Reliability Parameters of XLPE Underground Transmission Systems Based on EDF Experience

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ABSTRACT

The use of extruded dielectric transmission cables in the US is ever increasing. Experience with these types of cables in the past has sometimes been troublesome. EPRI members asked to provide useful data and knowledge of operators in other countries to improve the reliability of existing and new underground transmission circuits. EDF has more than 30 years of successful service experience with extruded dielectric transmission cable systems. This paper provides an assessment of methods and techniques EDF applies to design and operate reliable underground transmission circuits. The first part of the document address test issues such as routine test voltages and tests after laying. The importance of thermo-mechanical stresses during operation is shown in Part 2 together with appropriate test procedures. Part 3 describes the procedures EDF utilizes to design cable and accessories. One of the criteria is the determination of an insulation thickness optimized under economical considerations. Extruded dielectric cable insulation can demonstrate increased aging in a moist environment. Moisture barrier designs and performance testing of these cable components are shown in Part 4 of the report.

PART 1

QUALITY CONTROL AFTER MANUFACTURING

1 - GENERAL

To achieve high reliability of underground links, it is necessary to perform quality controls at each step of the installation
EDF's practice is the following :

* A selective test after manufacturing of the cables is carried out on each delivery length to reject products with limited performances, without damaging the main insulation of the cables and to check the expected reliability in operation from statistical analysis.

* Controls are performed to verify that mounting of joints and terminations are done by well trained and skilled fitters, following well-proven installation procedures, and that civil engineering is also executed according to well established procedures. These controls are part of a global Quality Assurance system, which includes also the control of raw materials and cables manufacturing processes.

* An after laying test is performed on the cable jacket to check that the cables were not damaged accidentally during shipping, transportation, handling, storing, laying and backfilling : as cables have a tough outer protection, it is believed that the insulation is not damaged as long as the jacket is sound. Up to now, EDF does not perform test on the main insulation of the installed system.

This part is split up into 3 paragraphs :
* Service experience.
* Definition of the routine test.
* Considerations about after laying testing.

2 - SERVICE EXPERIENCE.

In this section, available data on the French experience with underground HV links are updated. [1,2]

2 - 1 - HV and VHV systems operated by EDF.

EDF installed the first 63 kV thermoplastic polyethylene insulated cables in the network in 1964 and the first 90 kV ones in 1968. Low density polyethylene (LDPE) mainly and also high density polyethylene (HDPE) were used. The first cross-linked polyethylene (XLPE) insulated cables were installed in 1987.
On January 1st 1998, there were approximately 1270 km of HV circuits (63 and 90 kV) - among them 450 km with XLPE - 9650 terminations and 3040 joints.

For the 225 kV and 400 kV systems, EDF has been using extruded dielectric cables since 1969 and 1985 respectively. XLPE has been introduced in 1992 in the 225 kV system.
On January 1st 1998, there were approximately 555 km of 225 kV circuits (with 4280 terminations and 2825 joints) and 10 km of 400 kV circuits (with 132 terminations and 18 joints).

Date of first installation in the grid				
Voltage level (kV)	63	90	225	400
LDPE - HDPE	1964	1968	1969	1985
XLPE	1987	1987	1992	/

Table 1 : Date of first installation of extruded dielectric cables in the system

2 - 2 - Main technical characteristics of extruded dielectric cables.

Aluminium and copper cores are in use (maximum cross-section being 1600 mm²).

2 - 2 - 1 - HV links.

The thickness of insulation decreased from 13 to 11 mm for 63 kV and from 17 to 14 mm for 90 kV, during 80s.
The metallic screen is generally a lead sheath (with the exception of some lengths with copper tape screen installed until late 60s).
The jacket is made of either polyethylene or PVC.

Until 1972, terminations were of the on-site molded type with an oil-filled insulator. Since then, prefabricated stress-cones are used.
Today, 95 % of terminations are pre-molded.

Until 1972, joints were on-site molded type. Since then, vulcanized tape type (either adhesive or self-bonding tape) are used ; they represent about 95 % of the total.

2 - 2 - 2 - 225 kV

The thickness of insulation is 22 mm for LDPE, HDPE and XLPE cables.
Lead sheath is used.
The outer sheath is made of either polyethylene or PVC.

For terminations, pre-molded stress-cones in SF6 are now in use (on-site molded type or of the prefabricated condenser type terminations, with oil, have been used up to 1985).

Until 1988, joints were on-site molded or vulcanized-taped type . Since then, pre-molded joins are installed (today, they represent about 55 % of the total).

2 - 2 - 3 - 400 kV

The thickness of insulation is 28 mm for LDPE cables.
The metallic screen is composed of aluminium wires and a lead sheath or a laminate aluminium (see figure 1)
The jacket is made of polyethylene.

For terminations, pre-molded stress-cones in SF6 are in use. Joints are composed of 2 metal-clad terminations placed back to back

Figure 1 : Cable with lead-free composite screen.

2 - 3 - Installation methods.

Installation of cables in troughs is the current practice. The troughs, made of reinforced concrete are laid 1.4 m deep and are filled with sand and sealed.

