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catenary curve – this overcomes the conductor weight problem and the weight of the insulation system can be buoyantly compensated for by a relatively innocuous heat transfer fluid such as silicone oil
(iv) extrude horizontally into a long die so that the insulation is contained until it is well cross-linked – this technology is more suited to mass production of a limited range of cable sizes due to the high tooling costs.

To cross-link the polymer, the peroxide compounded into it must be raised to its activation temperature for a given time by passing the core through a tube filled with some heat transfer fluid held at a pressure sufficient to suppress bubble formation. Without pressuring to about 1 MPa, bubbles would form in the polymer due to the large amounts of by-products (typically methane gas and several other volatile substances). The most commonly used heat transfer fluids are:

(i) steam – very efficient heat transfer but leaves the insulation system saturated with water, provides no buoyancy and possibly induces microvoids
(ii) nitrogen – inert but no buoyancy and poor heat transfer
(iii) silicone oil – efficient heat transfer medium, good buoyancy for thick insulations but requires complex handling equipment.

Following cross-linking, the cable cores are heat-conditioned to adjust the levels of cross-link byproducts. Otherwise the long term effusion of methane, for example, could lead to hazardous installations. The finishing of the core proceeds with lapping operations to emplace copper screens and water stopping tapes etc. before applying outer protection. In the case of medium voltage cables made with water resistant dielectrics such as EP rubbers, this may be merely a mechanical protection or low permeability polymer sheath but for supertension XLPE cables it is likely to be an extruded metal sheath (as with laminated and impregnated insulations).

6.4.2 Accessories

The conflict inherent in accessory design is that they must be finally assembled in the field where conditions are less controlled than the factory environment in which the cable was manufactured but that they are by far the most vulnerable part of the system. To some extent this may be compensated for by reduction of electrical stresses and limitation of mechanical forces and thermal resistances. The manufacturing philosophy is to prefabricate as much of the accessory as possible to minimise site work and to ensure, as far as is possible, that the final assembly consists of easy to perform noncritical operations.

6.4.2.1 Medium voltage

Until recently (in cable terms), a medium voltage cable joint would have been made of materials of similar nature to those used in manufacture of the cables being joined, i.e. insulated by layers of paper, dried and impregnated with a viscous oil. The factory dried and impregnated paper would perhaps be crêped to accommodate the changing profiles of the ferrules joining the conductors. This hand constructed joint would then be sealed in a cast-iron or equivalent metal case sealed to the metal cable sheath. The terminations would be similarly constructed using porcelain insulators to provide the hermetic protection. Clearly the prefabrication level of this type of accessory was low and consequently the skill level of the personnel doing the assembly was correspondingly high.

The advent of polymeric cables and the drive to de-skill cable installation practice has led to several philosophies of accessory design which spilled over into paper cable use. The target has been to provide kits containing the fewest number of components, covering the largest range of cable sizes which may be assembled with the minimum skill and tool use in the shortest time at the lowest cost. The path followed has been to exploit the elastic or thermo-elastic character of polymers together with their ready formability and, in some designs, to use synthetic resins which may be poured into a shell surrounding the accessory, there to undergo a cross-linking chemical reaction to result in a form stable material. Because of size differences brought about by conductor cross-section, voltage levels and stress variations, the range-taking capability of an accessory presents particular challenges. The economics of production and procurement of stock (as ready-to-assemble kits) depends on how many sizes are required to cover the range of possible situations. This number is reduced to a minimum by a combination of design and material selection. For example, in an elastic accessory such as a joint, the tubular insulation wall may consist of a 6 mm thickness of rubber for an 11 kV component, the property of elastic modulus of this must be chosen to allow it to be stretched by up to 100% to accommodate the size range as the jointer threads it over the cables. This operation must not require forces outside those available from a jointer, e.g. 100 N sustained thrust. In addition to the elastic modulus several other mechanical properties of the rubber need to be defined such as sensitivity to tear when under strain during assembly or in service. In some designs elastic components are pre-stretched onto carriers for assembly but clearly must retain their elastic nature even after long periods of storage in such a stretched state. Both silicone and EP rubbers have been widely applied in this area.

The thermo-elastic behaviour of polymers has produced a range of designs in which the ability of a cross-linked polymer to be 'frozen' in the expanded state for location in the accessory. It is then unfrozen by applying heat to the component to shrink it down to the size required. Again there is a limit to the shrink ratio and the need for a controlled and carefully applied heat source to unfreeze the component. The classic material is polyethylene cross-linked by one of several means prior to expansion.

Cold cross-linkable synthetic resins have, in some designs, been used as primary insulation and in others as secondary to rubbers. The balance of desirable properties has included the safe handleability of active chemicals under site conditions, their sensitivity to moisture (in some cases), their inherent expense, tendency to degrade in service (certain families of resins) and limited shelf life in storage. Despite these considerations a number of designs exist using acrylic, epoxy and polyurethane resin systems.

Termination insulators have a specific requirement: they must be manufactured from polymeric compositions that tolerate the exposure to weather and pollution and the surface electrical activity that inevitably occurs. Porcelain is a very robust (electrically) material and the development of competitive polymer compositions has been the objective of several decades of work. Current materials based on silicone and EP rubbers which may be moulded by conventional polymer technology perform well in laboratory trials and are gaining successful service experience.

An example of the harnessing of polymer technology with electrical design is the use of voltage variable resistance components in both joints and terminations to relieve electrical stresses at the ends of the conducting cable screens. Particular constituents of the polymeric compounds (e.g. silicon carbide) impart this characteristic of decreasing electrical resistivity with increasing electrical stress. These compounds may be moulded to form the stress relieving tubes as with the termination insulators.

It is appropriate to mention the additional considerations necessary when applying polymeric accessories to impregnated paper cables. First, there is the incompatibility of many polymers with the impregnants leading to swelling or cracking. Second, the finite permeability of all polymers to water does not fit well with the hydrophilic nature of paper even when impregnated.

