Chapter 6

High voltage cables

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6.1 Introduction

The first rule to understand when considering the design of high voltage cables is that many of the design parameters are set by the system into which the cable will be incorporated. The designer must take a humble stance of respecting, for example, the circuit current rating and impulse withstand voltage of any overhead line to which the cable may be connected. Apart from such technical aspects there is the impact on cable design of the economics of manufacture, in-service running costs, reliability, service-ability and the ever-increasing influence of environmental concerns.

The expectation of an insulated high voltage cable is that it will be an entirely passive element in the power transmission system, nonperturbing to associated equipment and providing unremarked service for many (at least four) decades. This life expectation has arisen because previous generations of cables have already provided such service and, understandably, the customers for cables see no reason to accept a lesser performance. However, the incidence of faults of the British 275 and 400 kV transmission network due to insulated cables is a small proportion of the overall number of system faults. At medium voltage levels, cable failures are due principally to third party damage [1].

The design of cables is to a large extent regulated by a number of industry, national and international standards and guides. These may be related to voltage level, technology of production or customer preference. Table 6.1 shows how the technology of manufacture, and in particular the primary insulation material, relates to the various broad voltage categories and some of the standards reigning in these areas. A fuller list of cable construction specifications and other useful material is included in

Table 6.1 Insulation and technology of HV cables

Medium voltage, i.e. up to 33 kV	Super-tension, i.e. 33 to 400 kV +
Lapped paper, dried and impregnated with viscous or nondraining compound BS 6480[2], EA TS 09-12[3], IEC 60055	Lapped paper, dried and impregnated with low viscosity fluid (oil). Eng. Recom. C47, NGTS 3:5.1, IEC 60141-1
Extruded PVC	Extruded vulcanised (EP) rubbers
Extruded vulcanised (EP) rubbers. BS 6622[4], IEC 60502	Extruded crosslinked polyethylene TPS 2/12, IEC 60840[5], HD 632
Extruded crosslinked polyethylene BS 6622[4], IEC 60502	

the references. The document which guides the calculation of continuous power rating of a cable by a systematic and agreed method is IEC 60287 (BS 7769) [6]. The major part of insulated cable installations are for AC circuits and consequently the following account is more directed towards AC cables. However, DC cables have always been the appropriate choice for certain situations, e.g. long inter-ties, large controlled power transfers, connections between differing supply frequencies, etc. There is now a growing interest in wider application of DC for smaller power transfers [7], allowed by the availability of power semiconductors for rectification and inversion and warranting more attention to the specific problems of DC cables.

The brevity of this account of high voltage cables necessarily means that much detail of the technology, science and philosophy must be omitted, but it is hoped that such a broad approach will be useful to practising engineers.

6.2 The components of an insulated power cable system

The cable itself is only one of the components in any system. It may take several forms depending on technical considerations and customer preference. For example, in some cases all three phases are contained in the same sheath providing minimised installation space and economy in the laying operation with lower magnetic interference fields as a bonus. The sacrifices to be made are reduced power rating for equal conductor sizes, less flexibility in installation practice due to the size and weight of the cable and greater complexity of the accessories.

No cable ever operates without being included in a system which at the very least will have two terminations per phase. These terminations may be into air, either for outdoor or indoor locations, or directly into other equipment with which they must be compatible, e.g. as oil immersed for generator transformers or gas immersed for busbars or switchgear. More generally, a cable system will also contain a variety of joints: to allow lengths greater than can be transported (about 500 m for the largest cables) to be made-up in the field (straight joints), to join differing technology cable (transition joints), to provide a hydraulic barrier (stop joints in fluid-filled cables) or to branch a circuit (branch joints). Some cables require ancillary equipment such as that needed to maintain the hydrostatic oil pressure in self-contained fluid-filled cables. Other components such as sheath voltage limiters (SVLs), devices for earth bonding of sheaths (link boxes) etc. are frequently found in cable systems.

The few faults that arise in insulated cable systems tend to be associated with these accessories; very few derive from failure of the cable itself. Table 6.2 illustrates this [8].

To grasp what these failure rates would mean in practice it is informative to interpret them in terms of a model three-phase HV circuit. If we propose a 3 km circuit with two sets of terminations, one set of stop joints and ancillary equipment in the case of oil-filled cables, and five sets of joints in all, we arrive at the failure rate estimates shown in Table 6.3.

These statistics are more indicative than exact, due particularly to the limited service time with XLPE cables. However, they support the experience of those involved in insulated cable technology that the cable itself, taking into account its length, is the least problematic item in any

Table 6.2 Failure rates in the various components of insulated HV cables

Component	Index of failures	Cable type	
		Oil-filled 220–500 kV (Av. age 20 yrs)	XLPE 60–220 kV (Av. age 7 yrs)
Cable	Failures/100 circuit.km.yr	0.05	0.05–0.07
Straight joints	Failures/100 units. yr	0.08	0.01
Stop joints	Failures/100 units. yr	0.16	–
Terminations	Failures/100 units. yr	0.07	0.04
Ancillary equipment	Failures/100 units. yr	0.32	–

Table 6.3 Relative failures in three circuit kilometres of insulated HV cable

	Oil-filled system	XLPE system
System failure rate/yr	0.033	0.0084–0.0102
Proportion due to cable/%	14	54–62
Proportion due to accessories/%	86	38–46

system. Section 6.4.2 will deal specifically with those components of a system that perhaps provide the greatest reliability challenge, namely the accessories.

6.3 Design features

6.3.1 Rating and thermal design – mainly referring to super-tension cables

The use of IEC 60287 [6] was mentioned in the introduction for calculation of the rating of the cable. It is not possible to reproduce this lengthy document here but the principle is illustrated in the following figure. Figure 6.1. shows the various sources of heat which, with the thermal resistances, govern the temperature differences between the conductor and sheath and the ground.