For passing under roads and where public works have been planned, installation in ducts is preferred. PVC ducts are used, encased in lean concrete (one cable per duct).

Installation directly in weak-mix mortar at a depth of 1.3 m is also used for HV cables outside urban or suburban areas where there is already complex underground networks (water, gas ...). The cables are laid bond together in triangular formation, embedded in weak-mix mortar. When possible, mechanical laying is adopted.

2 - 4 - Thermal sizing of links.

The selection of the cable cross-section to be used is based on ampacity calculations according to IEC 60287 and IEC 60853.
The thermal resistivity of soil is assumed to be equal to 0.85 K.m/W and 1.20 K.m/W respectively in winter and summer ; the ambient temperature being respectively 10 °C and 20 °C in northern areas, 15 and 25 °C in southern areas.
Possible drying of the soil is considered.

Steady-state operation as well as exceptional conditions are taken into account
* in overload conditions (occasional situations which may last several hours), the maximum core temperature may reach the operating temperature plus 5°C.
*in emergency situations, which have a very low probability of occurrence and the duration of which does not exceed 20 minutes, the maximum core temperature may reach the operating temperature plus 10°C.

2 - 5 - Faults

Causes of breakdowns are illustrated in following diagrams (see figure 2)
The evolution of the fault rate is also given in the following (see figure 3).

63 and 90 kV

383 faults were recorded.

The main problem comes from early LDPE cables with copper taped screen : water treeing has been clearly identified as the breakdown cause.
One bad production from one of suppliers was identified and caused several faults in the system.
Not a single internal fault has been recorded on XLPE cable circuits.

225 kV

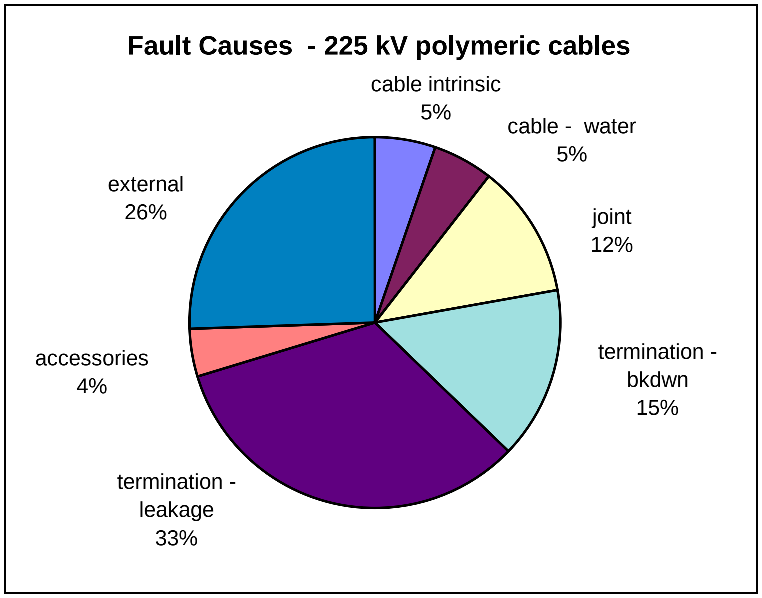
94 problems were observed in 29 years of operation :
* 31 are due to oil or SF6 leakages in terminations
* 24 are due to damages from external origin.

As regard the cables, 5 breakdowns are the result of water ingress from accessories; 5 breakdowns have no identified cause.
Poor assembly was identified as the cause of failure for 60 % of terminations.
This percentage is about 50 % for joints. The breakdowns affected mainly on-site molded joints : only 1 breakdown of premolded joint.

The fault rate of cables is about 0.19 breakdown per year and per 3-phase circuit, including faults due to water-treeing.

400 kV

3 faults for unspecified causes were observed a few weeks after commissioning. Mechanical damages were suspected but non proven.
A SF6 leakage was observed on a termination.



