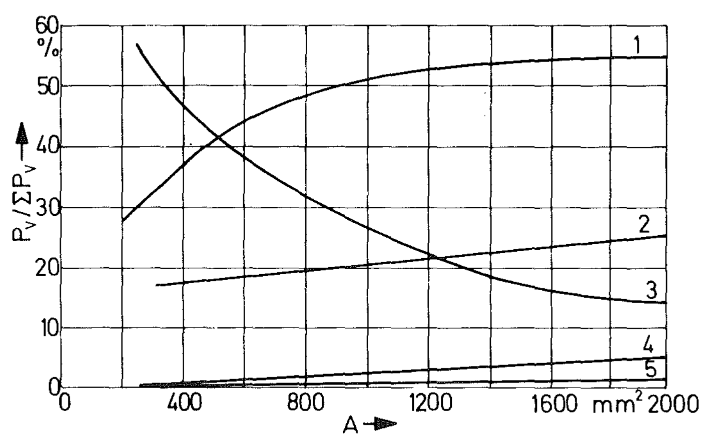

Fig. 2.6: Relative Losses $P_V/\Sigma P_V$ for a 380 kV Cable Line as a Function of Conductor Area A [2.2]. Conductor Temperature 85° C

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

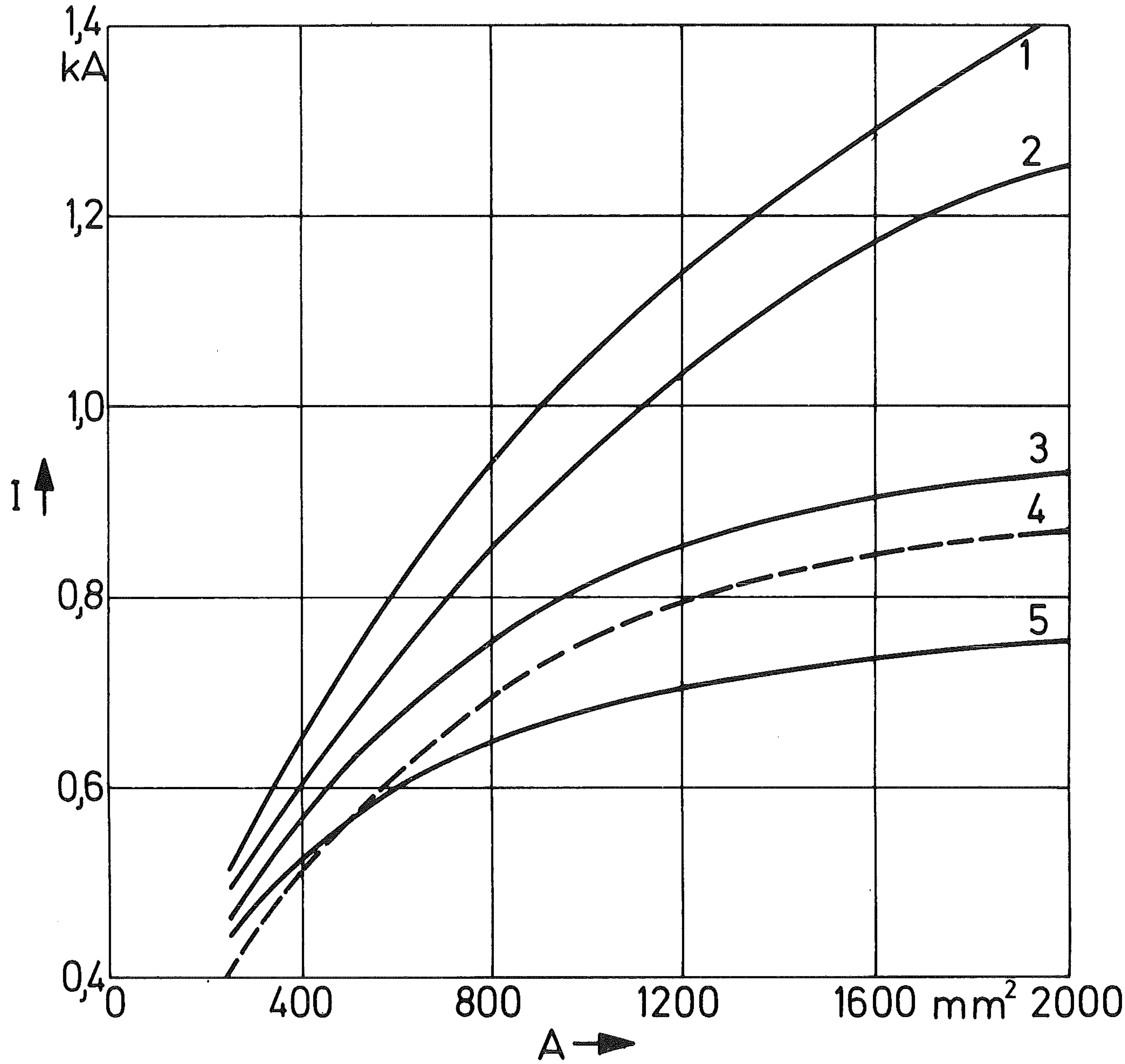

Fig. 2.7: Ampacity I of a 380 kV single conductor cable line as a function of conductor area A. [2.2]. Conductor temperature 85° C in all cases except 4.

1 - flat installation, sheaths cross-bonded

2 - trefoil installation, sheaths cross-bonded

3 - trefoil installation, sheaths bonded at both ends

4 - same as 1, but conductor temperature 40° C

5 - flat installation, sheaths bonded at both ends

length is given by the formula [2.11]

$$L = 2 \pi f C U^2 \tan\delta.$$

Here, f denotes the frequency, C the capacitance per unit length, U the voltage, whilst tan δ is a material factor in the range of 0.0015 - 0.0025 for oil paper. To reduce L, one must reduce C or tanδ. The capacitance could be reduced by enlarging the cable radius, which is impractical; the material factor cannot be reduced below 0.001 for paper insulation. Since the losses grow with the square of the voltage, they impose a feasibility limit upon the voltage to be applied in the range of 400 - 750 kV. In section 3 this particular point will be discussed in more detail.

The relatively high capacitance of a cable compared to an overhead line has another limiting effect: the capacitance must be charged by a current which is out of phase with the voltage, thus producing no net power drain [2.12,23]. On the other hand, this charging current produces losses. Since it increases with the length of the cable, there is a critical length at which all of the thermal rated capacity of the cable is needed to dissipate the heat caused by the charging current. Depending on the design and the voltage - the higher the voltage, the shorter the critical length -, conventional power cables have a critical length between 20 and 100 km [2.21].

2.2.2 Dissipation

It is the dissipation of the losses which imposes a limit on the ampacity of a cable, rather than the losses themselves. The ampacity is determined by the permissible loss per unit length, which depends on the capability of the cable to dissipate the heat caused by the losses to the environment.

Dissipation is the more effective, the higher the temperature of the conductor. Since the insulation cannot stand temperatures above 85° C, it fixes the maximum permissible conductor temperature to that value [2.1]. In cables buried the normal way, however, it is the surface temperature which plays the main role, for the following reason: temperatures above 40^{o} C the soil dries out, its thermal resistivity rising from a value of about 100^{o} C cm/W to 300^{o} C cm/W and more (Fig.2.8). If the cable were run at ground temperatures higher than 40^{o} C, the losses dissipated to the outside and hence the ampacity would consequently be reduced more and more. Therefore,in long term operation, the surface temperature of the cable must not exceed 40^{o} C by a large margin. This corresponds to a conductor temperature below 85^{o} C, reducing the ampacity, as Fig. 2.7 shows, to less than half its maximum value, which therefore can be used only for relatively short time intervals.

Average thermal resistivity and temperatures of the ground vary from one country to another (Table 2.1) and also over the year, but this only slightly modifies the facts mentioned above.

Tab. 2.1: Different geographical conditions for rating paper cables

Country	Soil Properties	
	Temp.	Therm.Res.
	^{o}C	^{o}C m/W
U. K.	15	1.2
Austria	20	0.7
France	20	0.85
Germany	20	1.0
Italy	20	1.0
Japan	25	1.0
Poland	15	0.8
Scandinavia	15	1.0
Switzerland	25	1.5
U.S.A.	20	0.9
U.S.S.R.	15	0.9

Since it is important to maintain the thermal conductivity of the soil during cable operation, sometimes a water pipe is in-

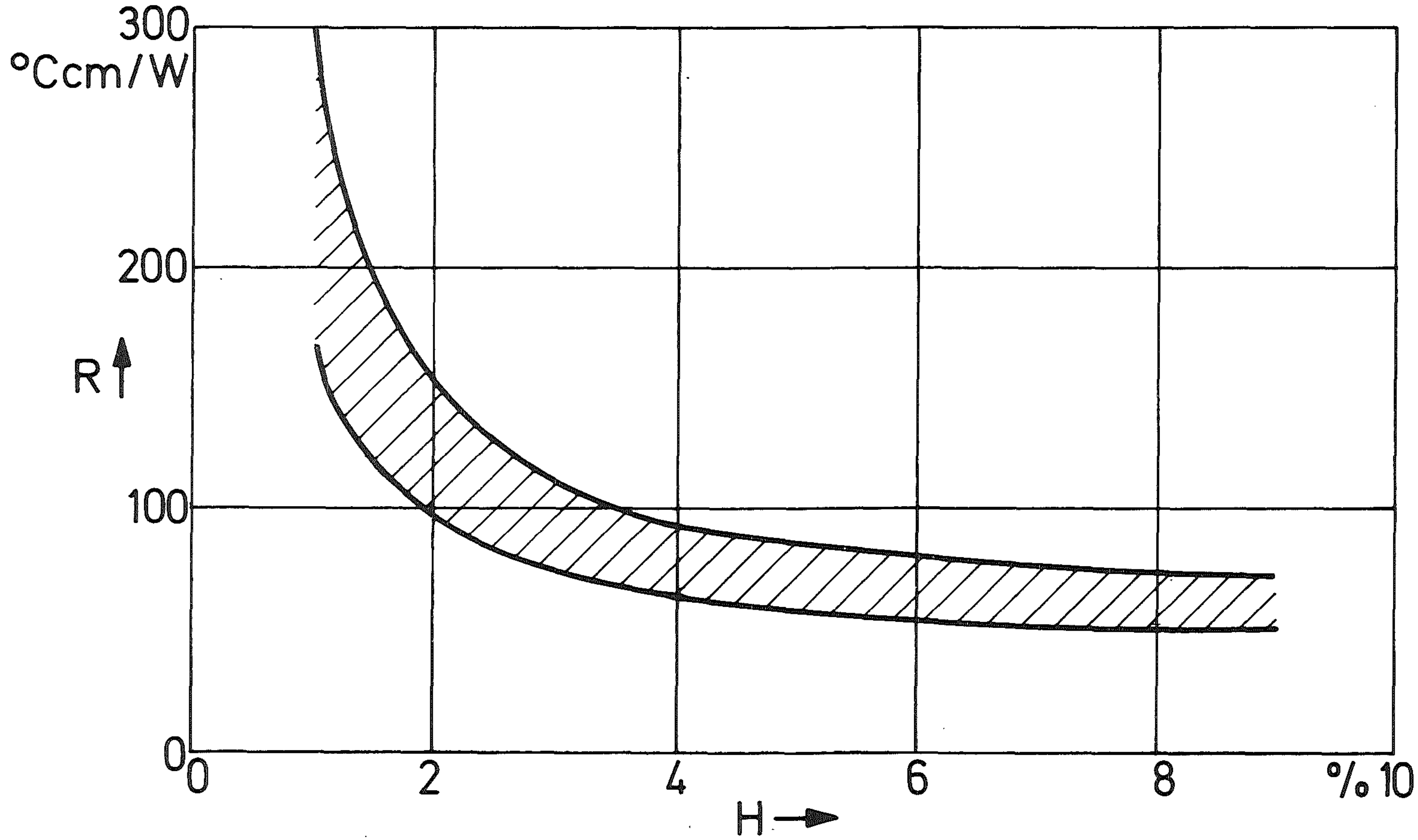

Fig. 2.8: Specific thermal resistivity R of sand as a function of humidity H [2.2].

stalled on top of the cable line to sprinkle the soil in order to keep it humid [2.3]. Another method is covering the cable with a backfill of good thermal conductivity even when dry, keeping the 40° C isothermal surface outside of the ground proper [2.2].

2.2.3 DC cables

In the case of dc cables there are no dielectric losses and no losses within the conducting material caused by induced currents. Therefore, the ampacity of a cable line is much higher - by a factor 2 or more - when run as a dc cable. If a cable is built to be used for direct current only, the insulation may be thinner than would be necessary for alternating current; thus also the thermal capability is higher [2.11]. However, in cables buried the normal way no benefit would be derived from this fact because of the limited thermal conductivity of the soil. Only if the cable were cooled - artificially or naturally, as in the case of under sea cables - a higher thermal capability would turn out as an advantage. Under sea power transmission is the main area of application for dc-cables anyway, but this is because of another property which is more important: there is no charging current limiting the useful cable length. For ac-cables, reactive compensation is used to overcome the problem of critical length rather than switching over to dc-cables. Only in the case of long under sea cables, where such compensation is not possible, dc-cables will inevitably be employed [2.12], but this is at the expense of installing complicated and costly converters at both ends of the line.

2.3 Reliability and Availability

The reliability of a cable line is on the order of magnitude of 1 fault per 100 km and year [2.20]. Japanese firms report a higher rate (4 faults/100 km/year), but this includes oil leakage events which make up 80 % of all faults [2.17]. The repair time for a cable is approximately 10 days per fault [2.12,17,20].

The life of a cable depends mainly on the fatigue of the insulation. A value of about 30 years is assumed in most calculations [2.16]. The first cable installed in Germany in 1927 is still in use [2.10].

Tab. 2.2 shows a subset of the most important cable parameters for some typical cable designs.

Table 2.2: Cable parameters for some typical cable designs

Company	AEG					Siemens	
Cable type+)	A	A	A	C,D	C,D	B	A
Voltage kV	110	110	380	110	110	110	110
Diameter mm	64	74	135	159	168,3	114	92
Conductor cross section mm^2	500	1000	2000	500	800	95	1400
Load MVA	101	131	560	91	108	51	300
Overload MVA (1h)	110	143	605	99	205		
Losses kW/km	49,5	52,5	67,1	50,2	52,4	38	
Capacitive Load MVA/km	1,5	1,97	15,78	1,35	1,5		

+) Cable types:

A - Single conductor oil cable

B - Oilostatic cable

C - Externally gas pressurized cable

D - Internally gas pressurized cable

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3. Advanced cables under development

In this section, the state of development of advanced cable systems is described. Aspects of reliability and availability are taken into consideration. Moreover the expected ultimate power transmission capability of these concepts is outlined.

3.1 Oil-paper-cables with forced cooling

The ampacity of conventional cables with oil impregnated paper insulation can be greatly enhanced by forced cooling. External cooling of the cable sheath (lateral or integral cooling) is rather simple technically. In this case, the ampacity is limited by the thermal resistance of the electrical insulation. The thermal resistivity of wrapped paper insulation is about 500 K·cm/W [3.14]. For this reason, lateral or integral cooling is not very effective at ultra high voltages that is at high insulation thickness. This cooling system is therefore a good way of stretching the limits of conventional cables, which are apparent even now, in a short time and without major technical and economic risks. But in the long run these cables will not be able to satisfy the requirements for high power cables [3.24]. Fig. 3.1 schematically shows the most important types of external cable cooling [3.16].

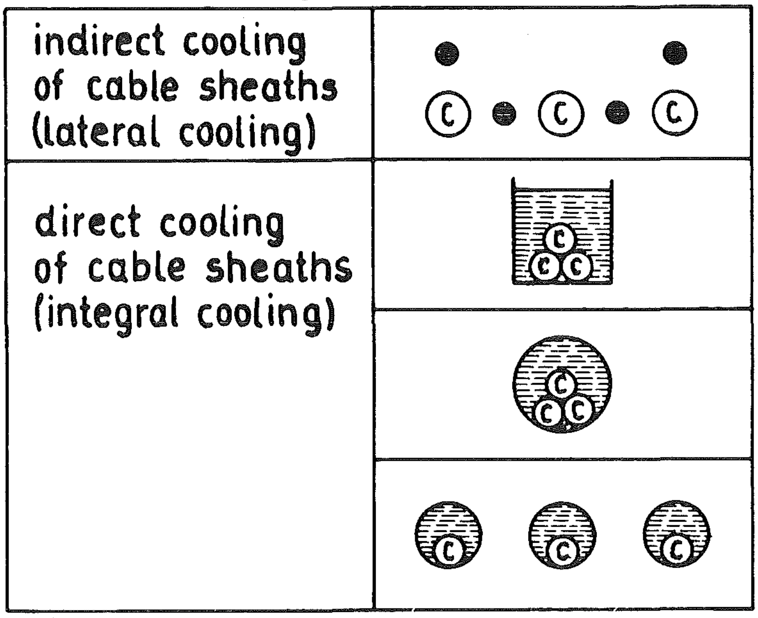

Fig. 3.1: Cooling of cable sheaths [3.16]

The simplest method, i.e.cooling by water flow in parallel tubes run close to the cable, can enhance the ampacity by about 50 to 60 % [3.25].

The ampacity of cables with forced cooling depends on the maximum temperature of the coolant medium. Fig. 3.2 and 3.3 show the power transmission capacity of 400 kV cables with direct cooling of the cable sheaths (integral cooling) [3.16]. For low temperatures of the coolant (<30° C) cooling machinery is necessary. Higher temperature, as shown in the diagram can be maintained by air coolers or evaporation cooling towers which are simpler and cheaper than cooling machines.

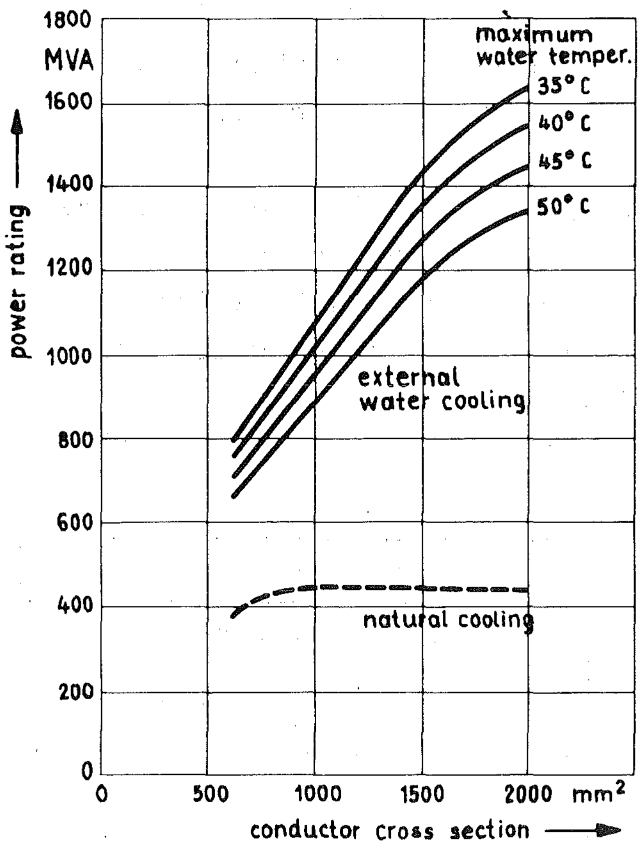

Fig. 3.2: Rating of 400 kV of self-contained oil filled cables under continuous load and with cross bonded sheaths [3.16]

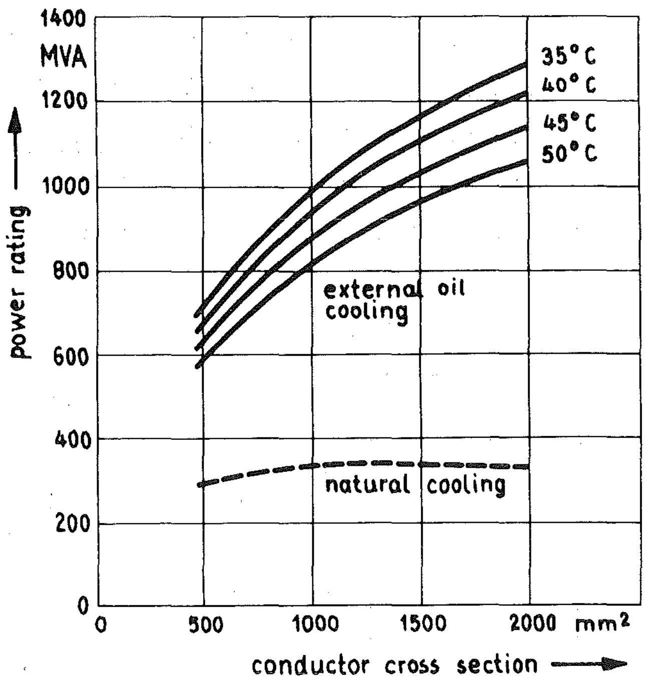

Fig. 3.3: Rating of 400 kV pipe type cables under continuous load [3.16]

Because of fabrication problems the limits of conductor area of stranded conductors today is mostly seen in the range of 2000 mm^2 [3.26]. Considerably larger areas will not be very useful economically, because already at 2000 mm^2 the ampacity grows at a considerably less than proportional rate to the conductor cross section.

The forced-cooling cables described so far can be characterized as the current state of the art and need no major development work as far as voltages up to 400 to 500 kV are considered. The reliability of these types of forced-cooling cables as against naturally cooled cables may be slightly better because they are independent of any irregularities in the heat dissipation properties of the ambient soil. Deterioration of reliability due to the probability of faults in the cooling stations is probably small compared with the advantage of controlled heat dissipation.

For example a forced-cooling cable system of this type (integral cooling) is planned for the network of West-Berlin to be installed in 1976 [3.26]. Tab. 3.1 indicates some data which can be taken as the power transmission limits of cables which are the present state of the art [3.24].

Tab. 3.1: Estimated ultimate power transmission capability of oil-filled cables

Cooling	natural		external	
	nominal voltage kV	ultimate power capacity MVA	nominal voltage kV	ultimate power capacity MVA
	60	85	60	260
	110	200	110	630
	220	350	220	1000
	400	500	400	1500

Energy transmission at considerably higher power can be done by direct cooling of the conductor. For this purpose conductors with a large internal duct are necessary.

Fig. 3.4 shows the cross section of a 400 kV cable with internal oil cooling [3.25]. A prototype of this cable has been installed in London and is presently being tested [3.3].

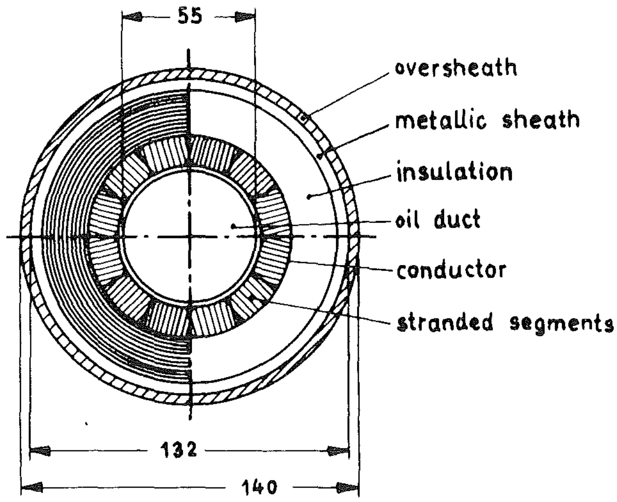

Fig. 3.4: Cross section of a 400 kV cable with large oil duct for internal cooling (conductor cross section: 1935 mm^2) [3.3]

An important advantage of this type of cooling is the possibility of allowing higher coolant temperatures. Air coolers may be used for recooling the oil. One important problem is seen in the fact that the coolant must be brought from high voltage to earth potential at each cooling station. The number of complicated feed and stop joints is small if the distance between cooling stations is large, that is, if the conductor cooling duct is large.
In principle, also water can be used for internal cooling, provided that the cooling duct is absolutely tight. But there might be the risk of water slowly diffusing trough very small defects of the tube, which cannot be detected after fabrication, leading to breakdwon of the insulation perhaps after several months or years. If such problems can be solved, an internally water cooled cable obviously offers important advantages over an oil cooled cable because of the high heat

capacity of water. The distance between cooling stations can be longer and so less feed joints are necessary which, on the other hand, are more problematic because of the electrical conductivity of the water. With constant thickness of the conductor the power transmission capacity is approximately proportional to the conductor cross section or the diameter of the cooling duct, respectively.

Fig. 3.5 shows the transmission capacity of cables with internal water cooling as a function of the cooling duct diameter and the distance between the cooling stations with a constant conductor thickness of 15 mm [3.24]. At short distances the economically optimum power rating is lower than the rating which is technically feasible.

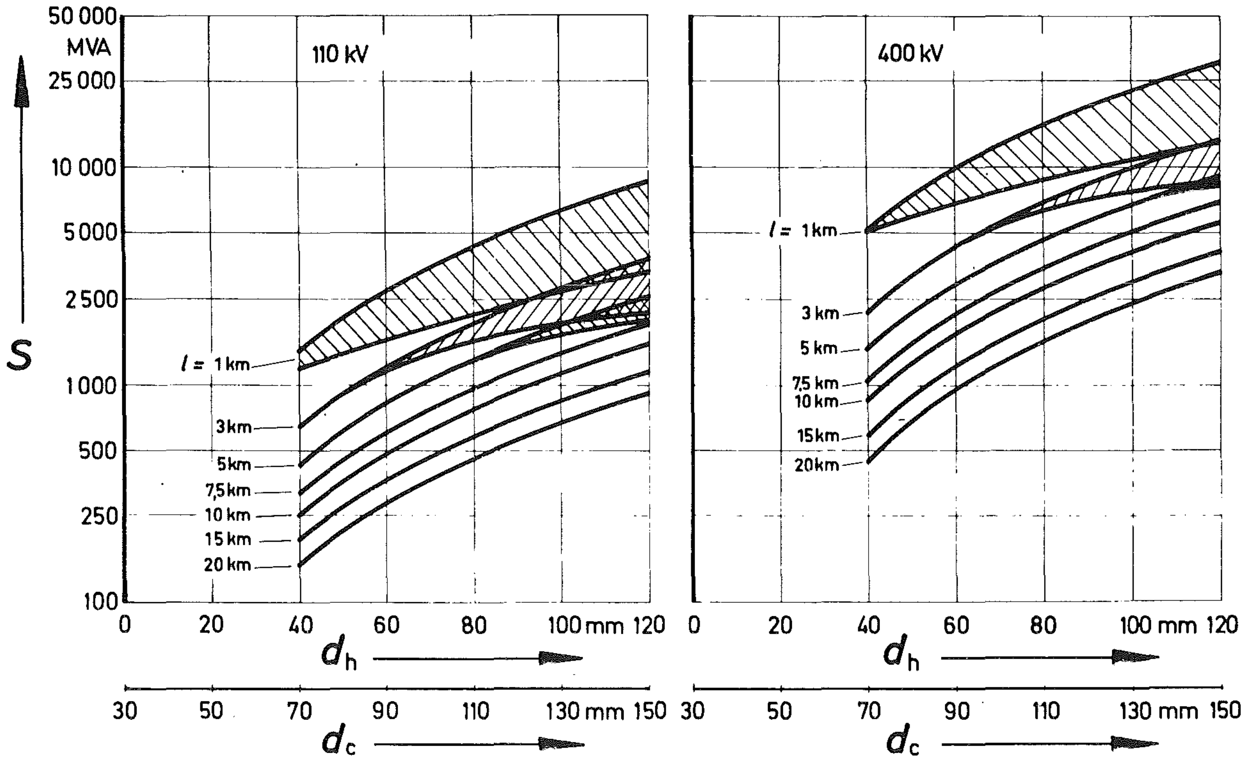

Fig. 3.5: Power transmission capacity (technical limit and economical optimum) of cable systems with internal water cooling (l = length between cooling stations, d_h = diameter of water duct, d_c = overall diameter of the conductor with internal water duct) [3.24]

With this type of cooling very high power can be transmitted. However, it must be pointed out that in these data (Fig. 3.5) considerably higher dimensions have been assumed than are usually applied.

It has not yet been proved whether cables of this size are flexible enough to be bent without risk during fabrication, transport and installation. Some preliminary experiments suggest that this at least seems to be no problem in the lower region of conductor diameters around 90 to 110 mm (about 60 to 80 mm diameter of cooling duct). Fig. 3.6 shows the cross section of this type of cable suitable for internal water or oil cooling at high pressure. The reliability of internally cooled cables may be impaired by joints and potheads which are not unproblematic. These are the most important areas for development. As the first field tests with internal oil cooling are performed already now [3.3], it is very probable that this type of cable will be ready for commercial use in the near future. Cables with internal water cooling will still need some years of development [3.24]. High power transmission at ultra high voltages (> 500 kV) is treated in some detail in section 3.3.

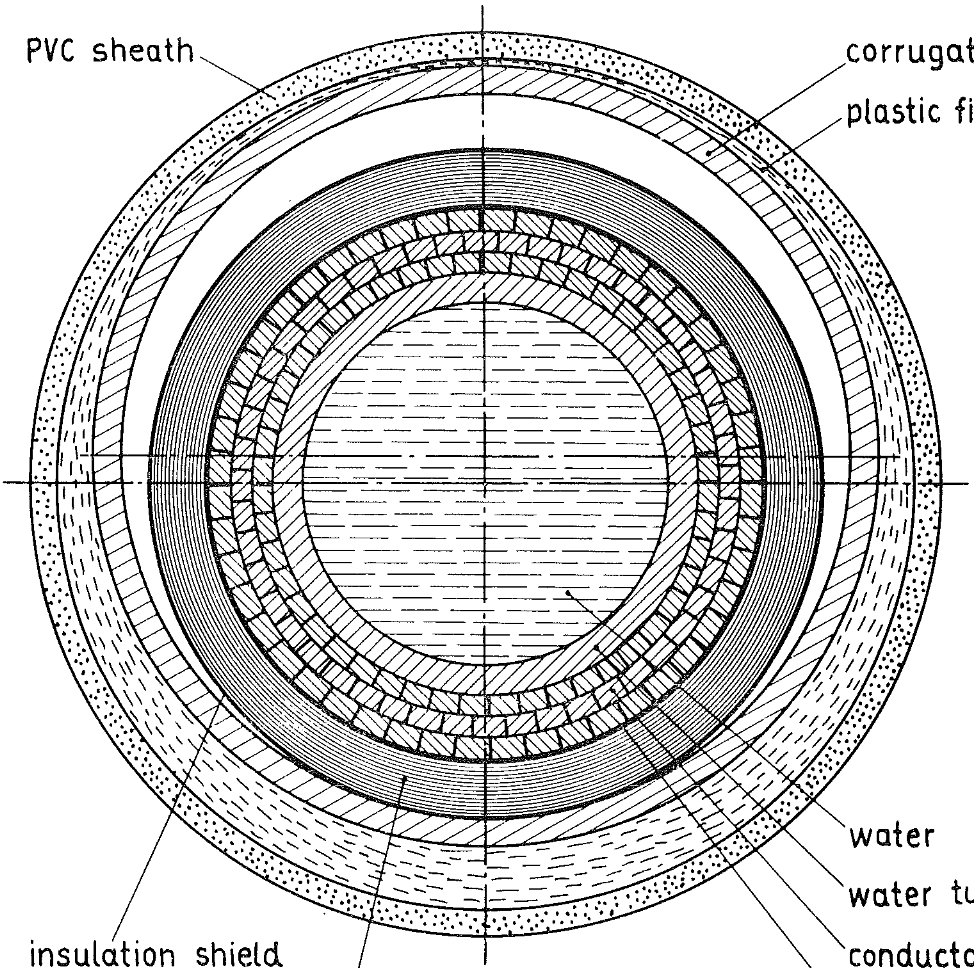

Fig. 3.6: Cross section of a proposed 110 kV cable with internal water cooling [3.24]

3.2 Cables with extruded synthetic insulation

The most important of the new insulation systems proposed for high voltage cables is polyethylene (PE). The advantages of PE compared with oil paper insulation are low dielectric losses (around 10 % of oil paper) and excellent temperature stability. With naturally cooled cables the higher permissible temperature is especially important in the case of short circuits. This advantage cannot be fully utilized in normal operation because of drying of the soil. However, with forced-cooling the higher temperature is an important advantage.
The PE-insulation is very sensitive to partial discharges which may occur in small holes of the insulation. Such microscopic holes cannot be avoided entirely, especially with thick extruded insulations which are necessary for ultra high voltage cables.

Fig. 3.7 shows the life expectancy of cables with and without defects [3.6].

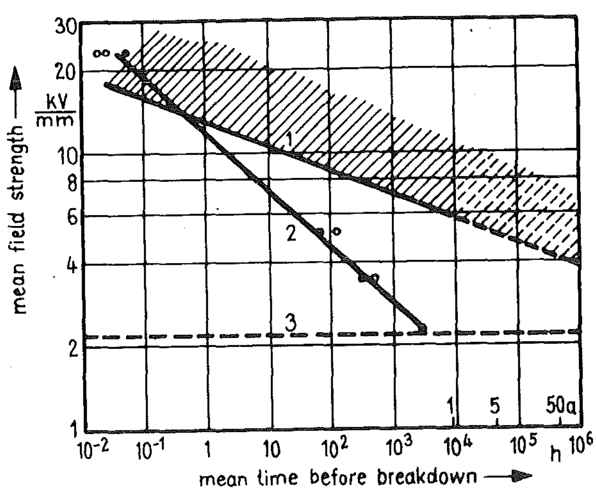

Fig. 3.7: Life expectancy of intermediate voltage cables with extruded polyethylene insulation. 1 - normal cables; 2 - cables with small voids (∿0.2 to 1 mm diameter); 3 - service stress [3.6]

The resistance to partial discharges can be substantially improved by adding so-called voltage stabilizers [3.11]. For high voltage cables PE of high density (HMPE; 0.96 g/cm^3) with voltage stabilizers (VSP) is becoming more and more important than PE of low density (0.92 g/cm^3). The disadvantage of the higher stiffness of high density polyethylene is set off by better values of breakdown strength and temperature stability [3.6]. The best insulating material as far as **temperature stability is concerned** is crosslinked polyethylene (XLPE). The polymer molecules can be crosslinked by chemical reactions or by irradiation. In cable fabrication chemical crosslinking is used practically exclusively. Certain peroxide compounds are added to the PE granulate. The vulcanizing process is carried out within 1 minute at around 170° C in a steam tube right after extrusion [3.27]. The breakdown strength of XLPE is slightly lower than that of pure PE [3.11].

Tab. 3.3: Selected characteristic of high voltage insulating materials

Material	Dielectric constant ε	Loss factor $\varepsilon \tan\delta$ %	Thermal resistivity ρ $^\circ$C cm/W	Operating temperature T_o $^\circ$C	Softening temp. T_{max} $^\circ$C
HMPE and VSP	2.3	0.10	350	80	90
XLPE unfilled	2.3	0.10	350	90	135
XLPE filled	2.7	1.56	350	90	135
EPR	3.3	2.25	610	90	135
Oil-Paper	3.5	1.00	500	80	-

Tab. 3.3 is a comparison of the most important insulating materials [3.1]. Ethylene-propylene-resin (EPR) is not fit for application in ultra high voltage cables because of the high dielectric losses. The same is true of PVC.

Extensive research work is being conducted on voltage stabilizers for XLPE insulations. Besides the use of suitable stabilizers [3.28] the application of semiconducting organic liquids is suggested [3.29]. Deposition of the semiconducting liquid on the interfaces of voids in the insulation field peaks and hence partical discharges in the voids are suppressed. Filling of the cable with pressurized SF_6 gas or silicon oil through a channel in the conductor has also been suggested. The fillers are supposed to diffuse slowly into voids of the insulation or into the inner surface of the insulation [3.1]. Fig. 3.8 shows the structure of a typical extruded dielectric cable for 138 kV [3.21].

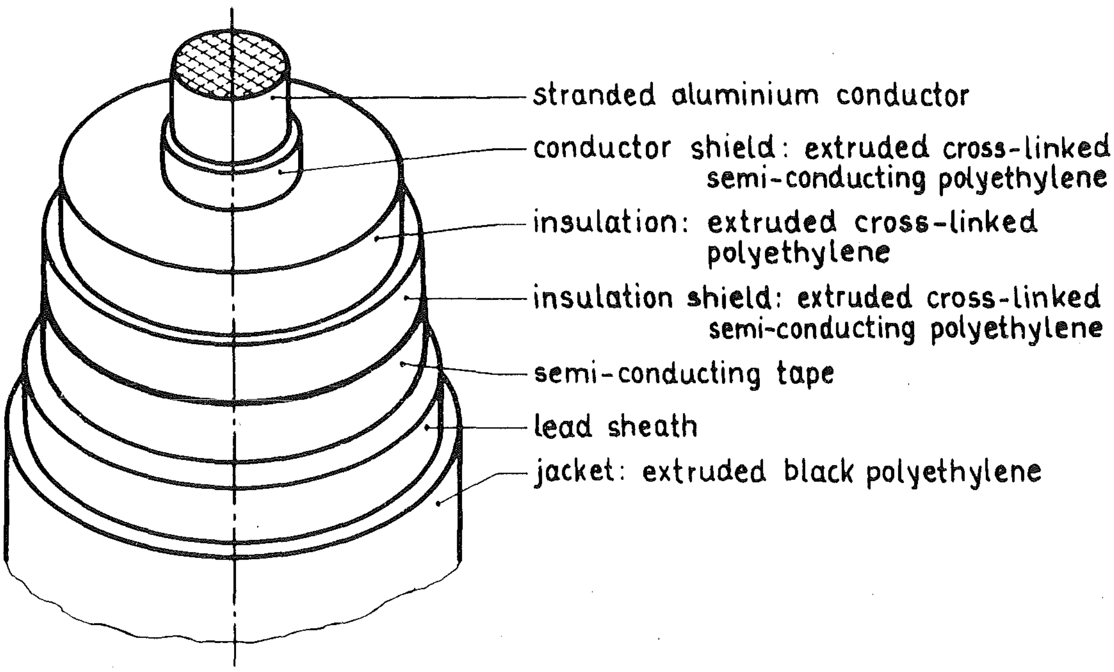

Fig. 3.8: Structure of a 138 kV extruded dielectric cable [3.21]

A very similar cable with 225 kV nominal voltage insulated with low density PE was installed in France and has performed satisfactorily in practical service [3.16,47]. Many designs use no lead sheath but wrapped copper tapes or wires under the synthetic jacket. Some manufacturers use smooth or corrugated aluminium sheaths. PE cables are designed generally with maximum field strength at nominal voltage of 4 to 5 kV/mm.

However, there is hope that this rather low value can be raised to about 10 kV/mm, which is typical of oil paper insulations. Because of the good thermal conductivity of PE these cables are especially suited for external water cooling. PVC or fibreglass reinforced synthetic tubes may be used to carry the coolant. Also tubes made of asbestous cement, which are cheaper and stronger than synthetic pipes, may be used. These tubes offer a degree of mechanical protection comparable with steel pipes, but installation is more complicated.

A newly developed material which can sustain very high thermal stresses is PE of extra high molecular weight; it has been applied even at cryogenic temperatures [3.43]. Because of the high viscosity of the material special extruding machines must be used; the price of the tubes will therefore be higher than that of normal PE tubes, on the order of the price of fibreglass reinforced synthetic tubes. Installation of cables without metal sheaths in a cast iron pipe providing sufficient electromagnetic screening has also been suggested [3.1]. It is hoped, but has not yet been proved in long term tests, that the outer synthetic jacket of the cables guarantees water tightness. Thus, most of the projects planned with external water cooling still use metal sheaths. Diffusion of water into the extruded insulation is very dangerous because of resulting partial discharges (treeing) which leads to breakdown of the cable.

With air coolers 600 to 700 MVA will be the transmission limit at 110 kV. If the temperature is lowered to about -20° C up to 1000 MVA per circuit can be transmitted at 110 kV [3.34]. This necessiates the use of a rather expensive cooling machinery.

The question of whether substantially higher voltages, for example 400 kV, can be realized with extruded dielectric cables is hard to answer at this moment. This depends, first of all, on further perfection of the extrusion process. A high degree of perfection has already been achieved in modern machinery where insulation is extruded together with the semiconducting screens in one step. If it is possible in the future to manufacture reliable cables for a least 220 kV with service stresses of about 10 kV/mm, which has been achieved in the French test cable mentioned above, the power limit of 600 to 1000 MVA can roughly be doubled.

No assured information is as yet available on reliability because of the lack of experience in long term application. The French 225 kV cable has been in use already for several thousands of hours in spite of the high field strength. In some places 110 kV cables have been used for years without any fault. In France field tests have been performed since 1968. Until now 30 km of 225 kV PE cables operated at rather high stresses have been installed and used without causing any problems.

On the other hand, however, there have been early breakdowns of conservatively dimensioned cables. The main problem with extruded dielectric cables is statistical scatter.