From this model, it is possible to derive an expression for the current capacity of a cable as $I = \sqrt{((\theta_g - \theta_c) - W_d(T_1/2 + T_3 + T_4)/R(T_1 + (1 + \lambda)(T_3 + T_4)))}$. However, as a cable circuit is generally three cables laid at a set spacing with a determined sheath earth bonding arrangement, there will be mutual electrical and thermal interference. This will reflect in the AC resistance of the conductor (R), the sheath losses (λR) and the ground temperature (θ_g). The calculation is made to rate the hottest of the three cables which is the central cable of a flat configuration. The following are the results of a calculation for a 132 kV XLPE insulated, 630 mm^2 copper cable, with lead sheaths cross-bonded, laid in soil:

Input data	**Value**	**Units**
Conductor diameter	30	mm
Insulation system diameter	70	mm
Sheath diameter	80	mm
Serving (polyethylene)	88	mm
Conductor resistance (DC at 20 °C)	36.085	ώϋ /m
Conductor temperature, ώ$_c$	90	°C
Dry thermal resistivity	1.2	°C m/W
Spacing between cables	250	mm
Temperature of ground, ώ$_g$	15	°C
Depth of burial	900	mm
Resulting parameters of the cable circuit		
Thermal resistance of insulation system, T_1	0.5044	°C m/W
Thermal resistance of servings, T_3	0.0531	°C m/W
Thermal resistance ground, T_4	1.4878	°C m/W
Dielectric loss, W_d	0.337	W/m
AC resistance at 90 °C, R	38.3667	ώϋ /m
Sheath loss ratio, ώ for centre cable	0.00976	
Current rating	**970.12**	**A**

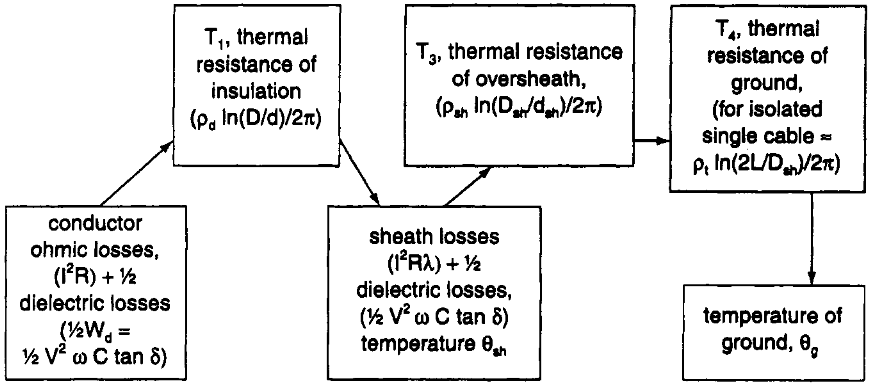

Figure 6.1 *Basis of continuous rating calculation*
ρ is the relevant thermal resistivity, D and d are outer and inner diameters, L is burial depth and the other symbols have their customary meanings

It has long been recognised that full realisation of the power transmission capabilities of a cable can only be achieved by using a cyclic rating taking advantage of the thermal inertia of a cable and working to peak temperatures rather than the steady-state rating determined in the calculation protocol of IEC 60287 [6]. This holds dangers of overloading a circuit unless there are means to monitor the temperatures at all points along its length. This is now possible and economic using optical fibre sensor technology (distributed temperature sensing, DTS) for circuit lengths up to 40 km; fibres are being located on many new major transmission links. The data being gathered may be used to predict the effects on temperature of a change in loading with the aid of cable simulation software and maximise the utility of cyclic loading rating of circuits as calculable by the protocol of IEC 60853 [9]. Additionally, other performance parameters may be monitored by optical fibre sensing cables such as mechanical strain or (in fluid filled cables) impregnant leaks both along the cable and at strategic points such as joints and terminations. Figure 6.2 illustrates the advantages that may be gained by applying cyclic rating methods and Figure 6.3 shows an option for the location of a fibre optical sensor in a fluid-filled cable.

6.3.2 *Medium voltage distribution cables*

The design variability of MV cabling is much wider than for super-tension because, in part, the systems are more variable. Of particular impact is the earth fault level, which may range from 2 kA for 1 s to 13 kA for 3 s and which therefore determines the amount of metal in the cable screen construction which, in turn, is reflected in the cost of the cable. MV cables are also more vulnerable than super-tension due to

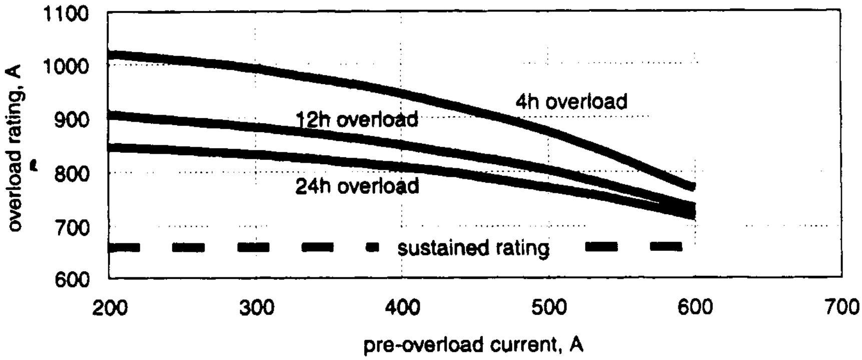

Figure 6.2 Effect of applying short time overload ratings
400 mm² 132 kV XLPE (S/B trefoil); UK summer

their more exposed locations, the lesser depths (e.g. from 450 mm at 11 kV to 800 mm at 33 kV c.f. 900 mm for super-tension) and consequently suffer from third party damage far more than actual failure of cable insulation; in some 75% of faults the damage is confined to the outer layers of the cable [1] (see Sections 6.3.5 and 6.3.6).

The majority of distribution cable in the UK is still insulated with compound impregnated paper, which is recognised to have provided an excellent service history. Among the considerations that have slowed the wider adoption of polymeric insulated cables there are:

(i) the concern that such cables are sensitive to the DC high voltage test applied subsequent to reinstatement following damage (this has been addressed in recent research and judged to be without foundation at the stresses appropriate to MV cables, but alternative testing methods such as very low frequency withstand voltages have been shown to be more sensitive than DC)
(ii) the uncertainty of resistance to water treeing (see Section 6.5.3).

The installation advantages of 'easy strip' extruded conducting screens have proven difficult to reliably achieve (and different utilities have differing concepts of 'easy strip'; current British practice requires a stripping force between 18 and 80 N on a 13 mm wide strip), especially when service aged cable has to be re-terminated. This has led to an increased interest in and acceptance of bonded screens by the UK users aided by their increased exposure to European practice.

6.3.3 Conductors

6.3.3.1 Material choice

Despite adventurous attempts to make power cable conductors from metals such as sodium (provoked by the high and variable price of

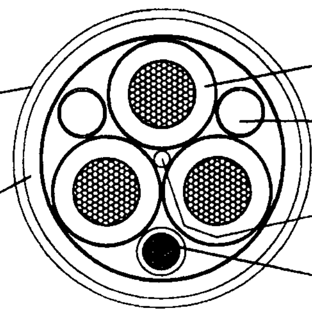

Figure 6.3 Cross section of 132 kV 3 core cable equipped with DTS optical fibres

copper at times and early difficulties of joining aluminium) and the future promise of high-temperature super-conductors or intrinsically conducting polymers, only copper (BS EN 1977:1998) [10] or aluminium are used as conductor material in present day practice. However, there is a great deal of variety in the form of the conductors made from these two metals. The choice of which metal, the cross-sectional area and the form and construction of the conductor is integrated with the overall cable design. This is related closely to the current rating and the jointing methods desirable or available and, in some cases, the handling characteristics. At the medium voltage level a solid circular or shaped rod (segments to permit close spacing of several conductors within a circular section) may be used in either metal up to 150 mm^2 (see comment in Section 6.3.3.2) but, for reasons of flexibility, most conductors are made up from strands compacted in one of several ways to reduce the free space and hence overall size (such a saving in size can have a significant influence in the costs of all the materials external to the conductor).