Very special selection and application of water and oil barrier materials (e.g. polyvinylidene chloride and varnished nylon fabric, respectively) resolves both these difficulties although their presence as separate items (e.g. as tapes) provided in termination or jointing kits is a move away from the sought after simplicity (see Figure 6.10).

6.4.2.2 Super-tension

At the higher electrical stresses employed at super-tension voltages the benefits of factory manufacture on accessory performance are even

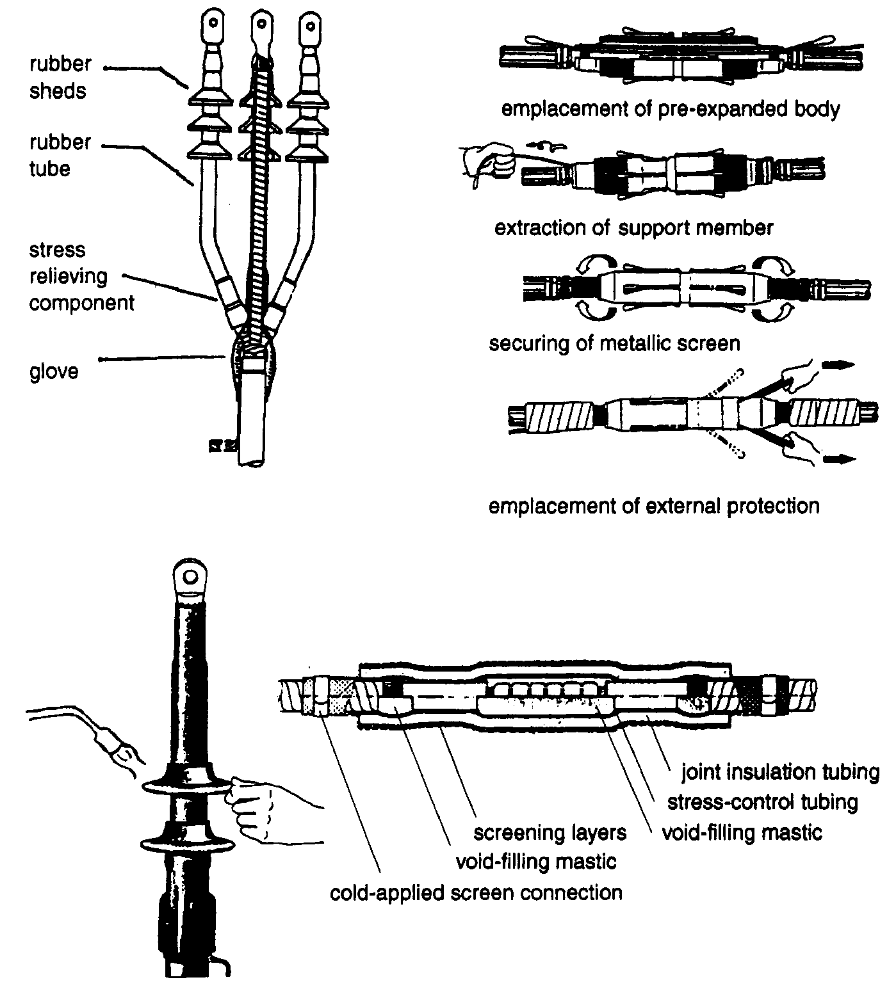

Figure 6.10 *Some examples of MV polymeric accessories: elastic outdoor termination for paper (belted) cable; assembly of a carrier borne elastic rubber joint; assembly of a heat shrink termination; insulating components of a 24 kV joint*

greater than at medium voltage. The main insulation systems for impregnated paper cables are also of paper dried and impregnated in factory conditions and hermetically sealed for storage and transport. These 'tube sets' must then be briefly exposed to ambient conditions during assembly operations (which may, in some cases, happen in an air-conditioned enclosure despite being on-site) but the reprocessing is much shorter and easier. In the case of hydraulic stop-joints, the greater part of the joint, its centre compartment, remains unexposed following factory assembly but the two cables it joins still need the building by hand of a paper tube cone to complete the assembly. In addition to impregnated paper, highly filled synthetic resins (principally epoxy filled with silica) provide the hydraulic but electrically insulating barriers and offer improved thermal performance in straight joints and terminations (Section 6.3.5). Mouldings in these filled resins often include metallic electrodes to geometrically control the electric fields. An alternative method of electric stress control is by the inclusion of conducting foils between layers of paper to form a series of concentric capacitors. Although effective, this method is very demanding of manufacturing skills and time.

Terminations still use porcelain insulators despite the disadvantageous weight, cost and their impact intolerance. These are part-assembled prior to transport to site where, apart from the sweating of cable sheaths to end bells, connections are made by bolt-up means with O-rings seals (employing oil resistant rubbers).

Vital to the integrity of oil-filled cables is the system of pre-pressurised tanks which maintain the hydraulic pressure of the oil. In these tanks are a number of totally sealed but flexible metal cells which contain an inert gas at an appropriate pressure. The oil surrounding these cells enters and exits from the tank as required by the thermal expansion and contraction of the oil and other items in the cable system, compressing or relieving the cells as it does so (see Figure 6.11).

The design and construction philosophy of accessories for polymeric super-tension cables is evolving as these compete with impregnated laminated cables at increasing voltage levels. Approaches adopted have included hand made insulation from tapes lapped and then heat consolidated and cross-linked, on-site injection moulding to reproduce the solid insulation of the cables and factory made mouldings. The first of these methods has been successfully applied despite the high skill level required of the jointers, the need to maintain factory cleanliness standards and the necessity of controlling a critical time and temperature sensitive chemical process in site situations. Injection moulding of sizeable quantities of (generally cross-linkable) polymer, as in the second method, adds the requirement that a large and complex machine be brought to site. This is not always feasible. The third approach allows the major and critical components to be fabricated, inspected and mostly tested in the controlled environment of a factory. It does, however, rely on the careful matching of dimensions of the accessory with the cable – not always a trivial matter – to avoid electrical weaknesses at the interfaces. This problem is alleviated by the use of elastic materials for the mouldings which, despite the great wall thicknesses at these voltage levels, accommodate some dimensional variation.