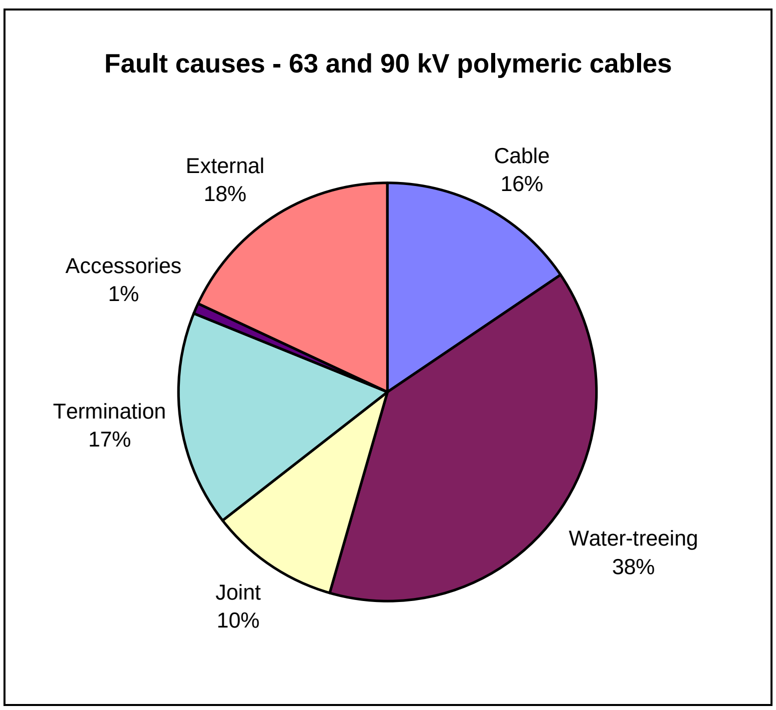
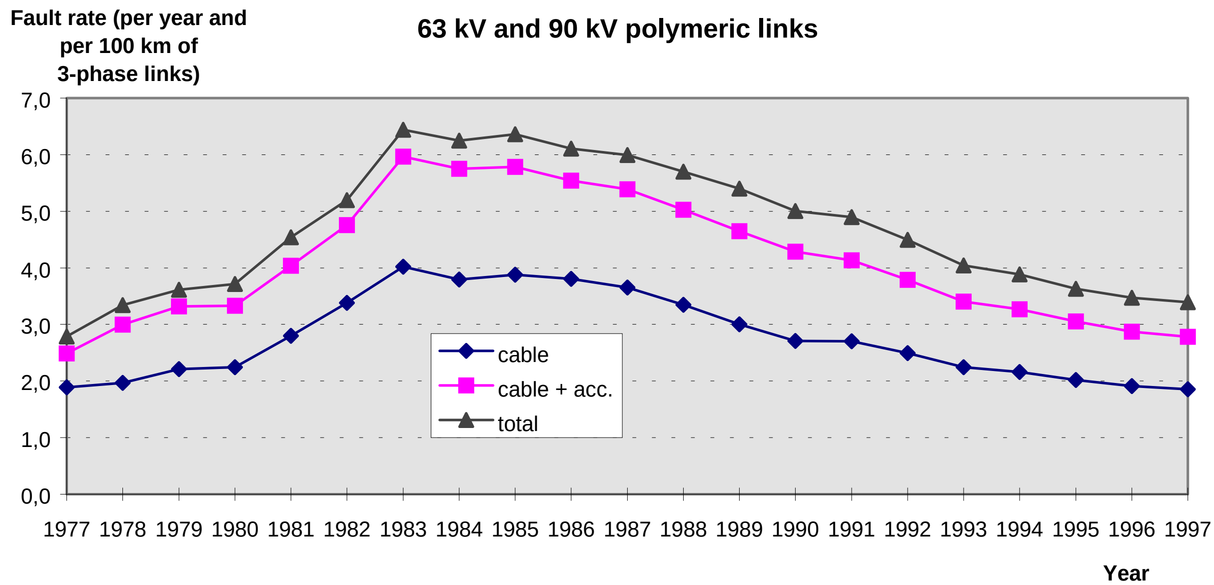


Figure 2 : Fault causes

Note : on these diagrams, « accessories » does not mean terminations or joints but ancillary equipment such as surge voltage limiters.



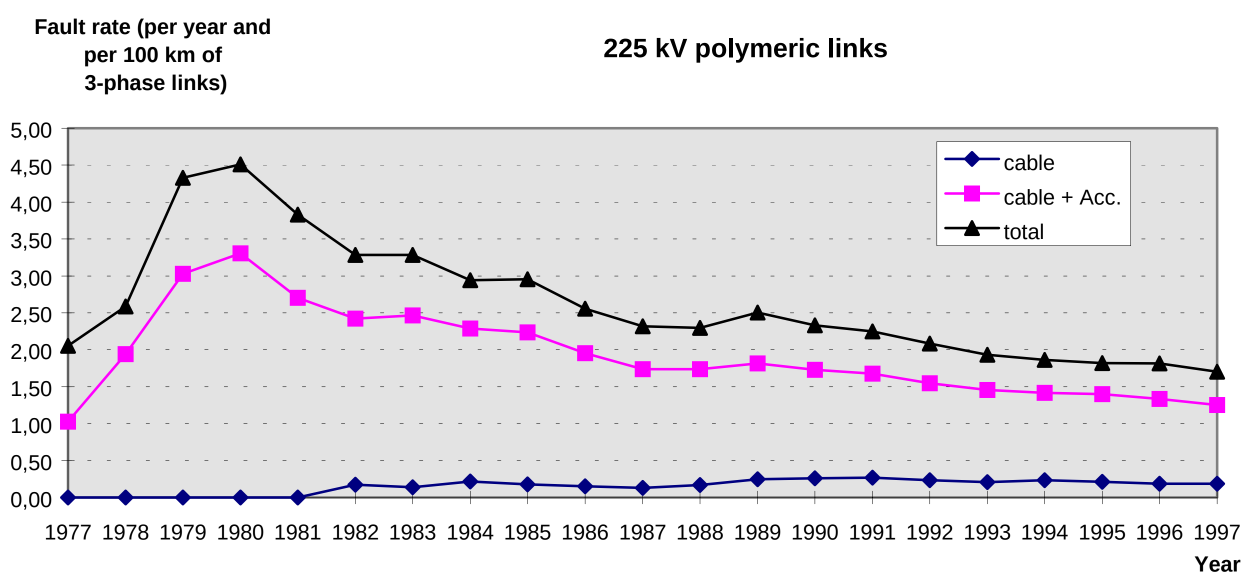


Figure 3 : Fault rate of polymeric underground links

Note : the difference between the 2 upper curves corresponds to damages due to external agressions.