3.3 Cables with wrapped synthetic insulation. Ultra high voltage cables

The ampacity of cables with oil impregnated paper insulation is limited essentially by the dielectric losses at very high voltages. For this reason, the application of wrapped synthetic insulation was suggested many years ago. Contrary to extruded insulations, very thick insulation walls of constant quality can be fabricated by wrapping thin tapes on the conductor. The wrapped synthetic insulation must be impregnated with a suitable fluid, just as the paper insulation. Normal cable oil cannot be used because of the chemical incompatibility of the PE foils with oil [3.3]. The following combinations are investigated:

- Application of exotic material combinations, for example polyphenyl oxide and silicone oil, which are chemically compatible. Practical realization is not very probable, also because of the high price of these materials [3.3]
- Polyethylene foils with SF_6 gas impregnation [3.9,30,31]
- Synthetic papers with oil impregnation [3.18]

The limits to high voltage dielectric are shown quite clearly in Fig. 3.9, where the power transmitted with natural cooling related to the conductor diameter is drawn. The technically useful limit of naturally cooled oil paper cables ($\tan \delta = 0.002$) according to the diagram is around 700 kV. Because of the high charging current, which must be compensated by expensive reactors, the economic limit will be still lower.

Forced cooling allows high ampacities to be attained by oil paper insulations at ultra high voltages. In Japan, the U.S. and the U.K. 500 kV cables with paper insulation are being developed [3.32,33,39]. In the cable testing plant of Waltz Mill industrially manufactured 500 kV cables are tested since some years. In a Tokyo substation a 500 kV cable has already been installed for long term tests. Cable and accessories including forced cooling equipment have furnished satisfactory results. Based on previous experience Japanese cable industries declare 500 kV cable systems including forced cooling to be ready for commercial use [3.39]. The first commercial 525 kV cable in the

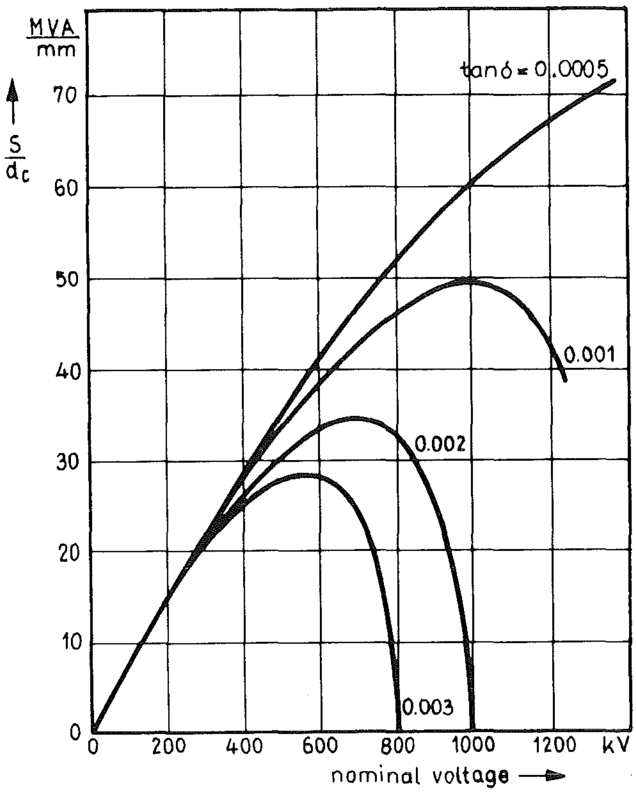

Fig.3.9: Power transmission capacity S related to the conductor diameter d_c of cables with natural cooling

U.S. fabricated by BICC has recently been installed [3.45]. It should be recognized that test requirements of UHV cables vary in different countries. This implies that, for instance, the same cable can be operated at higher nominal voltage in the U.S. than in the U.K. (for more details, see Section 5.)

Work on PE-foil insulation with SF_6 gas impregnation has been done in the U.K. and in Germany [3.9,30]. This insulation system has two grave disadvantages. Its thermal resistivity is relatively high compared with the compact material, and the permissible field strength at nominal voltage is at about 3.5 kV mm [3.9] which is still lower than with extruded PE insulation. The design is governed by the partial discharge inception voltage as partial discharges must be avoided under any service condition. The loss tangent tan δ of the wrapped insulation with SF_6 gas is the same as with compact material.

Insulations with synthetic paper are developed especially in Japan and the U.S. [3.18].The loss factor ε•tan δ of synthetic papers is higher than of PE-foil insulations, but considerably lower than with oil paper insulations. The mechanical properties and compatibility with oil seems to be rather good, according to the experience gathered until now. The impulse strength is 15 to 30 % lower than with paper insulation. Tab. 3.4 compares the properties of synthetic paper (PAP) made of a mixture of polyester and polycarbonate, pure cellulose paper and paper with synthetic additives [3.18].

Fig. 3.10 shows the maximum power transmission capacities of cables with these insulations and natural cooling [3.18].

Tab. 3.4: Electrical properties of insulating tapes in oil (80°C)

Property	PAP	Deionized water washed paper	Mica-loaded paper
Dielectric constant	2.65	3.40	3.15
tanδ %	0.045	0.22	0.12
εtanδ	0.0011	0.0075	0.0038
Impulse breakdown voltage kV/mm	100	115	130

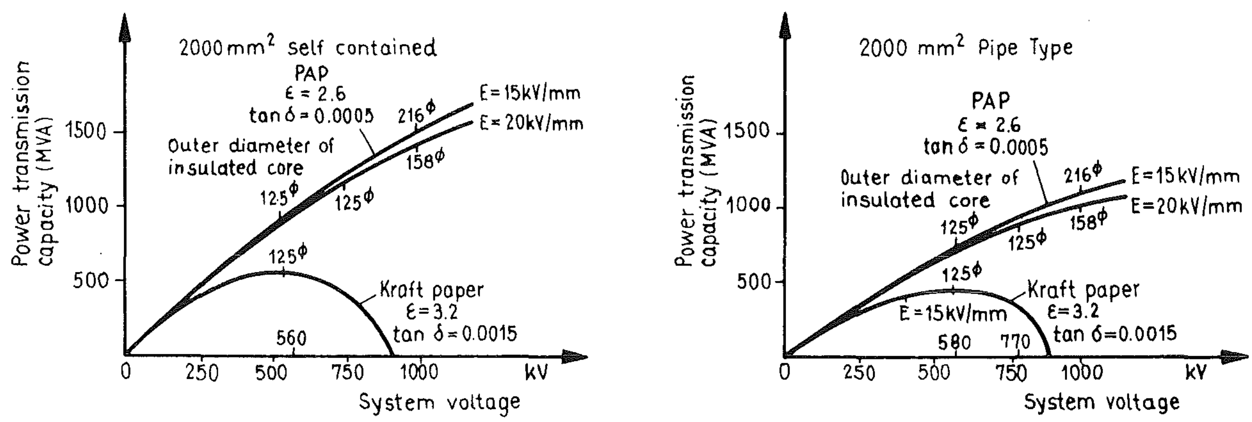

Fig. 3.10: Power transmission capacity of ultra high voltage cable [3.18]

Chances of the practical use of ultra high voltages cables in congestion areas can be visualized only in connection with the development of encapsulated switching stations. The feasibility of suitable SF_6 stations indeed is beyond any doubt, but no such stations have as yet been developed for ultra high voltage. Since cables with direct cooling of the conductors are also able to transmit very high powers at lower voltage, economics will be the decisive criterion. In this case, cost comparisons must cover the whole system including switching, transformer and cooling stations. In principle, the power transmitted by ultra high voltage cables can be further enhanced by forced cooling. But in this case the joints and potheads, which caused difficult problems even at normal voltage will be extraordinarily critical factors. The simplest type of forced cooling, that is lateral cooling, after all will stand the best chances. A special type of forced cooling synthetic insulated cables, cryogenic cooling with liquid nitrogen at 77 K, is covered in Section 4 below. The electrical properties of synthetic insulations with cryogenic fluids are generally better than the properties of the insulation systems discussed in this section.

3.4 Compressed gas insulated cables

Tube conductor cables with SF_6 gas insulation pressurized to a few bars of pressure have been field tested in the U.S. and in Japan for some years already. The first commercial transmission line was installed in New York in 1969, a line of 180 m length with a capacity of 2000 MVA at 345 kV. The first SF_6 transmission on a large scale in Europe will be installed in a power station in southern Germany for 400 kV and 900 A nominal current [3.16]. In Japan SF_6 cables for 500 kV nominal voltage are under development since 1970 [3.6,49]. Capacities of 3500 - 7000 MVA are considered for test programs.

Generally, SF_6 cables are built as three single core conductors coaxially arranged in three metal pipes. Arranging three cores in one common pipe has also been suggested [3.1] and recently been tested in Japan. All transmission lines installed until now use rigid tubes which are transported in short lengths of about 15 m and welded together in the field. This is the main problem associated with this technique. Jointing must be done under very clean conditions, for the electrical strength of the gas insulation is greatly reduced by pollution.To reduce this problem, flexible structures made of corrugated tubes have recently been investigated. If these cables are to be transported on cable drums, nominal voltages of 400 kV maximum are feasible [3.35].

The most important advantages of SF_6 cables, especially when rigid tubes are used, are these:

- there is no technological limitation of the conductor cross section and, hence, the permissible current. The optimum cross section may be chosen under economic aspects. Because of the electric field strength on the conductor which is about 2.5 kV/mm at nominal voltage and because of the minimum wall thickness of the tubes (about 5 mm) for mechanical reasons the minimum conductor cross sections are already very much on the high side for the individual voltage classes. At 400 kV, for example, the minimum conductor cross section amounts to about 3000 mm^2, which is already higher than the technical limit of stranded conductors. Tube conductors of this kind therefore are useful only at high currents in the range of kA;

- there is practically no limitation of the transmission voltage as the necessary electric strength can always be attained by sufficiently large pipe dimension and gas pressure;
- high conductor temperatures are permissible, the only limitation being the spacers of epoxy resin;
- heat transmission properties of the gas gap are considerably better than those of solid insulation. The average thermal resistivity is only about 100^{o} C·cm/W (about 500^{o} C·cm/W with oil paper insulation). Because of the small temperature difference between the conductor and the sheath the power transmission capacity is limited first of all, by the outer thermal resistance. The temperature limit of 40^{o} C the soil begins to dry is reached already at rather low power. Therefore thermally stabilized backfill should be used. Special backfill materials for cable trenches whose thermal resistivity in the dry state does not exceed 120^{o} C·cm/W have also been used with conventional cables [3.15]. As this provision causes additional expenditure, its use must be checked against economics;
- charging currents are very low compared with conventional cables and the dielectric losses may practically be neglected;
- the insulating medium is non-flammable;
- major differences in level do not give rise to static pressures.

The electric strength of the gas gap increases considerably at higher pressure, as shown in Fig. 3.11 [3.35]. The increase in design pressure is limited by the risk of liquefaction of the gas. This may occur at very low load in winter and lead to breakdown of the insulation. The vapor pressure curve, which correlates pressure and temperature for liquefaction, is shown in Fig. 3.12 [3.35].

The gas gap must be designed for the necessary impulse strength. A.C. and switching voltage strengths are given in most cases [3.16]. The weak points in the insulation systems are the spacers, especially the narrow gaps between the conductor and isolator

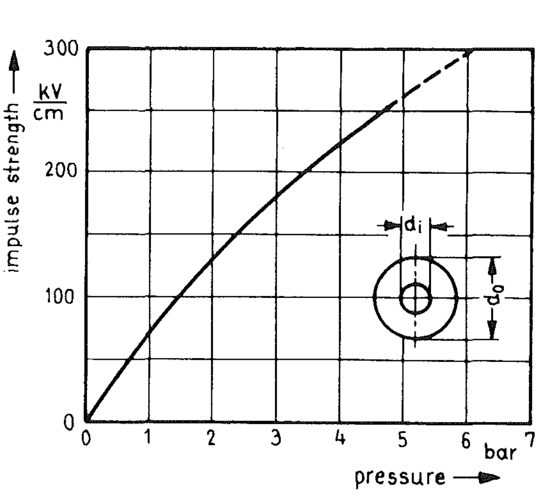

Fig. 3.11: Impulse strength as a function of the SF_6 gas pressure at 20°C. d_i = 110 mm; d_o = 300 mm; negative inner conductor [3.35]

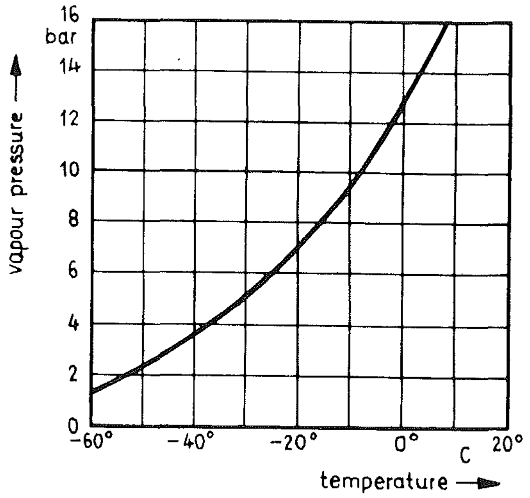

Fig. 3.12: Vapor pressure of SF_6 at saturation [3.35]

which are necessary to install the spacers. The electric strength of these weak points is improved if spacers with broad naves (80 to 100 mm) on the conductor side or metal field control electrodes are used. Then the breakdown strength will be about the same as with the undisturbed gas gap [3.35]. Fig. 3.13 shows an example of the design of a 400 kV SF_6 cable using funnel type spacers which are technically feasible but rather expensive [3.16].

The effect on the impulse strength of a broad nave with disk type isolators is shown in Fig. 3.14 [3.35]. Corrugated spacers are being investigated also to reduce the influence of pollution on electric strength [3.46]. One example of a flexible SF_6 cable with corrugated tubes is shown in Fig. 3.15 [3.7,50]. As mentioned above, this type of cable is feasible only for rather low voltages and powers. The chances of practical application can be assessed only after a cost analysis has been made.

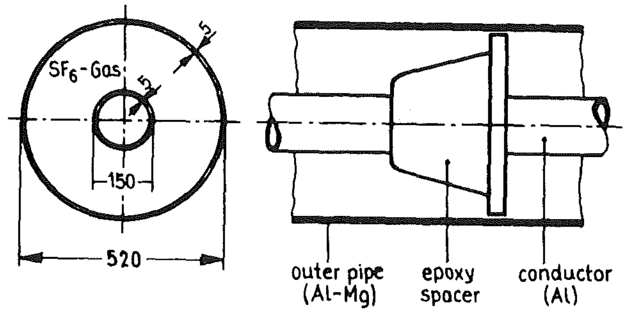

Fig. 3.13: Design of an SF_6 insulated pipe cable rated for 400 kV, 1000 A, 3.5 bar [3.16]

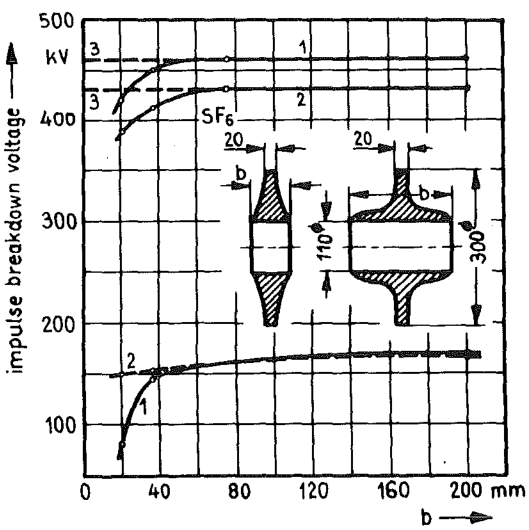

Fig. 3.14: Influence of broadness b of the spacer naves on impulse breakdown voltage (50 % probability).
1 - inner conductor positive; 2 - inner conductor negative; 3 - breakdown voltage of the gas gap [3.35]

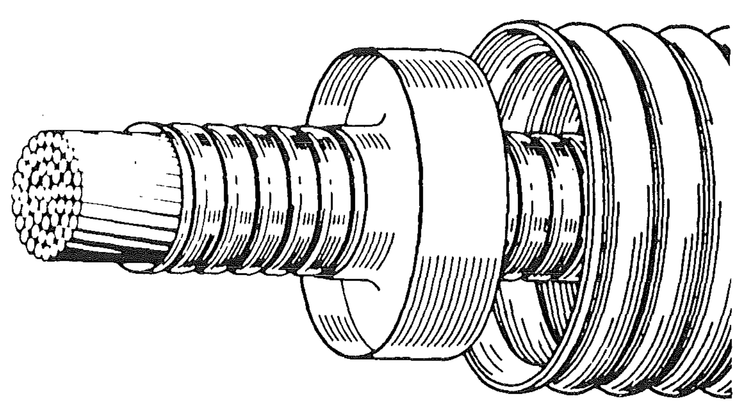

Fig. 3.15: Flexible SF_6 insulated tube cable [3.7,50]

Because of the low charging currents and dielectric losses SF_6-cables are more like overhead lines than cables. The limiting cable length, that is, when the uncompensated charging current equals the permissible current, is very large compared with conventional cables and is no real obstacle to those applications of cables that can be seen in the foreseeable future. Fig. 3.16 is a comparison of the transmissible real power as a function of length of overhead lines and cables [3.7].

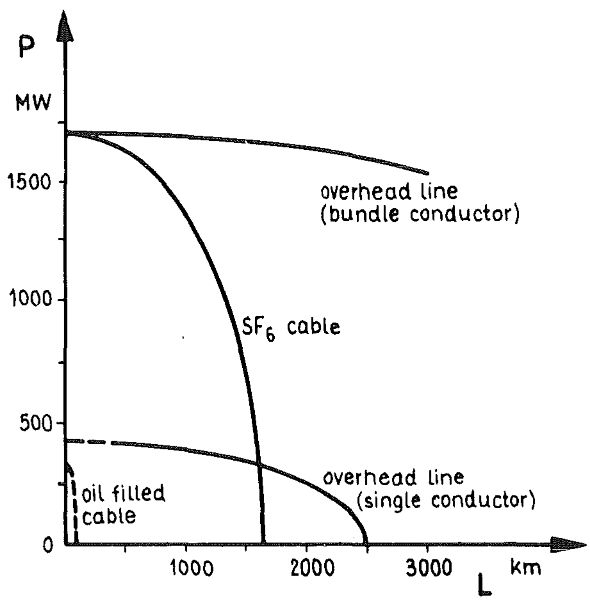

Fig. 3.16: Power transmission capacity P at 220 kV as a function of line length L [3.7]

The reactive power consumption of SF_6 cables is inductive in most cases and can be optimally fitted to the load by regulation of the sheath current. So, the cable can work approximately at natural loading, which is not possible with conventional cables. In this case, nearly zero reactive power is needed and there is no major voltage drop between the beginning and the ending of the line. In order to regulate the sheath current the sheaths are bonded only at one terminal. At the other end, the sheaths are bonded over a switchable resistance cascade. Fig. 3.17 shows this principle.

In case of short circuits, the spark gap triggers and shortens the resistance so that the sheaths are bonded at both ends.

This is important as the short circuit forces are too high if the sheaths are not bonded at both ends. This is the reason why crossbonding of the sheaths, which would considerably reduce the losses in normal service, is not a good solution.

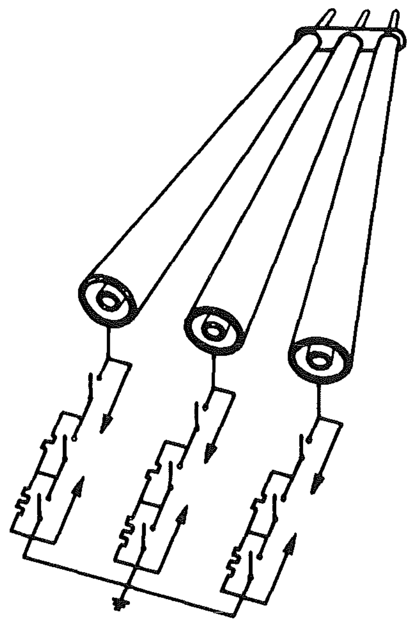

Fig. 3.17: Regulation of sheath currents of SF_6 gas insulated cables

Fig. 3.18 shows the curves of reactive power consumption of overhead lines and cables. The effect of reactive power regulation by the sheath current with SF_6 cables is evident.

No statistical experience is available on the reliability of SF_6 cables. It may be assumed in general that good reliability can be attained if the necessary absence of pollution in the gas space is guaranteed during installation and service. Forced cooling of SF_6 cables may be used at very high power compared with conventional cables when natural cooling with stabilized backfill is not sufficient. The ampacity can be greatly stepped up by external air cooling [3.36]. Because of the high thermal conductivity of the gas gap external cooling of SF_6 cables is very effective in general. Lateral cooling by parallel water pipes is one possibility. But anyway there are considerable additional expenses. On the other hand, there is much space in the conductor for internal cooling without

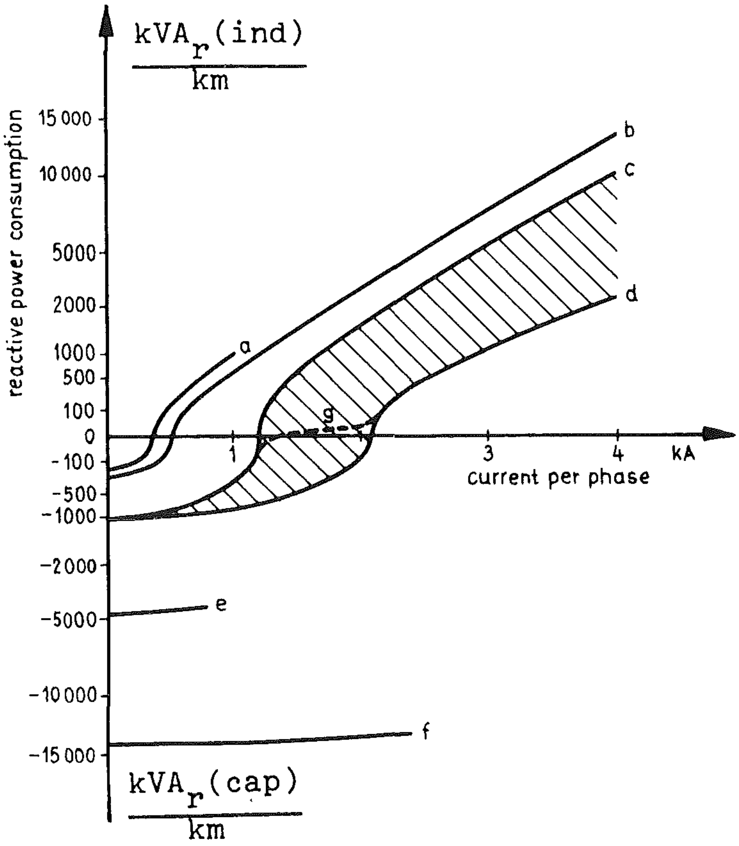

Fig. 3.18: Reactive power consumption of various power transmission lines at 245 kV.

a - overhead line 1 x 500 mm^2

b - overhead line 4 x 500 mm^2

c - SF_6 cable without sheath current

d - SF_6 cable with sheath current and overhead line with four systems according to curve b

e - oil filled cable, 500 mm^2

f - three parallel oil filled cables, 3 x 500 mm^2

g - SF_6 cable with sheath current regulation

increasing the cable dimensions. Internal cooling involves additional costs only at the terminal where the coolant (water or oil) has to be brought to earth potential and more spacers must be used because of the increase in weight of the conductor due to the coolant. Because of the skin effect it is ineffective to make the wall thickness of the conductor much more than skin depth (about 12 mm).

Because of the cost of losses it is necessary to use high conductor cross sections at high currents (the economically optimum current density is about 1 A/mm^2 with aluminium conductors). Therefore, the area inside the conductor which can be used for the coolant flow is the larger the higher the current of the cable. At high power there is no advantage in water cooling over oil cooling because there is enough flow area for the fluid with low heat capacity [3.37]. This is different in the internally cooled oil paper cables discussed in section 3.1 which require considerable enlargement of the conductor diameter. In this case a coolant with a maximum heat capacity should be used.

3.5 Summary of methods of cable installation and cooling

The following schedule presents a survey of methods of cable installation and cooling.

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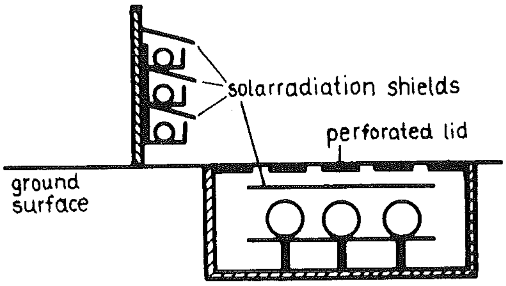
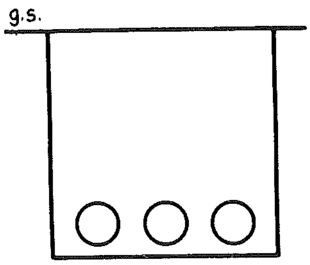
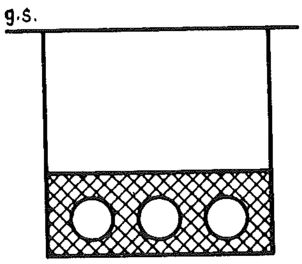


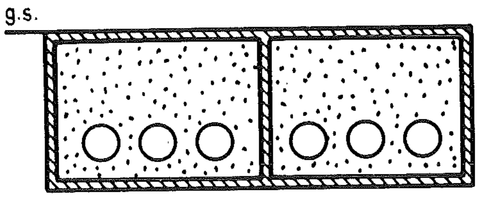
Installation in the air above ground or in a ventilated trough (air cooling); appropriate for short lengths to link overhead lines and cable tunnels; free area above the ground required; high ratings.



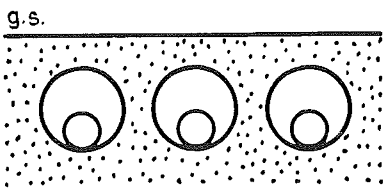
Normally buried with normal backfill material; simple installation; mechanical protection; not fit for congested areas of towns and cities.



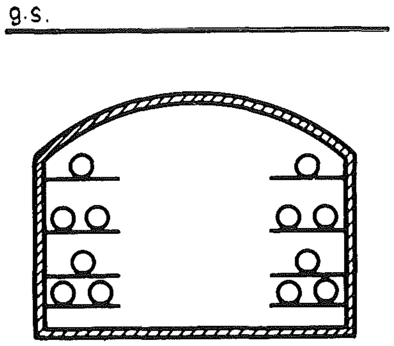
Normally buried with stabilised backfill material; higher ratings as in the case of normal backfill material.



Installation in a normal or irrigated surface trough; narrow space; only shallow excavation; close spacing of other cable circuits; suitable for congested areas of towns and cities.

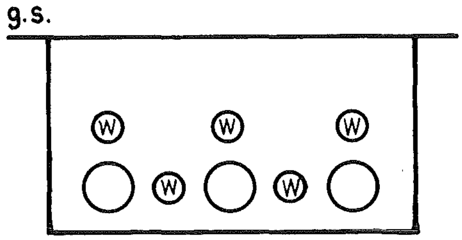


Buried ducts; suitable when crossing obstacles such as roads, rivers and railways.



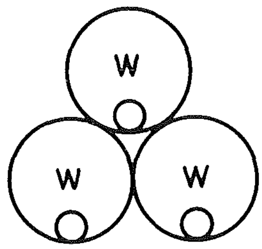
Comments:

Installation in a ventilated tunnel; high ratings; accessibility for control and repair.



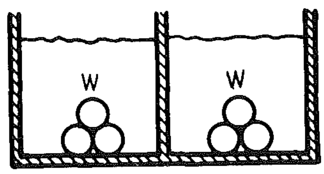
External water cooling

Installation with separate water pipes; independent of thermal resistivity of soil; suitable for congested areas.

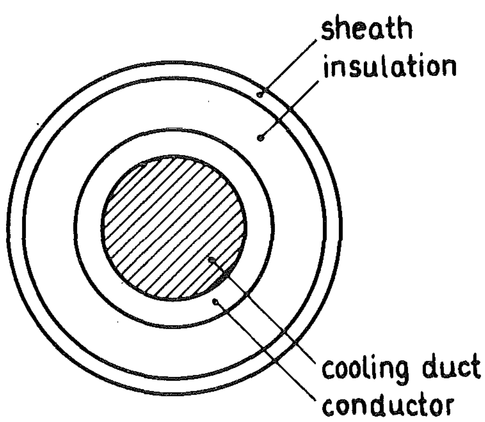


Installation in water tubes; (integral cooling); high ratings; close spacing.

Horizontal installation necessary because of cable movement.



Installation in water troughs; high ratings; close spacing.



Internally cooled conductor by water or oil for high power rating with minimum conductor size.

3.6 Summary of the data available on power transmission limits and availability date of advanced cables

The following schedule presents data on the maximum capacity and the availability for commercial service of advanced cables which can be found in the literature. Data for which no reference is given are the authors assumptions based on information obtained from companies engaged in this development. Information on power limits consists of rather conservative estimates, i. e., these data will be reached most probably. Further improvements due to technical progress is not impossible. For example, the upper limit for stranded conductors has mostly been assumed to be 2000 mm^2. The feasibility of even larger conductors to be designed different from conventional conductors because of a.c. losses, is regarded as being not impossible by some authors [3.12,38,41].

Type of cable	Ultimate power transmission capability MVA per circuit	Availability for practical service: Available	Soon available	Available in the future
3.1 Oil paper cables	<u>UHV-cable, natural cooling</u>			
	550 kV: 1400 [3.38]	x		
	750 kV: 1600 [3.3]		x	
	<u>External cooling</u>			
	110 kV: 600 [3.4,16,17]	x		
	220 kV: 1000 [3.4,16,17]	x		
	380 kV: 1600 [3.16]	x	x	
	550 kV: 2000 [3.38]		x	
	750 kV: 4000 [3.3]		x	
	<u>Internal cooling</u>			
	<u>Oil-cooling:</u>			
	225 kV: 1200 [3.13]	x	x	
	380 kV: 2500 [3.13]	x	x	
	500 kV: 3000 [3.40] (at 2500 mm^2)		x	
	<u>Watercooling</u> [3.24] unconventional conductor dimensions! $S = f(d_h, L)$; d_h = 120 mm, L = 5 km			
	110 kV: $S \cong 2000$ MVA		x	x
	380 kV: $S \cong 8000$ MVA			x
3.2 Cables with extruded synthetic insulation	<u>Natural cooling</u>			
	110 kV: 325 [3.34]	x		
	225 kV: ~650 [3.42] (if $E_{service} \cong 10$ kV/mm		x	
	<u>External water cooling</u>			
	110 kV: 660 [3.34]	x	x	
	225 kV: 600 [3.13] (at 2000 mm^2 Al)	x	x	
	400 kV: 1200 [3.48]			x

Type of cable	Ultimate power transmission capability MVA per circuit	Availability for practical service		
		Available	Soon available	Available in the future
3.3 Cables with wrapped synthetic insulation	750 kV: 1500 [3.3]		x	x
	1000 kV: 1500 [3.18]			x
	<u>External cooling</u>			
	380 kV: 2500 [3.3]		x	x
	750 kV: 4500 [3.3]			x
3.4 SF_6 cables rigid tube cables	<u>Natural cooling</u>			
	380 kV: 2500 [3.16,17]	x		
	500 kV: 3500 [3.6,16]	x	x	
	<u>Forced cooling</u> (function of dimension, no real technical limit)			
	500 kV: 7000 [3.49,6]		x	x
	500 kV: 10000 [3.13,16]		x	x
Flexible tube cable	<u>Natural cooling</u>			
	110 kV: 400 [3.7]		x	
	220 kV: 800 [3.7]		x	
	<u>Forced cooling</u>			
	245 kV: 1300 [3.50]		x	x

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4. Cryogenic cables

4.1 Cryoresistive cables

4.1.1 Introduction

Also non-superconducting cryocables offer the possibility of considerably increasing the transmission capacity and are therefore the objects of extensive studies. They make use of the reduction in resistance of pure metals and of the improvement in dielectric properties of many substances at low temperatures. In addition, they are cables with forced cooling and the refrigerant extracting the heat produced in the conductor can be part of the electric insulation, as in oil filled cables.

Aside from the economic optimum, the increase in power can be achieved both by raising the current density and by increasing the conductor cross section. However, more detailed investigation shows that the economic optimum - as in the case of conventional cables - lies at current densities below 2 A/mm^2. Since, due to improved conductivity, only a comparatively small amount of heat must be extracted via the electric insulation, the conductor cross section can be increased within broad limits, so that even at the 110 kV level transmission capacities of several GVA per circuit are possible.

The advantages resulting from conductor cooling must be paid for by high expenditures for installation and operation of the refrigeration facilities. These various problems and the solutions proposed by various groups will be discussed in the sections below.

4.1.2 Technical problems of cryocables and their major components.

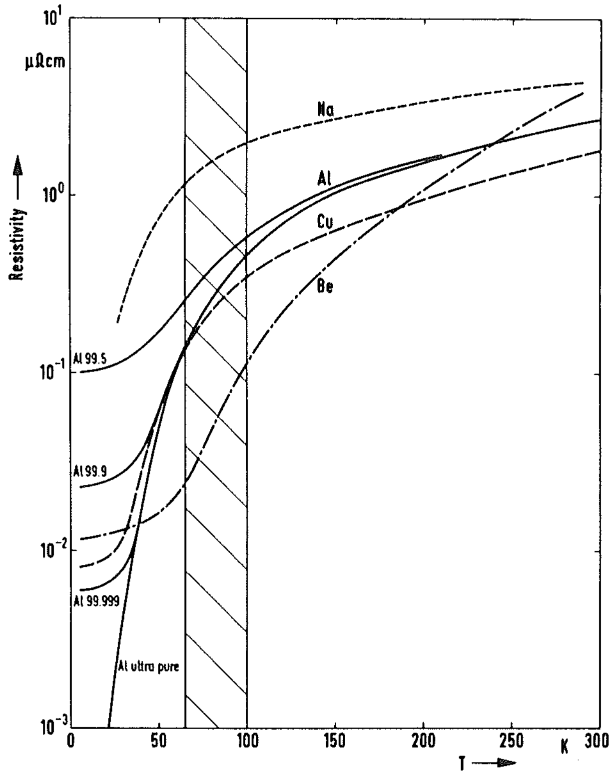
4.1.2.1 Conductors

As far as conductivity is concerned, aluminium, copper and beryllium seem to be particularly attractive conductor materials. The resistivity of beryllium is much lower in the temperature range of liquid nitrogen (LN_2) than that of all other materials (Fig. 4.1.1). Because of the high price (about 800 DM/l) and difficulties in processing, this material cannot yet be seriously considered a cable material. Only a reduction in beryllium costs by more than one order, for which there is presently no indication could offer an advantage over aluminium.
The more favourable resistance behaviour of copper against aluminium is also set off by the current transport costs on account of its higher material costs [4.1]. Consequently, aluminium is the only conductor material for more detailed studies used by all the groups.

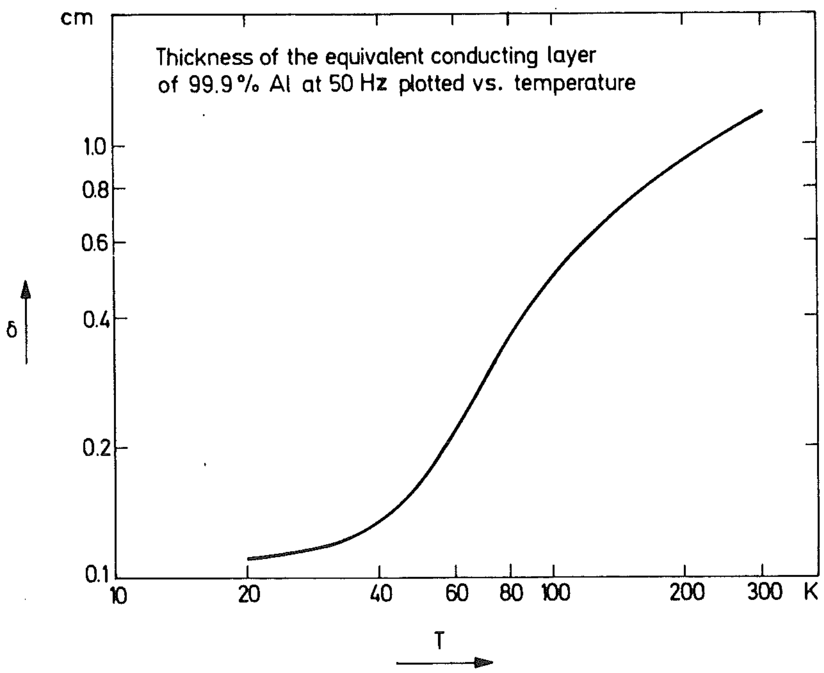
The use of pure metals at very low temperatures can decrease the dc resistance of an Al conductor by several orders of magnitude. With alternating current, however, the reduced resistance is accompanied by increasing current displacement effects (skin and proximity effects). The conductor designs applied must be adapted to these effects so that also for large conductor cross sections a uniform current distribution is ensured. In principle, this can be achieved by

a) tube conductors with sufficiently thin walls,
b) litz conductors whose sufficiently thin single conductors are insulated against each other and radially transposed.

Fig. 4.1.2 shows the penetration depth δ of 50 Hz alternating current for aluminium of 99.9% purity plotted versus the temperature. The depth of penetration, which strongly decreases with the temperature, calls for more expensive conductor assembly the lower the operating temperature and the better the conductivity of the cable. In spite of the present



<u>Fig. 4.1.1</u>: Resistivity of various conductor materials at low temperatures.



<u>Fig. 4.1.2</u>: Thickness δ of the equivalent conducting layer of 99,9% Al at 50 Hz plotted vs. temperature.

uncertainty with respect to fabrication costs, an estimate of the conductor and loss costs for transportation of a given current gives rise to the rather firm conclusion that cryogenic temperatures alone do not lead to a major reduction in current transport costs. This has been shown in [4.2] for both tube conductor (Fig. 4.1.3) and litz conductor cables (Fig. 4.1.4). Here the costs of the conductors and the costs of the losses including investment costs of the refrigerator plant have been plotted versus the conductor temperature for 110 kV cables with a transmission power of 1000 MVA. In the latter example, the largely uncertain cost part due to manufacturing a totally transposed litz conductor is described by two parts ($K/L = c_1A + c_2 \cdot n$). The first one, which is proportional to the cross section A; c_1 is taken in accordance with conventional conductors is assumed to be four times the material costs. The second one is proportional to the number of fabrication steps n, which, for a given cross section, depends on the diameter of the elementary wires. The specific fabrication costs have been varied over a wide range, but values of c_2 = 0.2 to 0.5 DM per cm and fabrication step are supposed to be the most realistic data. It can be seen from Fig. 4.1.3 and 4.1.4 that there is no distinct cost minimum in the whole temperature range.

Consequently, a reduction in current transport costs by the use of cryocables as against conventional cables can be anticipated only, if

a) the voltage required can be insulated at less cost, and
b) the transmission capacity can be increased to such an extent that the degression of specific costs due to size, which applies to all cables, can be fully utilized.

Since liquid nitrogen shows excellent dielectric values and LN_2-cooled cryocables can considerably increase the power there seems to be nothing to support the idea of using cryoresistive cables at even lower temperatures, which would imply the use of hydrogen or helium as refrigerants.

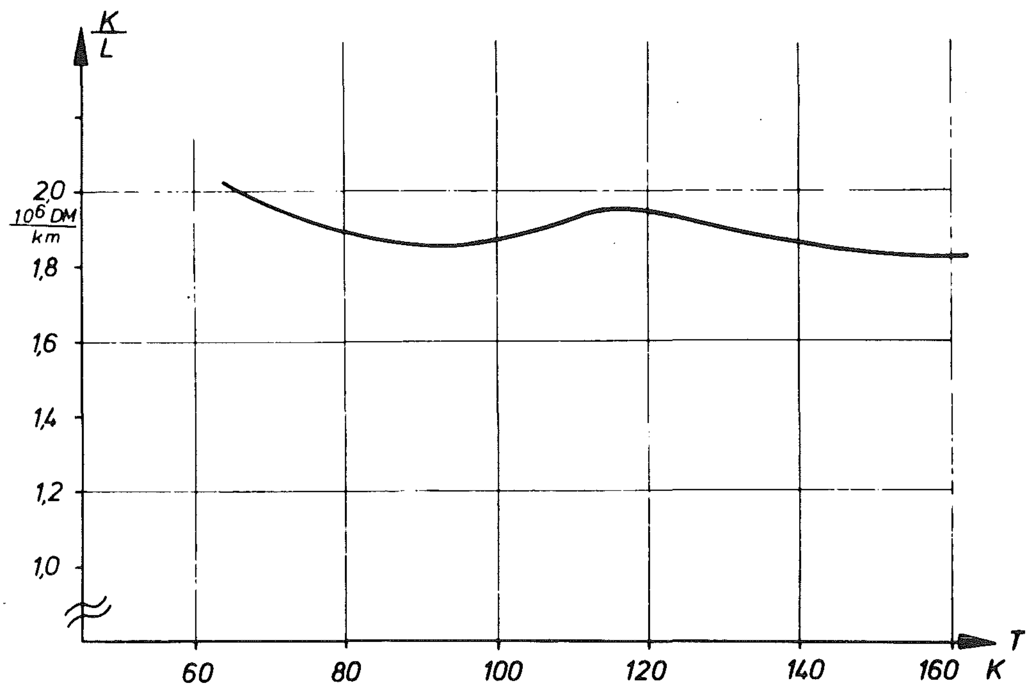


Fig. 4.1.3: Costs per unit length (K/L) of the losses and the conductor of a tube type cable for 500 MVA and 110 kV plotted vs. temperature [4.1].