Apart from merely compacting a bundle of initially round wires there is the possibility of forming larger shaped strands or segments which fit together to make up a very area efficient conductor (known sometimes as Conci after the shell-like shape of the individual segments). With very large conductors, e.g. 2000 mm^2 and above, consideration is given to the skin depth for conduction at 50 Hz and its effect on AC resistance. The resulting conductor is made up from a large number of individually insulated wires formed into segmental shaped bundles which are also insulated from each other (providing a nuisance during installation). This design is known as a Milliken conductor. Various conductor forms are illustrated in Figure 6.4.

In choosing the metal the other major consideration, aside from those already mentioned of cost and joining method, is electrical conductivity. This is of course tied closely to the rating calculations as described in IEC 60287. The ratio of conductivities is approximately 0.64:1,

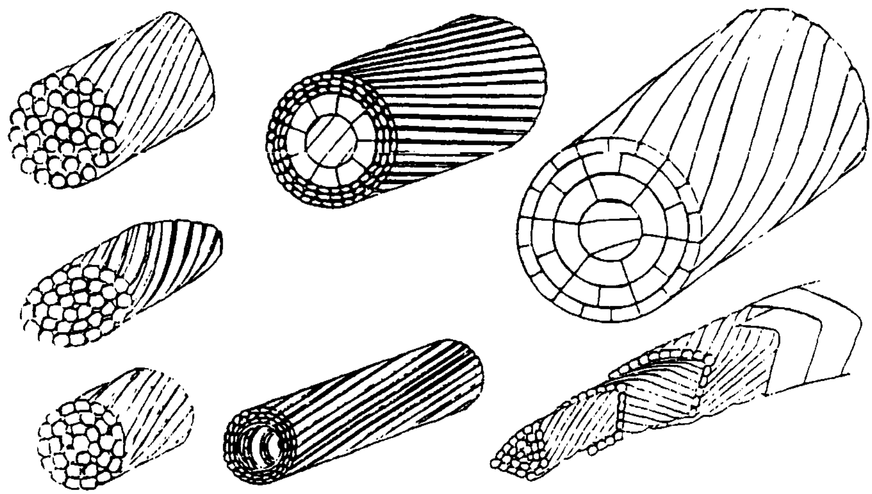

Figure 6.4 Illustrations of various conductors: uncompacted circular, compacted oval and circular, flattened strips on steel spiral and on segments, wholly segmented (Conci) and Milliken

aluminium to copper. Also interesting from design viewpoints are the ratios of specific conductivities relative to cost and weight, these being 2:1 and 3:1 copper to aluminium, respectively. The apparent disadvantage of copper is balanced in higher voltage cables by the smaller cross-sections and consequently lesser quantities of insulating and protection materials required to finish the cable.

6.3.3.2 Water blocking

The sensitivity of polymeric insulation to water at high AC electrical stress (water tree initiation and growth) encourages the selection of designs which, even if the cable is damaged, do not allow water to travel along the conductor (IEC 60840 [5] requires the resistance to penetration of water at 1 m head pressure for 10 temperature cycles, 8 h heating/16 h cooling, at 5 deg.C above the operation temperature of the cable). One solution is to use a solid conductor but this leads to an impractical stiffness in larger conductor cables (> 300 mm^2 aluminium, > 50 mm^2 copper) unless special annealing processes are applied. However, the water blocking methods applied under the sheath (see Section 6.3.5) may also be applied to stranded conductors. Options available include inclusion in the conductor strand of combinations of:

(a) a mastic, which in some cases, is based on isotatic polypropylene
(b) a cured rubber (especially for submarine applications where high pressures may be met)

(c) super-absorbent powder, which may be based in polyacrylates (sodium salts of acrylic acid)
(d) super-absorbent tape containing the same material as the powder filling.

6.3.3.3 High temperature super-conductors (HTSC)

The development of a flexible conductor strand or tape from the rather intractable high temperature super-conductors has led to the expectation that there will soon be prototype cable lengths operable at liquid nitrogen temperatures. Current densities of 10^7 A.m^{-2} (c.f. ~1.5 10^6 A.m^{-2} for copper at normal temperatures) have been achievable for some time with expectations of further advances. Changes may be needed in design philosophies to accommodate to the special characteristics of super-conducting links such as the incorporation of super-conducting current limiters, the single voltage transmission of power to eliminate transformation etc. Several projects are underway: these include retrofit situations as a solution to inadequate or failing old technology cables within the limits of an existing duct system [11, 12] at medium voltage (e.g. 24 kV, 100 MVA) or high voltage (e.g. 115 kV, 400 MVA), high voltage distribution (e.g. 132 kV, 680 MVA) and high power urban penetration (e.g. 225 kV, 100 MVA).

6.3.4 Insulation system

General requirements of an insulation system may be established irrespective of the materials used:

1. *Electric strength.* This is *not* the value often quoted in a manufacturer's literature determined by a BS 2918 test but a set of values related to the nature of voltage, e.g. waveform, 50 Hz or lightning impulse, and expressed as a set of statistical parameters (most usefully of a Weibull distribution) related to physical dimensions giving the probability of failure at a particular electric stress. The stress normally quoted is that found at the interface of the conductor screen and the dielectric material. In the cylindrical geometry of most cables this is given by $E_{max} = 2V(d \ln(D/d)$, where d and D are the inner and outer diameters of the cable and V the voltage applied in any particular case. Consideration must also be given to $E_{min} = 2V/(D \ln(D/d)$ at the interface of the outer conducting screen and the dielectric, especially in the design of accessories. When the insulation departs from the cylindrical geometry as within accessories, it is necessary to recourse to calculation of stress by numerical methods using techniques such as finite element modelling. In cables stressed by DC the situation becomes much more complex with temperature related resistivity and time related charge accumulation to consider [13, 14].