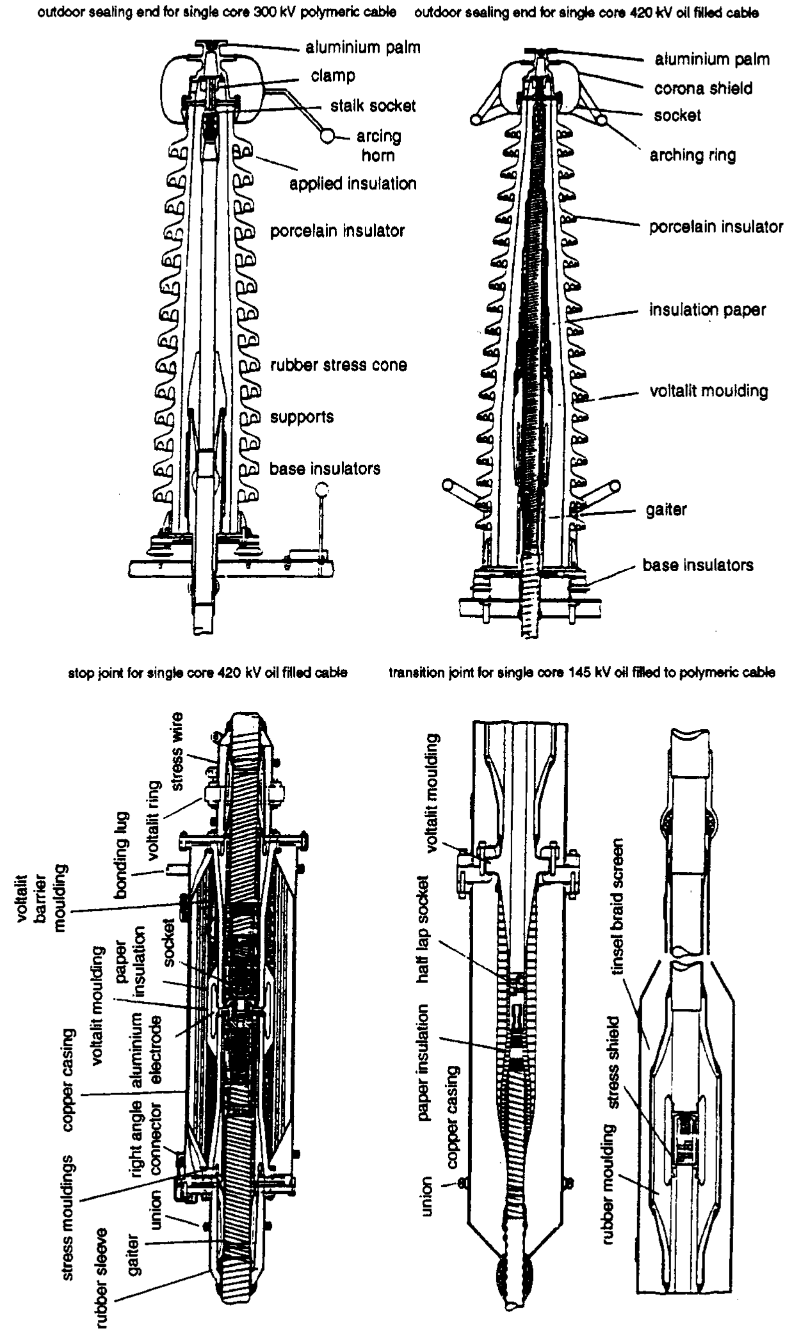

Figure 6.11 *Typical cable accessories. Termination for polymeric and oil-filled cables, a stop-joint for oil-filled cable and a transition joint from oil-filled to polymeric cable*

6.4.3 Environmental issues

6.4.3.1 In manufacture

Conversion of raw materials into any product involves the consumption of energy, the use of packaging for transport and the generation of by-products. Cable manufacture itself is, relative to many other industries, benign in that it uses materials which are already in an advanced state of conversion and merely require treatments and forming as described in previous sections rather than transformation from mineral or natural sources. However, this is not an area that can be ignored by cable manufactures. In forming conductors from the as-delivered rod, lubricants are used which consist of oil emulsions. These become contaminated with metal fines and metal compounds and therefore must not be disposed of carelessly but must be treated as toxic waste. As mentioned earlier, the residual lubricant must be removed to ensure good electrical characteristics of oil-filled cables. Until recently this process involved scrubbing with chlorinated solvents, which have also been used in the cleaning of many other parts of cable systems such as oil pressure tanks. Since the implication of these solvents in destruction of the ozone layer, alternative environmentally friendly materials and processes have been substituted, for example employing water-based detergents, water/hydrocarbon solvent mixtures and various hydrocarbon mixtures.

The sheathing of cables with lead demands that care is taken to prevent discharge of lead-bearing fumes into the environment. As a process registered with the HSE it is necessary to monitor such emissions to ensure that hazardous levels are never approached. Monitoring is an essential part of the production operation in any areas where the potential for causing a deterioration in the air, soil or water systems in and around the production facility are registered.

6.4.3.2 In service

Buried in the ground, mostly, and largely passive in operation, cables offer little threat to the environment in service. Some concern has been expressed over lead in sheaths and the possible contamination of surface waters. This is despite the corrosion protection plastic over-sheaths, the low solubility of lead alloys and the presence of naturally occurring lead ores in many regions. Concern over the effect of cable oil spillages on flora and fauna have been addressed by demonstration that they are very readily bio-degraded. The currently used straight chain alkylbenzene was shown to achieve an 80% ratio of biological to chemical oxygen demand in a 20 day test (test to OECD Guideline 301D). Despite the excellent bio-degradability of current (alkylbenzene) low viscosity cable impregnants, there is a strong interest in location of any leaks. Methods under development to supplement the traditional flow and pressure observation techniques include the dosing of the impregnant at very low concentration with a substance that can be readily detected emanating from the soil by chemical analyses [24]. Clearly this also offers advantages in terms of reduced disruption should leaks have to be repaired (see Section 6.6). Additionally, there is a continuing study to identify even more benign impregnants from such 'green' sources as vegetable oils.