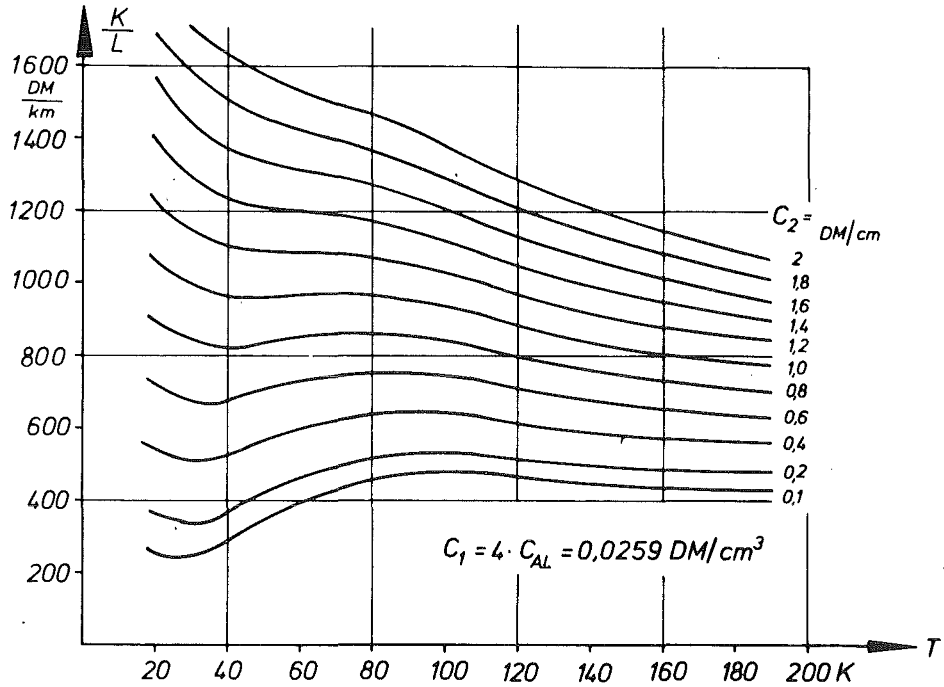


Fig. 4.1.4: Costs per unit length (K/L) of the losses and the conductor of a litz-conductor cable for various values of fabrication costs [4.1].

Further optimization within the LN_2 range yields a temperature span of 65 K inlet and 95 K outlet temperature and a current density of 1.5 A/mm^2 for stranded conductors and 2 to 3 A/mm^2 for tube conductors.

4.1.2.2 Electric insulation

The choice of the dielectric is an important factor in cryocable dimensioning. Three different types of insulation have been considered: LN_2, LN_2-impregnated paper insulation, and vacuum. At present, only the latter two types are considered as promising.

- Liquid nitrogen, generally used as a refrigerant, has dielectric properties at a pressure of 5 to 10 bar, which are even better than that of oil [4.3,4,5,6]. However, LN_2-insulated cables would call for a number of fixed isolators as a conductor support, and it is considered very difficult to find supports with a voltage strength similar to that of pure LN_2.

- The best results are presently achieved with synthetic papers (especially polyethylene tapes with a fibrous structure) impregnated with LN_2 at a pressure of several bars [4.3,7,8]. The voltage strength obtained with such insulations is approximately the same as that of pure LN_2 and the loss angle $tg\ \delta \sim 2 \cdot 10^{-4}$ is also sufficiently small. Based on test results obtained with cable sections of 10 to 30 m length at ac-voltages of 100 to 700 kV [4.7,8,9], cables with this type of insulation for 350 to 500 kV are being developed both in Japan (Furukawa, [4.9]) and the USA (General Electric [4.7]).

- Especially at low temperatures the insulating properties of high vacuum prove to be so favourable that the electric high vacuum insulation of cryocables can seriously be envisaged. Since thermal insulation requires a vacuum tight envelope of the cable anyway, major additional costs for providing the vacuum for electric insulation must be anticipated. The increase by 10 to 20% in voltage strength [4.3] and the very pronounced reduction in dark currents prove to be particularly phenomena at low temperatures. According to the present state of investigations, a limit of 250 kV must be accepted for alternating voltage [4.10,11]. Vacuum insulation can be considered only for cables with rigid tube conductors. Liquid nitrogen is circulated within the conductors. The spacers prove to be a particular problem. However, investigations by Graneau [4.12] on spacers equipped with ion shields show that inner discharges are self-extinguishing and do not greatly impair the function of the isolators.

Based on the encouraging results, some of which were obtained also with cable-like test models, the development of a vacuum insulated cryocable for 138 kV and 1000 MVA was initiated in the USA (P. Graneau at Underground Power Corporation and MIT, cf. section 4.1.3).

4.1.2.3 Cryogenic Envelope

The economy and, hence the technical feasibility of a cryocable depend very much on the quality and reliability of the thermal insulation. In recent years, high grade insulation systems have been developed, above all for LHe and LH_2 storage and transport systems. However, they cannot be used directly for LN_2-cooled cryocables in an optimum way, either technically or economically. Since there are considerable Joule losses in the loaded cable anyway (about 100 W/m for a 1000 MVA cable at 110 kV), a less effective insulation might be economical. The optimum solution largely depends on the respective cable concept and the application envisaged; however, the ideas developed by many research groups differ widely.

Hitachi [4.8,20] favours polyurethane foam insulation, which is supposed to be superior to multilayer insulation in construction, maintainance and costs. With an insulation thickness of 150 mm the heat leakage of a 275 kV/3000 MVA cable is reduced to 52 W/m. This is thought to be sufficient with respect to the 228 W/m conductor losses. Obviously, this type of insulation has been proved to be satisfactory in a 30 m long test arrangement [4.8] and it is used again in more advanced experiments [4.20].

A so-called superinsulation is much more effective. It consists of a multitude of radiation shields (aluminium foil or metalized polyester foil) insulated relative to each other by intermediate layers of a material of poor thermal conduction (polyester or glass fiber net) and placed in the high vacuum. To be effective, superinsulation requires a good vacuum ($p < 10^{-3}$ torr) and loose packing of the insulating foils (about 20 layers per cm). This insulation is used in most of the cable models investigated [4.7,9,13] and has proven to be effective in test sections already completed. An insulation thickness of about 10 mm proves to be sufficient for LN_2 cooled cryocables.To evacuate and maintain a vacuum, pumps are generally provided at distances of some hundred meters. After extended operating periods a pump distance will possibly do which is equal to the distance of refrigeration stations, namely 10 to 15 km [4.12]. However, after the first evacuation, the vacuum can also be maintained by better material with a high sorption capacity over very long periods of time at LN_2-temperature (e.g., zeolite) [4.15]. In this case it proves to be favourable to divide the insulation envelope into longer or shorter compartments evacuated and sealed during cable fabrication or field installation. This technique offers the advantage that a leak which might occur at a later date can easily be localized and does not necessarily entail cable breakdown because there will always be sufficient backup refrigeration capacity to cool a short, poorly insulated section.

Another group of authors [4.3] considers the use of powder insulation, which has also stood up well in cryoengineering.As to thermal conductivity, this type of insulation must be grouped between the insulation mentioned above. To achieve insulation values mearly as good as those of a superinsulation, 10 times the insulation thickness is required. However, full insulation capacity is reached already at a comparatively modest vacuum of about 10^{-2} torr. With a powder insulation of about 5 cm thickness the thermal losses e.g., for the 1000 MVA/ 400 kV cable [4.3], are reduced to less than 15% of the electric loss.

In summary, it can be said that thermal insulation is not so much a problem of technical feasibility than of economic optimization. For the time being, no clear statement in favour of a specific type of insulation can as yet be made.

4.1.2.4 Refrigerators

The cooling power needed for cryoresistive cables is 30 to more than 100 watts per meter. Because of the power dependent degression of refrigerator costs, the distance between the refrigerators should be as long as can be tolerated by the flow impedance of the coolant in the cable. This implies refrigerator distances of 10 to 20 km and cooling powers of several megawatts in the LN_2 range. Power consumption and heat rejection even amount to about seven times those values.

Refrigerators of this size represent existing technology in the fields of air separation and natural gas liquefaction. But as the power consumption of the refrigerator together with its capital costs amount to some 50% of the total power transmission cost of cryoresistive cable, a very careful optimization of refrigerators will be necessary. The two main systems discussed in the literature are the Claude cycle (Fig. 4.1.5) with N_2-refrigerant and the Bell-Coleman or Brayton cycle with neon (Fig. 4.1.6) [4.16]. The principal advantage of the Claude cycle is the low cost of the refrigerant (nitrogen) and the direct applicability of the well-developed technology of air separation plants.

The Brayton cycle is of a very simple set-up and its capacity can be adjusted economically to a growing demand just by the installation of additional compressors and expanders. By using ideal gas-like refrigerants such as He, H_2 of Ne it can produce subcooled LN_2 of about 65 K to feed the cable.

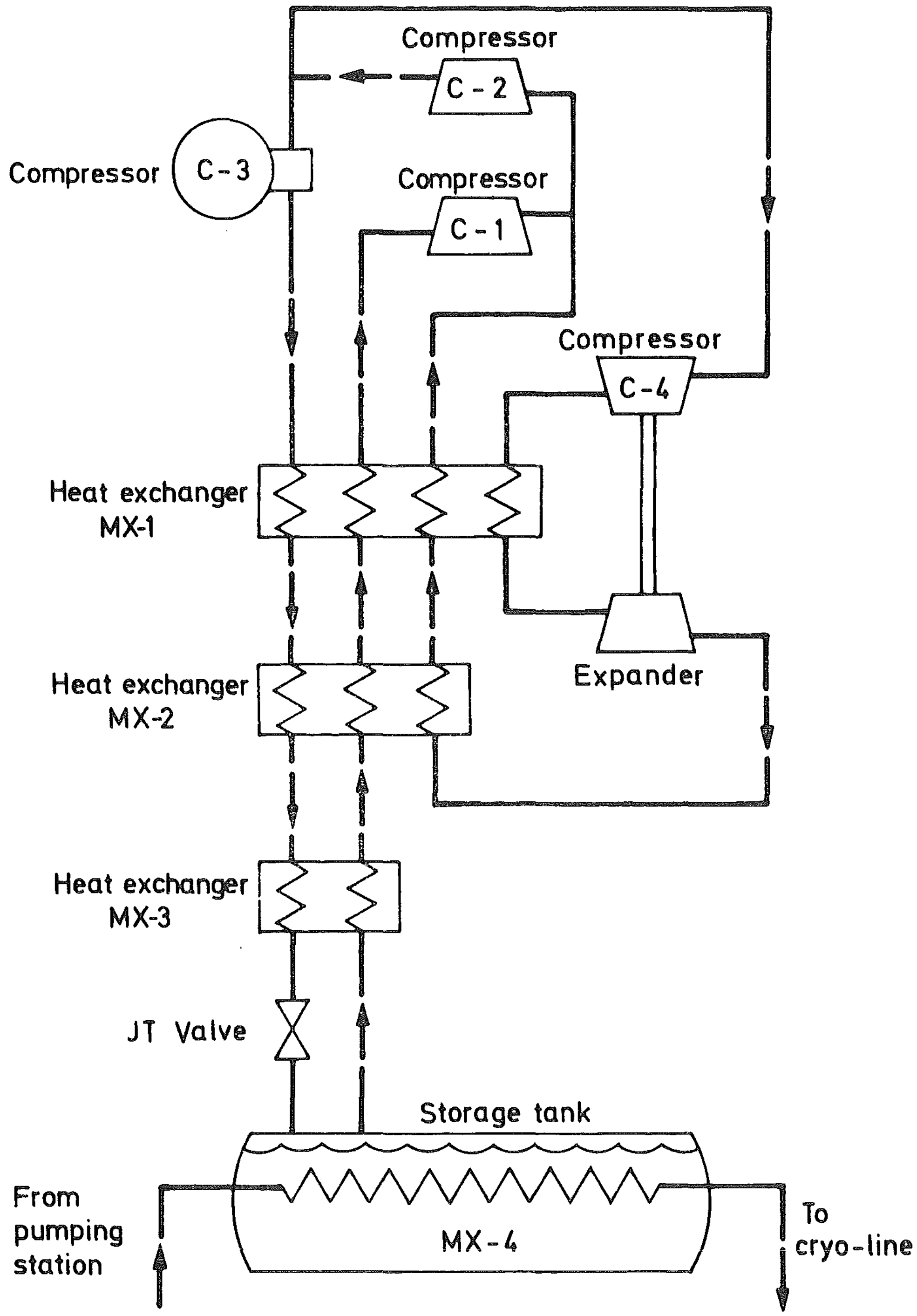


Fig. 4.1.5: Simplified flow diagram of an LN_2 refrigerator (Claude cycle).

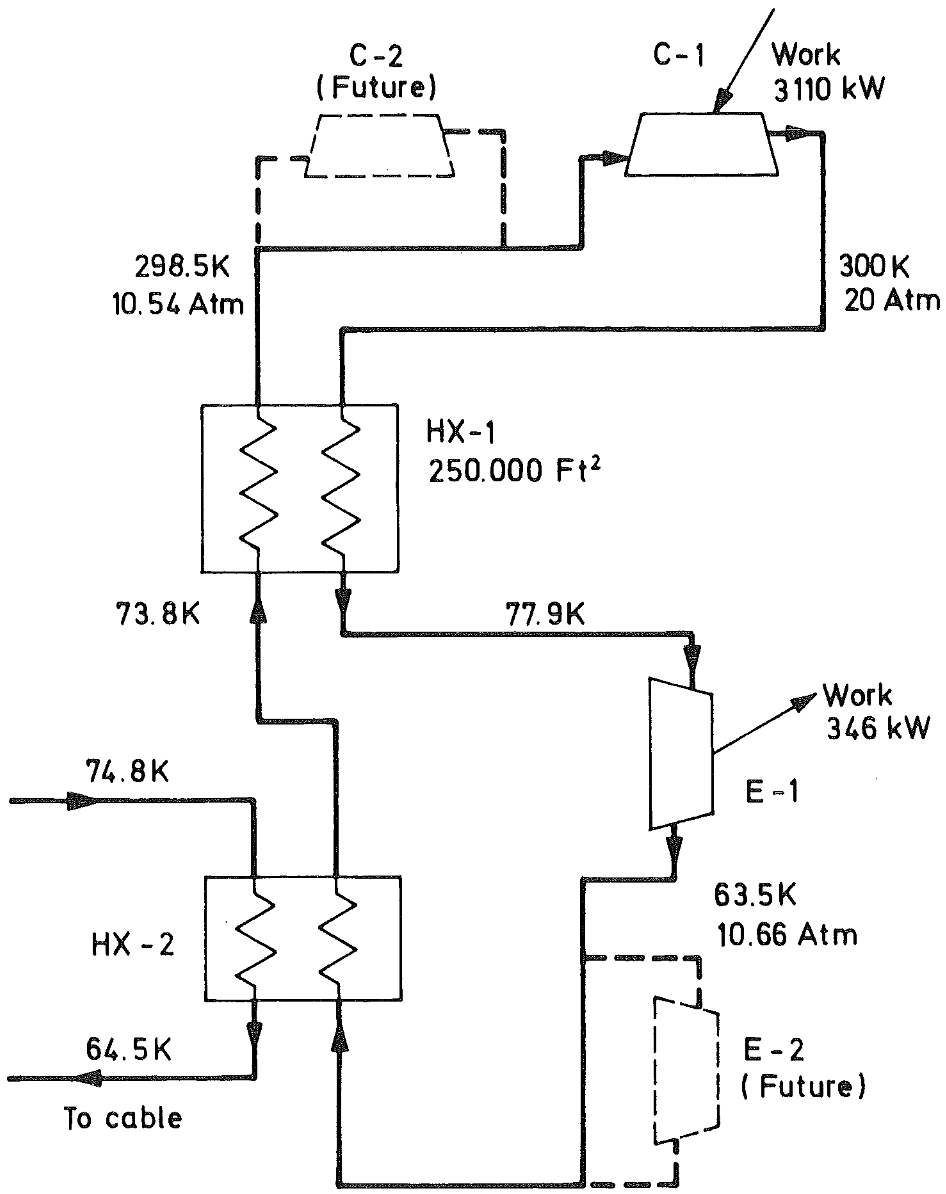


Fig. 4.1.6: Neon cycle refrigerator Bell-Coleman or Brayton cycle.

This will increase the refrigerator distance by about 100% against a 77 K-refrigerator [4.2]. The disadvantage of using the rather expensive neon is supposed to be balanced out by the reduced compressor costs compared with such lighter gases as He and H_2.

The refrigerator will be equipped with centrifugal compressors and expanders. Their reliability will be thus comparable to that of power stations and similar factors for amortization can be taken as a basis for calculation of the energy transport costs with cryocables.

The main field of cryocable application is to be found in the urban area. Most distances will be so short that the cable can be fed by one refrigerator plant situated in the suburban region. A closed loop is necessary to circulate the LN_2. For some cable concepts this implies a separate return line. It can be installed within the cryogenic envelope of the cable or separately. For a vacuum cable the conductors are thermally insulated; hence, one conductor can be used as a return line.

4.1.3 Special cable designs and summary of cryoresistive cable activities

Cryoresistive cables are developed by General Electric, USA, Underground Power Corporation with MIT and Vacuum Barier Corp., USA, and the Japanese firms of Hitachi, Furukawa, and Fujikara. Moreover, studies on economies and some fundamental investigations have been carried out by Electricité de France (EdF), Arthur D. Little Inc., USA, and KFA Jülich together with Felten and Guilleaume Kabelwerke (FGK) and Brown Boveri in Germany.

Actually, most of the activities are directed towards to the development of a.c. cryoresistive cables of the conceptional design shown in Fig. 4.1.7, i.e., a three-conductor cable with a flexible conductor and a polyethylene paper insulation. This concept is pursued especially by GE [4.7], Furukawa [4.9], and Fujikura and with some modifications (Fig. 4.1.8) also by Hitachi [4.8,20]. These firms fabricated cables of 10 to 30 m length which they subjected to current and high-voltage tests. The main design features and test results are listed in Tabs. 4.1.1 and 4.1.2.

At GE, the main effort is concentrated on very high voltage insulation. The electric breakdown voltage of the first cable was not as high as could be expected from measurements performed on smaller samples. But the results are not discouraging with respect to further efforts to build a 300 to 500 kV cable. Both Furukawa and Fujikura have reached their goals of completing a 154 kV insulation, and 500 kV tests are under preparation. At Hitachi, tests of a 30 m long 66 kV/100 MVA cable were finished successfully in 1972. On the basis of the test results a new cable for 3000 MVA at 275 kV rated voltage with a length of 20 m has been designed (Fig. 4.1.8). The thermal envelope of this test arrangement has been dimensioned with regard to the next class of cryocables in the 500 kV voltage range. The 275 kV experiments will terminate in 1976.

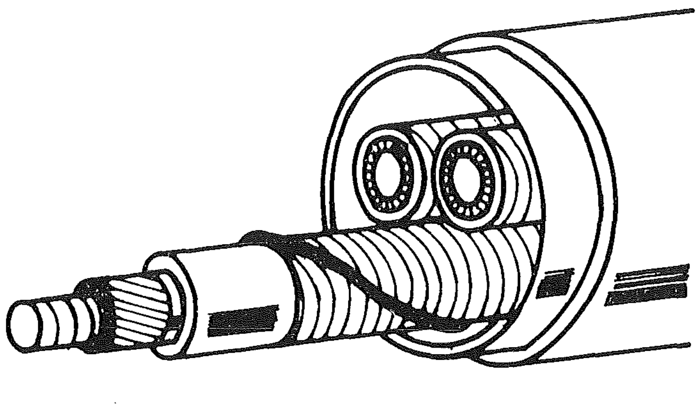


Fig. 4.1.7a: Conceptual design of a liquid nitrogen cooled cable system [4.7].

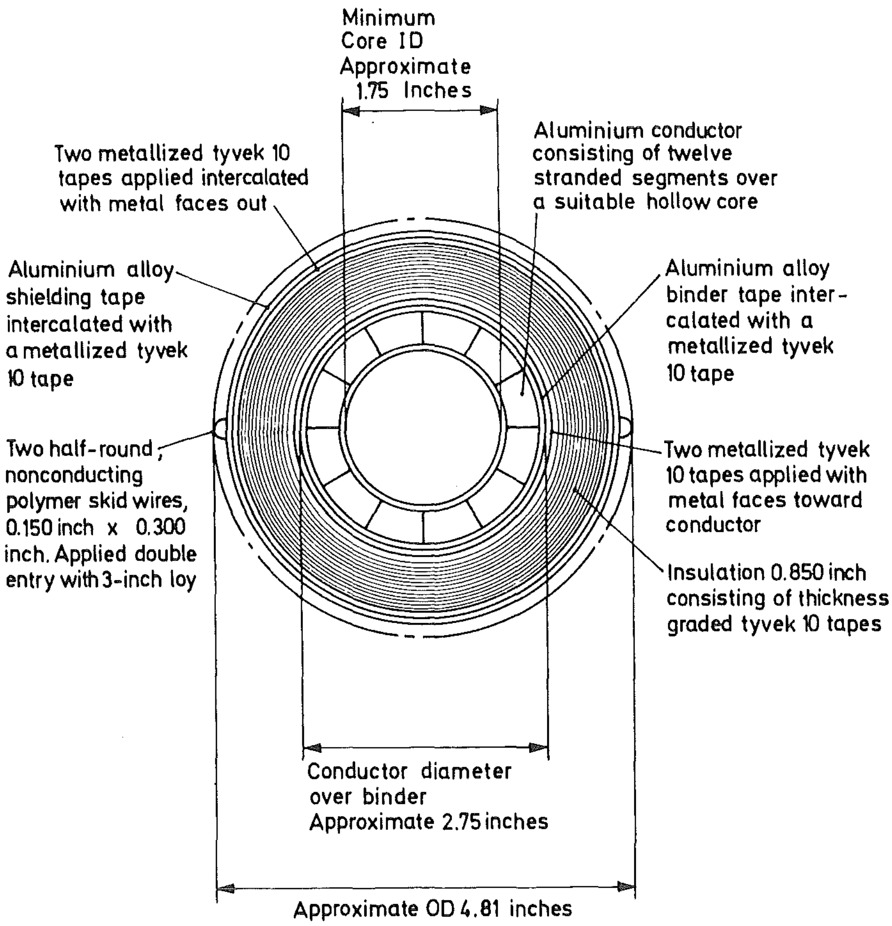


Fig 4.1.7b: Cross section of a prototype cable [4.7].

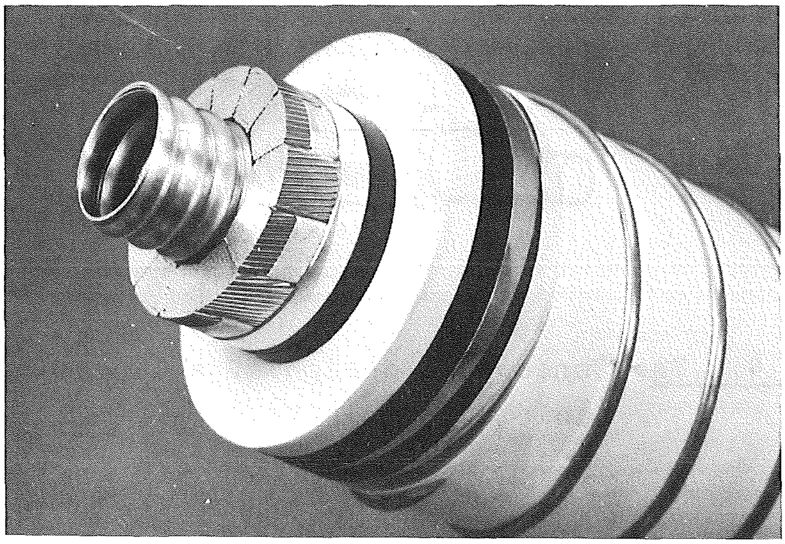


Fig. 4.1.8a: 275 kV cryoresistive cable by Hitachi. Cross section of cable core [4.20].

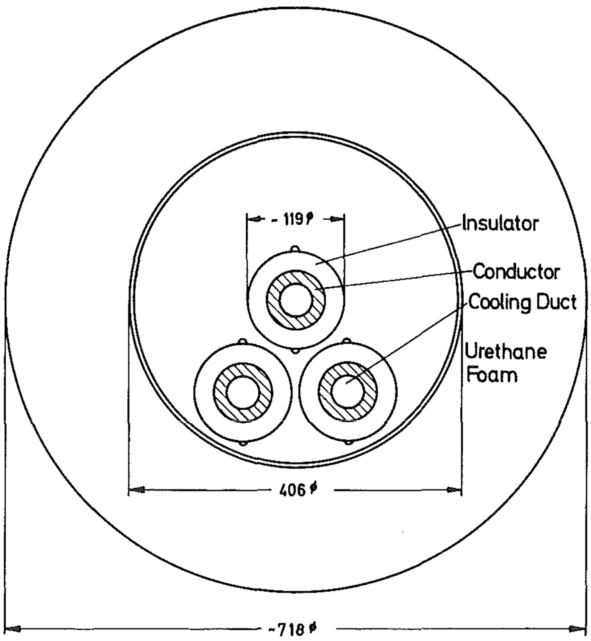


Fig. 4.1.8b: 275 kV cryoresistive cable by Hitachi. Cross section of cable [4.20].

Table 4.1.1: Synopsis of the manufactured test cables

	General Electric [4.7]	Furukawa [4.8]	Hitachi [4.9]	Hitachi [4.20]	Fujikura [4.19]	Underground Power Corp. [4.13]
Design values						
ac-Voltage (kV)	345/500	154	38/66	275	154	138
Power (MVA)	3000		100	3000		1000
Conductor	(s. Fig.4.1.7b)			(s. Fig. 4.1.8)		
	1 conductor	3 conductors	3 conductors		1 conductor	1 conductor
Material	Al	Al (99.99)	Al	Al	Al	Al
Cross section (mm^2)	1800	2400	104	2040	600	
Performance	12 segments wound on a spiral (45 mm i.d.), 37 strands (0,25-0,3 mm Ø) per segment	7 segments wound on a spiral (45 mm i.d.), each wire (2.0 mm Ø) formal coated	33 wires with 2.0 mm Ø wound on a spiral of 20 mm Ø	12 stranded segm. wound on a corrugated tube	ca. 2oo wires wound in 4 layers on a hollow core	
Diameter (mm)	70	75	24	$\approx$ 75	$\approx$ 30	50
Electrical insulation						
Material	Synthetic polyethylen paper (Tyvek)	PE paper (Tyvek) Polycarbonat film Polycarbonat film and PE film	PE paper	PE paper		Vacuum
Insulation thickness (mm)	21.6 (limited by the manufacturing capability)	12	7.75	$\approx$ 25	12,5	
LN_2-pressure a. temp.	5.6 bar at 80 K	5-10 bar at 77 K	5 bar at 77-85 K	16 bar 70-85 K		
LN_2-pipe		stainless steel	copper			
Diameter (mm)		380	122 x 2.5			
Thermal Insulation						
Material	Superinsulation	Superinsulation	Polyurethane foam	Polyurethane foam	Super-insulation	Super-insulation
Thickness (mm)			120	$\approx$ 150		
Overall diameter (mm)	ca. 700	650	360	718		

Table 4.1.2: Test results

	GE [4.7]	Furukawa [4.8]	Hitachi [4.9]	Fujikura [4.19]
Date of publication			1973	
Electric breakdown ac-voltage (el. strength)	435 kV (252 kV/cm) at the conductor surface; the cable was operated 5 days at 290 kV (167 kV/cm) without failure	Tyvek: > 230 kV (> 240 kV/cm)	250 kV (430 kV/cm). The cable was operated with 1000 A and 38 kV (66 kV/ $\sqrt{3}$) for 50 h without failure	> 410 kV
Impulse-voltage		Tyvek: 920 kV (950 kV/cm) Polycarb.: 780 kV (625 kV/cm) PE+Polycarb.: 820 kV (656 kV/cm)	526 kV (890 kV/cm)	
Dielectric loss	$< 5 \cdot 10^{-6}$ at 290 kV	Tyvek: $10 \cdot 10^{-6}$ Polycarb.: $450 \cdot 10^{-6}$	$< 10 \cdot 10^{-6}$ at 45 kV	
Current (conductor loss)	-	6000 A (61,6 W/m Ø) 8000 A (109 ") 12000 A (246 ")	100-1000 A (temperature rise: 5 to 8 K)	
Terminals	1 at one side for high-voltage only	3 at one side for current test, 1 at one side for high-voltage test	1 at each end for combined current and high-voltage test	1 at one end

The cable concept with a high vacuum dielectric is pursued only by P. Graneau at Underground Power Corp., USA. Experimental investigations by Graneau [4.18] have shown that the insulation for the 138 kV level can be made with a coaxial conductor arrangement having a 51 mm diameter inner tube, a 146 mm diameter outer tube and a length of about 5 m. The spacers consist of a series of concentric titanium rings of different lengths (ion shields) which are insulated against each other by Pyrex glass rods. It has been shown that there is little connection between the energy of the high voltage source and the damage produced by the sparks. Hence, it can be assumed that the cryocable connected to the bulk power transmission system will not suffer catastrophically from an internal spark.

Actually, a new single conductor test cable for 138 kV and 1000 MVA is being built. It will be tested with a 12 MW high voltage source at Waltz Mill. Connection to the utility system with a 500 MW short circuit capacity is planned at a later date. A parallel project was started on "Discharge experiments in vacuum insulation with high voltage capacitor equal to a capacitance of 50 miles cable length" [4.13,14]. It is assumed that this vacuum type cable can also be designed as a three conductor system (Fig. 4.1.9).

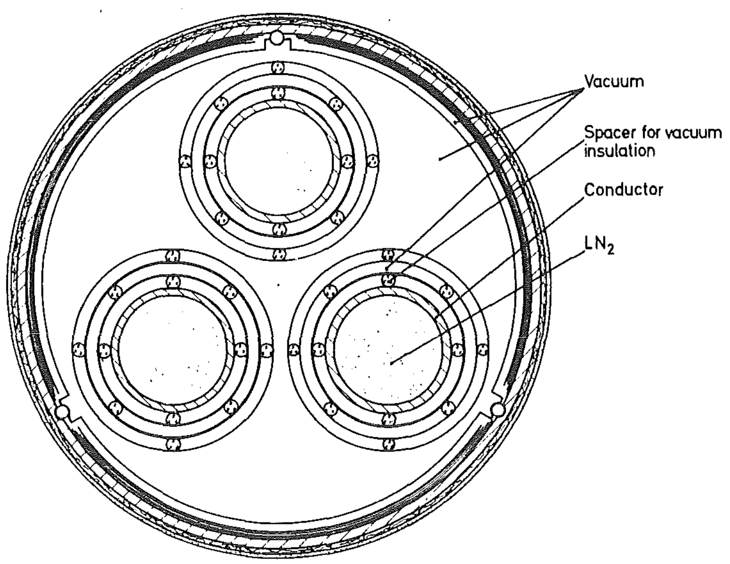


Fig. 4.1.9: Nitrogen cooled cable with vacuum high voltage insulation [4.1].

The use of vacuum for high voltage insulation will simplify the design of a cable in many respects. But since this concept is restricted to tube conductor cables, the overall diameter of a vacuum cable will be larger than of a litz conductor cable. Thus, the simpler design will not necessarily result in a cost reduction. (cf. section 6).

4.2 Superconducting cables

4.2.1 Activities in developing superconducting cables

The development of superconducting cables seriously began with the first proposals by McFee in 1961 and 1962 [4.21,22]. In 1963, the British company BICC (British Insulated Callenders Cables Ltd.) decided to design and build a superconducting link to test the feasibility of superconducting a.c. transmission. By the end of 1967 a superconducting a.c. transmission of about 2080 A was achieved with a three metres long single phase conductor system in a coaxial arrangement of tubular niobium conductors [4.23]. Since 1963, the Union Carbide Corporation in the U.S. began to study and develop superconducting cables [4.24]. In 1965, the ATF (Anstalt für Tieftemperatur-Forschung, Graz) in Austria started to work on superconducting cables [4.25]. Since 1970, the efforts undertaken in the U.S., in Europe and Japan to develop superconducting cables have increased considerably. Today several laboratories and companies work on superconducting cables.

European Activities: In the UK CERL (Central Electricity Research Laboratories) approximately since 1969 have worked on the superconducting cable development of BICC [4.26]. In France, the CGE (Compagnie Général d'Électricité) in collaboration with Air Liquide, ÉdF (Électricité de France) and LCIE (Laboratoire Central des Industries Électrique) work on superconducting cables [4.3,27]. In Germany, the Siemens AG and the AEG-Telefunken, Kabelmetal and Linde group began to develop superconducting cables around 1968 [4.28,29]. Other activities in Austria are due to the ATF and in the USSR to the Krzhizhanovsky Power Engineering Institute of Moscow.

Non-European Activities: In the U.S. the Union Carbide Corp., BNL (Brookhaven National Laboratory) and LASL (Los Alamos Scientific Laboratory) are engaged in the development of superconducting cables [4.24,30,31]. In Japan a national project has just been started on the basis of preliminary work at Furukawa, ETL et al. [4.32,33], whose development goals are a

1 km 500 kV a.c. and a ± 200 kV d.c. cable to be tested under service conditions within nine years.

Many laboratories all over the world are in search of new superconducting materials with high transition temperatures and of new methods of fabrication and incorporation of these materials into cables.

4.2.2 A brief description of some cable designs

All the superconducting cable designs proposed consist of at least two subsystems, the conductor system and the thermal envelope. The conductor system is a subsystem with temperatures from 4 K to 77 K. Here we have the inner and outer conductor, separated by the electrical insulation and cooled by helium flowing in helium ducts. In the case of a.c. cables, the triaxal arrangement of the three phases is most convenient. All conductors are enclosed in a helium pipe.
The temperature of the thermal envelope ranges between 77 K and 300 K. Here we have a radiation (or heat) shield cooled by liqiud nitrogen flowing in ducts or cooled by He-gas. This shield is thermally separated from the outer protection pipe by a thermal insulation (superinsulation or Alumina (Al_2O_3) powder).

Table 4.2.1 presents a survey of the most important features of some a.c. cable designs.
Table 4.2.2 indicates some tentative characteristics of superconducting d.c. cables.
Fig. 4.2.1 schematically shows the three mechanical designs under consideration (for one phase):

a) The rigid or pipe type concept
The conductor system and the thermal envelope consist of rigid tubes. This concept allows only fabrication length of about 20 m and entails many joints. To accomodate cable contraction during cooldown it is necessary to install bellows or, instead, use materials with low thermal contraction coefficients (such as Invar).

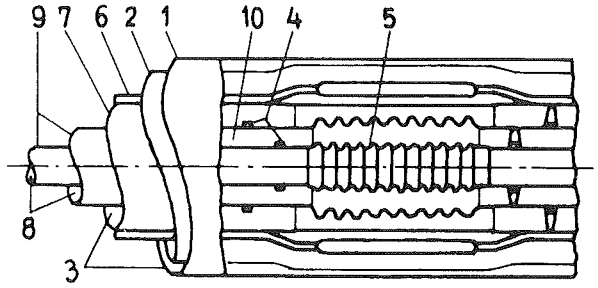
b) The semiflexible concept
The thermal envelope consists of rigid tubes with thermal contraction compensating bellows. The conductor system is flexible and consists either of corrugated tubular conductors or flexible hollow conductors made of wires or strips helically wound on the carrier. The fabrication length is about 200 - 500 m.

Table 4.2.1: Tentative characteristics of superconducting a.c. cables

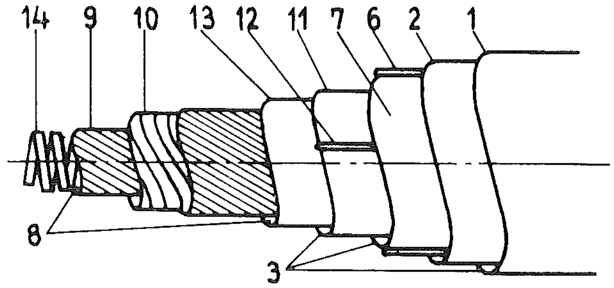
Company or Laboratory	CERL		Siemens	CGE/EdF		ATF	Krzhizhanovsky-Institute	Furukawa	BNL	Linde Union Carbide (UCL)			BICC
rated voltage (line-to-line) (kV)	132	275	120	140	180	110	35	154	132	138	230	345	33
rated current (kA)	6.1	8.5	12	12.4	16	2.65	10	3	13.8	7.1	11.8	17.75	13
rated power capacity (MVA)	(1400)	4000	2500	3000	5000	500	600	1000	3000	1690 (3400)	4710	10590	750
Principles of design	semiflexible three phases, triaxial arrangement. rigid tubular conductors	helically wound conductors	semiflexible three phases, triaxial arrangement. helically wound hollow conductors	semiflexible three phases		totally flexible three phases triaxial arrangement. corrugated tubes		rigid coaxial conductor pairs	semiflexible coaxial conductors, helically wound	rigid coaxial conductor pairs rigid tubes of Invar-Cu-Nb composite			rigid concentric tubes, triaxial arrangement
Conductor:													
Superconductor	Nb		Nb	Nb		Nb	Nb	Nb (foil)	Nb_3Sn (ribbon)	Nb			Nb (foil)
Stabilisation material	Cu/Al	(Cu)/Al	Al/Cu	Cu		Cu/Al		Cu	Al/Cu	Cu			Al
Linear current density on inner conductor (A/cm)	400	340	550	520	555			240	320	580	580	580	190
Electrical insulation	wrapped plastic multilayer foil (PE-tape) + He		wrapped plastic foil	wrapped foil insulation (PE)		He (10 atm)		wrapped plastic foil	He impregnated tape wrap	supercritical Helium solid dielectric spacers			Vacuum Helium
Cryogenic envelope	LN_2-shield Superinsulation steel pipe		LN_2-shield (Invar) Superinsulation	LN_2-shield (Invar) Alumina powder, Vacuum steel pipe		LN_2-shield Vacuum flexible Dewar		LN_2-shield Superinsulation	LN_2-shield Superinsulation	He-gas cooled Cu-shield Superinsulation			LN_2-shield Superinsulation
Overall diameter of cable (cm)		46,5	~50	60,4	70,8	25			42	~34 (60)	~47	~63	
Losses:													
cable (kW/km)		87	85 (100)						211 (6.2.-8.2.K)	(99)			
per terminal (kW)		~125	50-100 (150)							(75-150)			
Heat inleak at 4.2 K:													
cable (W/km)		288	200	300	400	300			1314 (6.2.-8.2.K)				
per terminal (W)		410											
Cryogenic performance coefficient (W/W)		~300	~400						161				
Comments	8 m-long one phase loss measurements actually test test model		30 m-model cable, one phase (120 kV, 12 kA) in preparation	18 m-full scale cryogenic envelope			12 m-long one phase test model	7 m-long test section, current tests	2 x 20 m long flexible cryogenic envelope in preparation	7 m-long test facility for a.c. measurements			historic 3 m-test cable. 2080 A 1967 1969 end of program

Table 4.2.2: Tentative characteristics of superconducting d.c. cables

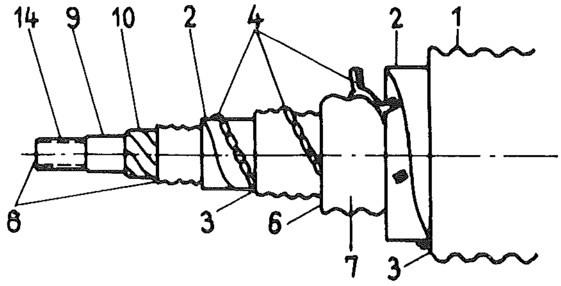
Company or Laboratory	AEG-Kabelmetal-Linde	CGE/EdF		LASL	Furukawa	CERL	Siemens
rated voltage (kV)	±200	±110	±140	100	110	230	230
rated current (kA)	12.5	13.6	17.9	50	45.5	17.4	44
rated power capacity (MVA)	5000	3000	5000	5000	5000	4000	10000
Principles of design	totally flexible parallel single conductors, helically wound	semiflexible coaxial conductors		semiflexible parallel and coaxial conductors	rigid coaxial conductor pairs	rigid (pipe type) coaxial conductors helically wound strips	semiflexible helically wound hollow conductors
Conductor:							
Superconductor	Nb_3Sn (ribbon)	Nb_3Sn		$Nb_3Sn/Nb_3(AlGe)$	NbTi	Nb-Ti-Zr	NbTi
Stabilisation material	Cu	Cu		Al/Cu	Cu	Cu/(Al)	Cu
Linear current density on inner conductor (A/cm)		2070	2180				
Electrical Insulation	wrapped paper	Mylar		Kapton or Mylar wrap	wrapped plastic foil	lapped polymer with He-gas	wrapped plastic foil
Cryogenic Envelope	LN_2-shield Superinsulation	LN_2-shield (Invar) Alumina powder, Vacuum steel pipe		LN_2-shield (Al) Superinsulation steel pipe	LN_2-shield Superinsulation	LN_2-shield Superinsulation steel pipe	LN_2-shield (Invar) Superinsulation
Overall diameter of cable (cm)		27,6	30	$\sim$25	$\sim$30		$\sim$45
Losses:							
cable (kW/km)	70					20	55
per terminal (kW)	55					63	125 - 250
Heat inleak at 4.2 K:							
cable (W/km)	110	51	64	30		66	
per terminal (W)	120					210	
Cryogenic performance coefficient (W/W)						$\sim$300	
Comments	joints constructed, 16 m current tests 20 m voltage tests in preparation						under study



a) Rigid or pipe type



b) Semiflexible type



c) All flexible type

Fig. 4.2.1: Mechanical superconducting cable designs (G. Bogner, Siemens AG).
1 - Protection pipe, 2 - Superinsulation,
3 - Vacuum, 4 - Spacers, 5 - Bellows,
6 - Nitrogen, 7 - Heat shield (77 K),
8 - Helium, 9 - Superconductor, 10 - Electrical insulation, 11 - Heat shield (∿ 10 K),
12 - Helium return, 13 - Helium pipe, 14 - Support

c) The all flexible concept.