2. *Dielectric properties.* The product of permittivity and loss tangent of the insulation determines the dissipation of energy as heat. Its value therefore bears on the rating of the cable, especially at the highest voltages as it has a '*V* squared' relationship, e.g. at 400 kV the dielectric losses may represent 20% of overall losses (see Figure 6.1). The permittivity governs, with dimensions, the capacitance of the cable (in cylindrical geometry $C = l\ \varepsilon_r . \varepsilon_0/\ln(D/d)$ which is relevant to system design and economics. Permittivity is largely invariable once a dielectric material has been selected but may be deliberately chosen to control electric stress distribution in AC service. The loss tangent provides a dimension-free measure of the perfection (or lack of perfection) of the insulation which may be interpreted diagnostically. Electrical resistivity and its relationship with stress, time and temperature becomes important under DC service conditions as it then controls the stress distribution within the insulation. This may be as equally relevant in AC systems as DC as commissioning tests most often demand the application of high DC voltages.
3. *Ageing characteristics.* Accepting that all organic materials degrade with time at a rate which is enhanced at higher temperatures it is necessary to know that none of the critical electrical or mechanical properties of an insulating material will become inadequate during the required service life of the system at the temperature of operation. These critical properties will be different with differing materials but, in general, it is possible to define the rate of degradation and its relationship with temperature using the parameters of an Arrhenius expression (rate of degradation $k = A \exp(-B/T)$, where A and B are constants and T is temperature in Kelvin) and a rate law ('life' $= (1/k)$ ln(initial property/end point property)) to predict the end of safe service operation.
4. *Mechanical properties.* The greatest demands on mechanical properties occur during the manufacturing and installation when materials are subjected to intense mechanical stresses the tolerance of which depends on rupture strength, elongation, elastic moduli, tear strength, etc. However, during service there are situations where vibrations, thermally induced movements or circuit changes may challenge the mechanical integrity of the insulation in its aged condition. The mechanical stresses within a cable system are not easy to predict and are often addressed by empirical studies and complex mathematical modelling.
5. *Thermal conductivity.* The ability of the insulation to transmit heat is one of the several influences on the temperature arrived at by the innermost parts of a cable and hence the degradation rate and therefore the cable system rating. The thermal resistance of the insulation may be the major contributor to the overall thermal resistance (Figure 6.1).

6.3.4.1 Paper-based (laminated construction)

The construction of an insulating wall (such as the dielectric of a high voltage cable) by building up its thickness with a large number of layers of a thin sheet material like paper has proven very successful. This is due to its great design and manufacturing flexibility, the availability of a high electrical quality material (cellulose paper) and the statistical merit of a multiple layer material where a defect in one layer only marginally weakens the whole either electrically or mechanically.

For paper to function as insulation at high voltage, and therefore high electrical stress, it is necessary to remove the water it naturally absorbs when exposed to ambient, normally moist, air.

The paper used for electrical insulation is made (by the Kraft process) from a cellulose wood pulp chosen for long fibres and freedom from contaminants to be, when dry, physically strong and of low electrical losses. The moisture content of paper is approximately proportional to the relative humidity to which it is exposed up to a maximum of about 20% by weight. Typically paper will be received from the suppliers with about 5% but for even medium voltage applications this must be reduced to < 0.2%. For the highest voltages a moisture level in the region of 0.05% is sought and must be maintained. Figure 6.5 illustrates a typical relationship between the critical electrical parameter of loss tangent and moisture content for an oil impregnated paper.

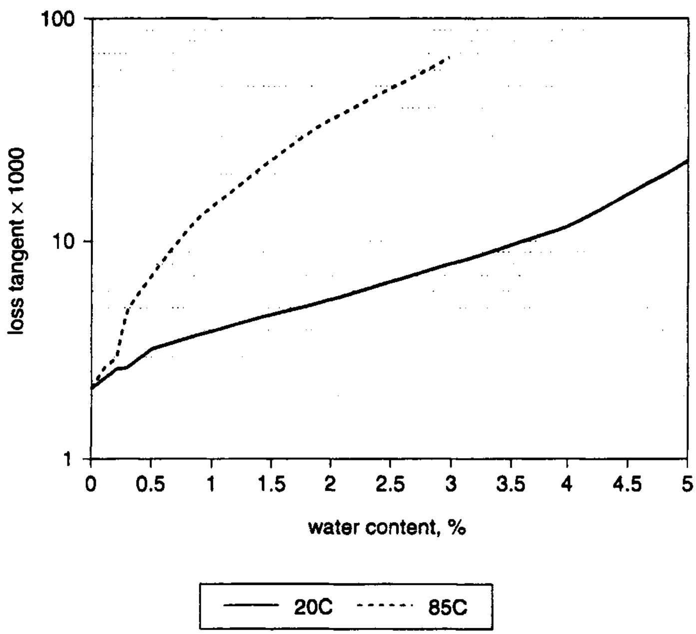

Figure 6.5 Relationship between loss tangent and moisture content of oil-impregnated paper

The purpose of the impregnant is two-fold: it radically reduces the re-absorption speed of water where the insulation is exposed to moist air as during installation operations (the diffusion coefficients of water through and along oil impregnated paper layers are 2×10^{-13} and 4×10^{-9} m^2/s respectively compared to 3×10^{-5} m^2/s through stationary air); and it radically increases its electric strength (under AC stresses the short term electric strength of oil impregnated paper is about 50 kV/mm compared with only 1 kV/mm for air).

The nature of the impregnant depends on the cable type, as indicated in Table 6.1. Viscous impregnants in current use are based mostly in polybutenes, chosen for their temperature viscosity characteristic, their chemical stability and compatability, tendency to emit gas when subjected to small electrical discharges (thus increasing the local pressure and suppressing the discharges) and their generally good dielectric properties. There still exist, however, many cables impregnated with viscous materials from the previous generations of impregnants based in mixtures of mineral oils with various waxes, resins and polymers. Low viscosity impregnants in current use are also largely synthetic oils and belong to the family of alkyl benzenes (BS EN 60867) [15]. These offer a selection of advantages over the previously used mineral oil blends. They exhibit good chemical stability, even in the presence of oxygen, excellent dielectric properties with the low permittivity characteristic of a non-polar organic liquid, may have a low viscosity and vapour pressure but, above all, their attractive feature is a very great tendency to absorb hydrogen under electrically active conditions. This means that should ever a void appear in an impregnated dielectric (which implies that electrical activity must occur under normal AC service stresses) then it will be self-correcting as the product of the activity, hydrogen, will be absorbed chemically into the oil. Under DC stresses the electrical activity in any void is greatly reduced so that viscous impregnants are more admissible at high stress.