There is continuing negative propaganda directed against PVC as a sheathing or low voltage insulation. Accusations include the liberation into the bio-sphere of organo-chlorine compounds in manufacture, plastisers in service and dioxins in disposal. The evidence for these threats to the environment is highly controversial.

Although not material related, there are two further environmental concerns:

1. Aesthetically, buried cables provide no detriment to the environment compared to the alternative of overhead transmission lines. This aspect, although claimed to be an expensive luxury by some, is an important gain wherever power has to cross a beautiful landscape.
2. The lesser contribution of buried cables to electromagnetic fields can also be claimed as an advantage compared to overhead lines. This is especially true with certain installation configurations. However, the possibility that electromagnetic fields deriving from cables may have some impact on the health of the public is still a topic that has high news media interest despite several authoritative publications in which such concerns are examined, quantified and put in perspective. More recently public attention has switched from the magnetic field component to the electric field. This does not change the relevance of a report deriving from the Institution of Electrical Engineers [25] in which the statement is made: 'The conclusion . . . remains that there is still no convincing evidence of health effects in man . . .'. Also, Dr Z. J. Sienkiewicz of the National Radiological Protection Board stated [26] '. . . there is no categorical evidence that exposure to weak fields causes any long-term or pathological effect'. A recent guide to this topic is the 'ICNIRP Guidelines' [27]

6.4.3.3 In disposal

Due to their longevity, disposal of cables falls to a subsequent generation. Recovery of valuable metals generally ensures care in retrieval. The less valuable materials are incidentally disposed of, generally by controlled incineration, whilst recovering the metals. As with the in-service spillage of cable oils, their intrinsic bio-degradability prevents long term damage should any be released into the soil.

6.5 Testing

6.5.1 Routine

To deliver a product such as a cable with the integrity that promises a service life of four decades demands that, as a routine matter, the quality of raw materials, the semi-finished products and the finished items be closely monitored. Due to the high proportion of the cost of a cable contributed by the raw materials it is a wise policy to determine their adequacy at an early manufacturing stage. This may be accomplished by measuring critical characteristics of the materials as they enter the cable maker's domain or, preferably, prior to dispatch from the suppliers. However, such testing costs time and money. It is customary, therefore, to avoid duplication of testing by sharing the tasks with the supplier, ensuring by audit that the supplier possesses satisfactory quality control schemes. It is the target of the cable manufacturer to be able to trace every material that forms a part of the product back through the processes of manufacture to its origins at the supplier. This is no mean task as the list of raw materials used by a major manufacturer of a wide range of cables runs to over a thousand items.

The laboratories carrying out routine testing are likely to possess a subset of the capabilities of the laboratories that would make the first selection of materials and be instrumental in establishing the agreed specification for each material. These capabilities would include electrical, mechanical and chemical testing methods with special areas such as polymer rheology and fire performance testing.

Semi-finished products such as cable core prior to laying up or accessory components prior to further assembly are often more inspectable than at any later stage. It is certainly less costly to reject substandard items as early as possible before more work and further materials are invested in them. Apart from dimensional checks, these tests may include electrical quality of oil from an impregnated cable or accessory, the completeness of cure of polymeric insulation or the freedom from defects of a resin casting determined by partial discharge measurements or ultrasonic testing.

Routine testing of the finished product is often regulated by the standards to which it is made and will include examination of small samples as well as tests on the ready-to-dispatch cable. These latter involve high voltage tests appropriate to the nature of the cable with specific parameters to be met such as loss tangent, capacitance, conductor resistance and, in the case of polymeric cables, partial discharge levels. This last area has been pressed in recent times to reach higher sensitivities in longer cable lengths. This has been achieved by employing sophisticated means of extracting the very small radio frequency signals evidencing the partial discharges from the electrically noisy environment of a heavy industrial plant.

6.5.2 Type testing

The various standards documents indicated in Table 6.2 prescribe performance levels that must be demonstrated for each new design offered or significant change in materials or technology of production. Some of the principal requirements are shown in Table 6.4. These are typical of existing specifications but the individual documents must be examined in each case to determine the exact testing details. These type tests have evolved to provide a high level of confidence that the cable system, including of course the various types of joints and the terminations, will perform well in normal and predictable excursions from normal service. In practice it is the thermal, mechanical and electrical stresses that are experienced by the system during the excursions from normal service that regulate the cable and accessory design. For example, the current rating of a buried cable will presume the highest likely thermal resistance of the soil with the highest temperature, that the strength of cleating of a nonburied cable (e.g. in a tunnel) relates to maximum short-circuit currents and the insulation thickness will be such that the electric stress during the pulse from a lightning strike will be less than the breakdown strength of that insulation. Some parts of type test protocols have a bearing on the longer-term performance under normal working conditions. Rapid thermal cycling, for example, is expected to accelerate any changes in dielectric properties of an oil-filled cable that might otherwise only show up after some time in service. Another example, more relevant to polymeric insulation, is the application of very high AC electric stresses for a period of time which may be relatable to life expectation at service stress using statistical transforms [18]. However, the trend in type testing philosophy is towards longer tests carried out in conditions closer to those which the system will meet in its normal working life – this is in recognition that nothing is more comforting than proven service experience.

Table 6.4 Typical type test requirements

System voltage (kV)	AC test voltage (kV)	Lightning impulse withstand voltage (kV)	Some of the other tests
11	18	95	Bend tests: 3 reverse cycles
33	54	194	Load cycles: 20 × 6–8 h load + 16–18 h cooling with 1.33–1.5 U_0
66	114	342	Loss tangent and capacitance at temperatures of 95°C and 2 × U_0
132	228	640	Partial discharge (polymeric only) at 1.5 U_0
275	375	1050	Switching impulse (oil-filled)
420	500	1425	DC voltage (polymeric)

6.5.3 Special testing

There is no limit to the special testing that may be required to satisfy particular conditions of employment of a cable system but two quite different areas of testing are worthy of individual mention: water tree resistance (see Section 6.3.2) and fire performance.