Both the conductor system and the thermal envelope are flexible. The thermal envelope consists of corrugated tubes. The conductor system is built up like the semiflexible concept. The fabrication length is limited to 200 - 300 m by transport on the drum. Transport problems limit the outer cable diameter to about 25 cm.

Presently, most cable designers prefer the semiflexible or flexible concepts because of the smaller number of joints.

The most important features of superconducting cables (conductor material, electrical and thermal insulation, cable cooling, terminals) are briefly described below. This is followed by a detailed discussion of cable designs.

Conductor: The choice of the superconducting materials is influenced by hysteretic losses to be expected at the operating current and temperatures, by the physical properties necessary for fabrication and subsequent satisfactory operation, and, last but not least, by overall systems design decisions with respect to cryogenics, cable design, electrical system, material properties and economics. The conductor materials preferred for a.c. superconducting cables is pure niobium, because of its high H_{c1} (= 0.126 T at 5 K), high critical temperature T_c (= 9.2 K at B = 0) and low a.c. losses. In the BNL design, Nb_3Sn is provided as the superconductor. Nb_3Sn has higher a.c. losses than Nb (cf. Fig. 4.2.2 a,b), but due to the high T_c ($\sim$ 18 K) the operating temperature of the cable can be raised, which reduces the required cooling power.

For d.c. cables, where no a.c. losses occur, the hard superconductors Nb_3Sn and NbTi are used. Also the ternary alloys Nb-Ti-Zr and $Nb_3(AlGe)$ are under study.

The superconductors are used in the form of thin surface layers (thickness 25 - 50 μm) on a normal material (Al or Cu) as the substrate, necessary for structural and stabilization (shunting) purposes. Coaxial conductor systems can be made out of rigid tubular conductors or corrugated tubular conductors or flexible hollow conductors built up of wires or strips. The conductors used must be able to withstand fault currents. This is a very

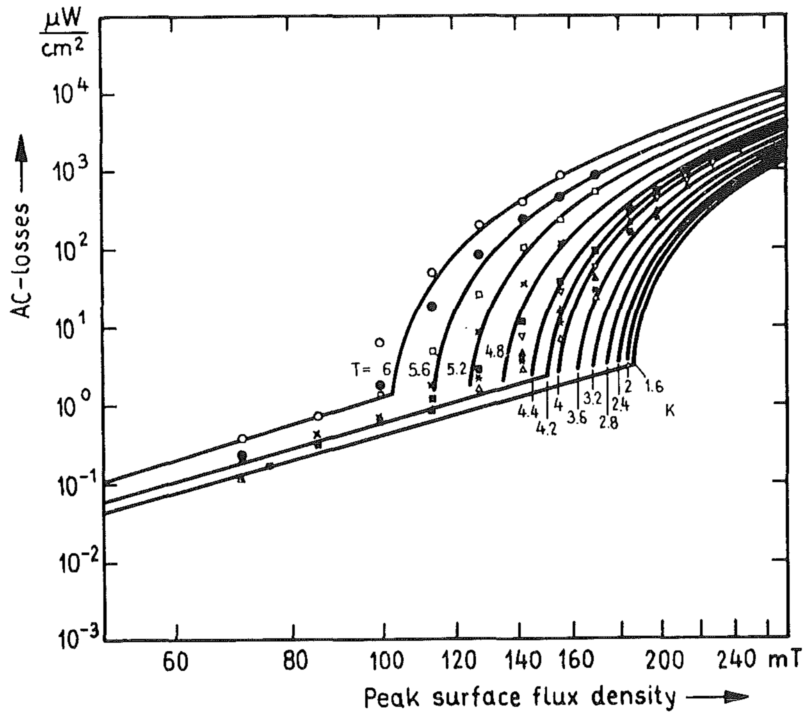


Fig. 4.2.2a: 50 Hz a.c. losses of Nb conductors at temperatures from 1.6 K to 6 K (P. Penczynski, Siemens AG).

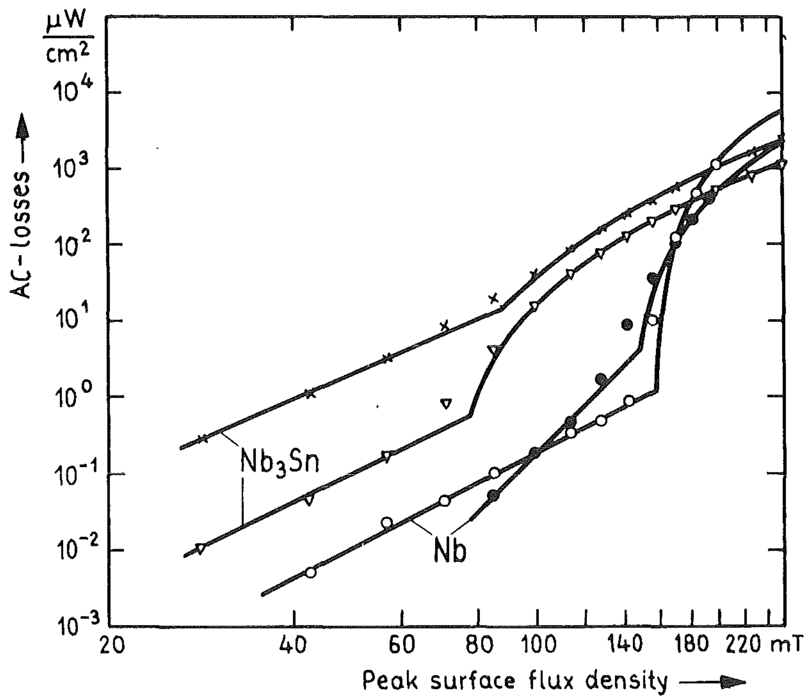


Fig. 4.2.2b: 50 Hz a.c. losses of Nb and Nb_3Sn conductors at 4.2 K (P.Penczynski, Siemens AG).

serious problem which needs experimental investigation. During a fault the a.c. wave amplitude may rise to more than ten times the usual value. In the case of Nb, it will be driven normal during the fault and an alternative current path must be provided. One alternative may be the use of high pure Al or Cu as the substrate, another one a layer of hard type II material, such as NbTi, placed between Nb and the substrate.

Electrical Insulation: The electric insulations between the inner and outer conductors considered are vacuum, liquid or supercritical helium and wrapped plastic foils (polymers) impregnated with helium.

For an a.c. superconducting cable the prime consideration in the choice of dielectric material is the (frequency and voltage dependent) dielectric loss, because the heat generated by the dielectric losses must be removed at a low temperature level. A $\tan\delta$ of $< 10^{-5}$ is required at operating temperature. The second quantity under consideration is the dielectric strength, which must be as high as possible.

Vacuum and helium have an extremly low $\tan\delta$ ($< 10^{-6}$), but vacuum can only be used with rigid or corrugated tubular conductors and requires absolute leak-tightness of the system. Helium has a low dielectric strength, which is strongly dependent on impurities, pressure and temperature. The most promising electrical insulation seems to be wrapped polymers impregnated with helium. These polymers (such as PE, polypropylene, PTFE, synthetic paper) have a $\tan\delta$ of about 10^{-5} at 4.2 K. Fig.4.2.3 shows the dielectric strength at 4 to 5 K vs the insulation thickness for vacuum, helium and PE and Tyvek (synthetic paper) impregnated with He. These results were obtained on laboratory specimens. Definitive information can only be obtained from long term experiments on prototypes of sufficient length.

In a d.c. superconducting cable no dielectric losses occur; therefore the choice of the dielectric material is dictated first of all by the dielectric strength.

Thermal Insulation: In the case of superconducting cables the heat influx from the outer cable pipe, i.e., from the ambient temperature to the helium-cooled conductor system, must be reduced as much as possible because Helium refrigerators have a very low efficiency.

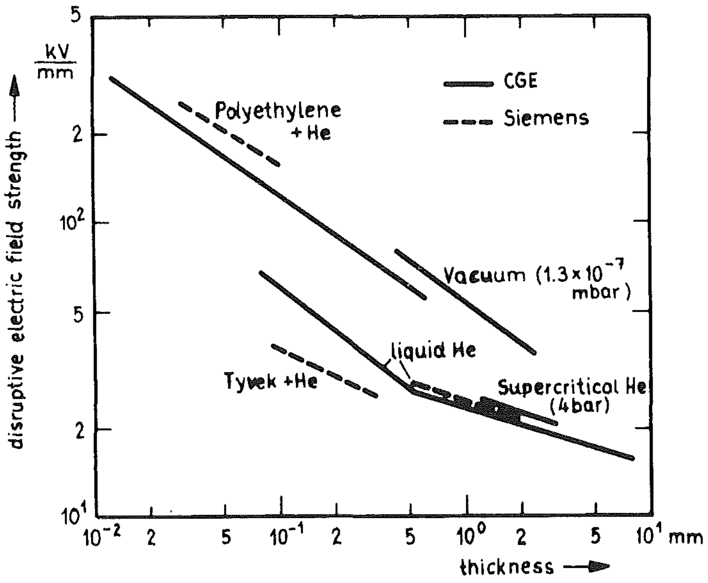


Fig. 4.2.3: Dielectric strength of various insulating media at 50 Hz and temperatures around 4 K (Measurements by CGE and Siemens AG).

Therefore, the inner cable system is enclosed in a cryogenic envelope. This envelope contains a screen to absorb the heat radiation and heat conduction down supports from 300 K. In most cases the screen is cooled by liquid nitrogen. Only in the Union Carbide design He-gas cooling of the shield is provided. Between the screen and the outer protection pipe there is a thermal insulation material to reduce the radiation heat inleak. The thermal insulation material used in most cases is superinsulation (many layers of aluminized mylar sheets) or Alumina powder (in the CGE/EdF design). The envelope is kept at a vacuum of about 10^{-2} Nm^{-2} ($\sim 10^{-4}$ torr) to prevent heat convection. The outer protection pipe is a steel pipe (rigid or corrugated), while the screen material is Cu, Al, or Invar (preferred for its low coefficient of linear thermal expansion, to reduce thermal stresses). The radiation shield is rigid or corrugated.

Cable cooling: The working fluid in the conductor system is helium because Nb or Nb-alloys must be maintained at a temperature below 8 K for adequate use of their superconducting properties. The radiation shield is cooled by liquid nitrogen or He-gas. Nitrogen or helium are cooled in the appropriate cryogenic aggregates. The optimum spacing of cable cooling stations can vary between 5 km and 30 km, depending on cable rating and design. In the case of the 120 kV, 2500 MVA a.c. design by Siemens, the losses per km cable at the 80 K temperature level (nitrogen-cooled radiation shield) are about 2500 W and at 4 K (helium-tube) about 200 W. For 10 km cable length and a CPC (cryogenic performance coefficient = ratio of watts of power to refrigerator to watts of cable losses plus heat leak) of 10 at 80 K and 400 at 4 K a cryogenic facility with a power input rating of about 1.3 MW (including terminal cooling) is required. Such facilities already exist.

A disadvantage of superconducting cables is the large quantity of liquid helium needed. The CGF/EdF a.c. designs for 3000 MVA and 5000 MVA need about 50 - 100 l/m liquid helium for cable filling. For a 10 km line this corresponds to about 500 - 1000 m^3 of liquid helium. The d.c. 4000 MVA design from CERL needs about 15 l/m liquid helium for cable filling. For a 100 km line (this is the approximate lower limit of application for d.c. superconducting cables) this corresponds to some 1500 m^3 of liquid helium (corresponding to some 10^6 m^3 gas at standard temperature and pressure).
Terminals: In an existing normal conduction system with a superconducting connection link large currents at a high voltage must be fed in at the cable terminals from ambient temperature (300 K) to very low temperatures (4 K) with losses as low as possible This requires additional cooling. This problem is augmented by the fact that at the same time the high potential must be insulated. So, the well known designs for optimum current leads for cryogenic devices are not directly applicable.

A comparison of estimated cable losses and terminal losses in Table 4.2.1 and 4.2.2 shows that superconducting cables are uneconomical for short lengths. In the 4000 MVA a.c. design by CERL with an Nb conductor the estimated loss per terminal of about 125 kW corresponds to an equivalent cable length of about 1.5 km. In the Siemens 10000 MVA d.c. cable design with an NbTi conductor the equivalent cable length is about 2.3 - 4.5 km. In the 4000 MVA d.c. design by CERL the equivalent cable length is about 3 km. With d.c. cables this problem is not important, because only large lengths are under consideration.

4.2.3 Discussion of a.c. superconducting cable designs

Many designs of a.c. superconducting cables have been published with different kinds and arrangements of conductors and different dielectrics. The conductor configurations proposed try to meet two requirements, first, to limit the electromagnetic fields between the superconductors to avoid hysteretic losses in normal conducting cable components; second, to keep the magnetic flux densities at the superconductor surface as low as possible to minimize superconducting a.c. losses.

Fig. 4.2.4 shows an example of an all-coaxial design of an a.c. cable. The phases of the cable are enclosed in a single cryogenic envelope which provides the thermal insulation; separate envelopes for each phase would be too expensive. To have a complete field compensation at symmetric load, one phase (S in this case) must be subdivided in two phases, S_1 and S_2, so that the currents in the succeeding coaxial conductor pairs are phase shifted by 180^{o}. This requires additional phase shifters. In a symmetrical arrangement there are no forces between conductors. In reality, no complete field compensation is achieved because of the different impedances of the phase conductors. Unbalanced load augments this effect. Slight axial misalignments of the conductors generate vibratory forces which are several times the weight of the conductors during faults. They have to be considered when designing the spacers. This all-coaxial conductor arrangement is the most compact design, but it would be difficult to assemble.

Fig. 4.2.5 shows the most popular trefoil design. Each phase of the cable consists of a coaxial conductor pair. The inner conductor carries the phase current at the phase voltage, the outer one acts as an electromagnetic screen and as the helium wall. The three phase conductors have equal impedances so that complete field compensation is achieved. One disadvantage of this configuration is the larger quantity of superconducting material needed. In addition, the a.c. losses are higher as a result of the larger surface. A possible circuit diagram of the three phase a.c. cable is also shown in Fig. 4.2.5, which allows complete field compensation in the case of unbalanced load.

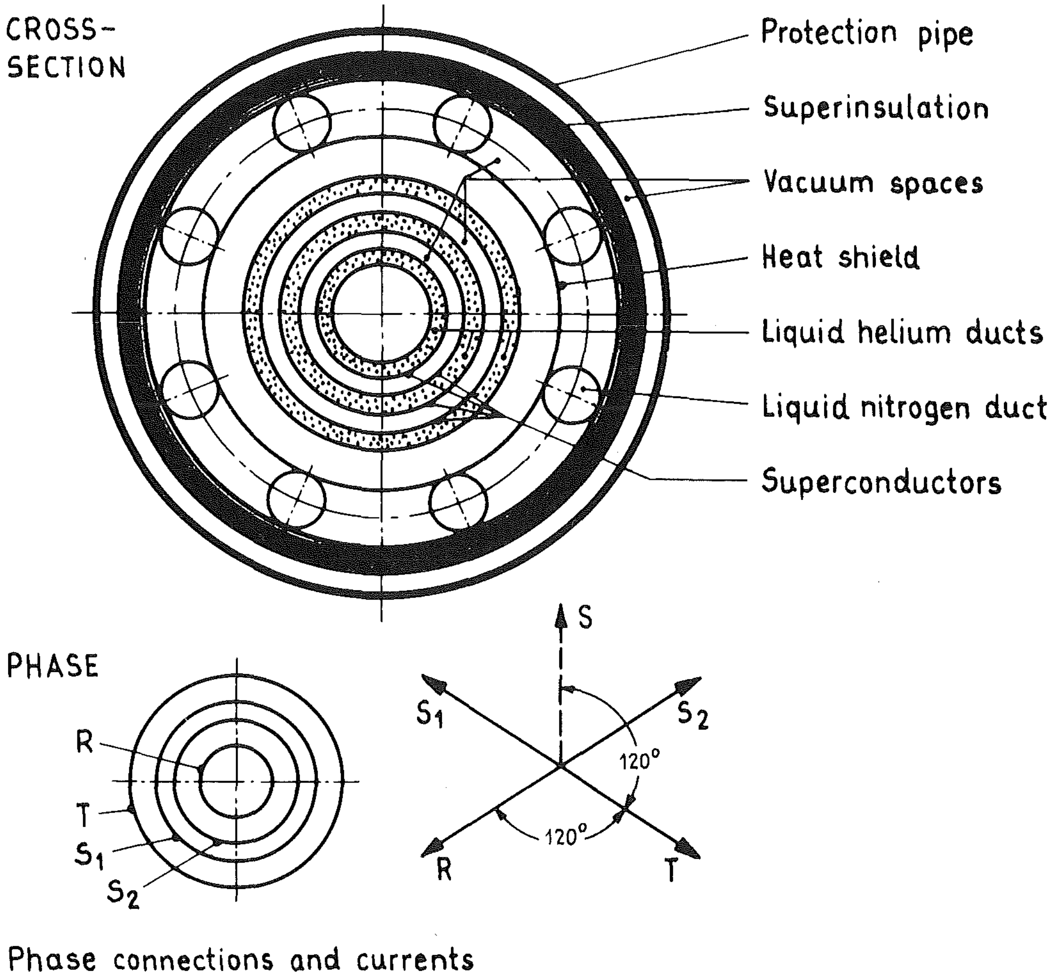


Fig. 4.2.4: All-coaxial design for a three phase a.c. cable (E.C. Rogers, D.R. Edwards: Electr. Rev. 181, 348 (1967)).

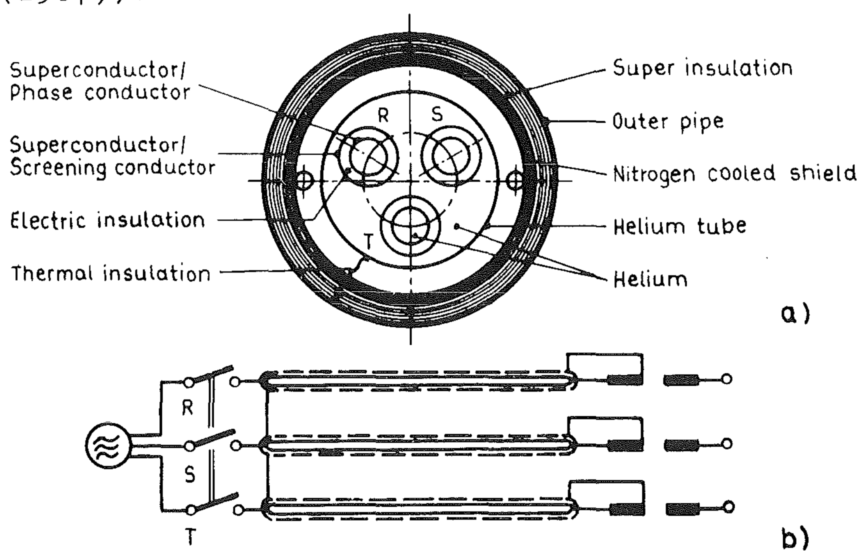


Fig. 4.2.5: Schematic set up and circuit diagram of a superconducting three phase a.c. cable (G. Bogner, Siemens AG).

Fig. 4.2.6a shows the principal structure of one phase, while Fig. 4.2.6b indicates a detailed design avoiding the problem of thermal contraction. The conductor is formed by helically laid strips and the electric insulation is made of lapped tape dielectric. The inner conductor is laid on a helical nonconducting former, the outer one on the outside of the dielectric held down with skid wires. This single phase construction is flexible and could be pulled into the helium pipe in long lengths. The lapped tape offers about three times the electric strength of helium alone, hence a higher operating voltage, a more compact cable, and lower total cost. The conductor plus dielectric would be very light, but would also be a mechanically weak structure. Satisfactory behaviour during drumming, pulling, cooldown, and during pressure transients from fault currents may be a problem.

Fig. 4.2.7 shows the CGE/EdF design of a superconducting three phase a.c. cable. In this design, Alumina powder under vacuum is used as a thermal insulation material between the split ambient temperature steel pipe and the radiation screen. This kind of thermal insulation is easier to handle during installation as it needs no spacers and no wrapping process.

Fig. 4.2.8 shows a 4 GVA a.c. cable design by CERL. The dielectric is polyethylene tape, and each phase of the cable is cooled by internal flow of helium. The two smaller pipes carry the 'go' flow, and the larger pipe, which absorbes most of the heat inleak, carries the 'return' flow. The screen is cooled by liquid nitrogen in eight ducts, four 'go' and four 'return' ducts, and the whole system is enclosed in a single steel pipe of 465 mm outer diameter. All the inner pipes and ducts are straight tubes made of low thermal contraction alloy with bellows at the joints. They are held in place by straps and spacers at intervals along their length and are supported by studs resting on the outer steel pipe.
The phase-to-phase voltage is 275 kV, and a working stress of 80 kV/cm at the inner conductor is assumed. The corresponding stress under the impulse voltage of 1050 kV is 530 kV/cm. A simple Nb/Al strip conductor is assumed with a linear current

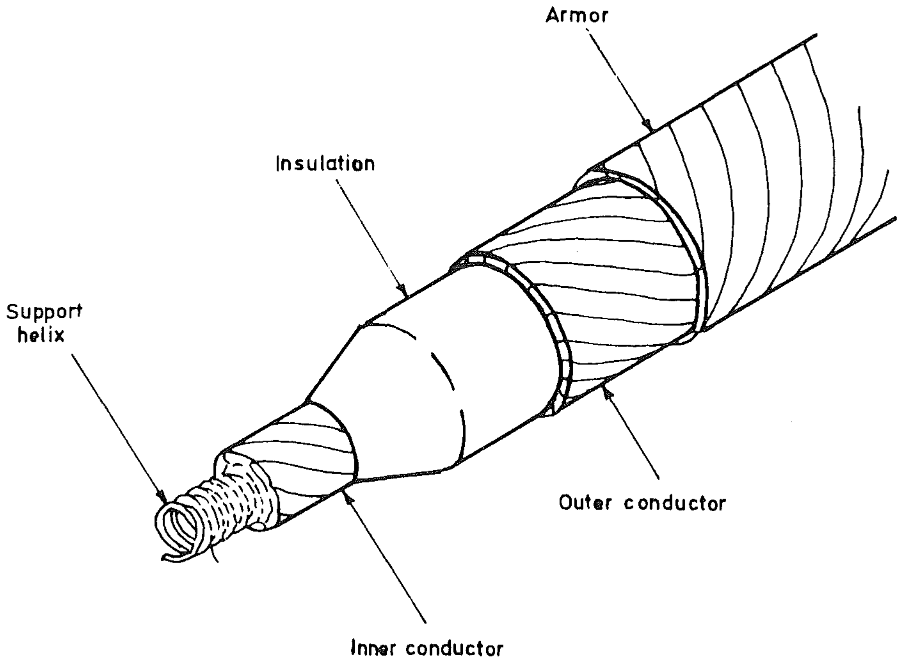


Fig. 4.2.6a: Flexible coaxial cable (one phase)
(E.B. Forsyth et al.: BNL 50325 (1972)).

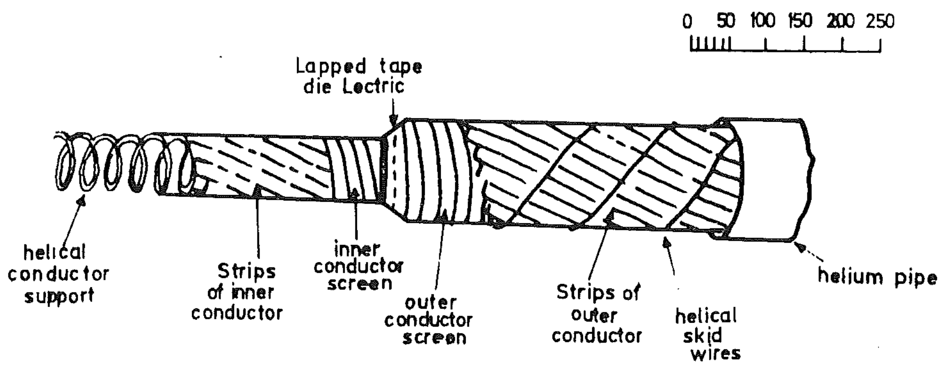


Fig. 4.2.6b: Details of cable construction with a lapped tape dielectric (J.A. Baylis: 1973).

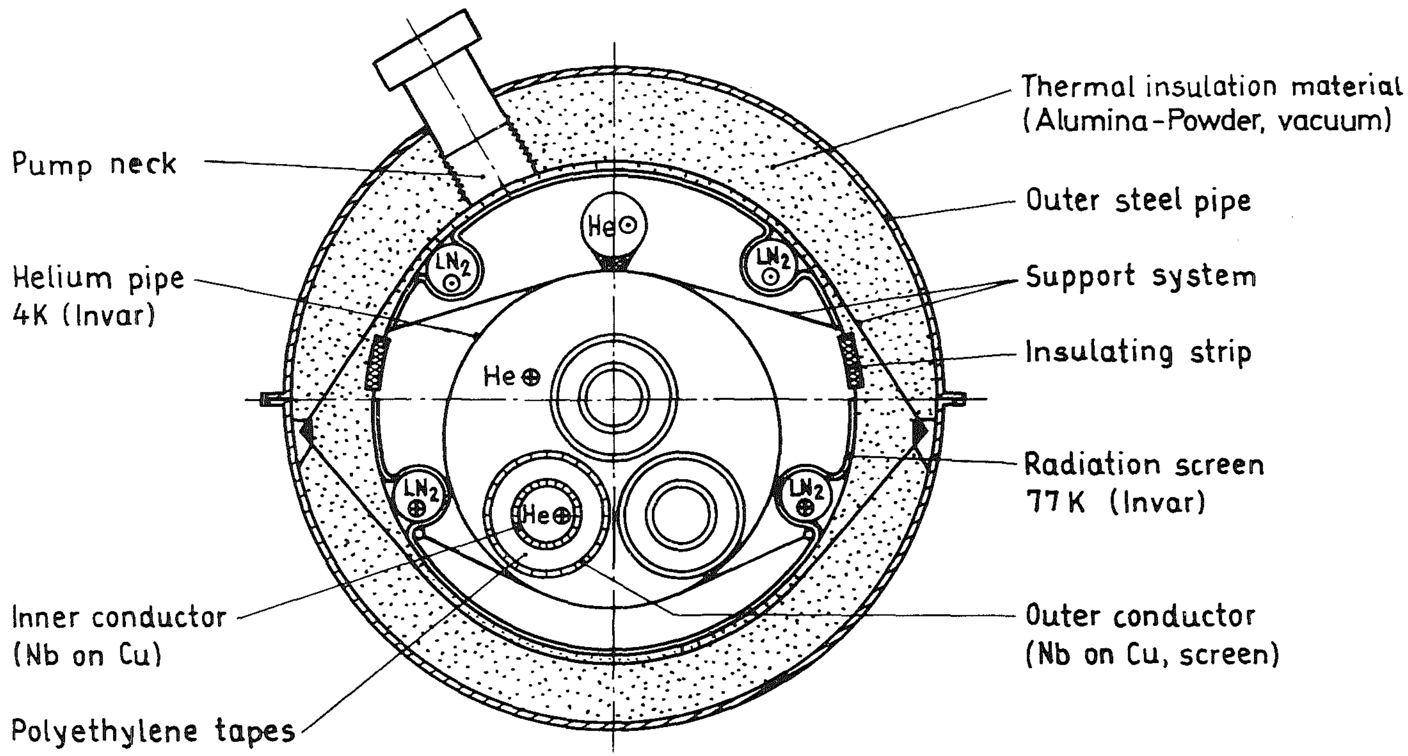


Fig. 4.2.7: Superconducting three phase a.c. cable (CGE/EdF).

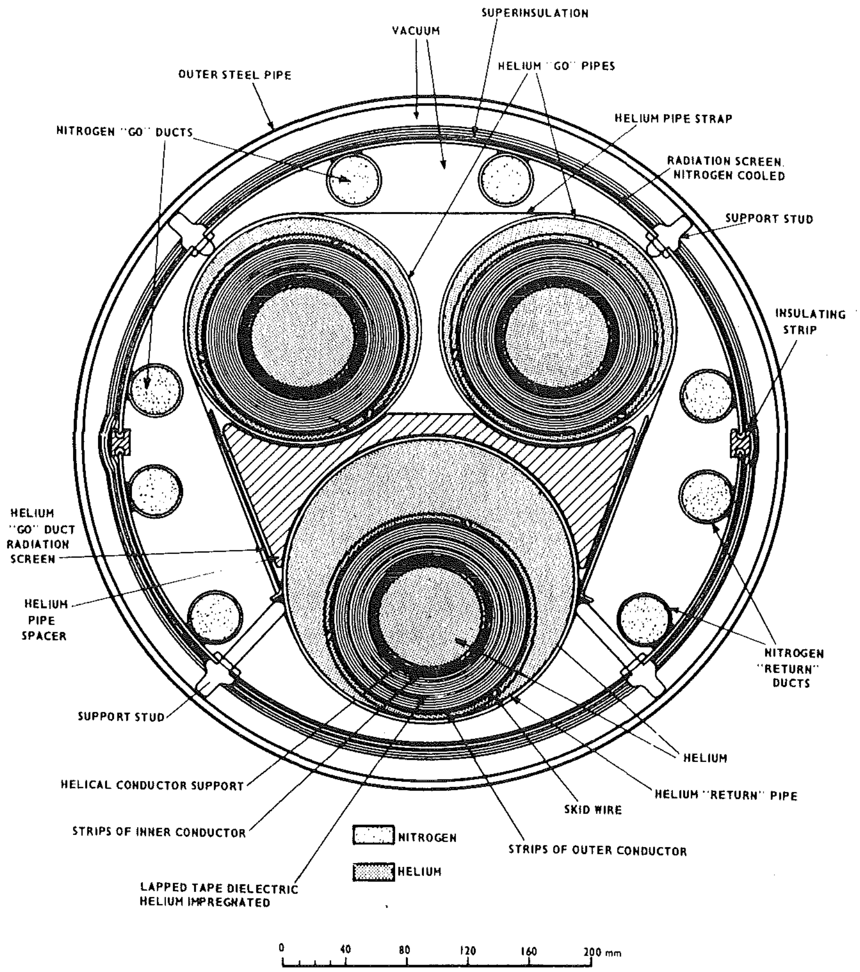


Fig. 4.2.8: Cross-section of a 4 GVA/275 kV superconducting a.c. cable with lapped tape dielectric (J.A. Baylis, CERL).

density of 340 A/cm. The niobium thickness is about 10 µm, as thin as can be manufactured, and the aluminium thickness is about 1 mm. The optimum radius ratio for a cable is $\sqrt{e}$. Hence, for the given voltage the inner conductor radius is 40 mm, the phase current 8.5 kA, the outer conductor radius is 65.5 mm, and the power is 4.05 GVA.

Fig. 4.2.9 shows a 110 kV-500 MVA flexible a.c. cable design (KLAUDY), cooled by flowing helium at around 4 bar. Electrical insulation is provided by resting helium at about 10 bar to use the higher dielectric strength. The cable is all flexible (made up of corrugated tubes); therefore, it can be fabricated in lengths of some hundred metres. The advantages of this type compared with the pipe type are the lower number of joints, and therefore the operational safety, as well the solution of the thermal contraction problem. The phase current in this design is 2.65 kA, the diameter of the inner conductor is 20 mm and the overall diameter of the cable is about 250 mm.

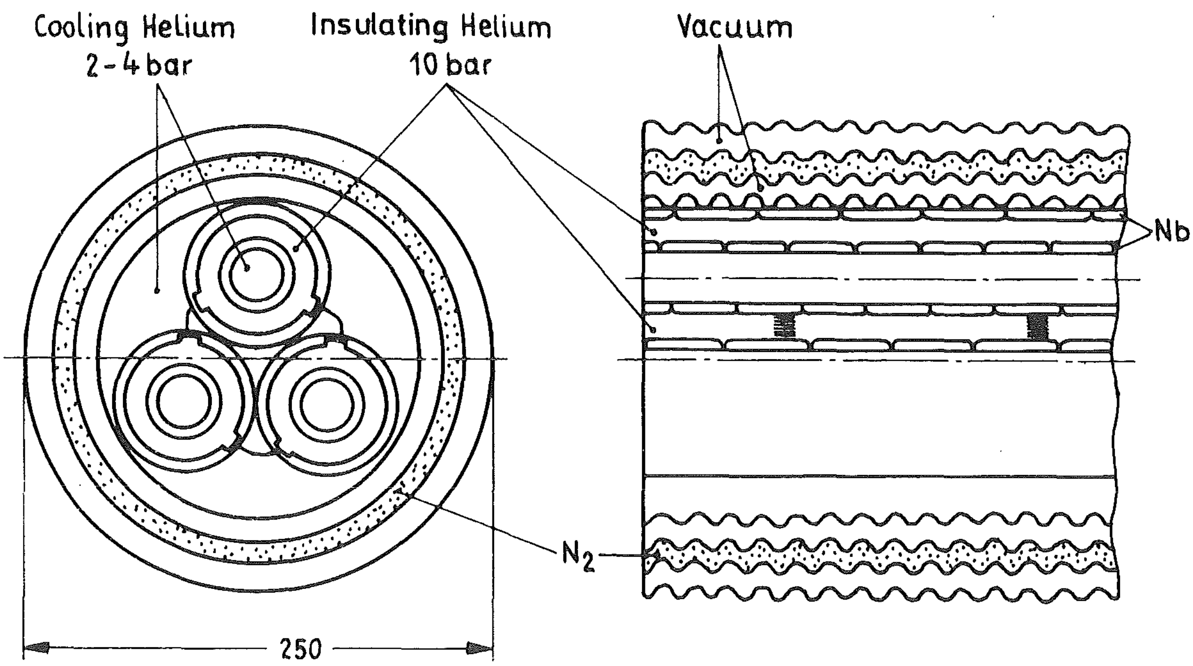


Fig. 4.2.9: Flexible 500 MVA 110 kV a.c. cable design (P.A. Klaudy, ATF).

4.2.4 Discussion of d.c. superconducting cable designs

Superconducting d.c. cables have some important advantages over superconducting a.c. cables:

- The design of the conductor system is simpler.
- No superconducting screen is needed.
- No a.c. losses occur in steady state operation and therefore the use of hard superconductors is possible.
- There are no dielectric losses.

Consequently, at the same transmission powers, the cable diameter of d.c. cables is smaller, and therefore the thermal losses are lower. Overall losses of the cable are lower and there is no limitation of the transmission length.

Most of the superconducting d.c. transmission systems proposed consist of two separate single conductor cables with voltages symmetrical to ground in a common thermal envelope. Consequently, the electrical insulation must be designed only for half the transmission voltage. In case of damage to one conductor it is therefore possible to transmit half the power. Hollow conductors are preferred for reasons of cooling.
Fig. 4.2.10 shows a d.c. cable design as proposed by Klaudy. The conductor is made up of helical segments of Nb plated copper, as in the case of conventional cables, cooled by liquid helium on both conductor sides. The electrical insulation here is between liquid nitrogen and ambient temperature. The high dielectric strength of liquid nitrogen may therefore be utilized or conventional paper insulation can be used. The space between the corrugated tubes must be evacuated. Klaudy proposed a special evacuation procedure. First, the air between the corrugated tubes is driven out by pressurized carbon dioxide (about 2 - 5 bar). Then the carbon dioxide is evacuated to about 1 - 2 torr ($\sim 1.3 - 2.6 \cdot 10^{-3}$ bar). Next, liquid nitrogen is filled into the cable. Due to the cooling to about 77 K the carbon dioxide is frozen out, which generates a vacuum of about $10^{-4} - 10^{-5}$ torr ($\sim 10^{-7} - 10^{-8}$ bar). This procedure avoids electrically insulated pumping necks, but the vacuum must be maintained during operation without pumping.

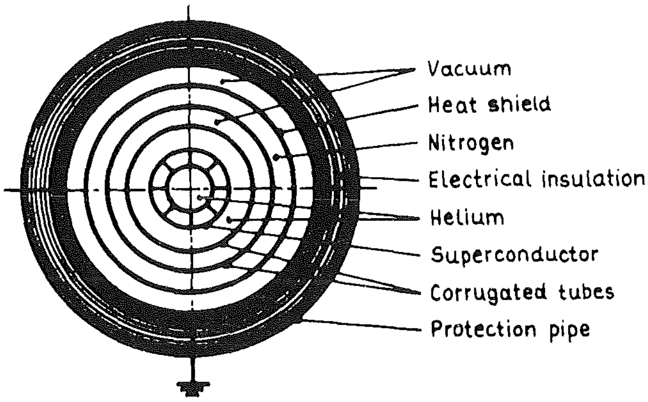


Fig. 4.2.10: Flexible d.c. cable design (P.A. Klaudy, ATF).

Fig. 4.2.11 shows d.c. designs discussed in papers by Carter and Baylis. Fig. 4.2.11a shows the principle of the arrangement, while Fig. 4.2.11b shows a detailed construction for a 230 kV, 4 GVA cable. The go and return helium streams pass through separate pipes, though, in some cases, the solid dielectric may be able to provide the thermal insulation as in Fig. 4.2.14a, so only one helium pipe is needed. The electric stress on the inner conductor is 200 kV/cm, and the linear current density is with a critical current density of 6×10^5 Acm^{-2} at H = 1.2×10^3 A/cm ($\hat{=}$ 0.15 T). The thickness of the inner conductor is 52 µm if fault currents are carried in the superconductor, and the thickness of the aluminium substrate is 1.0 mm (or 2.4 mm of copper). If fault currents are taken up by the normal metal, smaller thickness **is** obtained. The radii of the coaxial pair are 23 mm and 38 mm, the current is 17.4 kA. The absence of stress inversion effects in the dielectric and the ability of superconductors to carry very high d.c. currents gives a most compact cable. Fig. 4.2.12 shows a CGE/EdF design of a d.c. superconducting cable. The construction is similar to the a.c. design of Fig. 4.2.9.

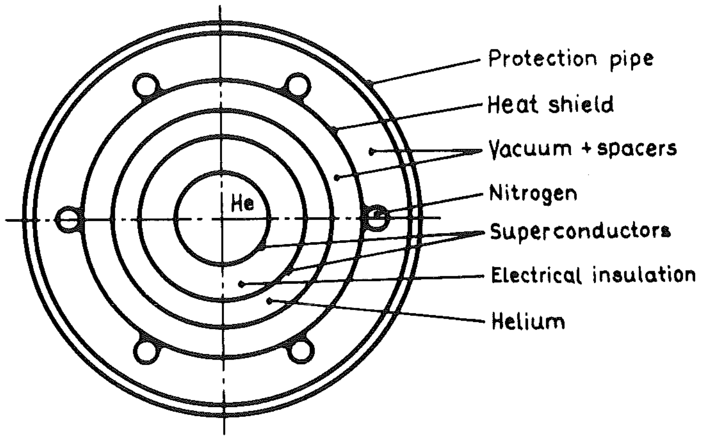


Fig.4.2.11a: Cross-section of a superconducting d.c. cable (N. Carter: Cryogenics 13, 207 (1973)).