The set of properties of an insulating paper (or other laminate material), including its dimensions, depend on the exact application in which it is to be used. The thickness of each individual layer of a laminated dielectric is inversely related to its electric strength (as it is the impregnant in the interturn butt gaps which fails first) so that the most highly stressed regions adjacent to the conductor call up the thinnest layer. Electric strength is also related to the impermeability of a cellulosic paper which, in turn, is coupled to its density. The higher the density of paper the higher and more disadvantageous will also be the permittivity and loss tangent. Attempts to overcome this conflict have included the manufacture of paper where a high impermeability to retain electric strength has been contributed by one layer of a multilayer paper while a second layer of low density has ensured an overall low dielectric loss. For the purposes of design, an AC stress of up to 15 kV/mm (or 100 kV/mm lightning impulse) is typical for low viscosity oil impregnated paper. Typical values of dielectric properties are loss tangent of 0.0025 and permittivity of 3.5. Vital to the ability to lap on an adequate thickness of a laminate such as paper are its mechanical characteristics. The elastic moduli in three dimensions and the coefficient of friction govern the relationship between the tension of a laminate tape during the lapping operation and the ability of the completed structure to bend without breaking or creasing (which would lower the electric strength). This last requirement has impeded the simple replacement of cellulosic paper (typical Young's modulus 10 GPa) with polymers (typical Young's modulus below 2 GPa) that have inherently lower dielectric losses coupled with high electric strength. The compromise that has some promise is a laminate that combines some of the electrical properties of a polymer such as polypropylene with the mechanical characteristics of cellulosic paper in a sandwich construction (PPLP). The advantage in current rating achieved by adoption of this compromise for a large 400 kV directly buried cable varies from 14 to 26% depending on installation conditions and ambient temperature [16].

Notable progress has been made in the development of polypropylene-paper laminate cables for circuits up to 400 kV. This type of cable is currently available from a UK manufacturer and is in service in the UK and elsewhere in the world. PPL insulation is now the preferred option for new fluid filled cables at 275 and 400 kV.

Essential to the successful performance of a laminated dielectric are the conducting screens which complete the insulation system. These must remain intimate with the insulating layers under all conditions of operation and therefore have closely matched physical properties. This is achieved by making a laminar material, generally of cellulose paper heavily loaded with carbon to have a volume resistivity in the region of 10 Ω m, sometimes laminated to insulating paper ('Duplex') and otherwise laminated to aluminum foil. Tapes made from these materials may then be lapped on to the cable, both on the conductor prior to the insulation and over the insulation before further processes. The choice of screen and its adequate placing can have significant effects on the electric strength of the cable and on the dielectric losses.

6.3.4.2 Polymeric

Extrusion of a polymer to form, in a single operation, the insulating wall of a cable, screen layers included, offers the prospect of high production speed with the merits of polymeric materials that can be demonstrated on a small scale. Polymers can be selected to have dielectric losses less than 10% of cellulosic paper or 20% of PPLP, 'intrinsic' electric strength four times as high as oil impregnated paper and thermal conductance 30% greater. The disadvantage is that a single defect can have a diastrous effect on the integrity of the whole cable due to the homogeneity of the dielectric. This fact is reflected in the parameters of the statistical distributions of electrical breakdown in polymeric insulation systems compared with laminated systems; whereas a lapped paper cable may have an electrical break-down level predictable within a few percent, that of a polymeric cable will only be predictable within some tens of percent with the same confidence. This inherent characteristic of extruded polymeric cables has forced the use of statistical methods employing the Wiebull distribution into the field of cable design [17, 18]. Its use to describe the electric strength and life of extruded cables is now so common that it warrants some elaboration here. However, as with all statistical methods, there are grave dangers in their use without an understanding of the phenomena they describe [19].

Using this distribution, the failure probability of an insulation system is described with reference to a particular size specimen of cable, for example based on a 20 kV 70 mm^2 design, with a characteristic parameter for time to failure (t_0) qualified by a scatter parameter (a), a characteristic parameter for electric stress at breakdown (E_0) qualified by a scatter parameter (b_p) and a further scatter parameter (b_l) which governs the effect of physical dimensions. Determining the values of this set of parameters following a change in materials or manufacturing technology is a major task consuming much time, manpower and materials. However, the expected gains in performance and eventually in overall costs and reliability have led to manufacture of 400 kV cable at design stresses of up to 15 kV/mm using the 'super clean' cross-linkable polyethylene (XLPE) now available and thus matching oil impregnated paper cables stresses.

The probability of failure in the Weibull distribution is $F = 1 - \exp\{-(E/E_0)^b (t/t_0)^a L r^2 L_0 r_0^2\}$, where the variables have the definitions as above and, additionally, L and L_0 represent the cable actual and reference lengths, r and r_0 the cable conductor screen and reference radii. When using this expression to transform a probability of failure, b is taken as b_p but when making a geometric transformation, b is b_l. The parameter sometimes called the life function of an insulating material, $N = b/a$. The time taken to arrive at the first electrical breakdown is normally taken as that given for the probability $F = 1 - \exp(-1)$, i.e. 0.632. The fault rate n is given from this statistical model as $(E/E_0)^b (t/t_0)^{b/N}$.

There is still debate over the 'correct' values of parameters to use in these calculations and whether the expression should be augmented to include minimum possible values of electrical stress below which the mechanisms of failure do not operate. As these parameters reflect the materials and processes of each manufacturer it is dangerous to generalise but Figures. 6.6 and 6.7 illustrate the outcome of applying this statistical model from best estimates of the parameters.

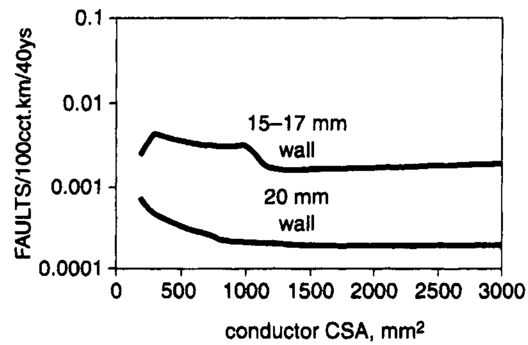

Figure 6.6 Fault rate prediction: 132 kV XLPE design

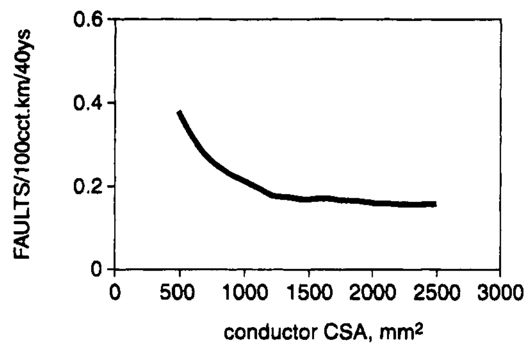

Figure 6.7 Fault rate prediction: 275 kV XLPE design

Some national specifications (e.g. Italian and French) recognise the statistical nature of the performance of cables in their qualification procedure. A plot of E/E_0 against b is established (see Figure 6.8) defining the minimum acceptable performance of the cable together with a minimum value for N which may represent a defect rate of 0.2 breakdowns per year for a 100 circuit km (see Section 6.1) over 40 years.