The mechanism of deterioration of polymeric insulation by the growth of large numbers of separate tree structured channels in the presence of water and quite modest AC electric fields has been known since the mid-1960s. Eventually a few of these interfere with the local electrical field, enhancing it to a level where discharge activity commences and electrical breakdown channels propagate rapidly to provoke a complete dielectric failure. Low density polyethylene is particularly prone to this phenomenon and a large quantity of initially low-cost cable, installed principally in the USA in the 1970s, failed, prematurely causing disaster to both manufacturers and customers alike. Since then the use of cross-linked polyethylene and EP rubber compounds has considerably reduced the hazard and, more recently, special treeing resistant grades of polyethylene (TRXLPE) have become available. The claim is that these improved materials permit cables to be made and installed in moist locations without a protecting water barrier and therefore more cheaply than metal sheathed cables. To test this claim a variety of test methods of differing complexity and running time have been proposed. The common aim is to discriminate between designs and materials that promise long trouble-free performance and those that do not. The conditions of test are intended to accelerate deterioration without departing from the mechanism that would occur in service. Table 6.5 illustrates some of the principal features of the dominant test protocols at this time in the UK.

The feature to note is the period of two years demanded in some cases which means that a manufacturer has to wait that time at least before the product is acceptable to the customer. Should it fail along the way s/he must start again with a new product. This means that a manufacturer cannot afford to gamble on passing such a test; it is necessary to run a programme of testing which includes in parallel all possible candidates. The resources, both in staff and equipment, required to meet this commitment are substantial and costly. It is to be hoped that the emerging understanding of the fundamental mechanisms of this form of deterioration will enable more certain selection of candidate materials before embarking on such long testing protocols.

Tests for resistance to water treeing have been progressing in the laboratories of all potential manufacturers of medium voltage extruded cables, and since 1997 it has been shown that several EPR and XLPE, both water tree resistant and standard insulation systems, satisfy the lengthy and demanding protocol of the Unipede test (Table 6.5), but some difficulties are being reported. There has been some renewed

Table 6.5 Some testing protocols for water tree resistance of polymeric cables

Origin of test	Conditions of ageing and test criterion	Time to complete
AEIC CS5	6 kV/mm, tap water conductor and screen, temperatures 90°C and 45°C, 8/16 h cycling, test: AC steps 7 kV/5 min	2880 h
CIGRE 21-11	5 kV/mm, 0.2 g NaCl/litre conductor and screen, temperatures 40°C and 40°C constant, test: AC steps 1 kV/mm/min	3000 h
Eastern REC	2.5 x U_0 (16 kV for 11 kV), tap water at screen only, temperatures 70°C and 70°C constant, test: AC 8 x U_0 (50 kV for 11 kV) 6 h	3000 h
Midland REC	U_0, tap water at screen only, temperatures 70°C and 70°C constant, test: AC 8 x U_0 20 h after first 7000 h, further 7000 h survival at U_0	7000 h + 7000 h
London REC	As Midland but final 8 x U_0 20 h at end of second 7000 h	7000 h + 7000 h
Unipede	25 x U_0, 0.3 g NaCl/litre conductor and screen, temperature 30°C and 30°C constant, test: AC steps U_0 5 min, 100% > 14 kV/mm, 70% > 18 kV/mm, 40% > 22 kV/mm	17500 h

interest in dry design polymeric cables and options such as copper or aluminium foil laminate water barrier are of increasing interest (see Section 6.3.5) with the requirements currently being defined between customers and manufacturers. It is perceived that dry designs may augment cable lives from the current expectation of > 25 years towards > 40 years.

Fire performance of a cable system implies a number of differing criteria. There is the ability of some cables to be resistant to the propagation of a fire to which they are exposed and of others (but generally lower voltage cables) to maintain some working capacity in a fire situation. There is the requirement that the smoke emitted from cables in certain locations should not exceed a certain density and not contain significant amounts of either corrosive species or toxicologically hazardous substances. Although not all cables, and as yet few super-tension cables, need to meet such requirement (e.g. a buried cable is unlikely to be caught up in a fire), this is a field of cable design growing in importance. Table 6.6 shows some of the common test regimes in specifying cables and Figure 6.12 illustrates a laboratory dedicated to such work.

Table 6.6 Some testing methods for fire performance of cables and accessories

Characteristic	Standard	Conditions
Propagation of fire	BS 4066/1	Single cable, mounted vertically, ignited by a 1 kW gas flame.
	BS 4066/3	Bunch of cables with volume of nonmetallic material up to 7 l/m, mounted vertically, ignited by 20 kW gas flame.
Smoke emission	BS 6724	1 m of cable, mounted horizontally, ignited by 1 l of burning alcohol.
Acid gas	BS 6425	1 g of material from nonmetallic parts of cable, pyrolysed in a tube furnace.
Toxicity	NES 713	4 g (approximately) of material from nonmetallic parts of the cable, ignited by a gas burner in a sealed chamber.

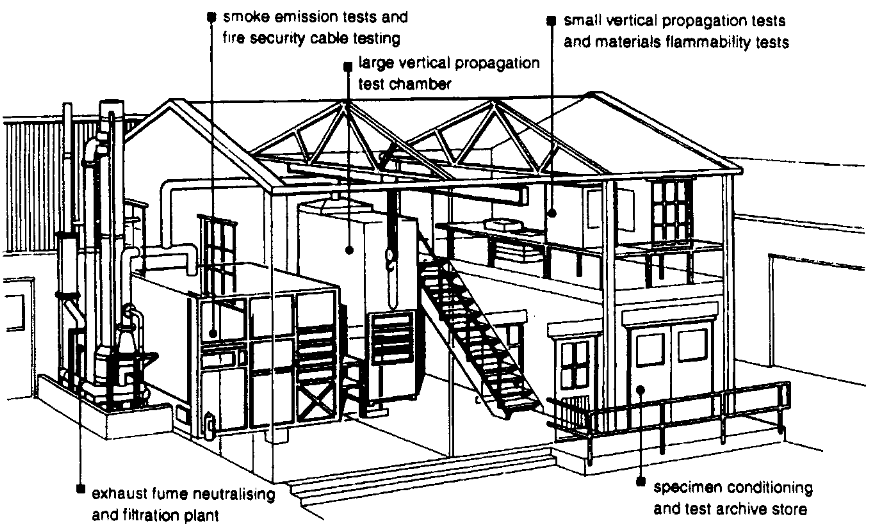

Figure 6.12 A fire test laboratory for cable testing

Once again these special tests represent a considerable investment by the manufacturer.