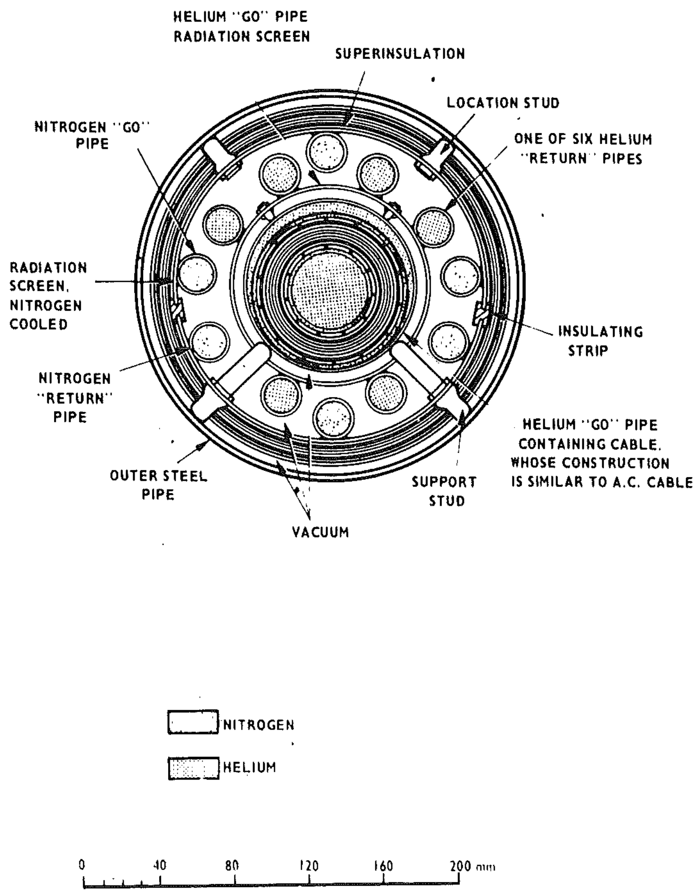


Fig.4.2.11b: 4 GVA/230 kV superconducting d.c. cable design (J.A.Baylis, CERL).

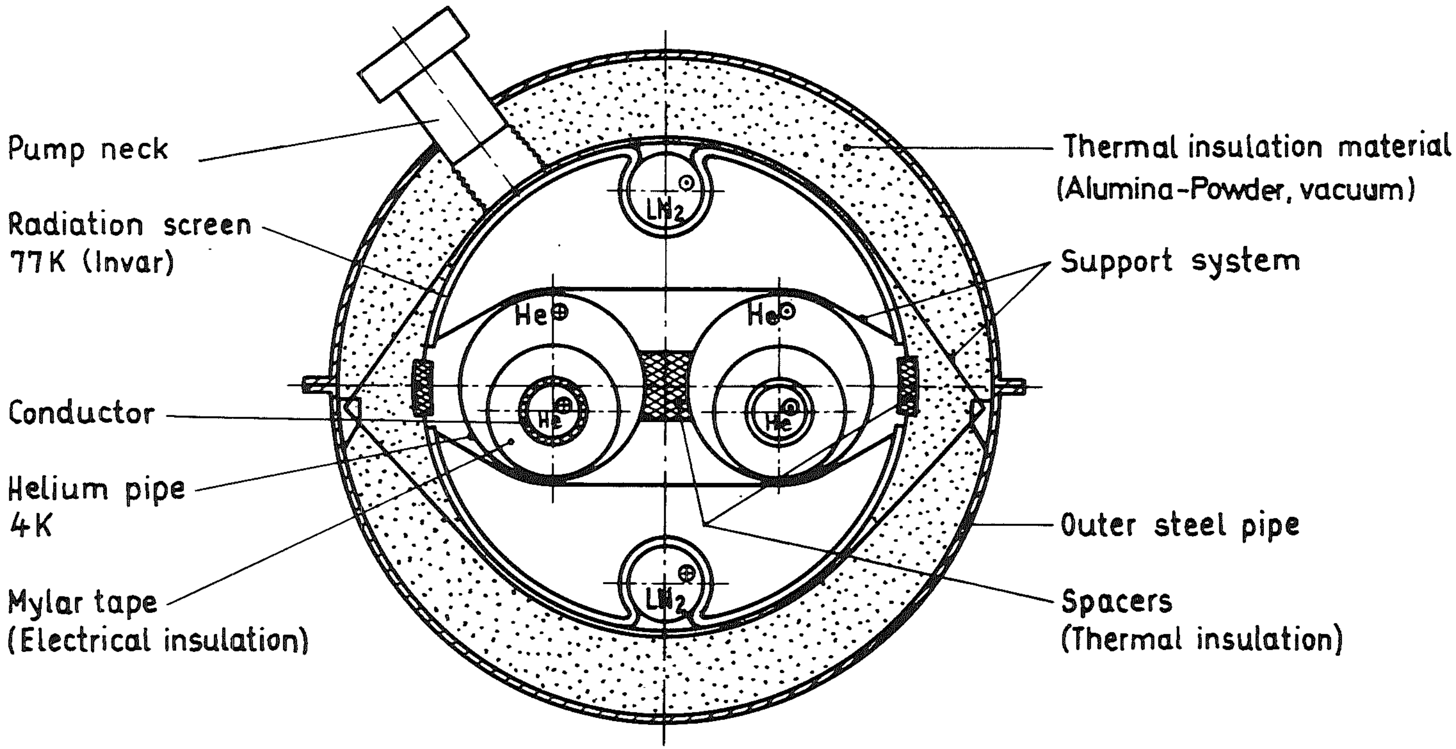


Fig. 4.2.12: Superconducting d.c. cable design by CGE/EdF.

Fig. 4.2.13 shows the AEG-Kabelmetal-Linde design. This cable is all flexible. Superconducting Nb_3Sn ribbons are helically wound on a flexible carrier with back-up rings. The electrical insulation is of paper impregnated with liquid helium. By choosing the pitch of the spirals it is possible to accomodate the thermal contraction and to avoid inadmissible mechanical stresses and mutual displacements.

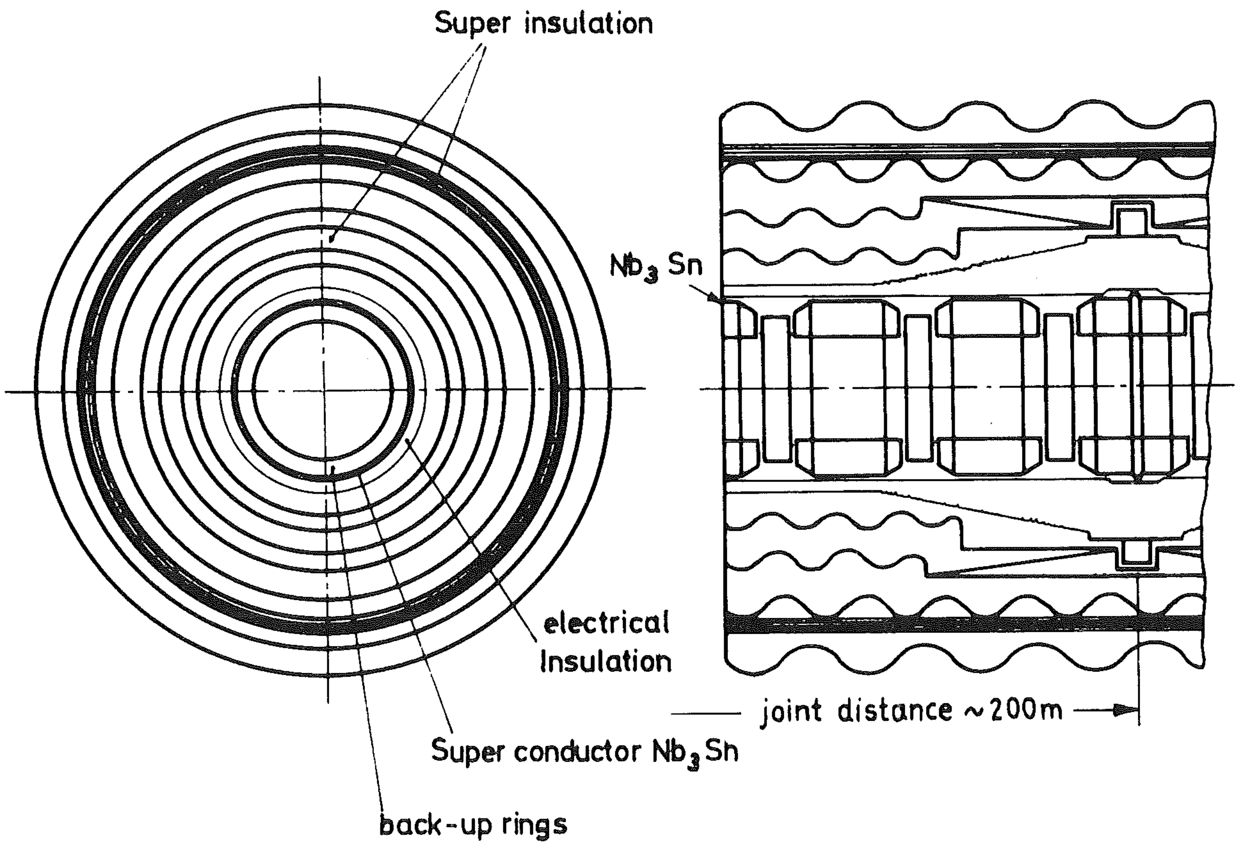


Fig. 4.2.13: AEG flexible superconducting d.c. cable design.

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Remark: Only specific references for superconducting cables are listed. A comprehensive list of references is given in "Research needs for superconducting cables" by CEGB.

5. Requirements for operation in the grid

5.1 Reliability requirements

The trivial statement that UHV-power cables should be as reliable as or even more reliable than the other elements of the power distribution system indicates the upper limit of reliability. Some theoretical work on this problem is reported in which the "operating risk of electrical grids" is assessed [5.1], and from this risk one obtains the number of permissible fault events. So far, most of the data on reliability have been calculated from long term observation of the grid. For orientation, Table 5.1 shows some reported data of shut down events and repair times.

From the structure of the grid it is evident that the reliability of UHV-cables must equal that of overhead lines. It seems impossible to reach repair times of cables as short as those of overhead lines, so it is necessary to reduce the number of shutdown events compared with overhead lines. At present, cable systems are built with double circuit for sufficient reliability. The reliability challenge is defined by the present state of the grid. Any change in these general conditions will also change the reliability requirements.

Table 5.1: Shut down events and repair times

	voltage level kV	shut down events per 100 km and year	repair time	shut down time
Furukawa [5.6]	> 60	4.1 (data collected since 1970 78 % oil leakage 12 % faults during constr. 10 % electric breakdown faults)	≈ 1 week for 275 kV oil cable	≈ equal to repair time
BICC [5.7]	> 132	2 (0.9 of the cable with 0.1 caused by electric breakdown 1.1 accessories)	268 h ≈ 1 week based on 2850 km 275 kV cable, 974 h ≈ 3 weeks based on 165 km 400 kV cable data collected since 1965	≈ equal to repair time
CGE [5.9]				several months for a cryogenic cable
Pirelli [5.8]	> 132	0.5		
Corry [5.22]		< 1		9-24 h for overhead lines 4-21 days for cables
Hendrich [5.1]		5		
400 kV Forschungsgemeinschaft [5.12]	110	0.61 overhead line 1.82 cable	several hours several days	≈ equal to repair time
Buter [5.2]	> 110	3-4 shut down events of the grid		

5.2 Short circuit cable performance

Short circuit stresses first are problems to be considered in the design of a cable system. It seems that in all conventional and advanced cable systems the effects of mechanical stresses must be considered. It should be mentioned that the breakdown voltage of the insulation materials used is reduced as a consequence of mechanical stress. Therefore, these stresses must be avoided. Stress problems in conventional and advanced cables can be solved more or less easily. More serious problems, which are either unsolved or difficult to solve, occur especially in superconducting cables. Because of the poor thermal capacity of metals at low temperature a short circuit in a superconducting cable will drive the superconductor normal and then overheat it. Different ways of eliminating this problem are discussed. There is the possibility to use a sufficient amount of backing material, to employ very fast switches(not yet available) or current limiting devices (CLD).

The currents which the cables must sustain in the worst case are determined by the condition of the grid (cf. Tables 5.2,3).

Table 5.2: Short circuit power at different voltage levels [5.3]

Voltage kV	Short circuit level MVA	Source unit size MVA	Power level MVA
33	1000	120 - 90	120 - 180
66	2500	180 - 120	430 - 640
132	3500	240 - 180	640 - 960
132	5000	360 - 240	960 - 1280
275	15000	1000 - 500	2000 - 4000
400	35000	2000 - 1000	6000 - 8000

Table 5.3: Maximum short circuit currents [5.2]

Voltage kV	Maximum short circuit current kA
110	66
220	107
380	135

5.3 Insulation requirements

The use of UHV-power cables in connection with overhead lines also sets the range of test voltages. In every case of possible application of the cable there seems to be a device which influences the overvoltages and so determines the test level the cable had to sustain.The worst case in electrical stresses is given by the overhead line. Therefore, the cable must sustain the test values proposed or standardized for UHV overhead lines. Although there is international cooperation in the field of high voltage testing and therefore the basic data defining the test values are quite the same, the ultimate test voltages and test modes in different countries do not coincide. In Table 5.4 several test voltages of different rated voltages are listed.

The design of insulation systems for UH voltages is becoming more and more expensive. This makes it a problem in economic optimization to weigh the permissible fault risk due to the insulation system against the costs of this system.

In the literature studied cable systems mentioned for application in Europe sometimes have rated voltages different from the rated voltage value for the same cable used in America. This difference is one mainly belonging to the different marking processes.

Table 5.4: Synopsis of voltage testing data

		rated voltage kV	lightning impulse volt. kV	test mode µs	switching impulse volt. kV	test mode µs	a.c. test volt. kV	test mode
According to IEC and Symposium on UHV laboratory planning IEEE Summer Power Meeting 1968		110	380	1.2/50	-	-	230	1 min 50 Hz
		132	650	1.2/50	-	-	275	1 min 50 Hz
		220	1050	1.2/50	-	-	460	1 min 50 Hz
		275	1050	1.2/50	-	-	460	1 min 50 Hz
		380	1425	1.2/50	-	-	630	1 min 50 Hz
		400	1425	1.2/50	-	-	630	1 min 50 Hz
		525	1800	1.2/50	1100	250/2500	670	1 min 50 Hz
		765	2300	1.2/50	1350	-	960	1 min 50 Hz
		1100	2800	1.2/50	1800	-	1410	1 min 50 Hz
		1500	3500	1.2/50	2200	-	1920	1 min 50 Hz
other values reported in Europe	U.K [5.4]	132	640					
		275	1050					
		400	1425					
	BBC	525	1900	1.2/50	1030	250/3000	750	50 Hz
	Siemens	420	1550	1.2/50	1775	250/2500	680	1 min 50 Hz
	Pirelli	400	1425				460	
	"	750	2100				870	
	CGE	225	1050					
	"	400	1300					
	"	750	1800					
other countries	Japan	500	1860	1/40	1490	100/1000	630	6^h, 50 Hz line to earth
							420	10 min, on the drum line to earth
	USA	500					625/ 690	56 d, 60 Hz

5.4 Stability and means of compensation

The shunt arm capacitance of the cables overhanging the series arm inductance results in a characteristic impedance nine to fifteen times smaller than that of an overhead line. The natural power belonging to this characteristic impedance, in the case of oil filled cables (cf. Table 5.5) and sometimes also in the case of SF_6- and PE cables, is significantly above the value of the transmissible power. These cables therefore work at a power level much lower than the natural power. The phase shift of the voltage between input and output of the cable is of no importance in normal current ratings. The cable in a first approach is a shunt series capacitance of considerable magnitude. This capacitance will generate stability disorders in the grid, not only in unloaded operation but also on load with a power factor of unity. To absorb the reactive power, the synchronous generators must operate in the underexcited mode. Their static and dynamic stability is diminished.

If a long section of an oil filled cable is used at the 400 kV level, a power factor of 0.9 is reasonable. Assuming a simplified synchronous machine, this will operate at a magnet wheel angle approximately similar to the overall angle allowed for operating overhead lines. The angle pertaining to cable operation is related to the less stable underexcited operation of the machine and may therefore constitute a risk.
It should be mentioned again that the previous considerations are valid only for a cable system with a thermal power rating considerable below natural power. This is true of almost any oil filled cable system. The cable length also should be in the range of a quarter to half of the critical length to make the consideration valid, because cables of only a few percent of the critical length also have only a low reactive power demand compared with the rated power. In the future, this stability problem will come up in loaded grids when the number of cables increases. Problems of unloaded cables will occur in every UHV-power cable installation because all cables have much higher capacitive loading currents than overhead lines.

Another problem of the cable and its capacitance are oscillations during switching. The overvoltages occuring at the reignition of the switch when switching a cable can also bring considerable risk to other components of the grid [5.17,18]. This difficulty occurs in all cable systems of greater length and, therefore, capacitance mentioned in this report. These internal overvoltages therefore must be considered in designing components, especially switches.

As in the overhead line, the effect of the shunt arm capacitance on the cable can be diminished by shunt arm reactors. Considering the magnitude of capacitive reactive power, a cable ring of 250 km of oil filled cable at the 275 kV level would have about 2000 MVA_r [5.19]; because of the additional costs, the question of reactive power balancing is determined by economics. Compensation coils are currently built in a 50 MVA to 100 MVA unit size; units needed for cables at a level of about 200 to 500 MVA_r will raise additional problems. Balancing the reactive power mentioned above by rotary phase advancer would require 4 or 5 blocks of the present state of the art. It may be trivial to say that reactive power compensation is a problem common to all power cables except the system with a sufficiently high thermal power rating to operate with natural power. Operating significantly above natural power will raise the same reactive power compensation problem as we saw with overhead lines.

On the other hand, it seems that cables may be a proper instrument to balance the reactive power demand of all electric machines. If cables were to be used for this purpose, oil filled cables would be the best type. In practice, only a part of reactive power can be balanced in this way in order to avoid resonance, which would be dangerous when the real power demand is low.

The grid configuration must be such that at times of low real consumption the cable also then can be switched off the grid. The reactive power of a cable grid therefore offers considerable problems. The effects of which have been neglected to this day because of the small percentage fraction of cables in the whole grid.

5.5 Transmission losses

For calculating the losses one first of all needs the d.c. resistance of the cable, which is easy to determine. Due to current displacement effects, the eddy currents in the sheath and nearby metal components, additional losses occur also at the technical frequency. The value of this additional resistance can be calculated only very inaccurately. Yet, it will be tried to find mounting and laying configurations which minimize the additional losses. The losses due to current displacement in the conductor can be reduced by special subdivided cross sections (cf. section 2). This subdivision is more efficient when the strands are insulated. For this reason aluminium is becoming more and more helpful at large cross sections, compensating its lower conductivity [5.20]. It is assumed that the oxide insulation of the aluminium filaments will make aluminium cables preferable at the overall ac resistance above cross sections of 3000 mm^2 or more [5.21]. In the cable systems discussed in this study the equivalent resistance for calculation of the transmission losses at the 400 kV level for oil filled cables with external water cooling results in values between 0.01 and 0.018 Ω/m and for SF_6 solutions at this voltage level in values between 0.007 and 0.01 Ω/m. All values apply to cable systems in the range of 2000 to 4000 MVA (cf. Tables 5.5.1 and 5.5.3). So, there is no detectable major difference between the cable systems discussed as far as transmission losses are concerned.

5.6 Summary of the electrical characteristics of cables

Tables 5.5 are a list of electrical data of interest of cable systems. To indicate the relation between cable systems and overhead lines, the equivalent values of overhead lines are also reported.

The symbols in the tables denote

- I_k - permissible thermal short circuit current,
- C' - line capacitance per unit length,
- L' - line inductance per unit length,
- R' - line resistance per unit length,
- Z_w - characteristic impedance,
- P_n - natural power,
- I_l - capacitive loading current
- L_c - critical length (cf. section 3)

Table 5.5.1: Summary of electrical characteristics of cables made by the contractors

		Overhead Lines (for comparison)				Oil filled cables							
						AEG				BICC	PIRELLI		
						nat. cool.	ext. water cool.	nat. cool.	ext. water cool.	ext. water cool.	external water cooling		
Rated voltage	kV	110	220	380	720	110	110	380	380	400	400	750	1100
Thermal power rating	MW	350	500	3500	5750	131	631	560	1500	2200 (2600)	2300	2850 (4180)	4280
Ampacity	A	1840	1300	5300	4600	690	3300	850	2280	3200 (3600)	3300	2200 (3200)	2250
Cross section	mm^2	Al 2x 435/55	Al 2x 240/40	Al 4x 805/103	Al 2x 680/85	Cu 1000	Cu 2000	Cu 2000	Cu 2000	Cu 2600	Cu 3000	Cu 2000 (3000)	Cu 2300
Insulation performance kV	1.2/50	380	1050	1425	2200						1425	2100	2300
Insulation performance kV	250/2500				1300								
Insulation performance kV	∿ 50 Hz	230	460	630	910						460	870	950
Short circuit performance	I_k A					107×10^3	214×10^3	214×10^3	214×10^3	60×10^3	$>100 \times 10^3$	$>100 \times 10^3$	$>100 \times 10^3$
Short circuit performance	t s					1	1	1	1	1	1	1	1
Overload performance p.U.	1 h					1.1	1.1	1.1	1.1		1.4	1.45 (1.43)	1.53
Overload performance p.U.	8 h										1.15	1.17 (1.15)	1.20
Overload performance p.U.	100 h										1.08	1.09 (1.08)	1.11
Line constants	C' $F/m \times 10^{-10}$					5.2	7.5	3.4	3.4	5.23	4.9	2.8 (3.7)	2.9
Line constants	L' $H/m \times 10^{-7}$					3.1	6.0	6.0	6.0	0.745	5.2	5.6 (5.2)	5.4
Line constants	R' $\Omega/m \times 10^{-5}$	3.6	6.7	1	2.5	3.28	1.26	1.33	1.33	1.8	0.95	1.38 (0.89)	1.17
Line constants	Z_w Ω	372	275	240	275	24.5	28.3	40.8	40.8	11.9	32	45 (37)	43
Line constants	P_n MW	32.5	175	600	1900	493	427	3600	3600	13500	5000	12500 (15200)	28000
Line constants	I_l $A/m \times 10^{-2}$	≈ 0.01 - 0.04				1.05	1.5	2.4	2.4	3.8	3.55	3.8 (5)	5.8
Line constants	L_x $m \times 10^5$					0.66	2.18	0.35	0.95	0.99	0.9	0.55 (0.6)	0.35

Table 5.5.2: Summary of electrical characteristics of cables (PE, VPE cables, pressurized gas cable, direct current solution of oil filled cable)

	CGE PE ext.water cooling	AEG VPE nat. cooling	AEG VPE ext.water cooling	AEG press. gas nat. cooling	PIRELLI direct current oil filled cable	PIRELLI direct current oil filled cable
Rated voltage kV	225	110	110	110	±700	±750
Thermal power rating MW	600	145	660	108	3200	3100
Ampacity A	1550	760	3450	565	2300	2060
Cross section mm^2	Al 1200	Cu 1000	Cu 2000	Cu 800	Cu 3600	Cu 2800
Insulation performance kV 1.2/50					1800	2000
Insulation performance kV 250/2500						
Insulation performance kV ∿50 Hz					1400+)	1500+)
Short circuit performance I_k A		$139 \cdot 10^3$	$278 \cdot 10^3$	$107 \cdot 10^3$	$100 \cdot 10^3$	$100 \cdot 10^3$
Short circuit performance t s		1	1	1		
Overload performance p.U. 1 h		1.3	1.3	1.9	1.08	1.06
Overload performance p.U. 8 h, 100 h					no more than 50 h per year and 100 days during the life of the cable	
Line constants C' $F/m\times10^{-10}$		2.1	3.6	4.0	3.7	2.9
Line constants L' $H/m\times10^{-7}$		3.3	6.0	3.0		
Line constants R' $\Omega/m\times10^{-5}$		1.76	1.29	0.94		
Line constants Z_W Ω		39.5	40.8	27.5		
P_n MW		305	300	440		
I_l $A/m\times10^{-2}$		0.42	0.7	0.82		
L_x $m\times10^5$		1.8	4.9	0.72		

+) DC type test

Table 5.5.3: Summary of electrical characteristics of SF_6 cables

		PIRELLI air laying nat. cooling		PIRELLI underground ext. water cooling	CGE			SIEMENS air vented channel laying
Rated voltage kV		400	750	400	225	400	750	420
Thermal power rating MW		3000	8500	4000	1000	2000	4000	1700
Ampacity A		4330	6500	5780	2566	2887	3079	2350
Cross section mm^2		Al 8000	Al 8000	Al 8000	Al 8200	Al 9800	Al 10600	Al 2400
Insulation performance	kV 1.2/50	1425	2100	1425	1050	1300	1800	1550
	kV 250/2500							1175
	kV ∿ 50 Hz	460	870	460				680
Short circuit performance	I_k A	$>100 \cdot 10^3$	$>100 \cdot 10^3$	$>100 \cdot 10^3$				$150 \cdot 10^3$
	t s	1	1	1				
Overload performance p.U.	1 h							
	8 h							
	100 h	1.22	1.2	1.07				
Line constants	C' $F/m \times 10^{-10}$	0.54	0.54	0.54	0.8	0.78	0.63	0.44
	L' $H/m \times 10^{-7}$	6.8	6.8	6.8				2.5
	R' $\Omega/m \times 10^{-5}$	0.75	0.75	0.75	0.97	0.8	0.75	2 estimated
	Z_w Ω	112	112	112				76
	P_n MW	1430	5000	1430				2340
	I_1 $A/m \times 10^{-2}$	0.39	0.735	0.39	0.33	0.565	0.86	0.335
	L_x $m \times 10^5$	11.1	8.9	14.8	7.8	5.1	3.6	5.1

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6. Cost comparisons

In this section cost data from publications or provided industry in fulfilling their contracts are summarized and compared for various advanced cable concepts. Evidently, the cost data indicated in some cases are not costs really but merely prices. This means that the ratio of prices and underlying component costs is different for the various cable concepts, higher for more advanced and lower for more conventional ones. The reason is obvious: the data on advanced cables include higher extra charges for development, risk and low fabrication quantities than the data for more conventional cables. This problem cannot readily be solved by the authors of this study, for cost data on semifinished products cannot be made available completely. Furthermore, it is almost impossible to obtain reliable data on fabrication and labour costs.

For this reason, the data furnished by industry are compared with each other and with the costs of semi-finished products or materials. In this way something like a lower limit of the costs of advanced cables can be found which allows the future chances of the different cable concepts to be judged a bit more objectively.

Another problem in comparing cost data of cable system of different origins are the very large differences in installation costs. Fig. 6.1 shows the costs of civil engineering work as taken from [6.7,8]. The cost data quoted by ADL [6.8] are recalculated on a DM basis using income in the building trade as an index which can be found in various yearbooks on statistics. The costs of civil works may differ by more than 100 %, depending on the region where the cable is installed. Even higher costs have been published. Pirelli [6.9] quotes 350 DM/m for civil works on 400, 750 and 1100 kV oil paper cables with lateral water cooling. If the much lower incomes in Italy are taken into account this would amount to about 650 DM/m on the basis of costs in Germany. For West-Berlin costs for laying the cable system (civil works and installation are quoted in [6.3] to be 1800 DM/m for forced cooled oil paper

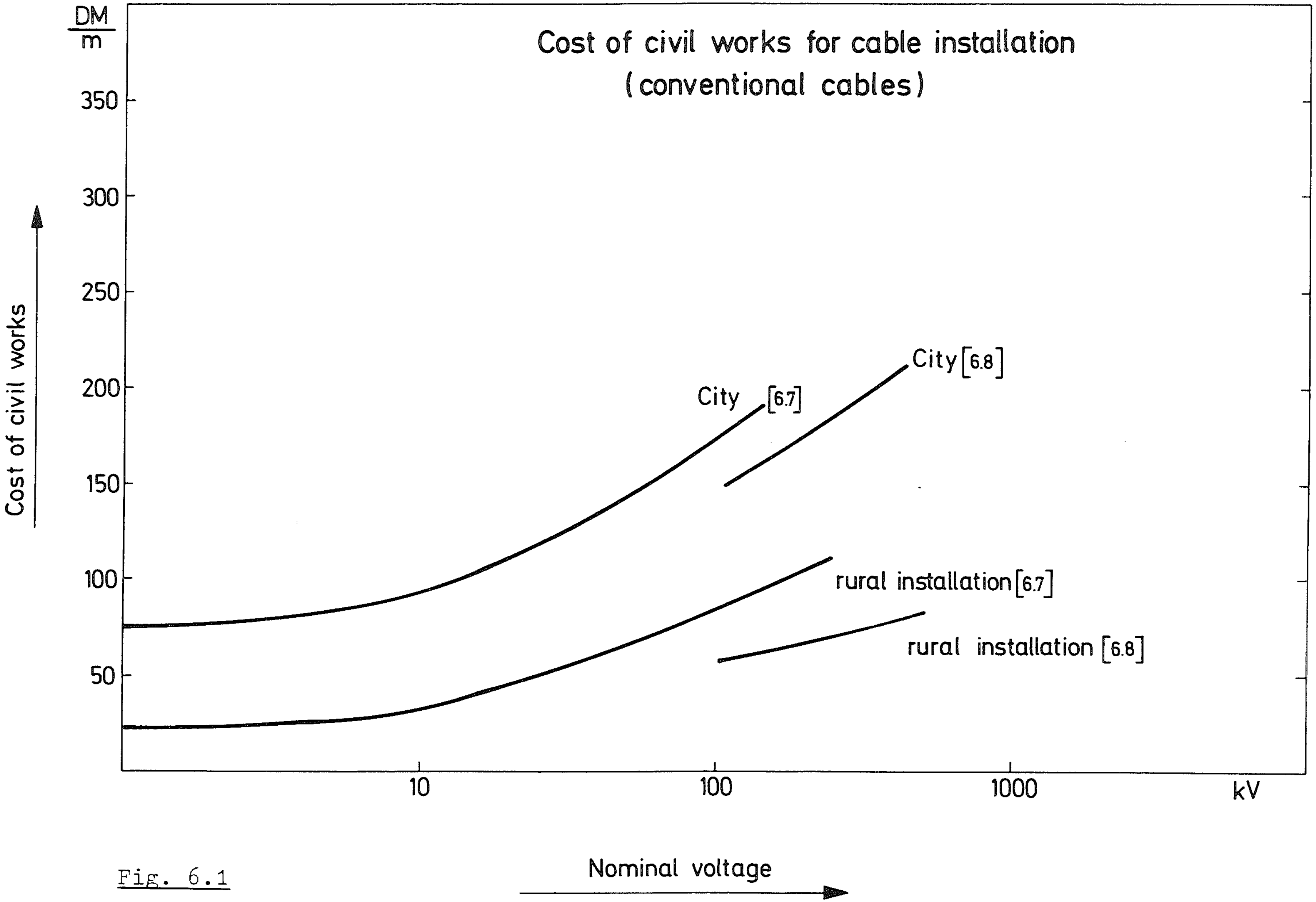

Cost of civil works for cable installation
(conventional cables)
DM/m
350
300
250
200
150
100
50
Cost of civil works
City [6.7]
City [6.8]
rural installation [6.7]
rural installation [6.8]
10
100
1000
kV
Nominal voltage

Fig. 6.1

cables at 400 kV and 3800 DM/m for 220 and 440 kV SF_6 cables. These figures apply to double circuits.

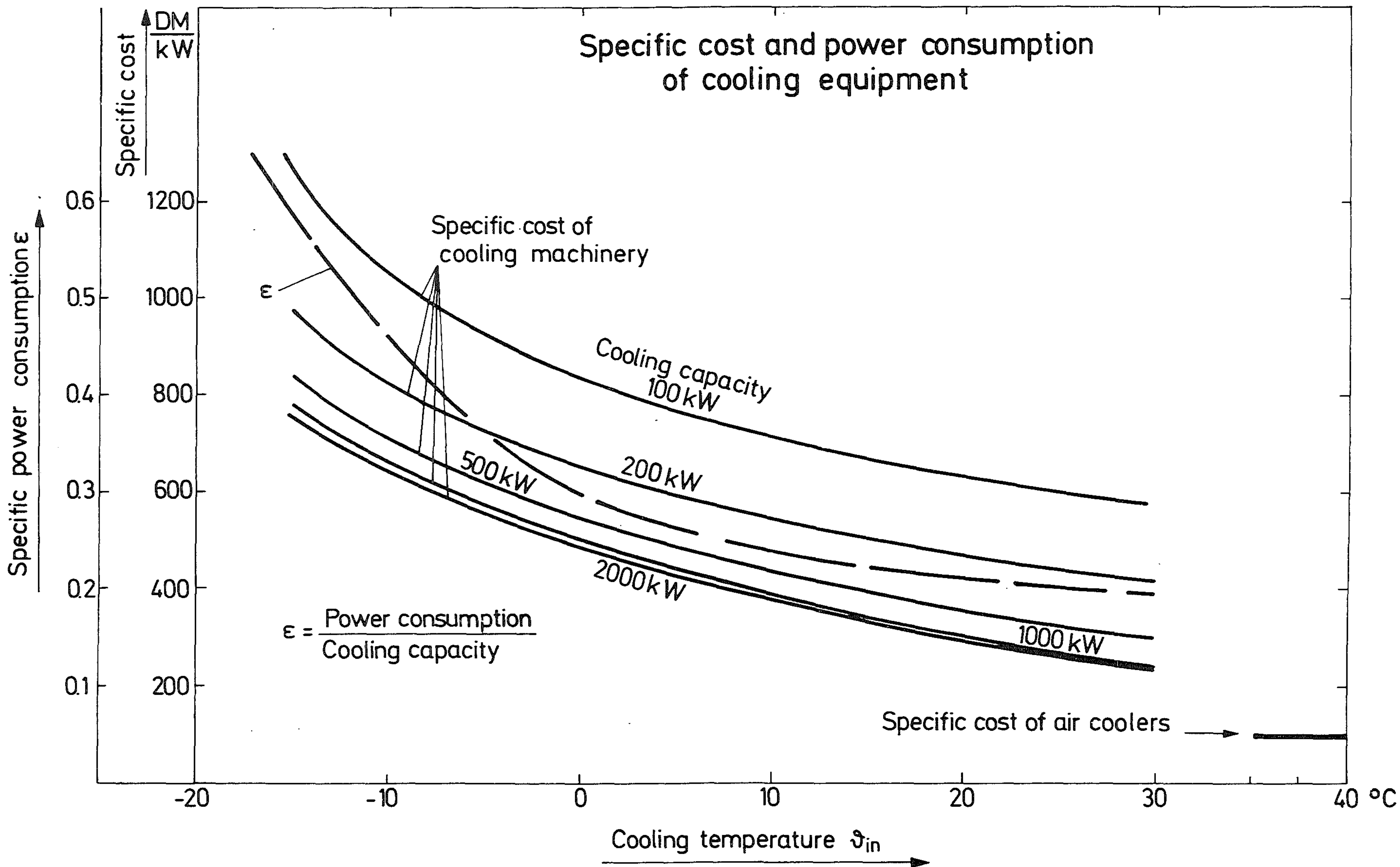
In view of these extremely large differences in the costs quoted for civil engineering work in cable installation it is probably useless to compare only the costs of complete cable systems including installation costs. It is clearly better to compare investment costs, including costs of capitalized losses, and present figures on the necessary width of the trench. So, if prices of two cable systems do not differ greatly, the cheaper cable which may need a wider trench will be less advantageous when costs of civil engineering work are high. The opposite is true when civil engineering work is cheap. There are also considerable differences in the specific cost of capitalized power losses on the order of magnitude between some 650 DM/kW to over 1000 DM/kW. A mean value of 900 DM/kW will be used in the following comparisons.

6.1 Forced cooled cables with wrapped or extruded insulation

In this section the cable concepts discussed in 3.1, 3.2 and 3.3 under their technical aspects are assessed economically.

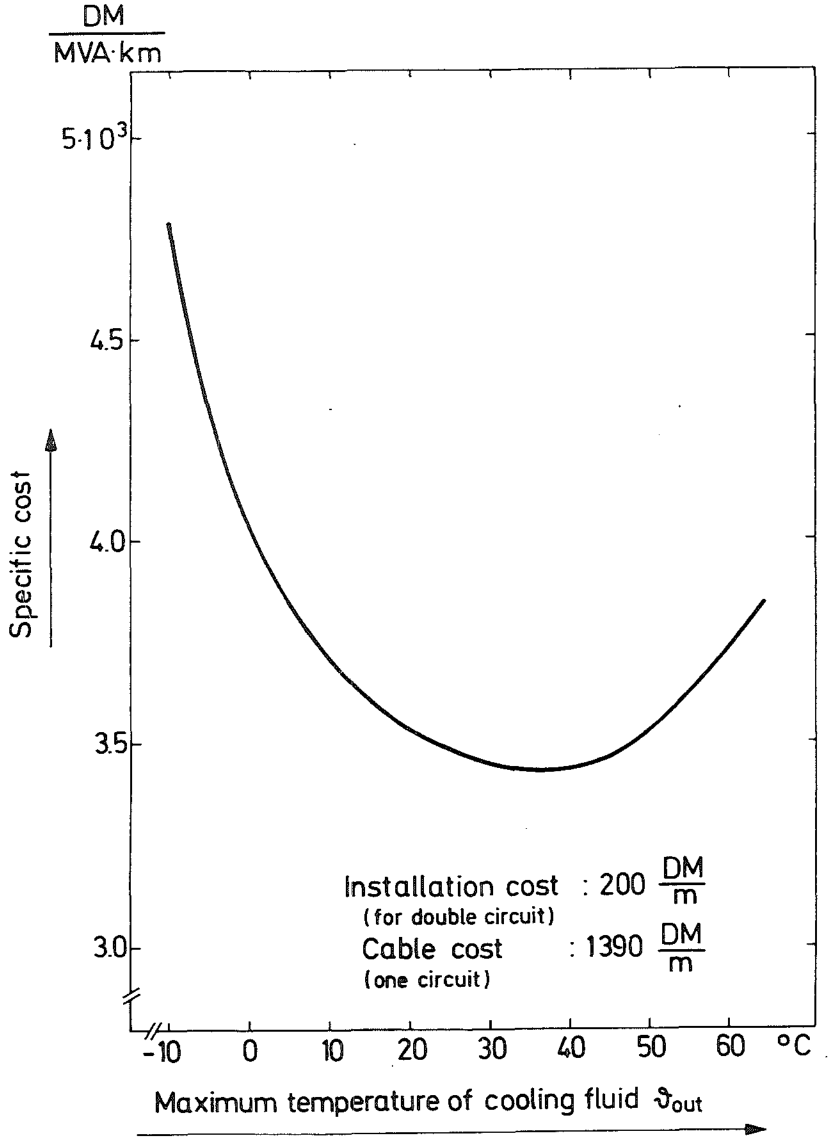
Before a comparison of available cost data is made some typical cable concepts, which have been published previously, are discussed in some detail. The ampacity of forced cooled cables can be raised considerably by lowering the temperature of the cooling fluid. With air coolers temperatures as low as 30 - 35°C can be reached. With evaporation cooling towers temperatures are not significantly lower. For lower temperatures comparatively expensive cooling machinery has to be used. A low temperature of the cooling fluid is especially effective with external cooling of cables. At fixed maximum conductor temperature the ampacity depends on the maximum temperature of the cooling fluid ϑ_{out}. The inlet temperature ϑ_{in} has to be lower. The difference $\vartheta_{out} - \vartheta_{in}$ determines the maximum length between cooling stations at a fixed hydraulic diameter of the pipe. At reasonable pipe diameters this length cannot be very long, perhaps on the order of 1000 m. Optimizing the different parameters is difficult. The calculations are done here under reasonable simplifying assumptions.