3 - DEFINITION OF THE ROUTINE TEST

3 - 1 - General.

Assuming that cable construction (materials and manufacturing process) has been properly designed and checked by tests, good reliability in service then depends on a sufficient manufacturing control. Routine test is a way for checking that there is no significant change between the prototype cable serving as a reference and the manufactured lengths.

A routine test is characterized by the voltage amplitude V, its time of application t, and the maximum number of breakdowns per given length q which may be considered as normal during testing. As a matter of fact, breakdown is possible during routine test, and the problem is to determine whether it is within the normal statistical scatter of the reference ("normal breakdown" in the following).

t, V and q have to be chosen so that testing time t be short, test voltage V not too high in order to reduce the risk of normal breakdowns, maximum number q of acceptable breakdowns not too low to avoid unjustified rejection of the production.

The determination of the test levels specified in EDF standards is based on the use of Weibull distribution [3] to describe breakdown probabilities and is designed according to a maximum fault rate in operation.

3 - 2 - Basic formula and terminology.

3 - 2 - 1 - Hypothesis

The cumulative probability of breakdown p (t) at time t, under a voltage V, on a cable length L, depends on t, V and L, according to a generalized Weibull's law :

$$P(t) = 1 - \exp\left[-\left(\frac{t}{t_0}\right)^a \left(\frac{V}{V_0}\right)^b \frac{L}{L_0}\right] \qquad (1)$$

where :

a : time shape parameter
b : stress shape parameter
t_o , V_o , L_0 : scale parameters, forming a set of values for which P=0.63

The values of a and b are characteristic of the supplies. They are determined and certified by the manufacturer.

The ratio b/a is designated n ; n is the parameter of the life curve $V^n.t$ drawn with bilogarithmic coordinates.

3 - 2 - 2 - Introduction of maximum fault rate in operation.

The supplies submitted for acceptance comprise a number N of production lengths L, for which the individual probability of breakdown is given by formula (1).

Taking the hypothesis where this probability has a low value ($p(t) < 0.05$), which corresponds to the present case, and where the number of production lengths exceeds 10, the individual probabilities Pk of observing k breakdowns on N lengths tested, are given by Poisson's law :

$$P_k = \frac{[N.P(t)]^k}{k!}.\exp[-N.P(t)] \qquad (2)$$

where :

N = number of lengths tested
k = number of breakdowns observed

The mean number of breakdowns on N samples being N.p(t).

In particular :

$$P_0 = \exp[-N.P(t)] \qquad (3)$$

or using relation (1), as p(t) is very low :

$$P_0 = 1 - \exp\left[-\left(\frac{t}{t_0}\right)^a \left(\frac{V}{V_0}\right)^b \frac{N.L}{L_0}\right] \qquad (4)$$

When comparing relations (3) and (4), it can be noted that for $t = t_0$, $V = V_0$, $NL = L_0$, the mean number of breakdowns N.p(t) is 1.

This interpretation of (t_0, V_0 , L_0) makes it possible to define the corresponding values solely from the maximum fault rate admissible in operation, namely 0.2 fault per 100 km of three-phase link per year, corresponding to an average of one breakdown per 1 500 km of cable during the first year.

The values of t_0 and L_0 , are fixed as follows : t_0= 1 year - L_0 = 1 500 km,
V_0 being the phase-to-ground nominal voltage.

3 - 3 - Determination of the test levels.

For any other set of (t, V, NL) values for which relation (5) below is also true, the average number of breakdowns is 1 per series of N lengths L tested

$$\left(\frac{t}{t_0}\right)^a \left(\frac{V}{V_0}\right)^b \frac{N.L}{L_0} = 1 \qquad (5)$$

Under these conditions, and taking account of both economic (repair cost) and technical imperatives, an acceptance test requirement of a mean rate of 1 fault per 50 cable lengths of 300 m is taken.

This leads to a relation linking the test voltage and the test duration.

For all values of test voltage and duration for which relation (5) is true, the individual probability of breakdown is the same for each length, taking a value of 0.02, as by hypothesis, where N = 50, N.p(t) = 1.

The individual probabilities Pk of observing k breakdowns can also be determined by relation (2), independently of the value of the test voltage, solely according to the number of basic lengths (or the total length manufactured). It is then possible to define the number of breakdowns accepted according to the total length manufactured.

With this method of calculation, it will be noted that determination of the test voltage, and calculation of the probabilities of breakdown can be entirely separate.