As indicated in Table 6.1 there is more than one candidate polymer at some voltages. At 150 kV and below it is possible to use compounds of ethylene-propylene (EP) rubber without disadvantage of its ten times higher dielectric losses than polyethylene. The benefit of water tree resistance (see Section 6.5.3) allows designs in which the cable core is unprotected from water and lesser rigidity eases installation practice and so offsets the small cost disadvantage of the insulation system. An alternative to EP rubbers to overcome the susceptibility of XLPE to water tree deterioration is tree retardant polyethylene (TRXLPE) with a cost level in between XLPE and EP rubber.

The conducting screen materials which are extruded simultaneously with the insulation are compounds of carbon with polymers chosen to accept a high carbon loading, be bondable to the insulation, be compat-

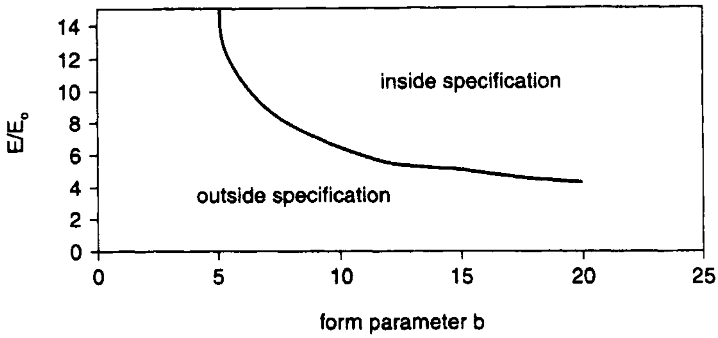

Figure 6.8 ENEL qualification diagram

ible with the extrusion conditions and be removable when required without damaging the dielectric. This last demand is most important in medium voltage cables where the operations of jointing and terminating may have severe time, tooling and skill constraints. For these cases an 'easy strip' screen is called for, presenting some problems with certain insulation types, e.g. TRXLPE.

6.3.5 Containment

The hermetic containment of impregnated paper cables is obviously essential to prevent loss of the impregnant and to maintain the paper in a state of dryness. The only materials of containment that are totally impervious to water are inorganic substances such as metals and ceramics. This leads to a necessary set of properties for self-contained cables including being nonmagnetic to prevent excess generation of heat, flexible in the case of sheaths to allow spooling of the cable and being sealable by site-available methods to permit termination and jointing. In practice these requirements are met by lead alloy and aluminium sheaths (some very special situations dictate welded stainless steel) and by porcelain insulators at terminations. The choice, to some extent, is made on customer preference but factors which are considered include the laying conditions and permitted weight of the finished cable, the internal oil pressure, external corrosion vulnerability and available jointing skills.

Lead alloys for sheaths are specified in BS 801 [20]. Particular alloys are indicated for various designs, e.g. unarmoured cables alloy E, unarmoured anti-fatigue alloy B and anti-creep (but reinforced with bronze tape) alloy 1/2 C. The relatively ductile lead sheaths require reinforcement by means of a nonmagnetic tape (e.g. bronze) to counter the internal forces from oil pressure. Aluminium, however, which is generally corrugated, needs no reinforcing but has a predisposition to suffer from corrosion; lead alloys with armouring are not immune so it is common to find anti-corrosion protection layers on both (see Section 6.3.6).

Containment of polymeric cables is necessary at all but the lower end of the high voltage cable range to prevent deterioration by water treeing. There is evidence and service experience to demonstrate that EP rubber cables tolerate the absence of a hermetic protection more ably than XLPE, thus eliminating the cost and complication of this component of a cable, and there are prospects that TRXLPE will be able to be used equally unprotected. This possibility has allowed the installation of submarine cables of tens of kilometres of circuit with no sheath, merely with armouring and soft sacrificial coverings. Otherwise, sheathing of polymeric cables and anti-corrosion coverings are closely similar to those of self-contained oil-filled cables. One special feature is the water blocking device incorporated under the sheath of polymeric cables to avoid longitudinal movement of water should the sheath be breached at any point. This generally takes the form of a spiral lapped tape loaded with a material which expands rapidly and enormously when in contact with water, but the material may alternatively be disposed as a powder filling of the space under the sheath.

In an alternative philosophy of cable containment the processed cables are installed into pre-laid rigid steel pipes which are then filled with the impregnant. Such a procedure demands that the impregnant be more viscous than that used in self-contained designs and incurs higher initial costs but allows the possibility of replacing the insulated core to extend the life of the installation or, with an improved core, uprating the circuit. It therefore has most appeal in highly developed and densely populated cities.

One new technology which attempts to bring the nearly zero permeability of metals together with the low cost and weight of polymeric sheaths is the metal laminate. With this concept a foil of a metal such as lead, aluminium or copper is supported by a robust polymeric layer so that any path for moisture migration through an overlap in the foil is extremely long. Countering the advantages cited above, this form of sheath is likely to be less tolerant of physical and electrical abuse (i.e. short-circuits) than the thick metal types.

Maintenance of hermetic containment and accessories presents its own problems. At joints the seals are effected by solder, welding and mechanical (with O-ring) means and various corrosion and mechanical protections applied. This may become somewhat complex if hydraulic pipes and earth bonding leads have to be brought out, which perhaps explains the high proportion of failures attributed to ancillary equipment in oil-filled cables (Table 6.2). At terminations the further problem is the interface with the ambient conditions which, as likely as not, will be moist and polluting on a surface along which a significant electric field will be acting. The inevitable resultant electrical activity can even be aggressive to ceramic materials (e.g. porcelain) with inadequate design of this surface (i.e. the length of creepage path and shape of the 'sheds'). For lower voltage cables with either viscous compound impregnated paper or polymeric insulation, joints and terminations may be contained by polymeric components as described in Section 6.4.2 but with the acceptance of lesser hermeticity and resistance to surface electrical activity.

6.3.6 Protection

Armouring layers consisting of galvanised steel wires (BS 1441 and 1442 [21, 22]) are a necessary protection against external forces in all except the most benign installation conditions for lead sheathed cables and polymeric insulation not using metallic sheaths. The variants might be designed to deter penetration by sharp objects or to resist crushing forces. Aluminium wires provide less protection, but this is adequate for some situations.