Cost data for the cooling machinery are presented in Fig. 6.2 where values for specific cost and power consumption are shown as a function of the inlet temperature ϑ_{in} and the cooling power [6.1]. Fig. 6.3 shows the power transmission capacity per circuit and the specific cost of a double circuit in one trench for an XLPE cable, 100 kV, 2000 mm^2 copper conductor as discussed in [6.2]. It is seen that in spite of the great improvement in ampacity the specific costs are higher at low temperature. At higher voltage, the thermal rating of self cooled cables is relatively lower and costs of cable and installation are higher. So, cooling at lower temperature is more profitable than at lower voltage. This can be seen in Fig. 6.4 where power transmission capacity and specific cost of a self-contained oil filled cable system (400 kV, 2000 mm^2 copper), as discussed in [6.3,4], are shown. The ampacity at low temperature

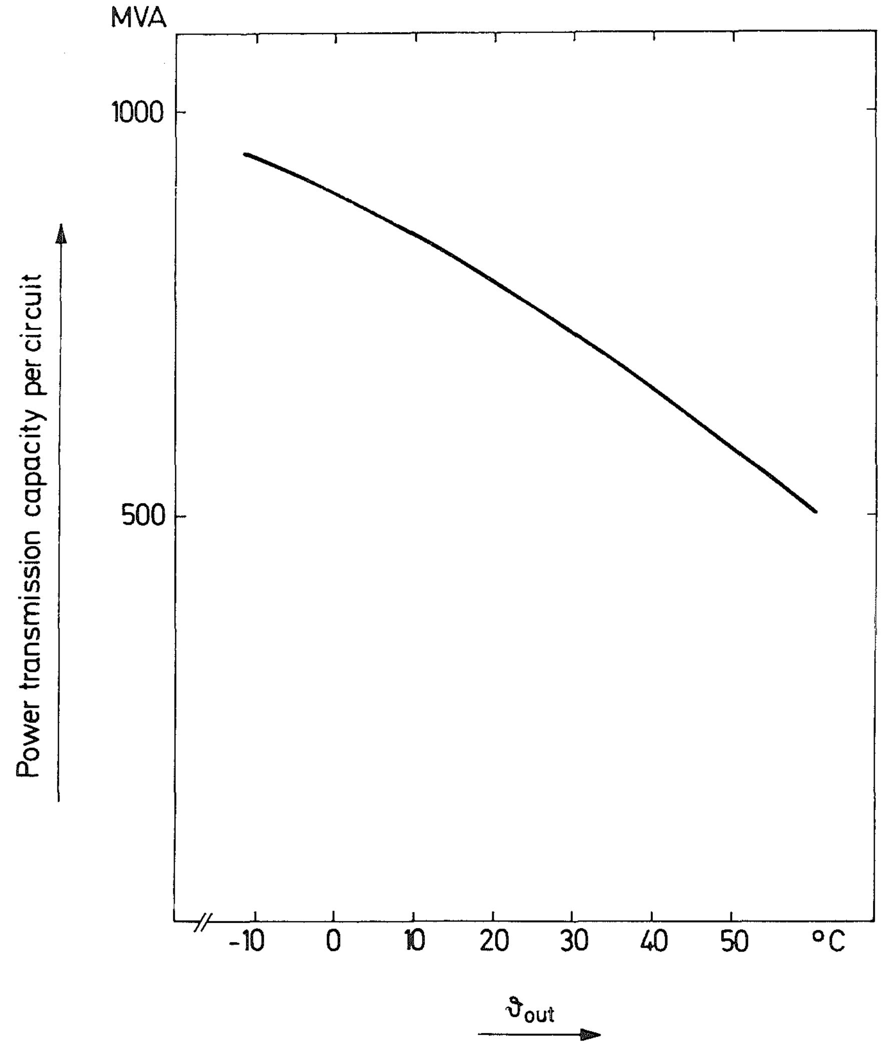


Specific cost and power consumption of cooling equipment
Specific cost DM/kW
Specific power consumption ε
0.6
0.5
0.4
0.3
0.2
0.1
1200
1000
800
600
400
200
Specific cost of cooling machinery
ε
Cooling capacity 100 kW
200 kW
500 kW
2000 kW
1000 kW
ε = Power consumption / Cooling capacity
Specific cost of air coolers
-20
-10
0
10
20
30
40 °C
Cooling temperature ϑin

Fig. 6.2



<u>Fig.6.3a:</u> Specific costs of a double circuit in one trench for an XLPE cable (100 kV, 2000 mm^2 copper conductor)



<u>Fig.6.3b:</u> Power transmission capacity per circuit for an XLPE cable (100 kV, 2000 mm^2 copper conductor)

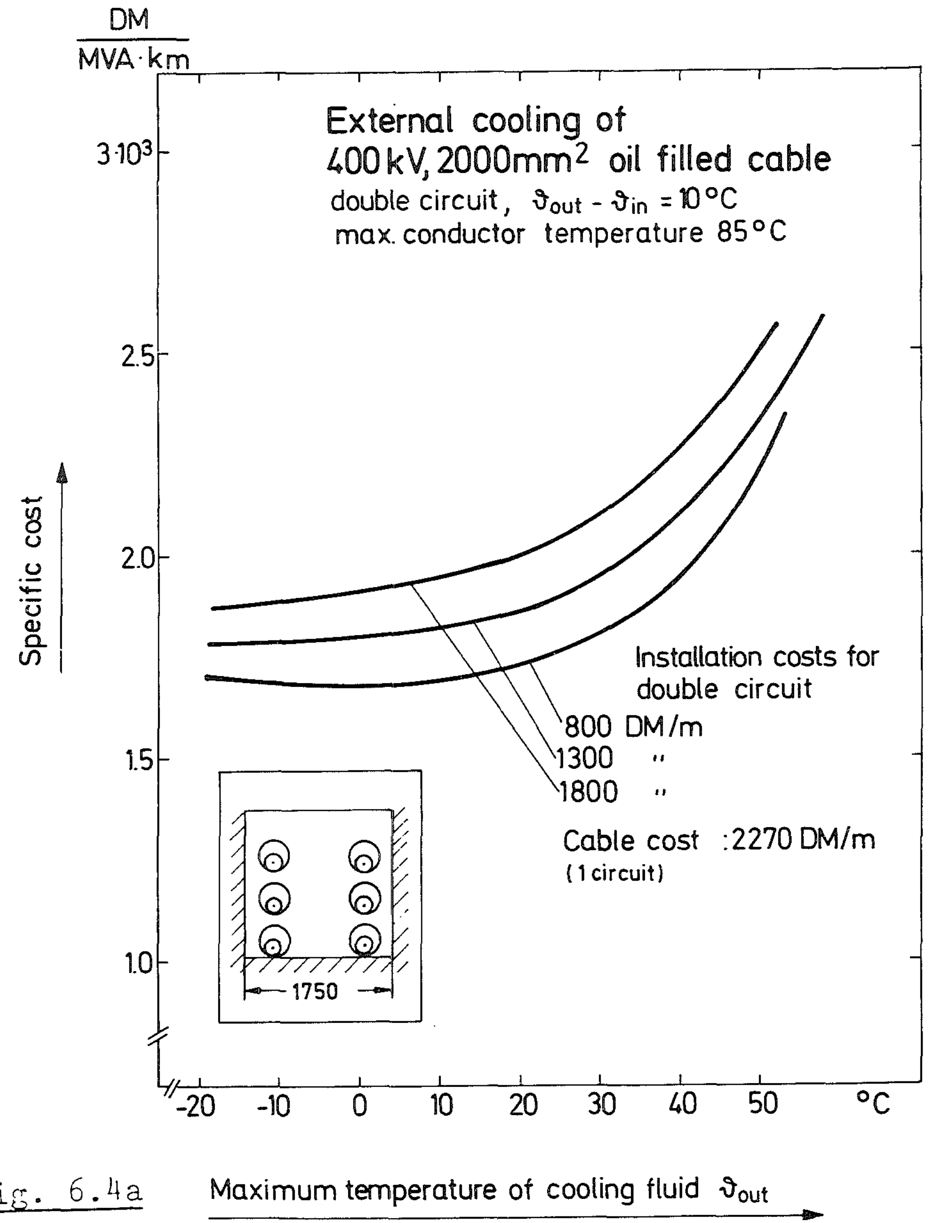


Fig. 6.4a

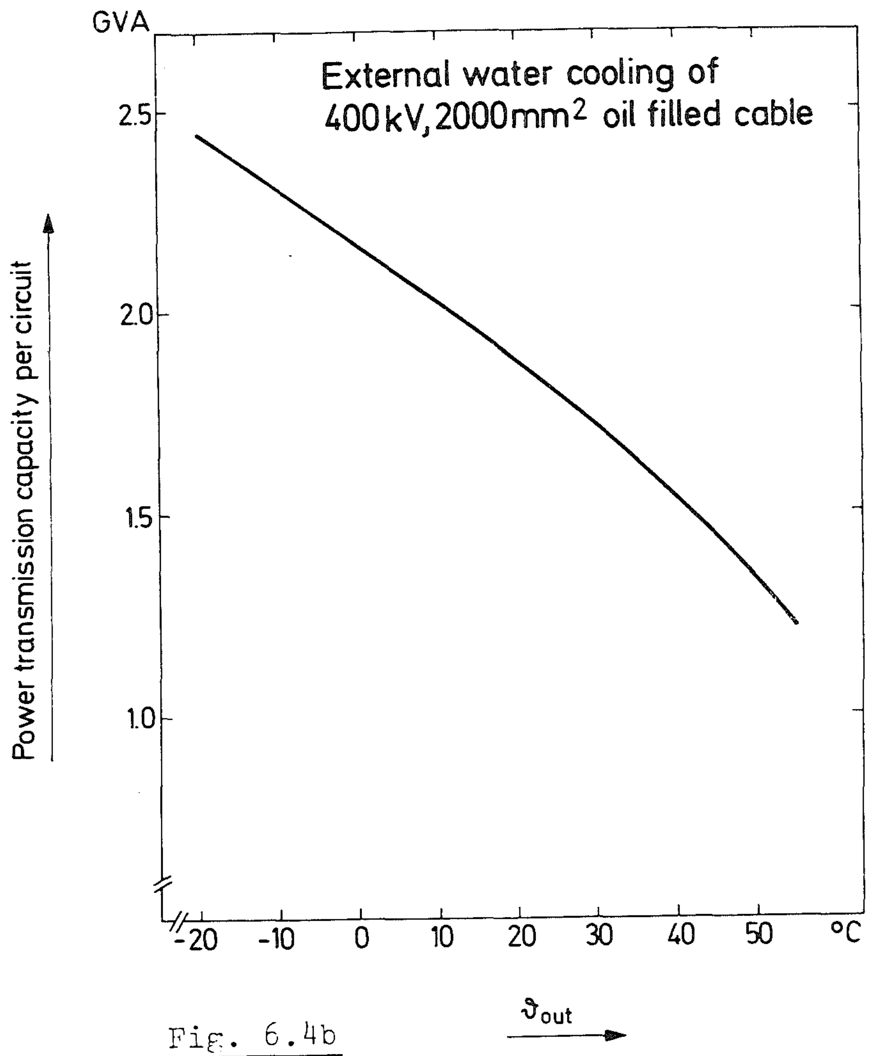


Fig. 6.4b

has been calculated according to the formula and with the values at high temperature given in [6.4]. The very high installation costs quoted in [6.3] result in an optimum temperature around -20° C. At lower installation costs the optimum temperature is higher (around 0° C) but still in the temperature range of cooling machinery and not of cooling towers.

A future high power cable system not yet developed is discussed in detail in [6.5,6]. This cable system uses a simple hollow aluminium conductor with internal cooling. The cost data given in [6.5] result in rather low cable costs. Ampacity and costs were calculated according to [6.5] for a 400 kV cable with 10 cm cooling duct in the conductor (see Fig. 3.5, 3.6). A double circuit in one trench has been assumed. The length of 10 km is cooled with one cooling station, so there is one cooling station at each end of the double circuit. The cooling fluid is oil, which is technically feasible in an earlier stage of development. With water cooling, the ampacity is even higher. Additional losses are assumed to be 50 % of d.c. losses for the cable types discussed here. <u>Fig. 6.5</u> given the capacity and the specific cost of the internally cooled cable. The optimum inlet temperature is about 10° C, but the curves are rather flat, so there is no distinct advantage in low temperature cooling.

In conclusion of the preceeding calculations it can be said that simple and inexpensive air cooling equipment does not always result in an economically optimum performance of a cable system. With cables of bad thermal characteristics and high investment and installation costs the use of cooling machinery and lower temperatures results in lower specific costs of the system. In all types of high power cables this is a good way of uprating a cable system when the load increases.

After these preliminary remarks on the merits of forced cooling at temperatures below ambient, the cost data available on cable systems with natural and forced cooling at ambient temperature will be discussed. <u>Fig. 6.6</u> is a summary of cost data on oil filled cable systems taken from references [6.3,5,9,10,11].

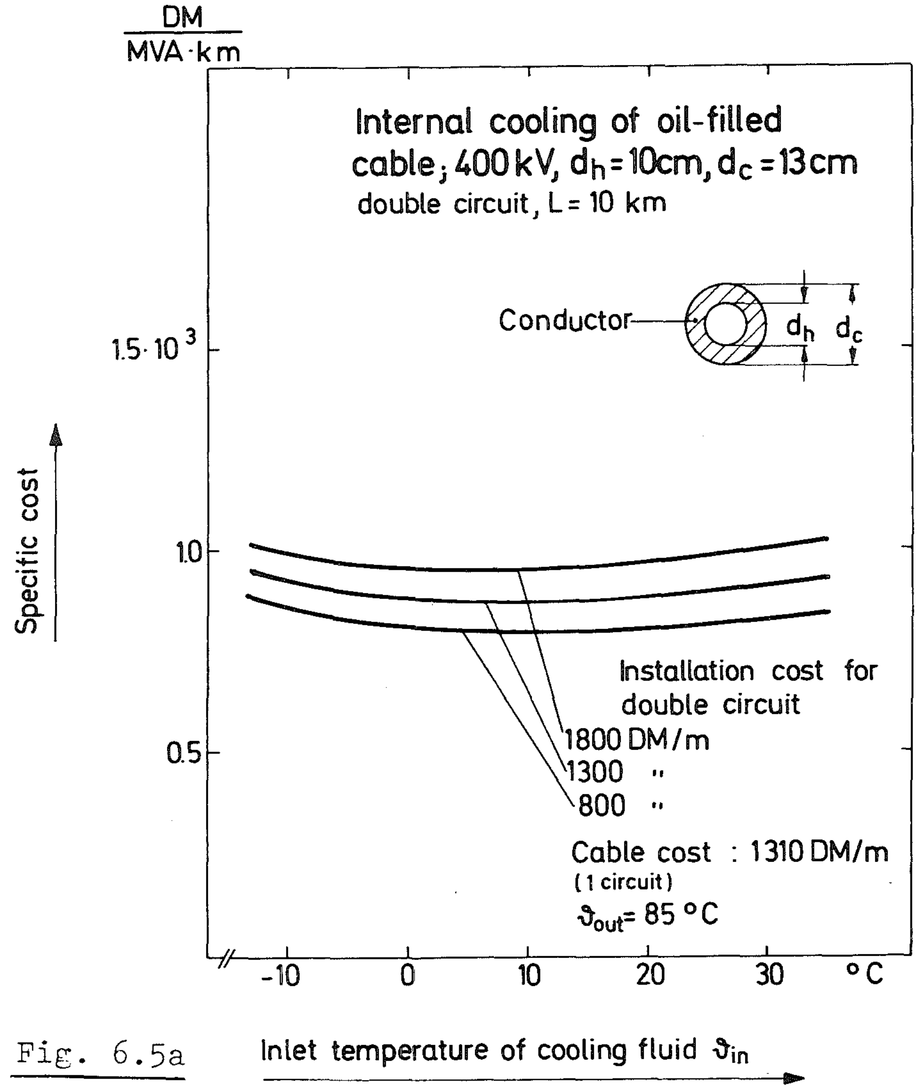


Fig. 6.5a

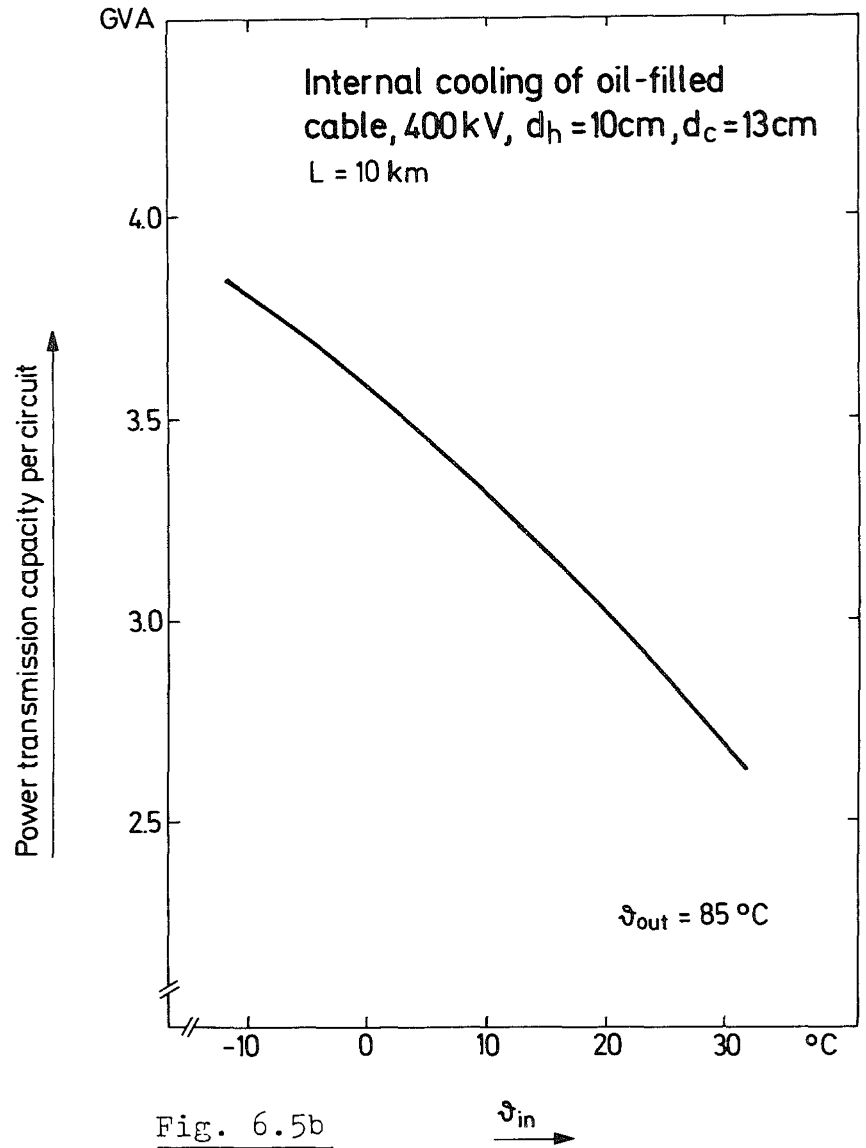


Fig. 6.5b

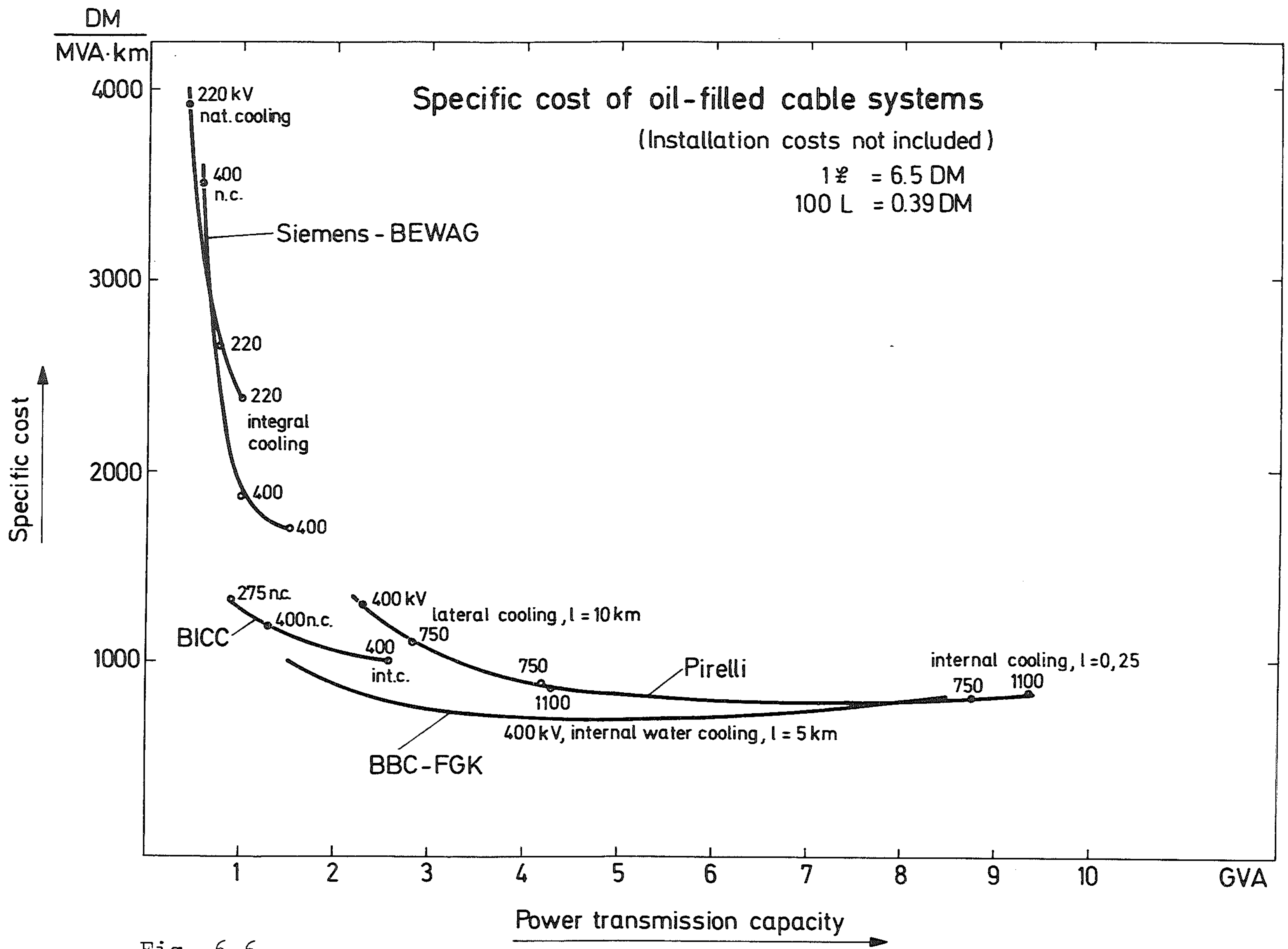

Specific cost of oil-filled cable systems
(Installation costs not included)
1 £ = 6.5 DM
100 L = 0.39 DM
DM / MVA·km
4000
3000
2000
1000
Specific cost
220 kV nat. cooling
400 n.c.
Siemens - BEWAG
220
220 integral cooling
400
400
275 n.c.
400n.c.
BICC
400 int.c.
400 kV
lateral cooling, l = 10 km
750
750
1100
Pirelli
internal cooling, l = 0,25
750
1100
400 kV, internal water cooling, l = 5 km
BBC-FGK
1
2
3
4
5
6
7
8
9
10
GVA
Power transmission capacity

Fig. 6.6

In these data costs of cable, accessories and capitalized losses are included, but not the costs of civil engineering work. In this cable category the internally water cooled cable seems to be in the best position. As some important technical problems of this cable discussed in 3.1 have yet been solved, the cost data quoted are still tentative. But some advantages of this type of cable are obvious. Very high power (more than natural load) can be transmitted at conventional voltages. The proposed conductor can be fabricated on existing machines after only minor modifications. An important problem of some new cable systems, namely the necessity of high investments into new machines producing small quantities, will be greatly diminished in this case.

As noted in the introductory remarks to this section, different types of cables should be compared not only on the basis of the cost data quoted for the complete cable system but also on the basis of costs of materials or semi-finished products. Fig. 6.7 shows the ratio between cable costs and material costs for oil filled cables with copper conductors as function of the rated voltage. The price basis assumed is

copper	5 DM/kg
lead	1.1 DM/kg
paper insulation	2.5 DM/kg

The ratio between cable costs and material costs is about 5 and does not depend very much on the voltage.

Specific costs of high voltage cables can be reduced in principle, if insulating materials with low dielectric losses are used. This is shown in Fig. 6.8 on the basis of the values for oil paper insulation given by Pirelli [6.9]. For this calculation it has been assumed that a synthetic insulation can be developed with losses ten times lower at the same price and electric strength as paper.

This is very optimistic assumption, for suitable synthetic papers are very expensive today. The reason can be seen, first of all,

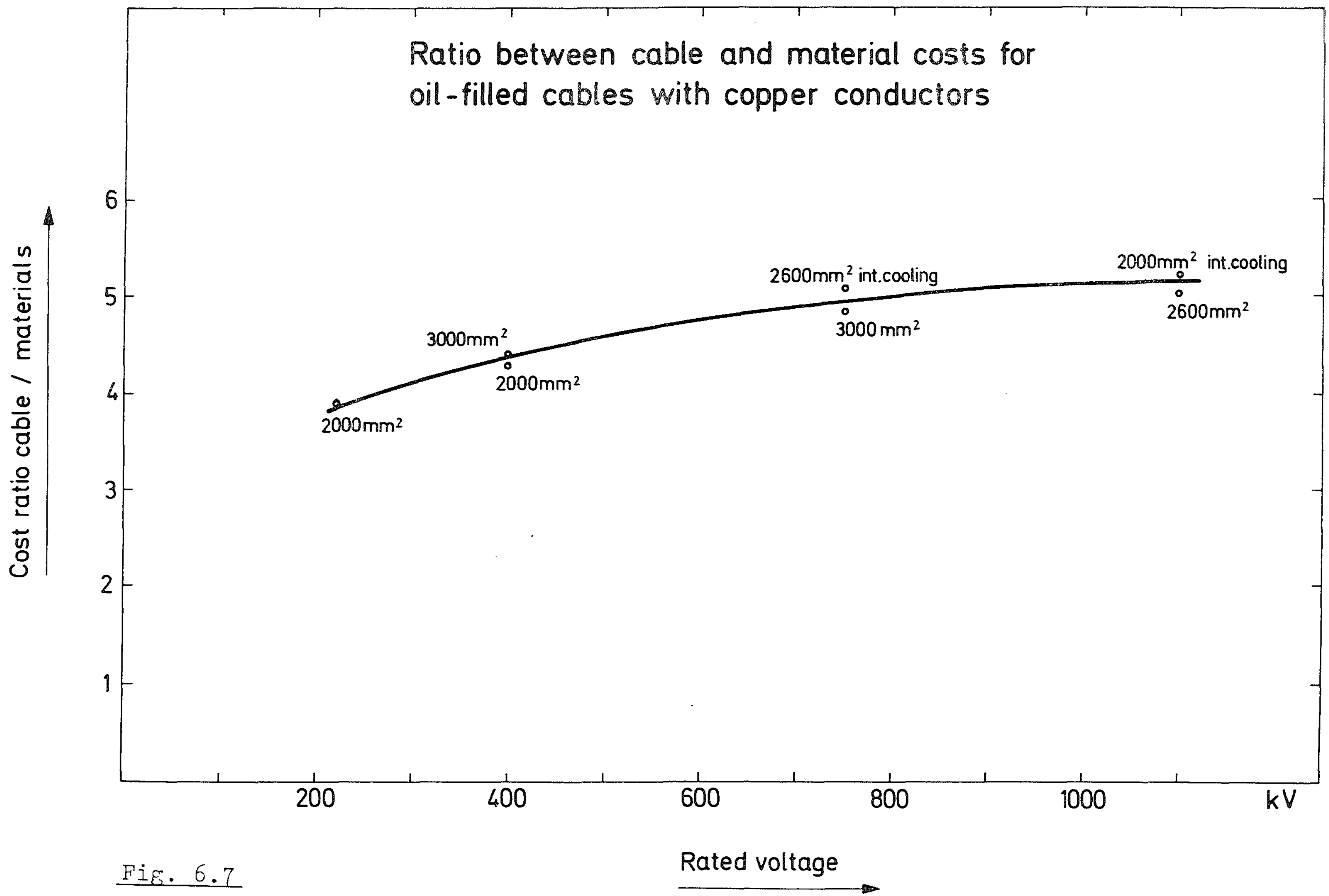

Ratio between cable and material costs for
oil-filled cables with copper conductors
Cost ratio cable / materials
6
5
4
3
2
1
200
400
600
800
1000
kV
Rated voltage
2000mm²
3000mm²
2000mm²
2600mm² int.cooling
3000 mm²
2000mm² int.cooling
2600mm²

Fig. 6.7

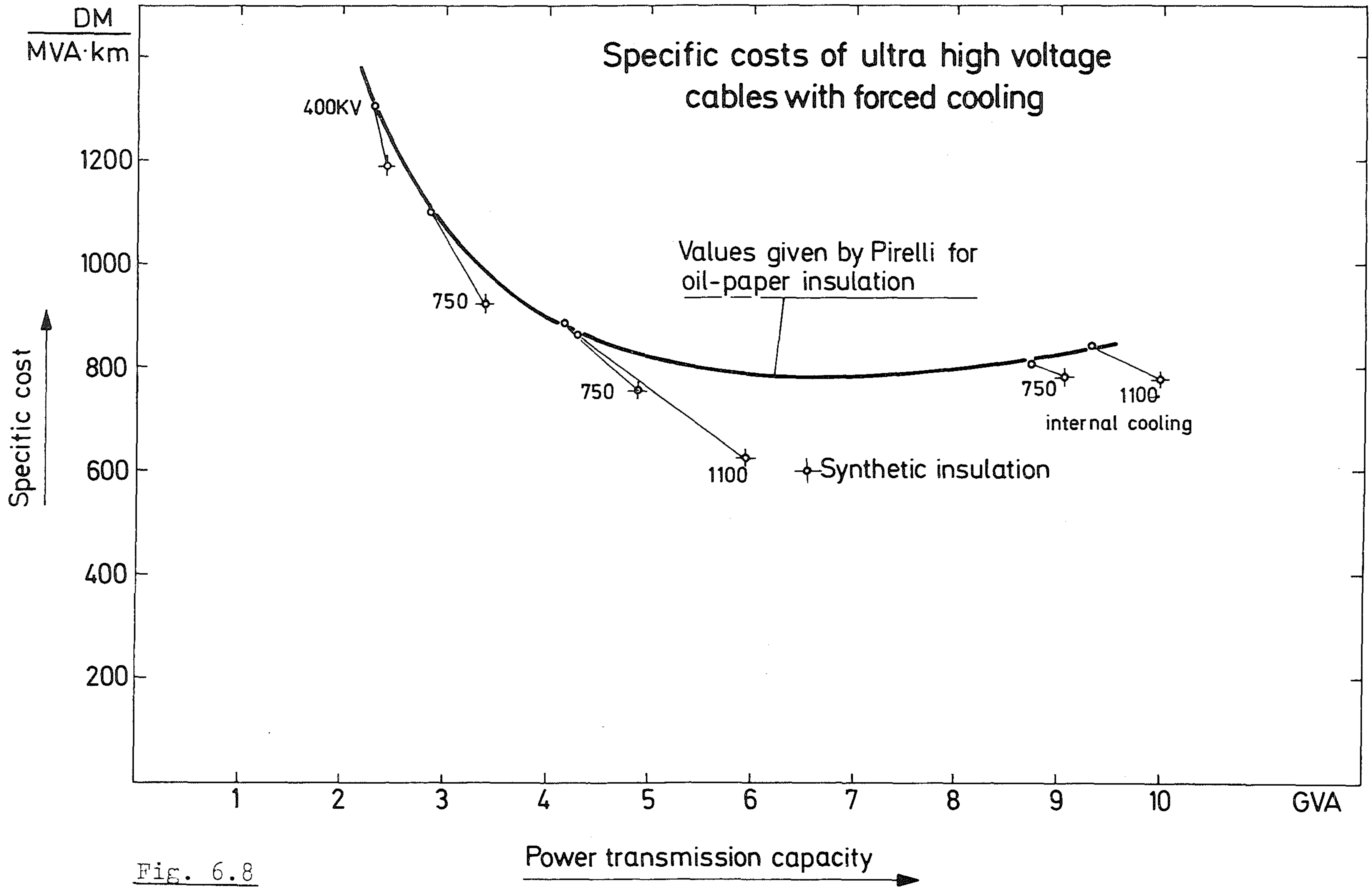

Specific costs of ultra high voltage cables with forced cooling
DM / MVA·km
Specific cost
1200
1000
800
600
400
200
400KV
750
750
1100
750
1100
internal cooling
Values given by Pirelli for oil-paper insulation
Synthetic insulation
1
2
3
4
5
6
7
8
9
10
GVA
Power transmission capacity

Fig. 6.8

in the small quantities fabricated whereas paper for cable insulations is taken from mass production and no special fabrication of paper for cable insulations is necessary. With ultra high voltage cables there may be an economic advantage of synthetic insulation, but not a very important one. Intensive cooling and lower voltage seem to be the better solutions, especially if the whole network is considered.

Cables with extruded PE insulation and external forced cooling have been developed in Germany only for the 110 kV level. The cost data indicated [6.14] present the specific costs in the same order as oil filled cables at rather low power around 500 MVA. The first part of the curves in Fig. 6.6 is also representative of these values. EdF in its study [6.11] mentions cost data for a forced cooled 400 kV PE-cable whose feasibility has not yet been proved. Specific costs of this concept are surprisingly low at 1200 MVA. These values are reproduced in the final comparison in section 6.5 (cf. Fig. 6.23).

Critical examination of the different types of cables requires knowledge of the necessary width of the trench. The figures quoted are somewhat arbitrary, since different configurations of cable laying are proposed. Fig. 6.9 **shows** the specific trench widths based on references [6.3,5,9]. The internally water cooled cable needs a rather wide trench because the coolant return line is placed side by side with the cables. These values undoubtedly can be reduced.

As mentioned before, the costs of civil engineering can vary over a wide range. A very thorough investigation of this problem has been performed by ADL [6.8]. Costs of civil engineering will largely depend on the wages per hour in the building trade. When the U.S. data are recalculated on this basis, for example, into costs in Germany, there is good agreement with the data published in Germany, as is shown by Fig. 6.1. So, the data published by ADL will be a good yard-stick by which to measure the costs of civil engineering work, if recalculated on the correct basis.

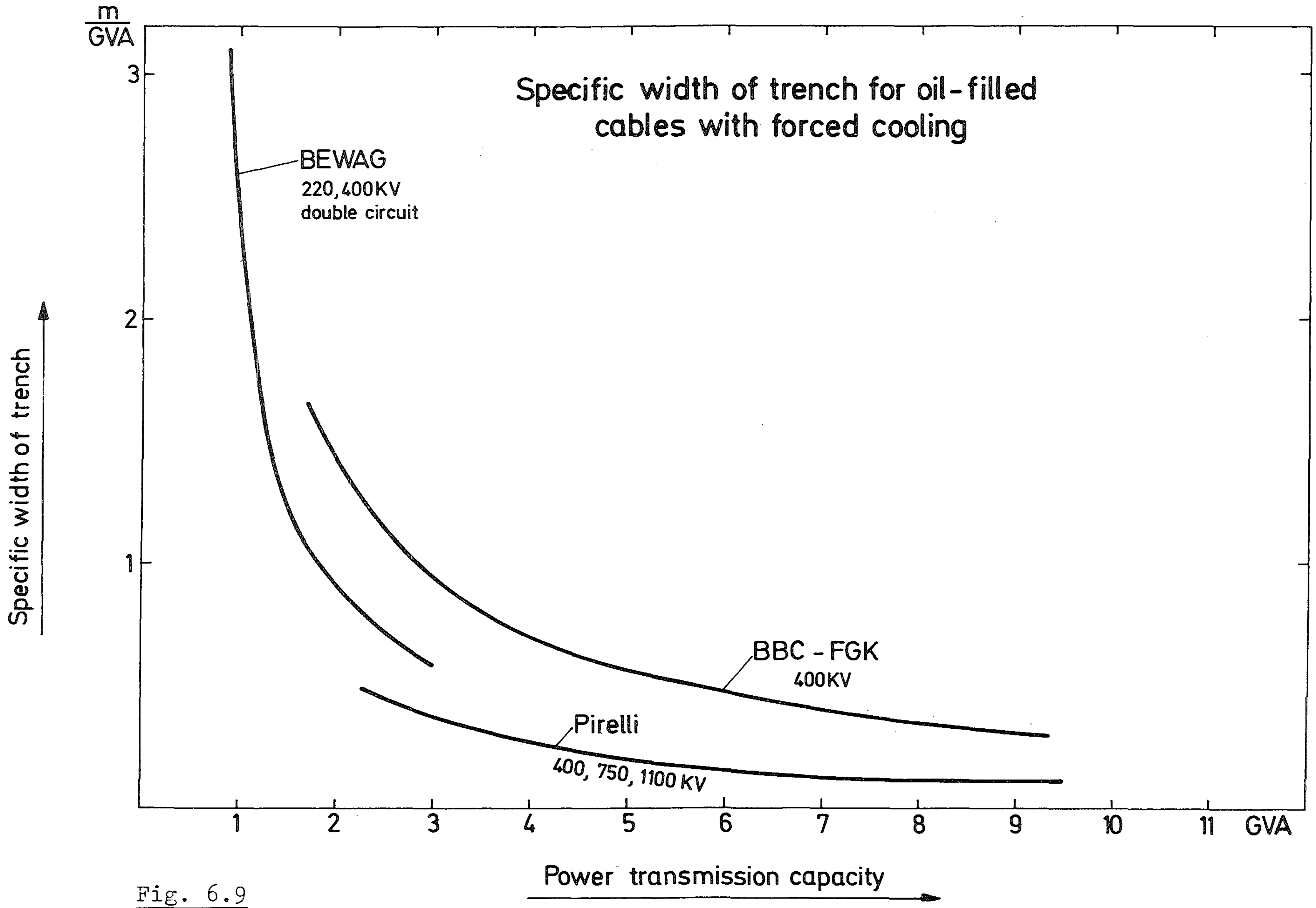
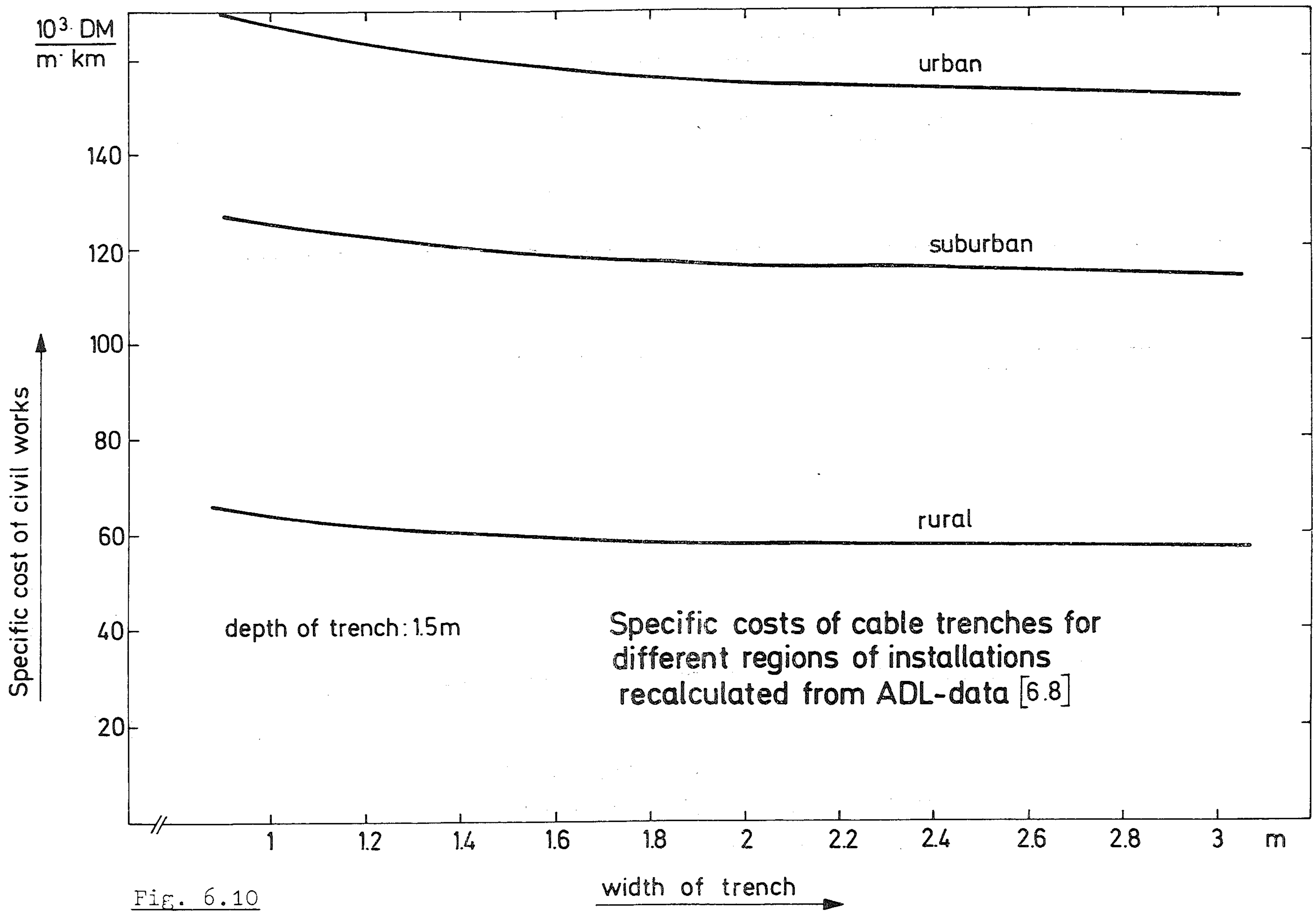

m/GVA
3
2
1
Specific width of trench
Specific width of trench for oil-filled cables with forced cooling
BEWAG
220,400KV
double circuit
BBC - FGK
400KV
Pirelli
400, 750, 1100 KV
1
2
3
4
5
6
7
8
9
10
11
GVA
Power transmission capacity

Fig. 6.9

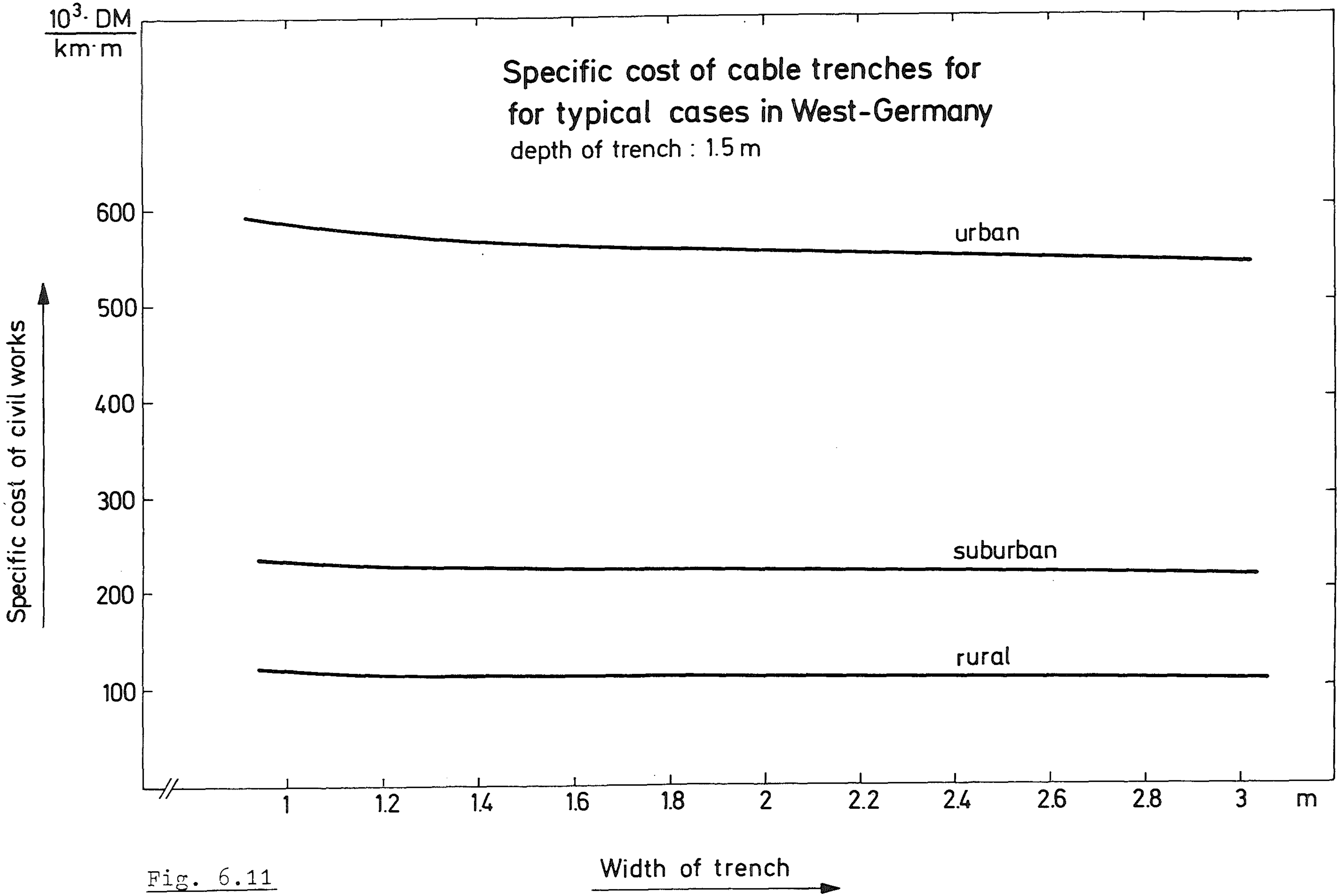
In the European countries wages and salaries differ greatly; so, it is self evident that no mean values can be indicated which apply to all European countries. Fig. 6.10 shows the costs of civil engineering work per m width and km length of trench at constant depth, recalculated from the ADL data to conditions prevailing in Germany. There is only a slight dependence of the specific values on trench width. This makes the specific costs something on the order of $160 \cdot 10^3$ DM/m•km for urban, $120 \cdot 10^3$ DM/m•km for suburban and $60 \cdot 10^3$ DM/m•km for rural installation.