Testing can be carried out at different voltage levels. In this case, the voltage values and voltage step times are determined so that :

$$\sum_{i=1}^{n} \left(\frac{t_i}{t_0}\right)^a \left(\frac{V_i}{V_0}\right)^b \frac{N.L}{L_0} = 1$$

with n = number of voltage steps ti = time of i-th step Vi = voltage of i-th step.

3 - 4 - Acceptance criterion

The acceptance test is carried out at a supplier's risk of 2.5 %, namely a 2.5 % risk that supplies complying with the specification will be rejected. [4]

The admissible number of breakdowns according to the number of production lengths derived from (2) is as follows :

Number of breakdowns (k)	Number of 300 m lengths (N)	Corresponding total cable length (km)
1	N≤ 13	3
2	14 ≤ N ≤ 32	9.5
3	33 ≤ N ≤ 60	18
4	61 ≤ N≤ 87	26

However, since only a small number of lengths (N = 20 or 30 for example) are often produced at a time, to accept, in accordance with the above principle, two breakdowns on each series of 20 to 30 lengths, would lead to an excessively high global admissible number of breakdowns, as the probability of observing two breakdowns on 20 to 30 lengths normally meeting the specification, twice in succession, becomes very low.

A statistic shall then be established for the last 100 lengths manufactured (approximately 30 km of cable), for which the total number of breakdowns, in accordance with Figure 4, shall not exceed 5.

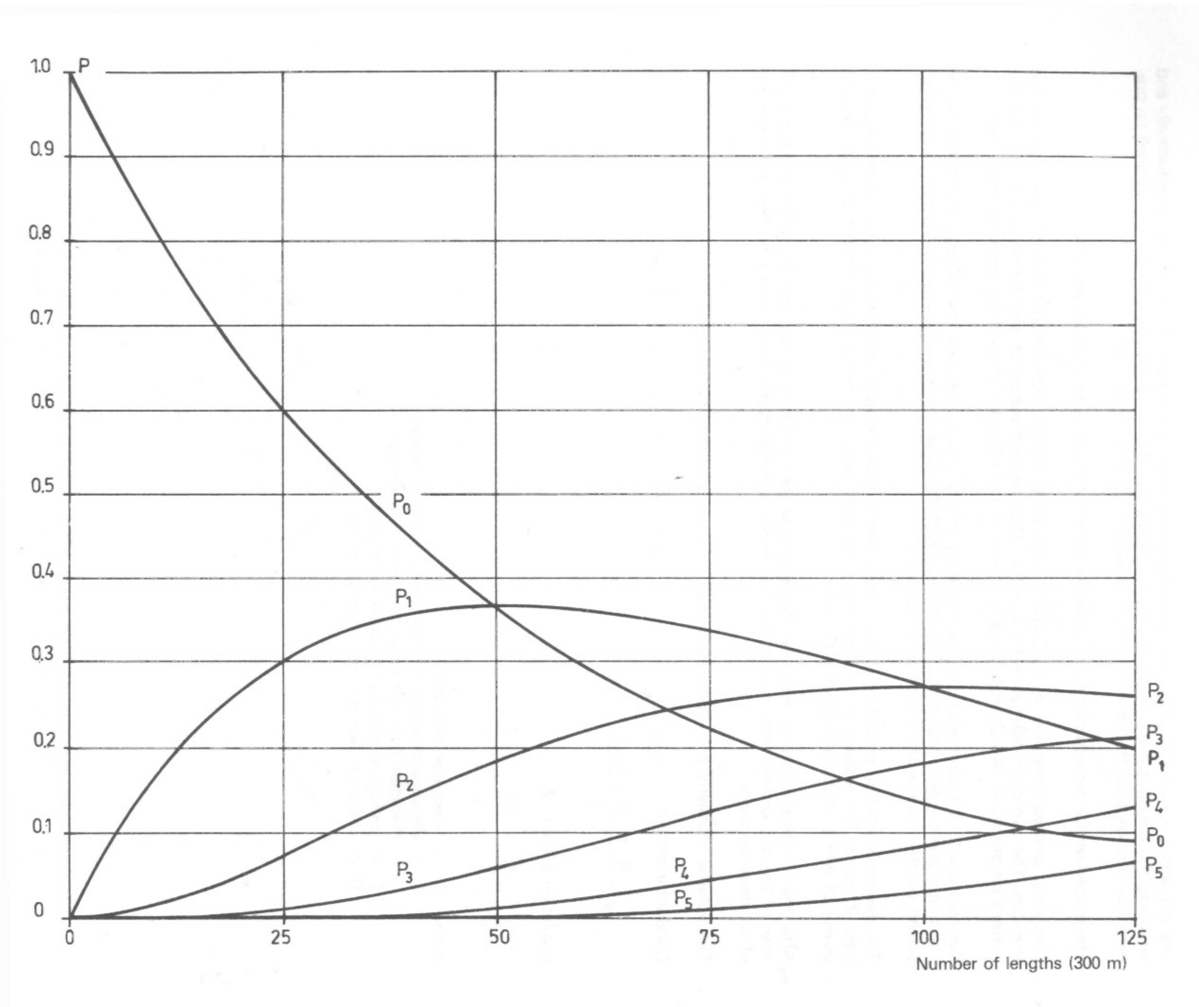


Figure 4 : individual probabilities of breakdown for supplies meeting the specifications

Thus, a manufacturer who has had his first delivery accepted with a total of three breakdowns on 40 lengths, will subsequently only be allowed a further two breakdowns on the next 60 lengths.