6.5.4 Site testing

Due to the interaction between cable system and site conditions and the possibility that the installation operation may have caused damage to a cable system, it is necessary to carry out both pre- and post-installation tests on-site.

To ensure that the rating calculation will be valid the variations in the thermal resistivity of the soil or trench backfill (see Section 6.3.7) must be known along the route length. This can be measured by means of a 'needle probe' device that applies a line source thermal step and evaluates the thermal resistivity from the temperature transient. Special backfills such as selected sands and cement bound sand are most readily tested by removal to a suitable laboratory.

Verification of the integrity of the anti-corrosion sheath (see Section 6.3.6) is made by applying a high voltage to the sheath (typically 4 kV/mm up to 10 kV but half this for retests). This test will also demonstrate that the insulation between sheath sections (for cross-bonded earthing) is sound. The effectiveness of this test is ensured by a graphite varnish layer over the sheath which guarantees earth contact along the sheath length, even when the cable is not embedded in a backfill. Some cable designs use a co-extruded partially conducting outer layer as an even more secure earthy electrode. Should there be any question of a failure of this anti-corrosion sheath, the faults (maybe caused by incidents during installation) must be located, as would be a fault in the insulation of the cable itself as described later. Where the sheath is accessible (as in a tunnel installation), other conductance methods can be applied to localise the damage.

Following installation, the resistance of the conductor is verified, remembering that there may exist a number of joints in the conductor where a high resistance would be disastrous in service. The sheath voltage limiter units (disconnected for the sheath integrity tests) must be verified to pass an appropriate current at the specified voltage (e.g. 10 mA at 5 kV).

On cross-bonded earthing systems, the connections are verified by passing a three-phase current of significant magnitude (e.g. 100 A) through the phase conductors to demonstrate that the sheath currents are very low. The standing sheath voltages should not normally exceed 65 V for 132 kV systems or 150 V for 275 and 400 kV systems. The resistance of the sheaths and any interconnections at link boxes are measured to verify the integrity of the connections.

High voltage commissioning (after laying) tests on the installed cable are necessary prior to service and subsequent to modifications and repairs [28]. On traditional paper insulated cables, a suitable DC voltage applied for 15 min provides assurance that the system will perform well when put into AC service. Typically, a 132 kV cable will be tested at 305 kV when new and 228 kV after a repair, but for systems more than 20 years old, at 152 kV. The logic for choosing these precise values derives from the multiples of service or type test voltages. Corresponding voltages for a 275 kV cable would be 525, 394 and 263 kV. Cable systems insulated with polymeric materials (particularly XLPE) and designed for AC service are reported to be vulnerable to failure when subjected to DC test voltages. The expensive solution at high voltages is a trailer mounted resonant high voltage test set providing an appropriate voltage (e.g. 132 kV or 1.7 U_0 for a 132 V system and 207 kV or 1.2 U_0 for a 275 kV system). An additional advantage of AC testing an AC cable system is that the stress distribution under test is the same as that in service and therefore the test is more relevant. Although there is no substantiation of hazard to medium voltage cables with DC testing, there is evidence that incipient faults are not detected at voltages up to 7 U_0. A solution that has been explored is the use of very low frequencies (VLF), e.g. 0.1 Hz. This allows the use of relatively portable and moderate cost test sets at voltage levels of 3 to 4 U_0.

Fault location in a cable, whether it be in the main insulation or in the anti-corrosion sheath, is facilitated by low resistance faults. When this is not the case, a fault position may be 'burnt' out by passing a current of several hundred milliamps to provide a carbonised path through the fault. This procedure can cause further damage to the cable and generally obliterates the evidence of the cause of the fault.

Precise location of a fault to allow repair with minimum disturbance of the cable route is important due to the high costs and time of excavation. Applying a pulsed high voltage allows the identification of the site of the fault. Three common methods are applied: (i) by measurement of the magnetic field produced by the current flow using a ground level magnetometer – the field diminishes significantly when the fault site is passed; (ii) by measurement of the potential gradient in the soil – the polarity reverses as the fault site is passed; (iii) by detecting the acoustic signal from the electric breakdown as the high voltage pulse is applied.

Other methods for location include Time Domain Reflectometry (TDR), in which a pulse is propagated along the cable as a waveguide and the time for its reflection to arrive at an end of the cable is interpreted as a distance, and the traditional methods in which the cable and associated nonfaulted cables are formed into a bridge circuit.

Some application of partial discharge techniques at power and very low frequencies has been made when the cable system has been suspected of having an incipient fault; this has been successful in identification of failing accessories.

6.6 Diagnostics

Despite the low incidence of failure in cable systems demonstrated in Table 6.3 and subjected to extensive type testing as illustrated by Table 6.4, a number of diagnostic methods have been developed. These are appropriate to different types of cables and permit some reasonable approach to quantifying a deterioration, proposing its cause, finding its location (if it should be discrete see Section 6.5.4), determining if it is progressive or stable and estimating its effect on system life.

A recent publication by Cigré WG 21.05 in *Electra* [29] has provided an excellent consensual account of methods of diagnosis of a cable's state. It covers both cables and accessories with thumbnail descriptions of diagnostic evaluation of such diverse parts of a cable system as the nonmetallic oversheath and the impregnating fluid and the interpretation of such differing tests as the examination of grain structure in a lead sheath and the dissolved gas analysis of the impregnant.

The following are examples of specific diagnostic methods applied to paper and polymeric cables – there are many others in current use [34].