In a recent German study, cost data on civil engineering work for typical places in West Germany have been summarized. The resulting values are even higher, especially for installation in urban centres as is shown in Fig.6.11.The overall costs of cable systems can be obtained directly by combining Figs. 6.9, 6.10 or 6.11 and 6.6. But it should be recalled that there may be major differences, especially in urban installation, depending on local conditions. Extremely high costs may occur in special cases, for example, when unexpected obstacles occur during cable installation or when it is impossible to dig an open trench so that the trench can only be built by tunnel construction methods. So, the greatest probability of wrong cost assessment may occur just in the field of the most important application of high power cables, namely the power supply to congestion areas.



10³·DM / m·km
140
120
100
80
60
40
20
Specific cost of civil works
urban
suburban
rural
depth of trench: 1.5m
Specific costs of cable trenches for different regions of installations recalculated from ADL-data [6.8]
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
m
width of trench

Fig. 6.10



10³·DM / km·m
Specific cost of cable trenches for
for typical cases in West-Germany
depth of trench : 1.5 m
600
500
400
300
200
100
urban
suburban
rural
Specific cost of civil works
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
m
Width of trench

Fig. 6.11

6.2 Compressed gas insulated cables

The fabrication and installation of SF_6 insulated cables is totally different from conventional cables, so it is not surprising that most cost data published until now are not consistent. A very thorough study on the costs of SF_6 cables has been done by EdF together with CGE and some other industries [6.11]. In this study, costs are assessed by splitting up the cable into costs of separate items the prices of which were furnished by the component suppliers. In Fig. 6.12, the main results of the EdF study are reported. According to these curves, SF_6 cables compared with advanced conventional cables will be economically attractive at 1000 to 2000 MVA and at voltages of 400 kV **and above (cf. Fig. 6.22).**

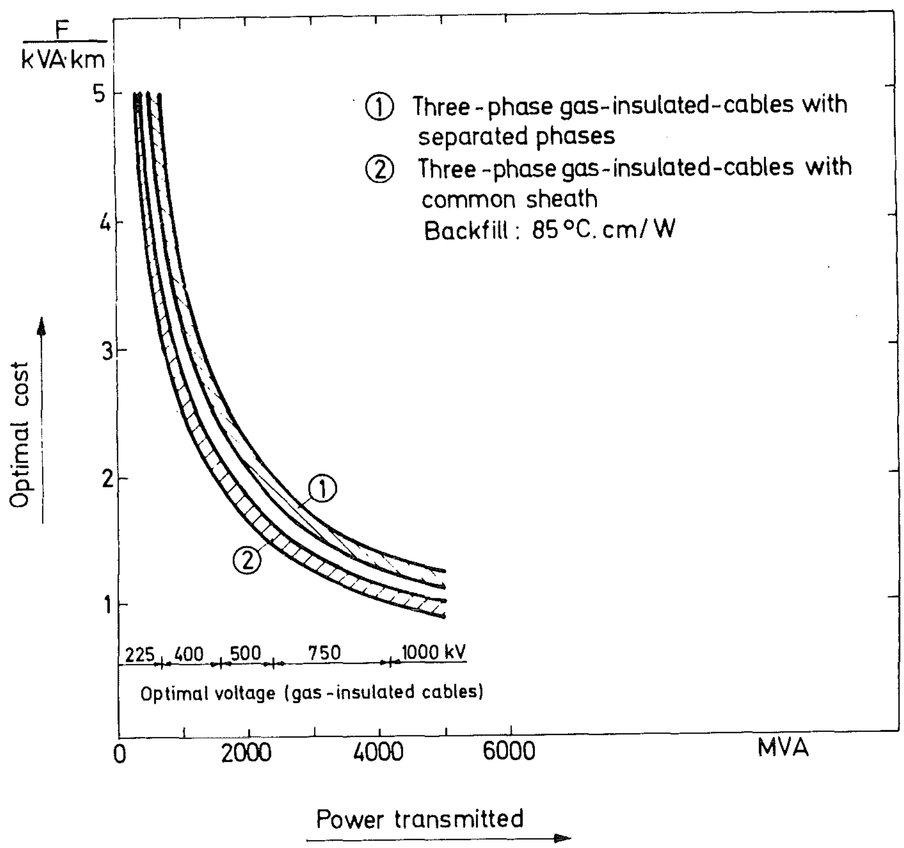


Fig. 6.12: Optimal cost of power transmission by SF_6 cables as a function of the power transmitted
Economic hypothesis: length of several km

These values can be decreased if the annual production rate is considerably higher. Especially when short links are discussed, SF_6 cables are economically attractive because costs of terminations, which are considerably cheaper than conventional cable potheads, have to be taken into account. Fig. 6.12 also shows the economic benefits of SF_6 cables of the three core type with one common sheath. But this concept as well as the flexible SF_6 cable concept have not yet been proved experimentally and they involve some important technical disadvantages. Thus, curve 1 in Fig. 6.12 should be used for a conservative assessment.

Fig. 6.13 is a comparison of cost data from different sources [6.3,9,11] for single core SF_6 cables. It can be seen that considerably higher costs than EdF's data are quoted. The main cost items of SF_6 cables are the pipes for the conductor and the sheath. According to [6.12] the prices of aluminium tubes with diameters ranging between 50 and 150 cm will be about 4 to 7 DM/kg. These figures do not apply to small quantities. If the prices given by Pirelli [6.9] are compared with prices of aluminium tubes or materials, the following figures result:

Basis: Al-tubes : 5.5 DM/kg
aluminium : 2 DM/kg

Ratio of costs:

$$\frac{\text{cable}}{\text{tubes}} = 4.5 \text{ at } 400 \text{ kV}$$
$$= 7.3 \text{ at } 750 \text{ kV}$$

$$\frac{\text{cable}}{\text{material}} = 12.4 \text{ at } 400 \text{ kV}$$
$$= 20.1 \text{ at } 750 \text{ kV}$$

According to Siemens-BEWAG [6.3], the cables are installed in tubes made up of asbestous cement. Costs of these tubes are taken to be 1.3 DM/kg, and the thickness is 2 cm. This results in

Ratio of costs:

$$\frac{\text{cable}}{\text{tubes}} = 2.25 \text{ at } 225 \text{ kV}$$
$$= 2.5 \text{ at } 400 \text{ kV}$$

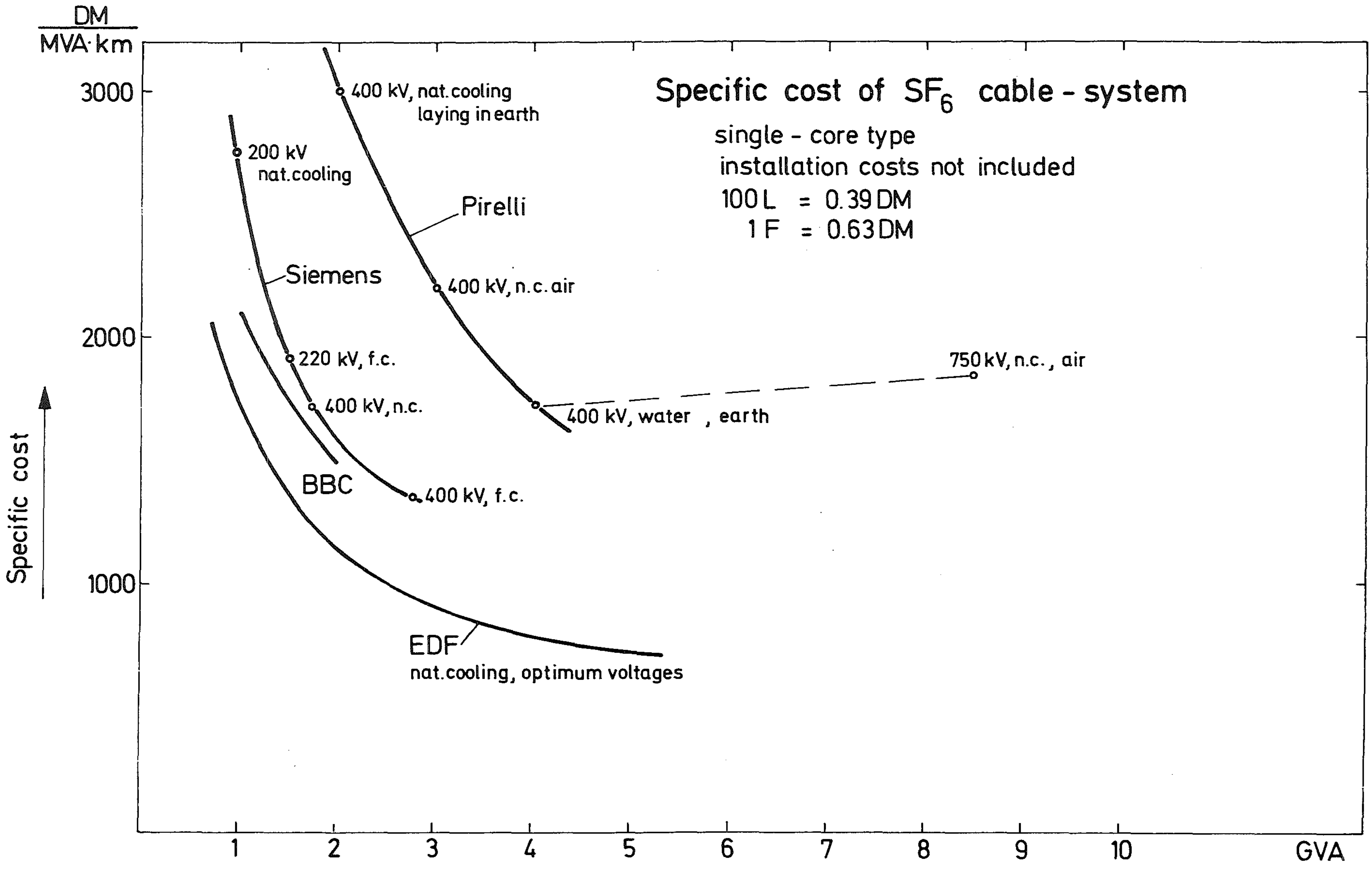

DM / MVA·km
3000
2000
1000
Specific cost
Specific cost of SF_6 cable - system
single - core type
installation costs not included
100 L = 0.39 DM
1 F = 0.63 DM
400 kV, nat. cooling
laying in earth
Pirelli
400 kV, n.c. air
750 kV, n.c., air
400 kV, water , earth
200 kV
nat. cooling
Siemens
220 kV, f.c.
400 kV, n.c.
400 kV, f.c.
BBC
EDF
nat. cooling, optimum voltages
1
2
3
4
5
6
7
8
9
10
GVA
Rated power

Fig. 6.13

In these data are compared with Fig. 6.7, which shows the ratio of costs between cable and materials for advanced conventional cables (about 5) it is quite clear that these very high prices for SF_6 cable systems cannot be taken as a basis for assessing the future chances of this type of cable. These values may apply to first prototype installation where high additional costs for development and ineffective fabrications will still occur.

Comparisons of SF_6 cables with other types of advanced cables can therefore only be made on the basis of studies, in which no prototype, but an established line of fabrication is considered, e.g., the EdF study. Specific costs of flexible SF_6 cables at about 1000 MVA, according to [6.15], are roughly the same as the EdF values for rigid systems. The specific width of trench for SF_6 cables is given in <u>Fig. 6.14</u>. These values apply to flat installation of the cables in one plane. In [6.3] installation of the three phases in asbestous cement tubes one above the other is proposed. This work will be more difficult to do than flat installation but may have advantages in big cities where it may be impossible in some places to open a trench several metres wide. Comparing Fig. 6.14 and 6.9, it can be seen that the specific widths of trench are on the same order, so costs of civil engineering for the types of cables discussed will not differ very much.

The specific costs of SF_6 cables can be reduced by improvements in cooling. The following table published by EdF provides an idea of the potential order of improvement.

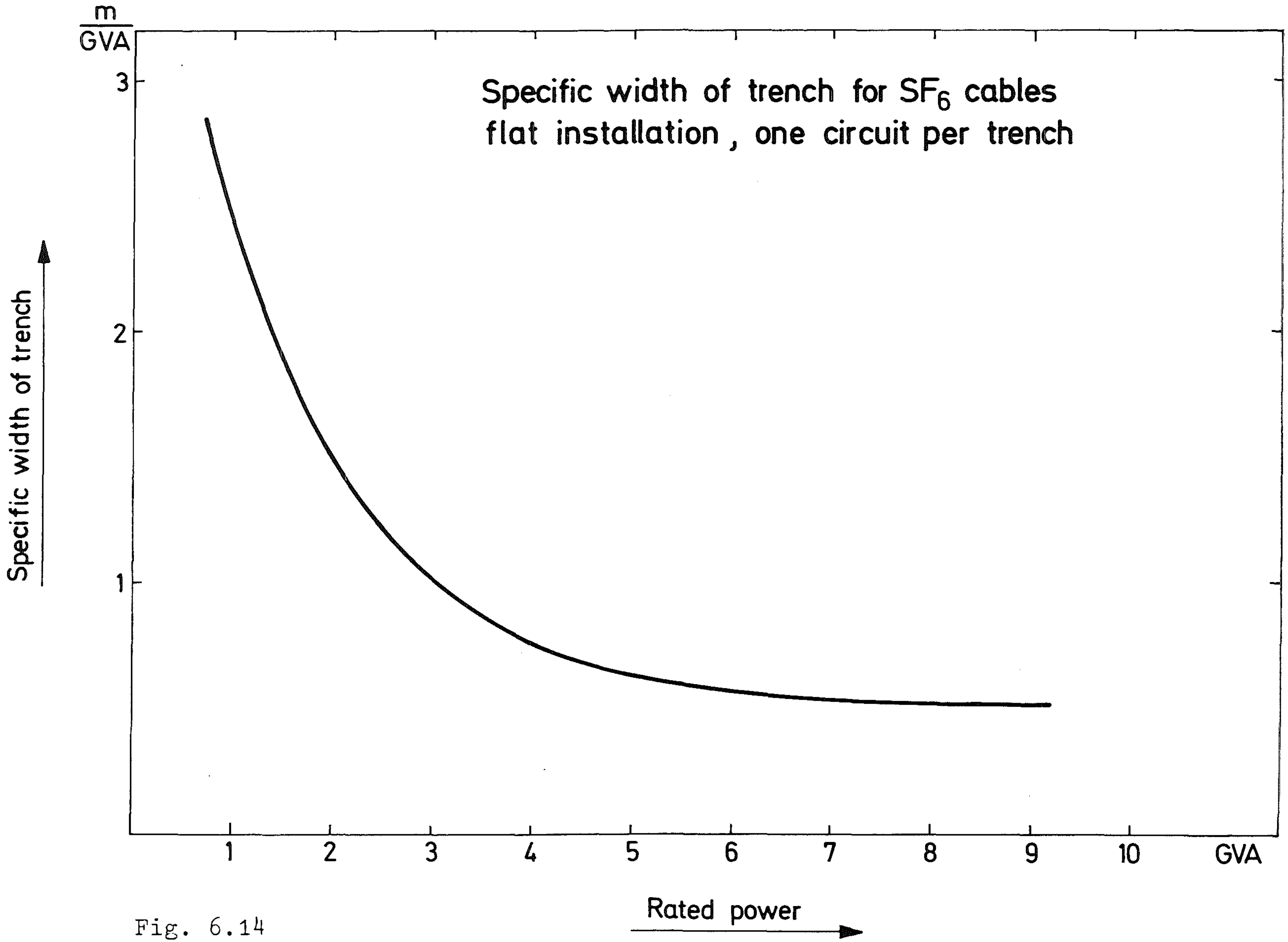

Specific width of trench for SF_6 cables
flat installation , one circuit per trench
m/GVA
3
2
1
Specific width of trench
1
2
3
4
5
6
7
8
9
10
GVA
Rated power

Fig. 6.14

Tab. 6.1: Transmission of 4000 MVA at 400 kV

	2 links buried in the ground 2 x 2000 MVA	1 link forced cooled 1 x 4000 MVA	1 link installed in open air 1 x 4000 MVA
Current density $(\frac{A}{mm^2})$	0.32	0.64	0.67
Relative cost	1	0.7	0.62

Whenever an SF_6 cable can be installed in the open air, this will be the most economical solution. As the operating current density already is close to its optimum (about 0.7 A/mm^2) cooling of SF_6 cables at lower temperature than ambient, as discussed for conventional cables in 6.1, is not useful and will result in higher costs.

6.3 Economics of cryogenic cables

6.3.1 Superconducting cables

Many cost estimates have been published for superconducting a.c. and d.c. cables. In Tables 6.2 and 6.3, a summary of cost data is given for some a.c. and d.c. superconducting cable designs. The cost estimates are based on different years of reference and therefore the data given are not representative for 1974.

In both tables, the percentage of total costs per km is given for the conductor system, the cryogenic envelope, the cryogenic supply, installation and the annual capitalized expenses. The costs of the "conductor system" include superconducting material, normal material, dielectric etc., the costs of "cryogenic supply" include He and N_2 refrigerators, LHe and LN_2 filling and storage, pumping, etc. The cost of "installation" include the costs of factory and field installation.

The cost estimates for superconducting cables are not very accurate, because of the uncertainties in the cost of conductor fabrication and the cost of installation in free field. Some cost items are well known: materials, thermal insulation, refrigerators, helium and pipes.

Due to the different economic structures of the countries covered in this study the specific costs per MVA•km are difficult to compare. Nevertheless, an attempt is made to compare the cost data supplied by taking the DM as common reference unit. Taking into account the rates of exchange in the reference years and the rise in the prices of industrial products in Germany, relative specific costs in DM per MVA km are calculated.

Fig. 6.15 shows these costs of superconducting a.c. and d.c. cables. In spite of the uncertainty of the cost estimates, the agreement is very remarkable.

Table 6.2: Cost estimates for superconducting a.c. cables

Company or laboratory	BICC	BNL	CERL	
Line-to-line voltage kV	33	132	275	400
Rated power capacity MVA	750	3000	4000	8500
Reference year	1971	1972	1968	1968
Overall costs per km	£165700[1]	$ 1166000	£317000	£471000
Percentage	%	%	%	%
Conductor system	22.3	26.7	17.4	18.7
Cryogenic envelope	22.9	16.0	25.9[2]	24.2[2]
Cryogenic supply (+ terminals)	32.2	30.7	31.5	30.4
Installation	22.6	16.0	13.9	11.3
Annual capitalized expenses	-	10.6	11.3	15.4[3]
Specific costs per MVA•km	£221	$ 373	£79.3	£55.3
Specific costs without annual capitalized expenses per MVA•km	£221	$ 347	£70.2	£46.8
Relative specific costs in DM/MVA•km	2480	1200	880	620

Comments

1) value from G. Bogner, according to BICC £244 000

2) including He-pipes

3) including costs for reactive compensation

Continuation of Table 6.2

Company or laboratory	Linde Union Carbide (UCL)			CGE/EdF		Siemens
Line-to-line voltage kV	138	230	345	140	180	110 (120)
Rated power capacity MVA	1690	4710	10590	3000	5000	2500
Reference year	1969	1969	1969	1973	1973	1971
Overall costs per km	$ 630900	$ 898000	$ 1320000	F 6000000	F 7750000	DM 3500000
Percentage	%	%	%	%	%	%
Conductor system	14.6	20.1	26.3	13.6	12.7	27.2
Cryogenic envelope	25.6	25.6	23.7	21.4	23.8	15.5
Cryogenic supply (+ terminals)	22.8	22.5	21.8	42.0	41.8	29.1
Installation	26.1	21.9	19.8	11.8	10.6	28.2
Annual capitalized expenses	10.9	9.9	8.4	11.2	11.1	-
Specific costs per MVA•km	$ 374	$ 191	$ 125	F 2000	F 1550	DM 1400
Specific costs without annual capitalized expenses per MVA•km	$ 333	$ 172	$ 114.5	F 1780	F 1380	DM 1400
Relative specific costs in DM/MVA•km	1720	880	580	1250	960	1400

Table 6.3: Cost estimates for superconducting d.c. cables

Company or laboratory	Estimate by B.C. Belanger	CERL		
Line-to-line voltage kV		230	230	230
Rated power capacity MVA	10000	4000	10000	16000 (4 circuits)
Reference year	1971	1968	1973	1968
Overall costs per km	$ 934000	£125000	£217700	£ 213000
Percentage	%	%	%	%
Conductor system	29.8	11.2	23.9	25.8
Cryogenic envelope	29.2	24.0 1)	17.9	22.5 1)
Cryogenic supply (+ terminals)	14.5	30.4	26.6	24.9
Installation	26.5	21.6	31.6	16.9
Annual capitalized expenses	-	12.8	-	9.9
Specific costs per MVA•km	$ 93.4	£ 31.3	£ 21.77 2)	£ 13.3
Specific costs without annual capitalized expenses per MVA•km	$ 93.4	£ 27.2	£ 21.77	£ 12.0
Relative specific costs in DM/MVA•km	310	350	250	150

Comments

1) including He-pipes and joints

2) for Nb-Ti-Zr/Cu and 19.5 for Nb-Ti-Zr/Al

Continuation of Table 6.3

Company or laboratory	CGE/EdF		LASL	AEG	
Line-to-line voltage kV	± 110	± 140		±100	±200
Rated power capacity MVA	3000	5000	10000	2500	5000
Reference year	1973		1973	1971	
Overall costs per km	F 2580000	F 2750000	$ 42800[3]	DM 3000000	
Percentage	%	%	%	%	
Conductor system	15.6	17.0	24.1		
Cryogenic envelope	19.0	20.0	26.6		
Cryogenic supply (+ terminals)	38.1	38.8	11.9		
Installation	15.8	14.1	37.4		
Annual capitalized expenses	11.5	10.1	-		
Specific costs per MVA•km	F 860	F 550	$ 42.8		
Specific costs without annual capitalized expenses per MVA•km	F 760	F 494	$ 42.8		
Relative specific costs in DM/MVA•km	540	340	140	1200	600

Comments

3) costs of laboratories and installation assumed to be equal to the material costs.

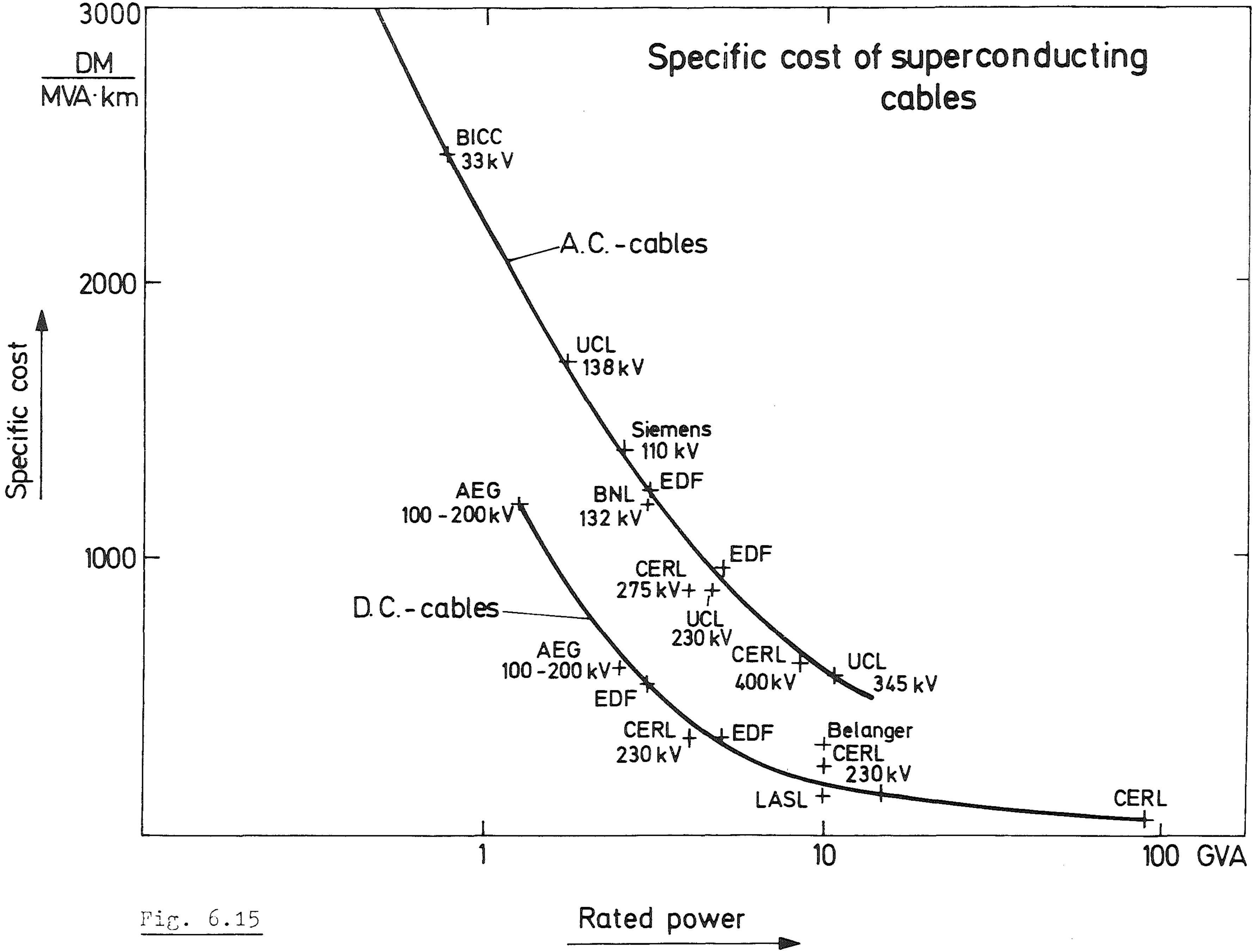

Specific cost of superconducting cables
3000
2000
1000
DM / MVA·km
Specific cost
BICC 33 kV
A.C.-cables
UCL 138 kV
Siemens 110 kV
EDF
BNL 132 kV
AEG 100 - 200 kV
EDF
CERL 275 kV
UCL 230 kV
D.C.-cables
AEG 100 - 200 kV
EDF
CERL 400 kV
UCL 345 kV
CERL 230 kV
EDF
Belanger
CERL 230 kV
LASL
CERL
1
10
100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

Fig. 6.15

The percentage of costs without annual capitalized expenses is shown in Fig. 6.16. The large percentage of cryogenic supply in the CGE/EdF cost estimates is due to the fact that the refrigerators are doubled for safety reasons.

Fig. 6.17 shows the specific width of trench for a.c. and d.c. superconducting cables. For attractive power ratings the specific width of trench is smaller than 0.5 m/GVA.

As mentioned above, the cost data given here for superconducting cables are not conclusive values, because it is difficult to accurately estimate the manufacturing and installation costs for future cable system and actual costs for superconducting cables may have escalated by the time the superconducting transmission system is needed.

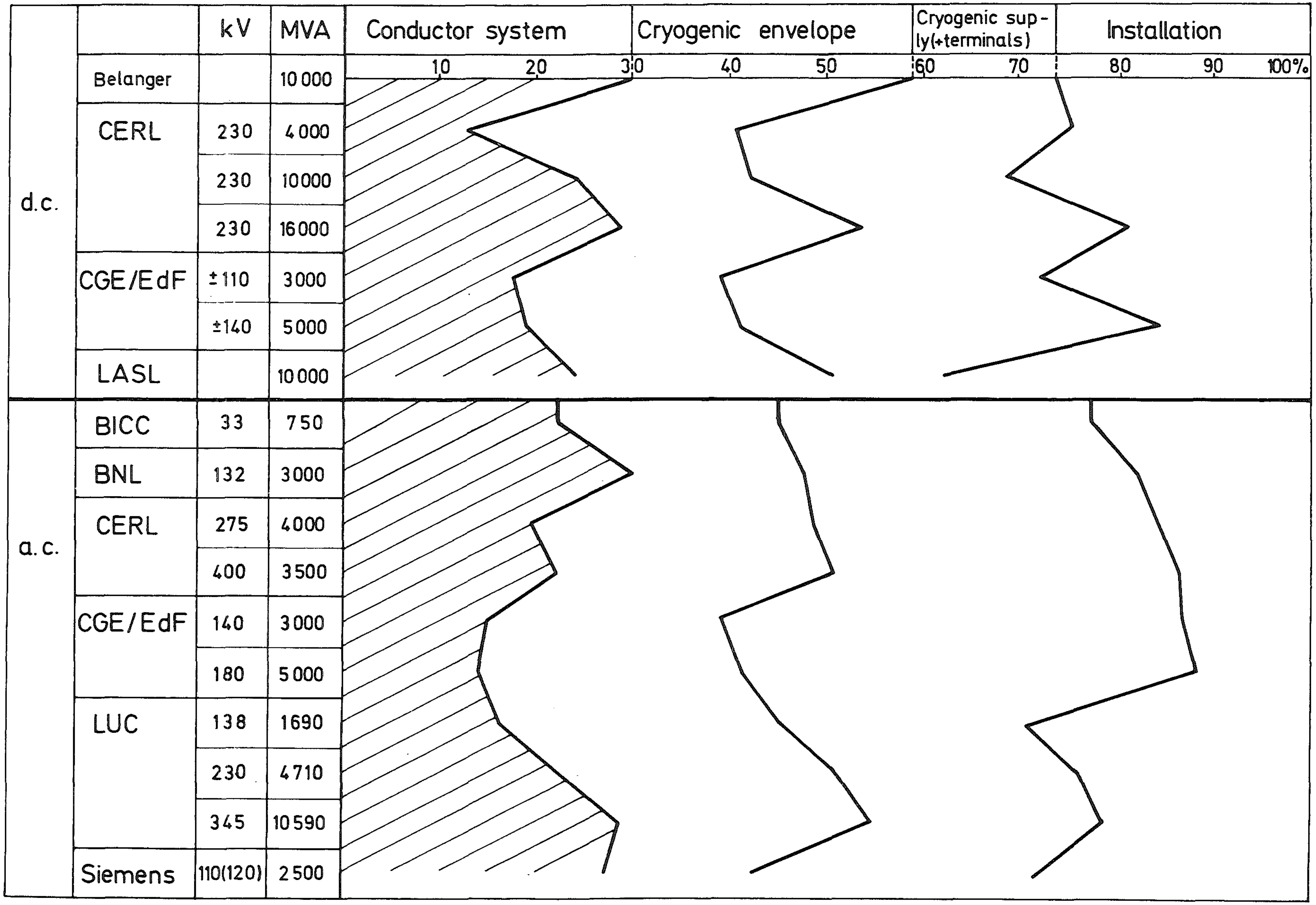


Fig. 6.16: Percentage of costs without annual capitalized expenses for superconducting cables.

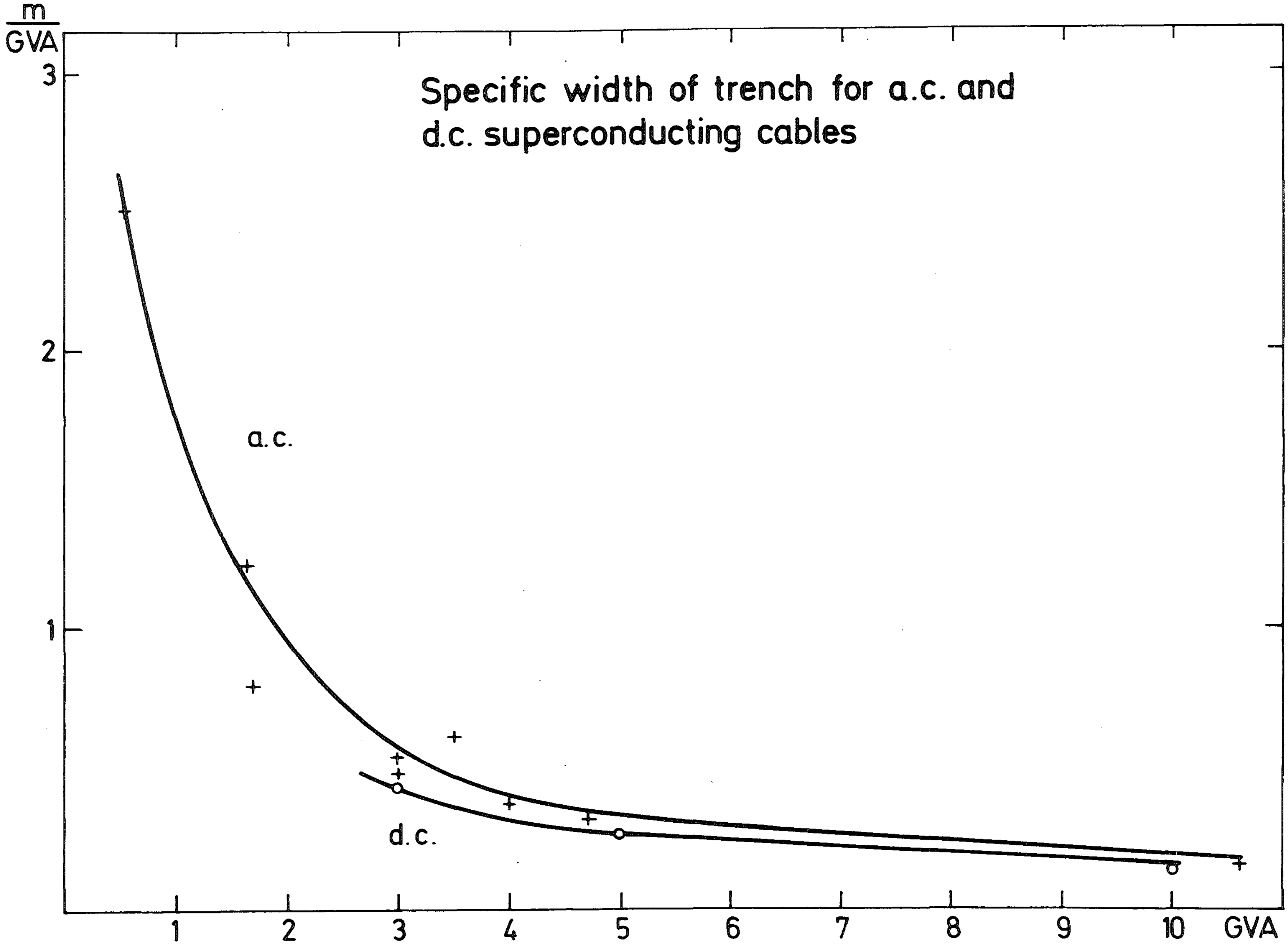

m/GVA
3
2
1
Specific width of trench for a.c. and d.c. superconducting cables
a.c.
d.c.
1
2
3
4
5
6
7
8
9
10
GVA
Rated power

Fig. 6.17

6.3.2 Cryoresistive cables

From the knowledge of the different cryocable components it can be assumed that cryoresistive cables for the 150 kV voltage range can be manufactured within the next few years and the 400 kV range also will not be prohibitive after some more years of fundamental investigation. Hence implementation will mainly depend on the economy. Studies of energy transport by cryoresistive cables have been published by many authors [6.8,16,17,18,19,20]. Because of the complexity of the problems studied the results are not summarized in a compact form. We therefore only present some typical and representative concepts.

The EdF group [6.18] in its study favours the LN_2-impregnated synthetic paper insulation. It is assumed to be more economical to place the LN_2-return line into the thermal envelope of the cable. Further details can be taken from Fig. 6.18. This cable has been studied for 1000 and 3000 MVA and voltages of 400 kV and 500 kV, respectively, between two phases.

The transmission costs of these cables have been calculated on the assumption that 100 km of cable length will be fabricated per year and that these cables will be used over distances which are not too short. The costs and their breakdwon are given in Tab. 6.4 [6.18]. A detailed description of the cost calculation has not been published.