An effective means of corrosion protection, both for the metal of the sheath and armour, is the application of bitumen layers under extruded polymeric over-sheaths. The polymer is chosen for toughness required to resist installation conditions and, in some cases, compatability with the installation environment (e.g. presence of chemicals in the soil or voracious insect species). Commonly used polymers are various grades of polyethylene (lower density for flexibility and insensitivity to cracking, higher density for abrasion resistance) and PVCs (formulated for the expected temperature conditions, e.g. tropical, temperate or arctic, and for easy jointing), (see BS 7655 [23]). Recently, evidence has emerged that PVC provides significantly less protection against corrosion due to the greater permeation of water compared with polyethylene. All of these polymers must be protected against UV degradation for those locations where the cable may be exposed to prolonged sunlight by the addition of carbon or, when the sheath cannot be black, with a chemical UV degradation inhibitor. For protection against tropical insect attack specific insecticides are also added, previously gamma BHC but in this environmentally conscious time more likely to be a synthetic pyrethroid.

6.3.7 Thermal and mechanical environment

Except in tunnel installations, few insulated cables are laid in air, although ducted (air filled ducts) cables may be said to be not 'directly buried'. Whether they be in air, in ducts or directly buried, the thermal resistance of their environment is a highly significant part of the overall thermal resistance between the conductors and the outside world and thus vitally important to the current rating of the cable (see IEC 60287 and Figure 6.1 [6]. In directly buried cables the material which fills the trench in which the cables are laid must have a predictable, stable thermal resistivity as low as possible. Conservative values are generally used for design purposes, e.g. 1.2 deg. C m/W for a dried but granulametrically specified sand, whereas in its most normal moist state its resistivity will be 0.8 deg. C m/W. Unfortunately moisture tends to migrate away from warm objects such as cables so that, where a guaranteed lower value is required, options such as weak-mix concrete (also providing mechanical support and protection) or wax-mixed sand are available. Artificial irrigation has been used to maintain the cable trench filling moist despite the consequent nonpassivity of the installation. To avoid the thermal disadvantage of air-filled ducts but retain their advantage of post-installation recabling the duct may be filled with a semi-solid/semi-liquid mix of a clay slurry (bentonite) and cement.

There was, in the 1960–1970 period, a great deal of interest in forced cooling of cable systems to enhance the heat removal and thus increase their rating. Systems were devised and constructed in which, in the simplest form, heat was removed from the soil adjacent to the cables by water pipes with flowing water, thus defining the ambient thermal conditions. In opportune locations some cables have been laid in troughs immersed in water where the water flow has been controlled by a series of weirs. Considerably more complex are designs in which water which is in direct contact with the sheath or a fluid such as the insulating oil of an impregnated cable is circulated and cooled. But, to gain rating, these systems sacrifice simplicity and passivity and must therefore have increased probability of nonavailability for service.

Tunnel (and bridge) installations have at least three complicating features: the determination of the heat flow path and hence external thermal resistance, and the nonstationary nature of a cable held in cleats and perhaps subject to recurrent vibrations and exceptional corrosion conditions. Mathematical models have been successfully used to determine the rating of such cables incorporating convective modes of heat flow but also having to recognise that in deep tunnels there may be a source of heat (e.g. hot rocks) other than the cable. Thermal expansion and contraction of a cleat suspended cable will flex it and challenge the integrity of the insulation system and sheathing, especially after the insulation may have thermally aged or the metal changed from its original crystal structure. The corrosive nature of a submarine tunnel may demand titanium alloys to survive for the life expectancy of a cable installation.

Both thermal and mechanical design features may become critical at accessories as, at these points of a system, the heat paths from the conductor to the environment are more lengthy and less well defined and the mechanical forces built up along a constrained length of cable may be concentrated. The lower electrical design stresses of joints, for example, increase the insulation thickness some five-fold. This may be compensated for to an extent by the use of materials with higher thermal conductivity than the insulation of the cable (e.g. impregnated paper has a thermal resistivity of about 5 deg. C m/W but silica loaded epoxy castings may have a thermal resistivity of less than 2 deg. C m/W). More important is the longitudinal alleviation due to the high thermal conductivity of the conductor (attempts have been made to augment this further by the inclusion of heat-pipes into accessories). Tolerance of the thermally derived mechanical forces must generally be designed into the accessory by ensuring the component parts are strong enough (e.g. the epoxy castings of a stop joint) or movements are absorbed (e.g. by flexible connections in terminations). These forces may turn from compressive to equally high tensile forces after thermal cycling.

6.4 Manufacturing processes and materials

6.4.1 Cables

6.4.1.1 Conductors

The essential feature of low resistance of a conductor may be readily sabotaged by inadequate manufacturing processes. Of the seven categories of copper described in BS EN 1977:1998 [10], one particular grade is chosen (ETP1). The electrolytic refining method produces an extremely pure material but trace quantities of certain substances can have a significant effect on such characteristics as annealability and conductivity. Copper 'cathodes' (ingots) are turned into a few sizes of circular section rod for further drawing down to the particular sizes and, in some cases (see Section 6.3.3), shapes. This drawing process of pulling the rods through very hard and well finished dies in the presence of very special lubricants plastically deforms the copper and inevitably causes changes in state of anneal. This may have to be remedied between and after the various stages of drawing until their desired size and shape is achieved. In the case of conductor wires destined for low viscosity oil impregnated cables it is essential to remove all traces of the drawing lubricant to prevent subsequent contamination of the oil and possible disastrous effects on the dielectric properties of the insulation. An aluminium rod is drawn and shaped in a similar manner to copper but, due to its different set of physical properties, requires somewhat different treatment in areas such as choice of lubricant and speed of production.

The building of a conductor in a laying-up machine may bring together from a very few to several hundred wires spiralled generally in alternate directions (lays) to cancel twisting forces. Passage through a die or sequence of dies gives the final form to the conductor before, in many cases, it is bound with tapes to maintain its integrity until it may be passed to the next manufacturing stage of insulation.

6.4.1.2 Laminated insulation

The lapping operation consists of spirally winding any number of layers of tape from 20 to 200. These layers must be placed one on the other so that the butt gaps between adjacent turns in any one layer do not coincide with those in the next layers above or below as this would cause an electrical weakness – they are neither so tight that the tapes are unable to slip to allow the cable to bend without creasing or breaking the tapes nor so loose that the tapes are able to shift with thermo-mechanical cycling to cause alignment of butt gaps, in either case threatening the electric strength of the cable. The machinery which accomplishes this is a co-ordinated line of up to 20 individual machines through which passes the conductor, each of which may place, typically, a 12-layer thickness of insulation. The critical setting of these machines is the tension maintained on the tapes as they are applied as this controls the initial tightness (interfacial pressure). Interacting with the tension of the tape is its elastic modulus; low values of modulus demand low tensions which are more difficult to set and control. The low modulus of all synthetic polymer laminate materials compared with cellulosic papers has been one of the difficulties only recently overcome by sophisticated tensioning devices, as mentioned in Section 6.3.2.1. It is necessary to locate these lapping machines in a controlled humidity environment as cellulosic paper varies in thickness and, to a lesser extent, in length with humidity so that the tightness of the lapping would radically change with the subsequent drying operations. Depending on the cable, relative humidities between 1 and 50% are chosen.