3 - 5 - Application to LDPE and HDPE 225 kV cables.

The manufacturer first determines the values of Weibull parameters on the basis of statistical tests. The results of these tests are supplied to EDF and the manufacturer has to subsequently certify that the values of these parameters, for all cables supplied, meet the following requirements with a minimum confidence factor of 90 % :

$a \leq 1$

$n \geq 17.5$ where n is the ratio b/a

A test duration of 1 hour is chosen and the test voltage is determined according to these parameter limit values.
This leads to a test voltage of 2.2 V_0 .

3 - 6 - Further extensions.

For HV cables, the same approach was firstly followed then modified to take into account international practice for routine testing.

To get the same test levels (duration and voltage) as in IEC 840 standard, keeping the same values for the fault rate in operation and the admissible number of breakdowns during test, then the following condition is obtained.

$$\left(\frac{t}{t_0}\right)^a \left(\frac{V}{V_0}\right)^b \frac{N.L}{L_0} \geq 1$$

From this relation, the requirement on the parameter n was turned into :

$$n \geq \frac{1}{a} \cdot \frac{ln\left(\frac{L_0}{N.L}\right)}{ln\left(\frac{V}{V_0}\right)} + \frac{ln\left(\frac{t_0}{t}\right)}{ln\left(\frac{V}{V_0}\right)}$$

For a test duration of 0.5 h and a test voltage of 2.5 V_0 : $n \geq \frac{5}{a} + 10.7$

For VHV cables, another concern is taken into account in the definition of test levels.

A maximum value of the voltage test is taken into account to avoid breakdowns from defects which are not harmful for service conditions.
This maximum value was specified on the basis of tests performed on cables with calibrated impurities, which demonstrated a maximum stress compatible with « normal » contaminants that may be found in cable insulation [5,6] :

Gmax = 27 kV/mm

For VHV XLPE cables, the requirement on parameter n is : $n \geq 15$

From this limit value, test voltage and duration are :

* for 225 kV cables : 2.45 V_0 - 1 h
* for 400 kV cables : 2 V_0 - 1 h

3 - 7 - Procedures for determining values of parameters

Many procedures are encountered for determining values of parameters. Those described here are common ones in the field and fitted to the cases of application discussed. [7,8]

3 - 7 - 1 - Short time tests, determination of b

A continuous voltage rise (ramp test) with a rate of rise between 1 and 3 kV/s, starting from 50 % of the estimated breakdown voltage, is recommended.

The breakdown probability is given by :

$$P\,(G) = 1 - \exp\left[-\left(\frac{V}{V_0^{'}}\right)^{c}\right] \qquad (6)$$

where the parameter c is :

$$c = b + a = b.\frac{n+1}{n}$$

The breakdown stresses V_i are ordered from smallest to largest. The cumulative probability of the i^{th} value V_i is approximated by the following formulae :

if $p \geq 10$ then $$P\,(V_i) = \frac{i}{p+1}$$

if $p < 10$ then $$P\,(V_i) = \frac{0.69}{p} + (i-1).\left[\frac{1}{p-1} - \frac{1.38}{p.\left(p-1\right)}\right]$$

The parameter c is the slope of the line obtained when plotting [1], [6]. :

$$\log\left[\log\left(\frac{1}{1-P(V)}\right)\right] = Fn\left[\log(V)\right]$$

To be accurate would then need to determine the value of parameter a or n first. Nevertheless, the error when identifying b+a to b may often be disregarded.

Another more accurate way for determining b is the "comparison method" [9,10] in which short time tests are applied on two populations of samples differing only by the insulation dimensions.

3 - 7 - 2 - Life tests, determination of a or n

Testing cable samples under constant voltage allows the determination of parameter a within relation (7) :

$$P(t) = 1 - \exp\left[-\left(\frac{t}{t_0^{'}}\right)^a\right] \qquad (7)$$

using the same principles than for parameter b described in § 3-7-1 :

It is generally preferred to get an estimation of parameter n from several tests carried out at different constant voltages.
From a linear regression applied to the logarithm of voltages function of the logarithm of corresponding mean times to breakdown, value of exponent *n* may be derived.

This is not strictly valid, and a more accurate calculation may be applied, but the error is generally minor. [8]

For every test voltages V_i, plotting the distribution of values of time to breakdown allows for determining the value of t'_{0i} corresponding to 63,2 % cumulative probability. The different test voltages V_i and t'_{0i} comply with :

$$V_i^n . t_{0i} = C^{ste} \qquad \text{where n is the ratio b/a}$$

3 - 7 - 3 - Confidence intervals

For a significant use of Weibull distribution, it is necessary to get an estimation of the accuracy of the parameters values, or of the confidence interval of the distribution model.
This may be done with the maximum of likelihood method. [3, 7, 11]

4 - AFTER LAYING TEST.