A German team [6.16,17] studied various ac-cable concepts including those shown in Fig. 6.19 for both 110 kV and 380 kV. The power transmission costs of both these cryoresistive cables and various conventional cables have been calculated under similar assumptions (Fig. 6.20). The litz-conductor cable (concept b), which corresponds to the GE and the Japanese concepts (cf. Fig. 4.1.7), proves to be the most economical cryogenic solution. It should be mentioned however, that it has not yet been proved wether the rather simple six-segment-conductor will give a.c. losses sufficiently low. The breakdown of costs (Fig. 6.21) shows for all the concepts that the refrigeration costs (installation and capitalized running costs) contribute

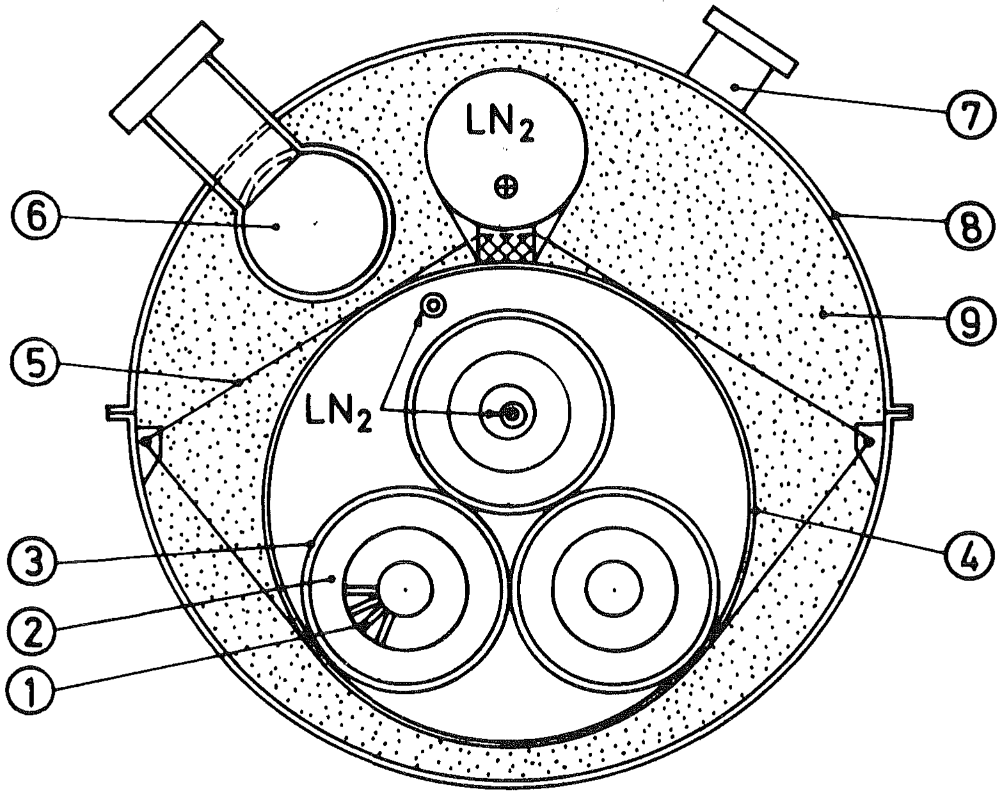


Fig. 6.18: EdF design of a cryoresistive cable

1 - Conductor (aluminium)

2 - Fibrous polyethylene paper (Tyvek) ribbon

3 - Electromagnetic shield (aluminium)

4 - 77 K enclosure (Invar)

5 - Suspension system

6 - Pumping tube

7 - Aperture for filling the powder

8 - 300 K enclosure (steel)

9 - Thermal insulation (evacuated powder)

Tab. 6.4: Cost breakdown of cryoresistive cables

(Results obtained by EdF collaboration with Air Liquide [6.18])

Rated power	1000 MVA	3000 MVA
Cable (electr. component)	18.6 %	15.1 %
Cryogenic envelope	20 %	17.5 %
Refrigerator	27 %	31.2 %
LN_2 pumps	2.7 %	1.6 %
Installation and civil engineering (posed)	13.5 %	24.6 %
Capitalized losses and amortization	18.2 %	24.6 %
Power transmission cost (F/kVA•km)	4.78	2.86

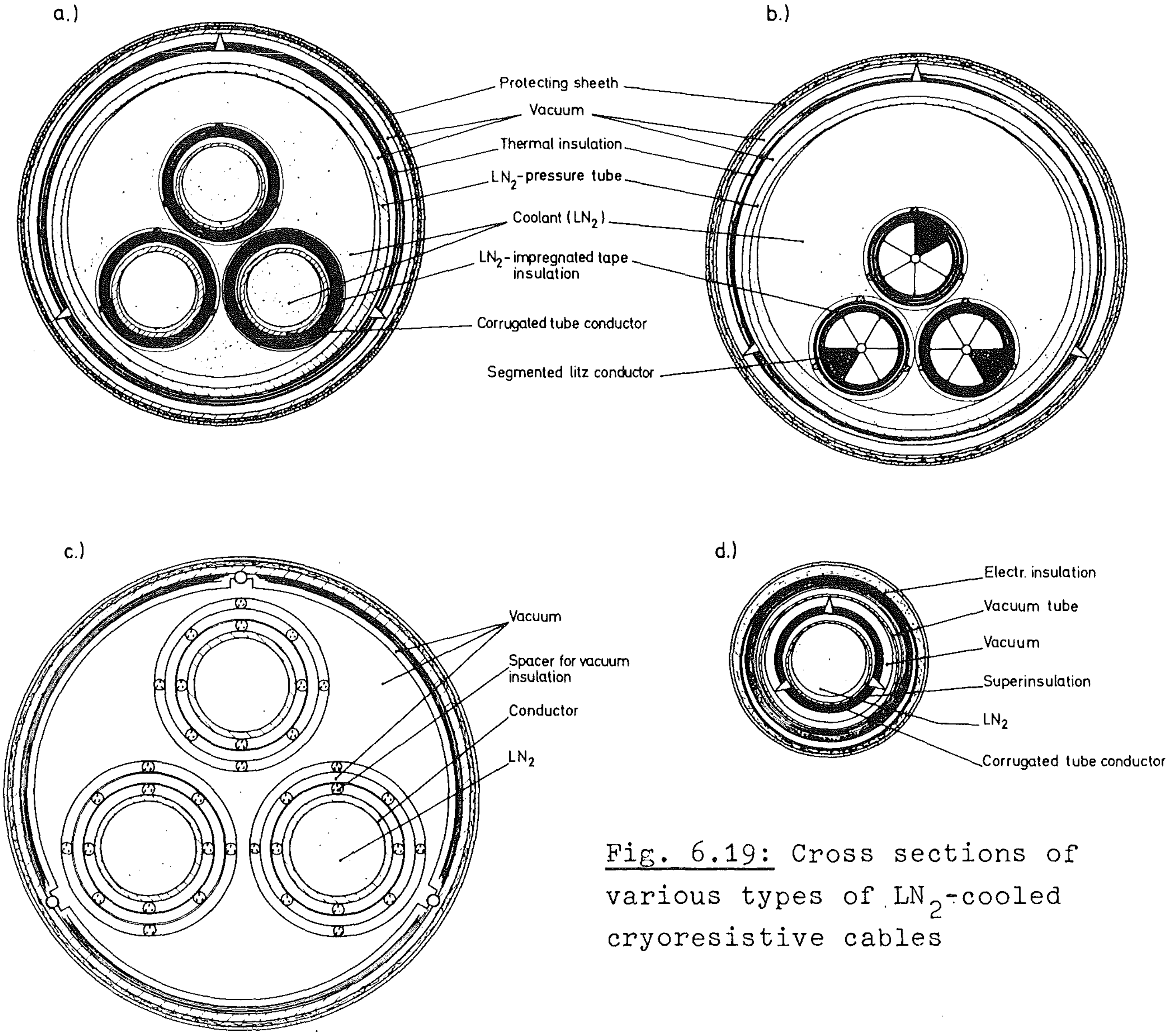


Fig. 6.19: Cross sections of various types of LN_2-cooled cryoresistive cables

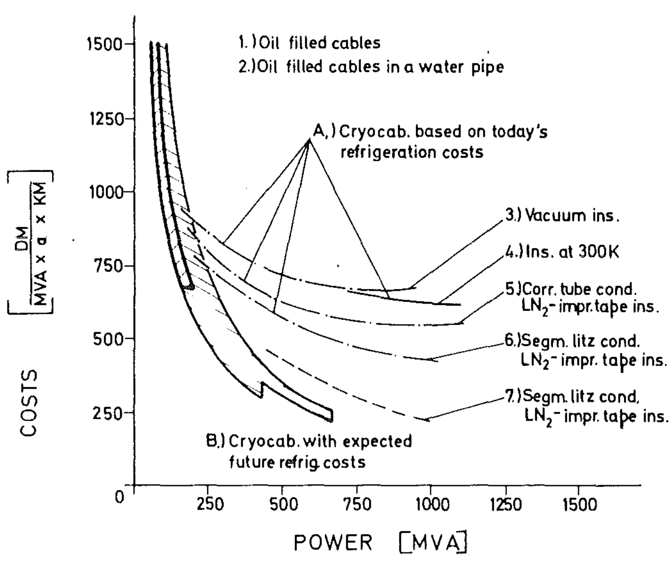


Fig. 6.20: Power transmission costs for various 110 kV a.c. cables

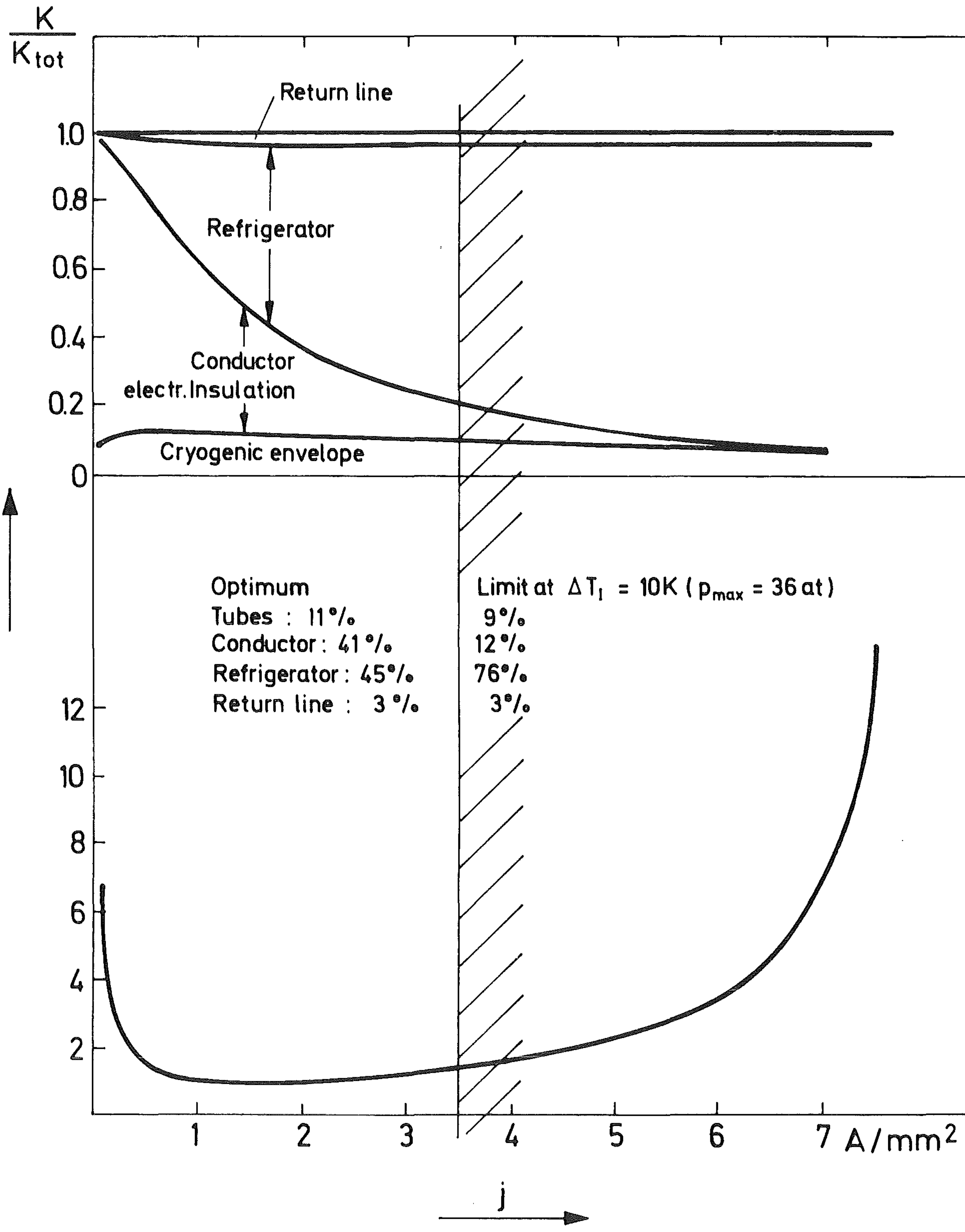


Fig. 6.21: Litz-conductor cable. Cost breakdown and dependence of the costs on the current density. (Refrigerator costs include capitalized running costs)

by more than 50 % of the total transmission costs.

Hence, transmission costs can be expected to drop below those incurred by conventional techniques only if both the performance and the costs of refrigerators can be improved (plot 7 of Fig. 6.20). Similar results are obtained for the 380 kV range. These results also agree with other investigations.

A further improvement of economics is discussed by a Japanese group [6.19]. In Japan, liquid natural gas (LNG) will be widely used for thermal power stations. Use of LNG to precool the LN_2-refrigerator allows an appreciable reduction of costs to be achieved. For a 500 kV/10 GVA transmission line, estimated savings are about 15 % in construction costs and about 75 % in running costs. In this case, cryoresistive cables undoubtedly will be an economical solution. A detailed study on the anticipated volume of application does not yet exist.

6.4 Direct current transmission

Specific costs of d.c. cables are considerably lower than the costs of a.c. cables. According to [6.11] specific costs of a.c. cables can roughly be taken to be about 3 times higher than the costs of d.c. cables. For superconducting cables the ratio is on the same order. On the other hand, the costs of converter stations are very high and show no marked degression as the power increases. For this reason, direct current transmission can only compete with a.c. in the case of long transmission lines. As the specific cost of the cable falls sharply with rising power, the minimum length for economical d.c. transmission is the longer the higher the power transmitted. A simple calculation indicates the lengths.

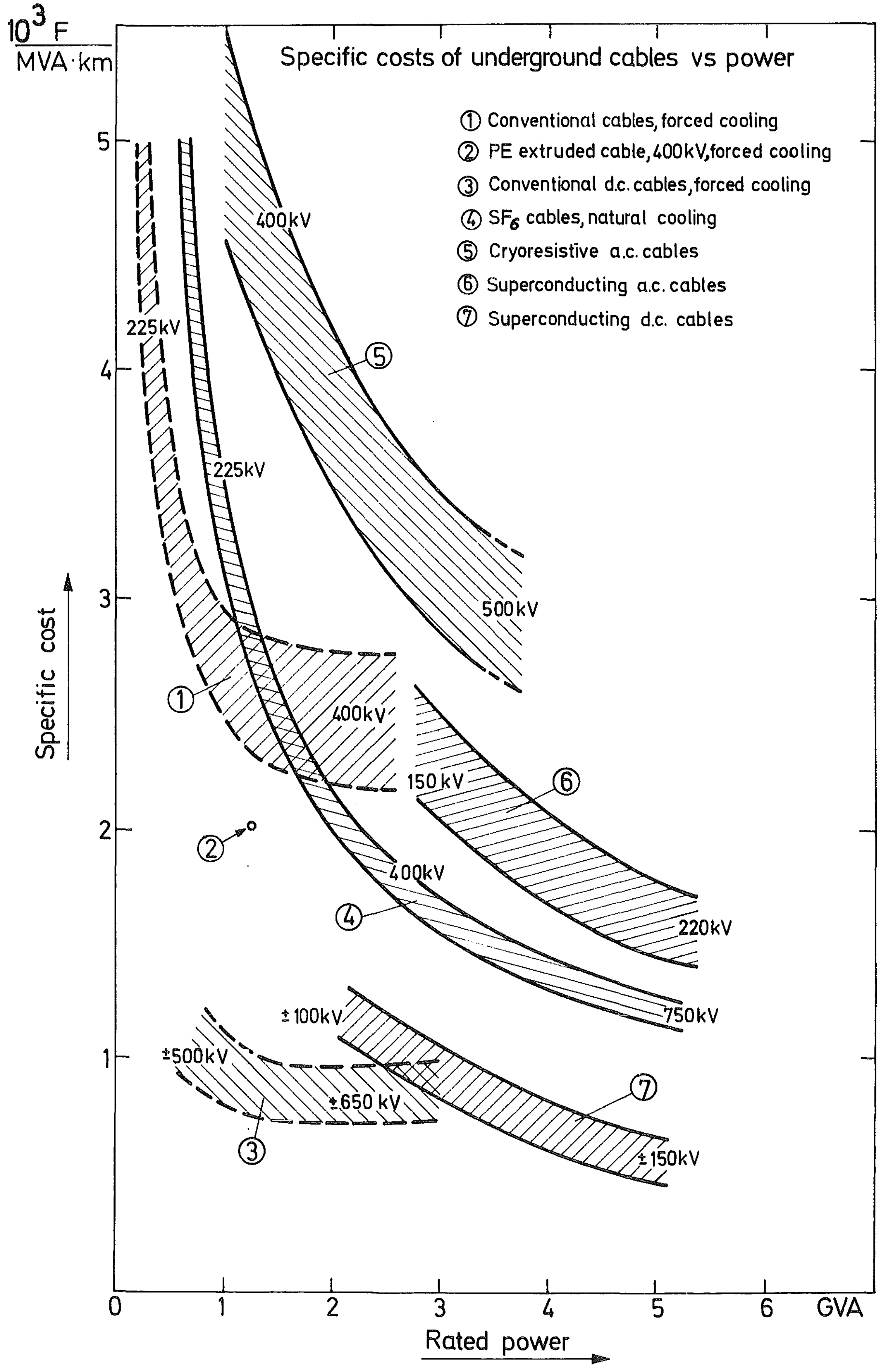
Present costs of converter stations for a two point connection are about 200 DM/kW [6.3]. This may perhaps drop to about 150 DM/kW because of technical progress in the field of semi-conductor valves.If the specific costs of a.c. cables at 1000 MVA are taken to be 1900 DM/MVA•km, according to Fig. 6.6, this results in a minimum length for economical d.c. transmission of l = 120 km. The costs of d.c. cables are assumed to be one third of a.c. cables. For 3000 MVA and specific a.c. cable costs of 1000 DM/MVA•km, the minimum length is l = 220 km. It is obvious that the future economic situation of d.c. transmission will not become better but worse. Presently, the minimum length for d.c. transmission is mostly seen on the order of 100 km. This value will doubtlessly be considerable higher when advanced cable systems are used. Power transmission over a length of several hundred km will surely be realized in the foreseeable future by overhead lines. As the minimum length for economical d.c. transmission by overhead lines is on the order of 500 to 800 km, it is not probable that d.c. transmission will find major applications in the European Community. There may be a field of application for technical reasons, putting up with economic disadvantages, such as the connection of large power stations to the grid without increasing the short circuit power. For these reasons, d.c. cables are not discussed in detail in this study.

6.5 Conclusions from the cost comparisons

Concluding this section on the costs of advanced cable systems means trying to decide on what, economically, will be the best cable. Before presenting a comparison of the data assembled for this study, a comparison made by EdF [6.11] is shown in Fig. 6.22. This comparison shows that at medium power levels around 1000 MVA forced cooled extruded dielectric cables may stand good chances if this type of cable is feasible at 400 kV. At very high powers, SF_6-cables will have the lowest costs. Flexible SF_6-cables are not very attractive because of their low power limit of 1000 - 1500 MVA (cf. section 3.4) which is clearly the field of oil filled or extruded dielectric cables.

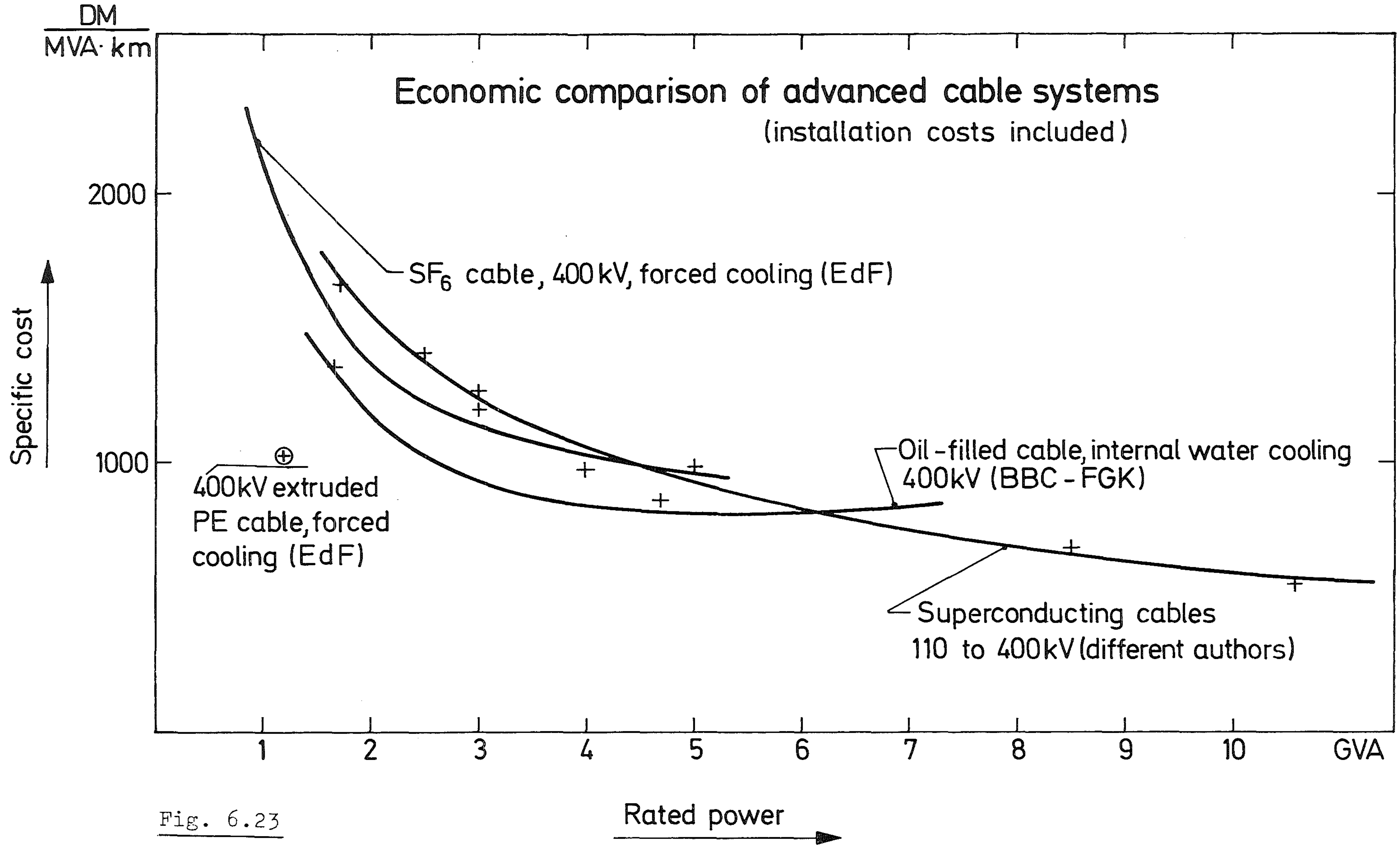
Cryoresistive cables seem to offer no good prospects. In this comparison, cables with different voltages are compared. In special cases this may result in erroneous conclusions, since the optimum voltage of the cable is not necessarily also the optimum voltage of the whole system. For the supply of big cities it will be advantageous to use no ultra high voltages. So, from the data assembled for this study, cables on the 400 kV level (and less which is optimal for superconducting cables) have been selected for a general comparison. In Fig. 6.23, the costs of four types of cable discussed in detail in the preceeding sections are shown together. There are some minor differences between the data on installation costs, but this does not alter significantly the comparison. This figure also shows the advantage of extruded PE-cables at the lower power levels. A very promising new type of cable clearly is the oil paper cable with internal water cooling. It may push the break even point of superconducting cables to about 6 GVA, a power level which may never be transmitted by a single line.

When examining cost data on future high power cables it should be remembered that these parts of the grid contribute only a small fraction of the costs of electric energy. Other criteria besides costs are important when deciding on a cable system for a specific transmission problem. This will be discussed in the next section.



Specific costs of underground cables vs power
10³ F / MVA·km
Specific cost
Rated power
GVA
0
1
2
3
4
5
6
① Conventional cables, forced cooling
② PE extruded cable, 400kV, forced cooling
③ Conventional d.c. cables, forced cooling
④ SF6 cables, natural cooling
⑤ Cryoresistive a.c. cables
⑥ Superconducting a.c. cables
⑦ Superconducting d.c. cables
400kV
225kV
225kV
500kV
400kV
150kV
400kV
220kV
750kV
±100kV
±500kV
±650 kV
±150kV

Fig. 6.22



DM
MVA · km
Economic comparison of advanced cable systems
(installation costs included)
2000
1000
Specific cost
SF_6 cable, 400 kV, forced cooling (EdF)
400kV extruded
PE cable, forced
cooling (EdF)
Oil-filled cable, internal water cooling
400kV (BBC-FGK)
Superconducting cables
110 to 400kV (different authors)
1
2
3
4
5
6
7
8
9
10
GVA
Rated power

Fig. 6.23

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7. Additional criteria for choosing cable systems

There are many parameters which are important when choosing a cable system for a specific transmission task.

Reliability

It seems to be reasonable to require new cable systems to be just as reliable as existing cable systems, or even more so (∿ about 2 faults per 100 km and year, cf. Tab. 5.1). The advanced cables discussed in section 3 seems to attain the reliability of the cables presently in operation, while for cryogenic cables this is difficult to say. No quantitative investigations into the reliability of cryogenic cable systems have been made till now. The reliability of a cryogenic cable system is determined by the cable itself and essentially by such auxiliaries as the refrigerators and pumps. For safety reasons the duplication of these auxiliaries is suggested. The repair times of cryogenic cables greatly exceed those of conventional cables, because of very long cooling up and cooling down times(several weeks). Therefore, cryogenic cables must be developed so that the probability of failure is substantially reduced as against conventional cables.

Trench width

In the low power range the required widths of trenches for the cables discussed here differ (cf. Fig. 6.9,14,17). This fact can be important for the choice of a cable to be used in urban areas. In the high power range (> 2 GVA) the differences in trench width are of minor importance. Special local conditions, e.g. circumventing obstacles, influence the choice between flexible or rigid cables. With respect to trench width, SF_6 cables are most disadvantageous, while superconducting cooled cables need the narrowest specific width.

Reactive cable behaviour

The cables discussed here show different types of reactive behaviour while in operation. Oil filled and most PE cables are operated below their natural power and therefore are capacitive. Internally forced cooled cables and SF_6 cables can be operated beyond their natural power, which makes them inductive (cf. Section 3, Fig. 3.18 and Section 5.4). By adequate choice of a specific type of cable one can meet the reactive requirements of specific transmission problems. In this way the reactive power requirement can be reduced and additional reactive elements may be saved.

Short Circuit Behaviour

For all the cable systems discussed in this study - superconducting cables excluded - the short circuit problem is regarded to be soluble without any major additional expenses. Some possibilities to solve the short circuit problem for superconducting cables are suggested, but a considerable research effort will continue to be necessary in order to solve this difficult problem.

Adaptation of Growing Demand

The costs of a cable system can be influenced crucially by the way in which they can be adapted to increasing power requirements. The power capacity of conventional cables can be increased by providing an additional external cooling system. An increase in the power capacity by a factor of about 2 to 3 can be achieved. In order to increase the power capacity of an internally cooled cable, the cooling fluid velocity can be increased, the input temperature of the cooling fluid can be decreased, cooling machinery can be added successively, if necessary, and last but not least, the cooling fluid can be changed, e.g., oil can be replaced by water. By adequate investments the transmissible power can thus be uprated by a factor of up to 10. As far as cryoresistive cables are concerned, limited uprating is possible. In the case of superconducting cables the margin of action is much smaller.

The following scheme offers a rather personal judgement by the authors on the cable systems compared in the final cost figure, 6.23. This opinion holds true for today and may be altered in the future by development work on critical problems.

	Reliability	Short circuit performance	Adaptation to growing load	Trench width
PE cable ext. water cooling, 400 kV	not yet proved, but hopeful	no problem	good	as usual
Oil paper cable, int. water cooling 400 kV	probably no problem	no problem	very good	as usual
SF_6 cable ext. cooling 400 kV	probably no problem	no problem	good	rather wide, in special cases prohibitive
Superconducting cable, 400 kV	can not be estimated	critical (cost problem)	poor (uprating small)	narrow

Additional comments with special regard to superconducting cables

If superconducting cables are choosen for operation in the grid, they can operate beyond their natural power just as overhead lines, internally cooled cables and SF_6 cables. So, with respect to reactive behaviour they bring the same advantage and disadvantage as the cables mentioned above.
As mentioned above, the duplication of cooling machinery for cryogenic cables is suggested. In the AEG contribution a failure probability of the cooling machinery of 0.3 faults per 100 km and year in the case of the 200 kV d.c. superconducting cable is given with a repair time of ten days per failure. No experimentally well-founded estimates of electric faults of a superconducting cable are available. Therefore it is impossible to calculate presently the redundance performance. But there is no must for superconducting cables to be less reliable than conventional cables.

To warrant the safety of supply it is reasonable to suggest the duplication of the feeder circuit, i.e. in the case of superconducting cables to duplicate the cable itself, so that each circuit normally operates at half its full rating, and use is made of the full rating only when one circuit is out of service. This consideration is valid for all supply systems with very high power to be transmitted.

Superconducting cables seem to be attractive for a power level of several GVA. Some utilities have the opinion that it would be an intolerable risk to transmit such an enormous power with one cable, for it is general practice to make provision for maintenance of power supplies under all anticipated conditions when lines may be out of service for fault or maintenance reasons.
Another point considered in cable operation is the energy loss during transmission. In the following survey both the efficiency and the specific cable losses are given. For comparison an arbitrary line length of 10 km is assumed. This survey shows that the specific losses of a.c. superconducting cables and advanced cables differ not very much.

Survey on Cable Losses and Efficiency

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 mm^2 Al	110	350	366	1.05
	4 systems, 4x265/35 mm^2 Al	400	7600	2750	0.36
	1 system	725	5800	705	0.13
	Oil cables				
AEG	1000 mm^2 Cu, single core, nat.cool.	110	131	52.5	0.4
AEG	" " " , ext.cool.	110	398	324+16 1)	0.86
AEG	2000 mm^2 Cu, " " , " "	110	631	418+20 1)	0.7
Siemens-Bewag	2000 mm^2 Cu, " " ,forc.cool.	220	1000	420	0.42 2)
"	2000 mm^2 Cu, " " ," "	400	1500	300	0.2 2)
AEG	2000 mm^2 Cu, single core, nat.cool.	380	560	67.1	0.12
AEG	2000 mm^2 Cu, " " ,forc.cool.	380	1500	225+12 1)	0.16
Pirelli	2000 mm^2 Cu, lateral cool.	750	2850	297	0.13 2)
Pirelli	2300 mm^2 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 mm^2 Cu, single core, nat.cool.	110	145	58.2	0.4
AEG	1000 mm^2 Cu, " " ,forc.cool.	110	448	386+18 1)	0.09
	SF_6 cables				
Siemens	13000mm^2 Al, three core	110	1800	480	0.27
Pirelli	8000 mm^2 Al, single core, nat.cool. air laying	400	3000	450	0.15
Pirelli	8000 mm^2 Al, " " ,earth laying	400	2000	200	0.1
Pirelli	8000 mm^2 Al, " " , ext.water cool.	400	4000	800	0.24 3)
Siemens	9000 mm^2 Al, single core	400	4800	270	0.056
Siemens	9000 mm^2 Al, " " ,forc.cool.	400	7800	1260	0.162 3)
Pirelli	8000 mm^2 Al, " " , nat.cool. air laying	750	8500	675	0.08
AEG	9000 mm^2, single core	380	527	75.6	0.143
AEG	13000mm^2, " "	380	1265	80.1	0.064
AEG	28700mm^2, " "	380	2050	93.0	0.046
AEG	9000 mm^2, " "	525	727	75.6	0.104
AEG	13000mm^2, " "	525	1750	80.1	0.046
AEG	28700mm^2, " "	525	2830	93.0	0.033
	Cryoresistive cables				
Pirelli	1700 mm^2 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

8. Summary

This study is a survey of the present state of high power cables and outlines the trend of further developments. A comparison of advanced high power underground cables is made on the basis of information ordered from European industries (AEG, BICC, CGE, Pirelli, Siemens), spontaneous contributions by EdF, France, BBC and FGK, Germany, and Hitachi, Furukawa, Fujikura and Sumitomo, Japan, and the most important international publications as well as earlier studies carried out by German national research centres.

The comparison of the technical performance of different cable systems and identical cable systems installed in different countries is difficult because both the requirements and the test conditions in various countries frequently differ. All statements on transmissible power and rated voltages must be viewed under this aspect. A comparison of costs is even more problematic. In the case of conventional cables it is impossible to see whether real costs or commercial prices have been reported. Cost studies on cables under development have been made at different times and in various countries. In this study an attempt is made to compare these data on a common basis.

Natural cooled oil filled cables are called conventional in this paper. The power capacity limit of these cables is around 500 MVA at 400 kV. This report essentially deals with cables which promise further increases the power to be transmitted. Especially the following systems are covered:

- Cables with external forced cooling
- cables with internal forced cooling
- ultra high voltage cables with synthetic dielectric
- extruded polyethylene cables
- SF_6 cables
- cryogenic cables (cryoresistive and superconducting cables).

The following aspects are regarded:

- State of the art
- technical limits of performance
- foreseeable date of availabilitiy
- economy.

Moreover other criteria, such as reliability and behaviour in the grid, are discussed. The main results are listed below.

Cables with external forced cooling

These cables may be regarded as a further development of conventional cables involving no major technical and economic risks. They improve the power capacity by a factor of about 2 to 3 (cf. Section 3.1, Table 3.1 and Section 3.6) as against conventional cables. They are practically available. Their reliability is possibly better than that of natural cooled cables because of controlled heat dissipation.

Cables with internal forced cooling

Internally oil and water cooled cables allow a considerable increase in the power that can be transmitted (cf. Section 3.6). Economical operation is expected in the power range of about 1000 to 5000 MVA. In principle, there is no upper limit of the conductor cross section and, hence, the transmissible power, but large conductor cross sections cause considerable problems of fabrication, transport and installation. In the case of internal water cooling there are further problems of the long term tightness of the coolant duct and at the potheads. Most probably, though, these problems can be solved. First field tests with internal oil cooling show that this type of cable will be ready for commercial use in the near future. Cables with internal water cooling will still need some years of development.

Ultra high voltage cables with synthetic dielectric

The power capacity of conventional cables with oil impregnated paper insulation is limited at the very high voltage end chiefly by the dielectric losses. Wrapped synthetic insulation impregnated with a suitable fluid has very low dielectric losses and is thus suggested for ultra high voltage cables (> 400 kV). The practical use of UHV cables in congested areas can only be seen in connection with the development of encapsulated switching stations. SF_6 stations up to 220 kV constitute the present state of the art, but such stations have not yet been developed for UHV. In principle, the power transmitted by UHV cables can be further stepped up by forced cooling (cf. Section 3.6). But in this case the joints and potheads, which raise difficult problems even at lower voltages will be extremely critical components, especially for internally cooled cables. So the simplest type of forced cooling, that is lateral cooling, will stand the best chance of technical implementation.

Extruded polyethylene cables

For voltages up to 400 kV and power capacities up to 1200 MVA with external water cooling (cf. Section 3.6), cables with extruded synthetic insulation (PE) are very well suited because of their low dielectric losses and excellent temperature stability. Because of the good thermal conductivity of PE these cables lend themselves well to external water cooling. The construction and maintenance of such cables is simple. Therefore, such cables promise to be cheap, especially when designed for high service stresses (cf. Fig. 6.23) and provided the main problem of extruded dielectric cables, the statistical scatter of irregularities in the dielectric, can be solved satisfactorily. Partial discharges which may occur in small holes of the PE insulation, may easily cause defects of the cable. Such microscopic holes are difficult to avoid when thick extruded insulations are fabricated. Feasibility of PE cables up to 220 kV,has been proved, naturally cooled cables up to 600 MVA are being tested.

SF_6 cables

SF_6 cables in general are designed as three single core conductors, each of them arranged coaxially in a metal pipe. Arrangements of three cores in one common pipe have also been suggested and are being tested. Capacities up to 7000 MVA are considered for test programs. Until now only lengths of several hundreds of metres have been installed as interconnections in the grid or as transmission lines from underground power plants. In southern Germany (Schluchsee power plant) an SF_6 transmission line will be installed for 400 kV and 900 A rated current with a total single core length of about 4000 m. All transmission lines installed till now use rigid tubes, which are transported in lengths of about 15 m and welded together in the field. Jointing has to be done under very clean conditions because the electrical strength of the gas insulation is reduced considerably by pollutions. So, this rigid concpet raises many problems. They might be reduced by flexible designs. Recent designs are made up of corrugated tubes. In principle, rigid SF_6 transmission systems have no technological limits of voltage and power in the foreseeable range, while flexible systems have a limit of about 1300 MVA at 245 kV, due to drumming problems (cf. Section 3.6). SF_6 cables have been proposed for operation approximately at natural loading by regulation of the sheat current, which is not possible with conventional cables (cf. Fig. 3.17). SF_6 cables also allow the power transmitted to be raised considerably by the application of forced cooling when natural cooling with a stabilized backfill material is no longer sufficient.

Cryogenic cables

Cryogenic cables offer the possibility of greatly increasing the transmission capacity. Work on cryogenic cables is in the stage of component development. Problems of high voltage insulation at low temperatures, of short circuit behaviour, and of terminals still need to be solved. Laboratory current and voltage tests of cable sections about 50 m long are underway. Thermal insulation and refrigerators are not so much a problem of technical feasibility as of economic optimization.

In the field of cryoresistive cables only few activities can be detected. Two projects in Japan and the U.S. pursue the development of a 500 kV cable (1000 - 3000 MVA), which seems to be possible from the point of view of the electrical insulation. Presently, test lengths of about 30 m are being investigated. A development time of about 5 - 10 years is estimated by the research groups.

In the field of superconducting a. c. cables the three phase, coaxial design (e. g. Fig. 4.2.8) with Nb or Nb_3Sn conductors is considered to be most promising by many research groups. A voltage level of 400 kV is favoured. With reasonably sized superconducting cables the foreseeable requirements of underground power transmission can be met. One of the major problems of superconducting cables is the reliability of the cable itself and of the auxiliaries. So, as a next step, full scale and long term tests of cable sections linked to existing grids to prove operational safety and monitoring are envisaged. With respect to d.c. power transmission, the superconducting d.c. cable seems to be very attractive.

The time of development to commercial availability of superconducting cables is estimated at 10 - 20 years by the different research group.

Costs

Specific power transmission costs for the cables discussed above are shown in Figs. 6.22 and 6.23. The cost data reported are investment costs including capitalized costs of losses. Costs of cable trenches are given separately in Section 6. Other components, such as a.c./d.c. converters or switching stations for UHV have not been taken into account. The data show that at intermediate powers around 1000 MVA forced cooled extruded dielectric cables may stand a good chance if this type of cable is feasible at 400 kV. At very high power, SF_6 cables will have the lowest cost of advanced a.c. cables. Flexible SF_6 cables seem to be not very attractive because of their low power limit of 1000 - 1500 MVA (cf. Section 3.4), which is clearly the field of oil filled or extruded dielectric cables. Cryoresistive cables seem to be the most expensive design. A possible use of cryoresistive cables can only be anticipated for special applications.

In this cost comparison cables with different voltages are compared. In some cases this may result in erroneous conclusions, since the optimum voltage of the cable is not necessarily the optimum voltage of the whole system. For the supply of large cities it will probably not be advantageous to use ultra high voltages. So, from the data assembled for this study, cables on the 400 kV level (and less, which is optimal for superconducting cables) are selected for general comparison. The costs of four types of 400 kV cables discussed in detail in this study are compared (cf. Fig. 6.23).

This figure shows the advantage of extruded PE cables,also at lower power levels. A promising new type of cable clearly is the internally water cooled oil paper cable. It may push the breakeven point of superconducting cables to about 6 GVA, a level at which power probably will never be transmitted by a single line.

It should be mentioned here that the choice of a special cable is not only determined by the costs given here. Many other criteria, such as reliability, trench width, reactive cable behaviour, short circuit behaviour and adaptation of growing demand (cf. Section 7), are important when choosing a cable system for a specific transmission problem. So, this study cannot recommend one and only one cable system which could be the technical and economical optimum in every case. Nevertheless, examination of the gathered data, especially cost and reliability aspects, will give an impression of priorities for the next development work on advanced cable systems.