6.6.1 Impregnated paper insulation

As mentioned in Section 6.3.4.1, ageing of cellulosic paper is an inescapable phenomenon and is accelerated by higher temperatures. As ageing proceeds, various properties of the paper change and the chemical degradation of the cellulose liberates a variety of chemical species into the impregnant [30]. Access to the paper insulation is generally only possible when carrying out works such as diversion of a route or reinstatement of damage. On these occasions, small specimens of paper retrieved from the cable can tell a great deal about the life history of the system and, by comparison with laboratory and field studies, allow prediction of future life under a particular working regime. Figure 6.13 illustrates the deterioration of some readily measured paper characteristics; one of these at least, burst strength, may be measured under site conditions. Setting a lower limit to such a property based on the service demanded of each cable system is not an exact science but reasonable end-of-life criteria may be proposed. Ten percent of original physical properties has been assumed by some authorities [31] provided the cable is not disturbed. Comparison of the deterioration of the papers in the conductor region with those at the outer screen together with the known thermal transmission characteristics allows some estimate to be made of the service conditions, i.e. if the current rating of the cable has been exceeded.

In low viscosity oil-filled cable it is possible to withdraw small quantities of the oil from locations at the accessories without entering and disturbing the insulation system proper. Extraction and analysis of the dissolved gases provides a complex but informative view of any deterioration mechanisms in progress in the cable. The main complicating factor in interpretation is the geometry of the system as the source of production of the dissolved gases may be kilometres or only a few metres from the sampling point. Although similar analyses are performed for other impregnated paper insulated equipment such as transformers, its application to cables has an additional demand, that of sampling and transporting the oil under high vacuum conditions to permit the fullest

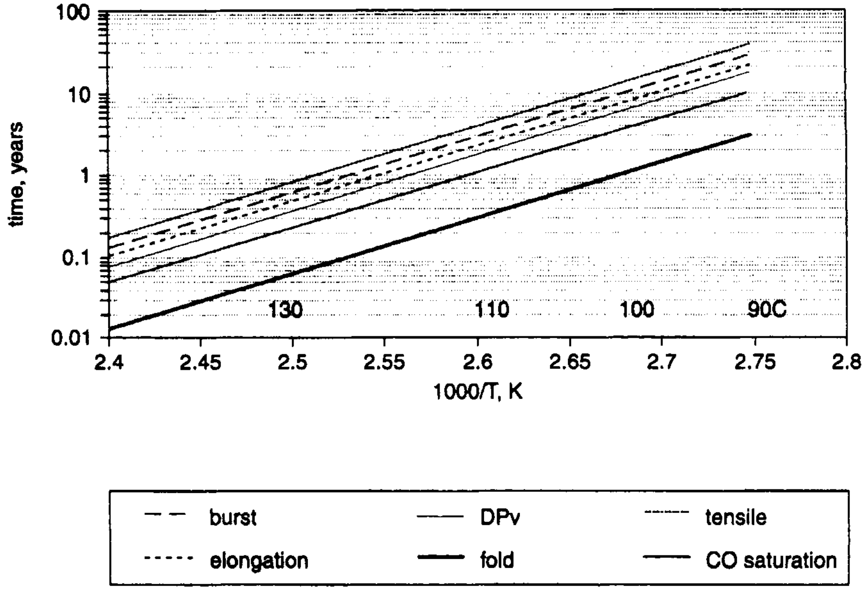

Figure 6.13 The ageing of paper insulation. The relationship between temperature and time to reach critical values of properties of the insulation

understanding of the appearance of any gas into a hermetically sealed system. The qualitative interpretation of analyses is close to that applied to other hydrocarbon oil filled equipment (silicone oil impregnants are a little different): hydrogen with methane indicates partial discharge activity, acetylene principally points to arcing under oil, carbon monoxide dioxide signals thermal ageing of cellulosic paper [32, 33]. Special to cable systems can be hydrogen diffused from aluminium sheaths, carbon dioxide leaked from pressure elements in oil pressure tanks and the interpretation of the oxygen to nitrogen ratio in terms of residence time of air leaked into a system. Particular interest is focused on the build-up of carbon monoxide as this is a relatively low solubility gas which, if sufficient were to be produced by thermal ageing of the paper, would lead to saturation of the oil, bubble formation and then rapid cable failure.

6.6.2 Polymeric insulation

Retrieval of specimens of polymeric cable insulation is sometimes possible, as with impregnated paper cables, when work is being carried out on a system. When there has been exposure to water (and even when not) a microscopic examination of carefully prepared slices may reveal water trees or micro-voids and any progression of these to electrical trees. The slices have to be only a few tens of micrometres thick, cut with a well-honed microtome blade and then stained to show up water trees when viewed with an optical microscope. Some automation of these observations is possible with image processing to reduce the subjectivity of the determination of water tree number and size but interpretations are still a matter of debate. Such examinations adjacent to a failure induced during developmental testing can reveal the less strong regions of a polymeric insulation system. For example, it may become apparent at which screen the failure initiated with implications on the perfection of the extruder dies, or which path through an accessory the failure ran indicating the relative importance of electric field distribution and materials interfaces. One technique widely applied to unfilled XLPE as used in super-tension cables is to prepare a substantial piece of cable, say 50 mm long, with smoothed (microtomed) end faces. On heating to above the crystalline melting point of the polyethylene (generally to about 150 °C), the insulation becomes glass-like and transparent, allowing a visual inspection of significant volumes of material and areas of surfaces – very much more than can be observed by means of slicing.

Ageing of polymeric insulation other than by treeing may be estimated by deterioration of physical properties of specimens cut from cable samples and by a variety of chemical analytical techniques. These may, for example, determine the depletion of anti-oxidant or generation of species formed by the oxidation of the insulation. A technique (differential scanning calorimetry) that is used to reveal the thermal life of cross-linked polymers measures the heat flow into a microscopic specimen of insulation as its temperature is raised at a predetermined rate. The temperatures at which these heat flows occur and the quantity of heat flowing may be interpreted as changes in the microcrystalline structure of the polymer, this structure having been established by the time and temperature history of the cable. Thus it is often possible to say that a cable has been loaded at a certain level or, more interestingly, has suffered an overload reaching temperatures in excess of the design limits.