As already mentioned, an after laying test is performed on cable jacket to check that the cables were not damaged accidentally during shipping, transportation, handling, storing, laying and backfilling : as cables have tough outer protection, it is believed that the insulation is not damaged as long as the jacket is sound.

Taken into account the good service experience gained with HV and VHV underground links, especially since the installation of premolded accessories on one hand, and, on the other hand, the cost of insulation testing, EDF decided not to perform test on the main insulation of the installed system.

Nevertheless, some investigations were carried out and are still performed in the view to define an after laying insulation test : laboratory tests allowing to evaluate the efficiency of d.c. voltage and oscillating waves, measurements of tan δ on installed links and measurements of partial discharges, mainly in accessories during long duration tests.

Today, an a.c. tests either at power frequency or at frequencies near to power frequency (30 - 300 Hz) seems the most appropriate if an after laying test on the main insulation is required.

4 - 1 - Tests on outer jacket.

Immediately after laying of the cables and after the partial filling of the trench but before fitting of joints, a d.c. voltage of 20 kV is applied to the jacket of the cables, between the metallic screen and ground for 15 minutes.
The test is repeated when the accessories have been installed.
If a breakdown occurs during the test, the manufacturer has to repair the cables until the tests are executed satisfactorily.

In case of installation in ducts or in tunnel, a semiconductive coating over the jacket is a practical solution to provide a ground electrode.

Previously, the dielectric strength of the jacket is checked in the factory , by application of a 30 kV d.c. voltage between the metallic screen and the water of a test bath or external conductive layer, such as graphite, or by a d.c. spark test during extrusion where the voltage to be applied is defined by

$V_{test} = 4 * (5 * e + 3)$ where V_{test} is expressed in kV and e is the thickness of the jacket in mm

4 - 2 - Tests on main insulation.

4 - 2 - 1 - D.C. test

EDF carried out a lot of tests on small size cables with or without artificial defects (such as knife cuts) resulting in very high breakdown levels. [12]

There is general agreement that DC tests should to be avoided, as they are ineffective and, also, may be dangerous [13].

4 - 2 - 2 - Oscillating waves.

The principle of the test is the following : the cable is charged with a d.c. voltage and then discharged via a triggered spark gap into an inductance with a resistance in series.
Thus a damped oscillating wave is obtained.
The parameters relevant for a practical testing procedure are : initial d.c. voltage level, frequency, damping constant and number of shots.

The technical feasibility of the test method was studied during eigthies [14] .

Many tests were carried out by EDF on samples of MV cables (core cross-section 150 mm² ; LDPE insulation thickness 5,8 mm), with « standard » defects that may be encountered in accessories, such as needle perforations or knife cuts.
As a result, the figure 5 presents the breakdown stress on the insulation as a function of the defect depth, for 10 shots with a frequency about 10 kHz.

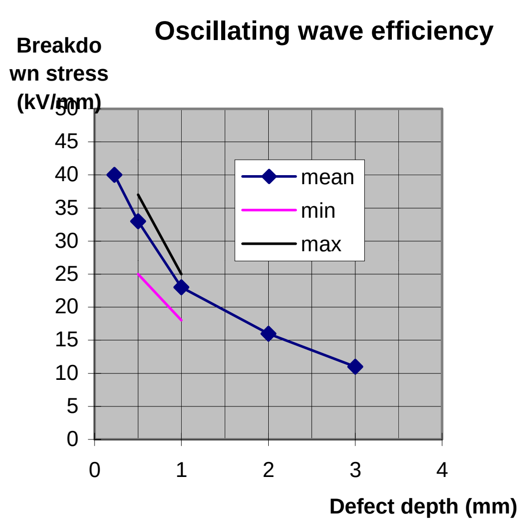


Figure 5 : Oscillating wave efficiency

The detection of bad positioning of the stress cone in accessories was also investigated : high breakdown stresses (typically 2,7 times the a.c. operation stress) were recorded, even for large defects.

The general conclusion, supported by CIGRE working Group 21-09, is that the oscillating wave test is shown to be more effective than a d.c. test, but less effective than an a.c. test : the breakdown stress with oscillating waves is about 1,2 to 1,6 times the a.c. breakdown stress. [15]

4 - 2 - 3 - Measurements of tan δ

Measurements of tan δ were performed at very low frequency (VLF) on several MV links. [16]
Some of the tested links had very high tan δ values, well above the standard degradation criteria ($2.2\ 10^{-3}$) : most of the time, tan δ could reach up to 10.10^{-3} (in one case tan δ even reached more than 100.10^{-3}). No direct correlation with the cables age could be clearly noticed even though recent installed links have more chance to have reasonable tan δ values ($< 1.2\ 10^{-3}$).
As a matter of fact, it was finally found that joints were the cause of such high tan δ values.
In some cases, joints have been expertised and showed different mounting faults (figure 6) such as water penetration (especially on phase 3 with the highest tan δ), bad semi-conductor screen cuts (which generate large amount of PD), joint bodies displacement, etc.

bad cut

Figure 6 : This bad cut in the semi-conductor in the joint leads to a very high tan δ.