The lapped cable core is generally wound on to a transportable bobbin for further processing unless it is of exceptional length (for example submarine links). In this case it will be wound directly into a coil in the processing chamber as illustrated in Figure 6.9.

The removal of residual moisture from the insulation is accomplished by heat and vacuum over periods which may be only a day for the lower voltage thinner insulation wall cables but much more for supertension cables. In the case of submarine cables the quantities of water removed are measured in tons, all of which must be extracted from a compact thickness of perhaps 20 mm of paper surrounded by hundreds of turns of cable core. The heat applied must be carefully controlled so as not to prematurely age the cellulose paper and the vacuum cycle designed to optimise the transfers of heat and water vapour. In most operations the conductor is heated by passing very high electric currents through it and the conductor temperature monitored by measuring its change in electric resistance. The end point of drying may be, in some cases, judged by measuring the dielectric properties of the insulation.

The viscous impregnant of the lower voltage and submarine cables is treated by vacuum and heat to reduce its gas and water content to a

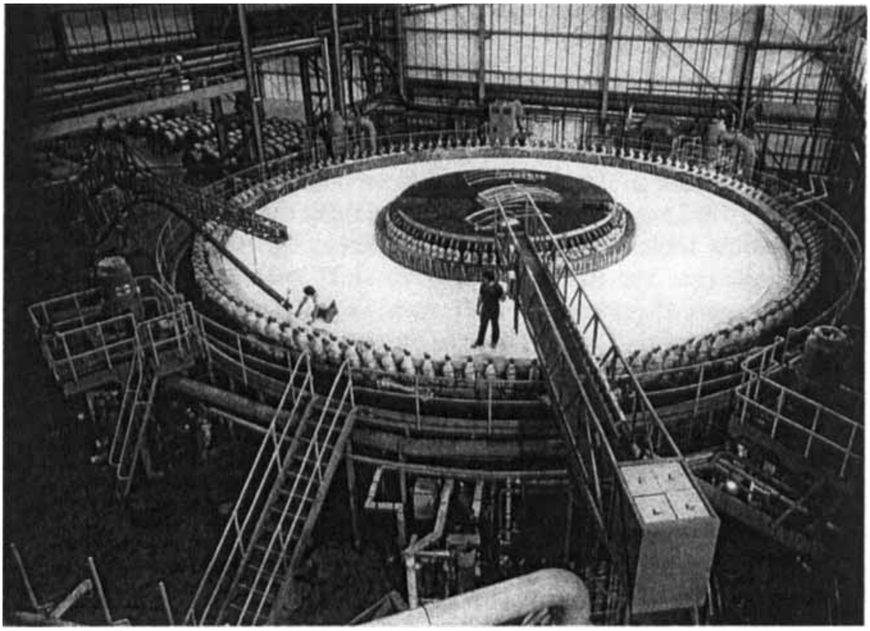

Figure 6.9 Operations in a submarine cable factory; coiling the cable into the vacuum drying and impregnation tank

reasonably low level before introducing it into the processing tank to saturate the cable core. However, in the case of the low viscosity oils used for super-tension cables, an extremely thorough degassing procedure is employed to achieve a residual equilibrium gas pressure (RGP) of less than 1 mb (oil received from suppliers will have an RGP of 1000 mb, i.e. be saturated with air). An alternative processing method, used when an unusual (possibly experimental, sensitive to handling or expensive) impregnant is called for, is vacuum sheathing. The cable is first dried in a large tank under vacuum and then sheathed whilst maintaining this vacuum. The impregnant is then introduced into the sheath to saturate the insulation and fill the sheath space.

Following the normal mass impregnation process with viscous impregnants, the cable core may be exposed to air (or better, dry nitrogen) whilst the metal sheathing process is carried out. The low viscosity oil impregnated cables, on the other hand, are maintained under degassed oil at all times during this next manufacturing procedure. The current practice is to extrude directly on to the cable core either lead from a pot of the molten alloy or aluminium from high purity billets. Previous technologies have made the sheath separately as a tube (particularly aluminium) into which the cable has been drawn or, in the special case of stainless steel, seam welded the sheath over the core. Drying of a core which is already sheathed is a lengthy and inefficient

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process so that pre-processing sheathing is generally reserved for short experimental cables.

The final stages of manufacture require the placement of reinforcing, armouring and corrosion protection sheathing which demands one or two more passages of the cable through appropriate machinery. In the case of the low viscosity oil impregnated cables these processes will be carried out without losing the hydraulic pressure of the oil and without admitting any inward leaks of air that would degrade the electrical integrity of the oil/paper system.

6.4.1.3 Extruded insulation

The formation of the extruded insulation system of inner conducting screen, dielectric and outer conducting screen is almost always carried out in a single pass through a tandem arrangement of two or three extruders. The dimensions of these layers is determined by a series of dies in the extrusion head which are carefully designed to respect the rheological characteristics of the polymer melt. This melt must be at a temperature high enough to allow thermo-plastic forming to take place but low enough not to activate yet the organic peroxide cross-linking agent. It is extremely important to consider every stage of the delivery of the polymer from the supplier to the entry point of the extruder. Nowhere, especially in that polymer destined for the mostly highly stressed insulations, is it permissible to allow contamination to enter as, with extruded rather than laminated dielectrics, we can no longer tolerate any defects. For this reason such humdrum details as the packaging and granule transfer methods can assume high importance in the assurance of quality of the cable core, even with filtering of the polymer melt and monitoring the melt for the presence of foreign particles.

As the core leaves the extruder the polymer is extremely soft and incapable of supporting the conductor or even maintaining the form given by the dies through which it has passed. It will remain this weak until it has been cross-linked (cured/vulcanised) and cooled to a temperature well below the crystalline melting point of the polymer (in the case of unfilled polymers such as polyethylene, filled EP rubbers are more robust). Four solutions have been applied to minimise distortion:

(i) extrude vertically – this demands the expensive and less flexible arrangement of mounting the extruders on a high tower
(ii) extrude into a fluid of sufficient density to buoy up the cable core – such fluids tend to be difficult to handle (e.g. molten salts) and matching the average density of a range of cable sizes is needed
(iii) extrude nearly horizontally onto a conductor tensioned into a