6.7 Case studies

Although this section has been divided into 'typical' and 'specialist' it is one of the features of the high voltage insulated cable field that almost every product is special, particularly so as the voltage level increases. However, there are, as already indicated, general design philosophies and these may be illustrated by reference to an individual cable.

6.7.1 Typical

For distribution of power in urban and suburban areas at medium voltage (principally 11 kV), cable might well be supplied on a contract covering a period of years for a few particular conductor sizes, constructions and accessory sets. In this case the customer was intending to adopt polymeric insulation to realise the economic benefits of lower installation skill and time requirements. Clearly these cost savings needed to exceed any price disadvantage compared with the previously used impregnated paper system. For both cable price and complexity of installation reasons it was necessary to adopt a design without a metallic sheath, therefore demanding a polymeric insulation system with proven resistance to water treeing. An EP rubber composition was chosen which had been developed to perform well in the Cigré water tree resistance test (Table 6.5, Section 6.5.3) and was of a family of materials with some 20 years' satisfactory service experience. The type test included the protocol indicated as Eastern REC in Table 6.5, otherwise the cables were to be in compliance with BS 6622 [4]. The conductor was chosen to be solid circular (the circuit was to be laid as separate cores rather than three core to simplify installation techniques) aluminium. The outer conducting screen was matched to the insulation system to be cold strippable (to minimise jointer skills and tooling). The earth screen was to be formed by copper wires laid over the outer conducting screen. As the final cover, a sheath of extruded medium density polyethylene was chosen to provide an abrasion resistance and water impermeability superior to low density polyethylene without the sensitivity to cracking of high density polyethylene. This sheath needed to be coloured red for identification purposes with careful choice of a pigment and anti-oxidant combination to avoid deterioration with exposure to solar radiation.

For transmission of power at super-tension system voltages a cable will be described that involved a single 275 kV circuit passing through a road tunnel under a wide river, the Mersey, and which was replacing an old technology gas compression cable. Of major interest to the customer were safety due to the presence of the public in the tunnel and reliability, this latter being one of the motivating reasons for recabling. The overall circuit length was 14 km, of which 2.7 km was in the tunnel, the two substations at either end of the route being 4 and 6 km distant inland. The system was rated at 748 MVA summer load (831 MVA winter) and to meet this, copper conductor sections of 1300 mm^2 were required in the tunnel and 2000 mm^2 in the land section (this difference being due to the better cooling brought about by forced air circulation in the tunnel), and the circuit was fully cross-bonded. The insulation system was chosen to be oil-impregnated paper at a design service electrical stress of 15 kV/mm (lightning impulse withstand of 99 kV/mm). The containment was of corrugated aluminium with a medium density polyethylene protection except for the lengths running in the shafts at the ends of the tunnel where a fire retardant PVC was used to enhance the safety of the installation. The installation in the tunnel was in concrete troughs filled with cement bound sand to provide the highest level of security due to the nature of the location, allied to good and stable heat transfer capability. The land sections were directly buried but also in cement bound sand to ensure stable and optimum heat transfer to the soil. The circuit was arranged to exclude the more complex stop joints (which require oil feeds) from the tunnel section and, where straight joints were needed, these were also enclosed in cement bound sand.

6.7.2 Special

Although long submarine power links are generally thought of in terms of DC connections there are situations where an AC system is more appropriate as when the power flow is relatively modest into a discrete area and without other interconnections. Such a case is the single cable circuit linking the mainland grid to the Isles of Scilly. The route distance is 56 km passing through extremely busy sea lanes and avoiding the very rough sea bed lying directly between St Mary's and Lands End and the important fishing grounds. The cable was to be a three-core construction with conductor chosen to be 70 mm^2 compacted circular copper. The insulation system of EP rubber designed for a service stress at the conductor screen of 3.1 kV/mm with a highly bonded conducting outer screen covered with a double layer of interlocked tinned copper tapes. A 'wet design' was adopted benefiting from the service-proven water resistance of the dielectric and providing a light-weight (without metal sheath), flexible and significantly less costly to lay cable. The three cores were laid-up with polypropylene string fillers to provide a good overall circularity and two layers of galvanised steel wire with polypropylene string bedding as protective armouring. A final serving of UV and oxidation resistant polypropylene string finished the cable.

A very different mainland to island link is the cable supplying Sardinia from Italy where the maximum laying depth of 500 m and transmission voltage of 200 kV DC with a submarine route of 105 km demanded very special solutions. Tolerance of the pressure at these depths (some 5 MPa) was achieved by an oval cable cross-section (circular cables suffer pinching of metal sheaths during thermal cycling) based on an oval copper conductor of 420 mm^2. The forming operations produced a very hard conductor, this hardness was retained so that some 70% of the tension on the cable during laying at these depths was supported by the conductor itself. The insulation system of viscous compound impregnated paper was dimensioned to give a maximum calculated stress of 25 kV/mm on the conductor at uniform (nonloaded) temperature. At working temperature profiles this stress is relieved on the conductor as the resistivity of the warmer insulation falls, thus throwing more stress onto the outer layers of cooler insulation. On cooling, following loading, very high (up to double) stresses can occur under DC conditions, threatening the integrity of the insulation; otherwise, a higher design stress would have been permissible. The containment chosen was a rather hard lead alloy (E) sheath which has a good fatigue characteristic and is able to withstand concentrated mechanical forces with an oversheath of low density polyethylene to act as a distributor or absorber of torsion and tension stresses. The consequent danger of overvoltage development between sheath and reinforcement during voltage transients was overcome by making electrical bonds at every third kilometre of cable. Above the polyethylene oversheath, a reinforcement of galvanised steel tapes was placed in two 50% staggered layers. The armouring of individually textile wrapped galvanised steel wires was laid on a jute bedding allowing them freedom to expand radially and avoid transmitting dangerous mechanical stresses to the conductor. A very important consideration in mechanical design was the minimisation of twisting tendency and maximisation of rigidity (within the bounds determined by handling operations) to avoid kinking on release of tension during laying.

6.8 References

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