As a conclusion, the measurement of the loss angle at very low frequency (VLF) seems to be adapted to the detection of bad assembling of accessories (and, in some extent, as a diagnostic tool for aged cables when water-treeing is concerned).

4 - 2 - 4 - Partial discharge measurements.

PD measurements carried out on some MV links in the grid confirmed the conclusion of tan δ measurements : joints or terminations were found to be the main discharging locations.

Partial discharge measurements could provide a significant improvement in on-site testing as discharges may occur on defective accessories at test voltages, whereas breakdown does not usually occur in the course of the short duration of the after-laying test.

The main consideration is being given to very high frequency and ultrasonic partial discharge detection as they enable the local detection of defects in joints and terminations.

EDF is starting using this technique for long duration qualification tests.

4 - 2 - 5 - A.C. Test.

An a.c. test either at power frequency or at frequencies near to power frequency (30 - 300 Hz) seems to-day the most appropriate.
IEC 60840 recommends AC test, either $\sqrt{3}$ times the nominal phase-to-ground voltage U_0 during 5 minutes or the nominal phase-to-ground voltage during 24 hours.
The test with a voltage of $\sqrt{3}$ times U_0 is not easy to perform for practical reasons (access to the neutral point of transformers, knowledge of the network behavior with respect to ferroresonance, protection relay settings...

On the other hand, there is some doubt whether tests at U_0 for 24 hours or a little more are sufficiently thorough to find harmful defects.

A CIGRE Task Force (TF21-05) has in charge to collect and review the use, techniques, experiences and results on a.c. tests after installation.
The first conclusion is that the use of series resonant test sets is increasing in many European countries, which allows for the detection of poor workmanship in assembling joints.

5 - RECOMMENDATIONS.

The routine test to be applied on every delivery length of cable may be designed from the expected fault rate in operation, using Weibull's statistics.

According to EDF experience, the objective of a fault rate in operation of 0.2 fault per year and per 100 km of 3-phase link - correlated with the « intrinsic » quality of manufactured cables has been achieved for the 225 kV level.

For HV cables this objective has also been reached, if an identified bad production of one manufacturer over a period of about one year is not taken into account. To possibly detect such a bad production, PD measurements will be included in routine tests.

The main problem with cables is due to water-treeing, specially with cables without water-tight screen.

The use of Quality Assurance procedures for on-site operations, and completion of a d.c . test on the jacket of cables after laying is considered sufficient to asses the quality of installed links.

Taken into account the good service experience gained with HV and VHV underground links, especially since the installation of premolded accessories on one hand, and, on the other hand, the cost of insulation testing, EDF decided not to perform test on the main insulation of the installed system.

Nevertheless, investigations are conducted to evaluate PD measurements efficiency to check accessories fitting.

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PART 2

THERMO-MECHANICAL STRESSES ON CABLES AND ACCESSORIES

1 . INTRODUCTION

The mechanical stresses occurring during operation may be a significant cause of failures.

They depend upon cable construction, installation and operating conditions.

There are 2 fundamental installation designs, generally referred as « rigid » and « flexible » designs.
With the first method the cable is restrained from any movement due to thermal expansion or contraction caused by temperature changes; when heated, the cable develops a thrust and the components of the cable circuit are subjected to a corresponding compressive force.
In the second method, the cable is allowed to move more or less freely as a result of its thermal expansion or contraction, so that stresses are reduced.

In this section, the influence of cable construction and the main features of installation conditions are discussed.

Then different kinds of tests are described :
* some tests are carried out to measure mechanical characteristics of cables to be taken into account to design installation conditions,
* the shrinkage tests are performed to deal with shrinkage phenomena of insulations and jackets.
* the long duration type test required by EDF standards : the purpose of such a test is not only to evaluate dielectric performances of cables and accessories, but also to assess the satisfactory behavior of both cables and accessories when installed in the system

Finally, recommendations, based on test experience, for the construction of underground links are proposed.

2 . INFLUENCE OF CABLE CONSTRUCTION

2 - 1 - Conductor expansion.

When heated the conductor tends to elongate.

This trend is characterized by the elongation coefficient α : $\Delta L = \alpha . L_o . \Delta T$

where, Lo being the original length, ΔL is the length increase for a temperature rise ΔT when the cable is free to elongate.

If both ends are rigidly fixed and no lateral movement is possible, the incoming thrust is maximum.
If creep relaxation is neglected and the conductor is treated like a straight rod, the thrust F is :

$$F = \alpha . E . A . \Delta T$$

E being the effective Young's modulus of the conductor and A is its cross-section.

The elongation coefficient α and the Young's modulus E depend upon the core material and design (stranded, milliken or solid) and also of the insulation material.

These 2 parameters are very important to design cleating of cables in tunnels, when a rigid laying is adopted.

2 - 2 - Dielectric expansion.

Important factors for cables with an extruded insulation are the relatively high coefficient of thermal expansion and the relatively low compression modulus of the insulation material, particularly at elevated temperatures.

For reliable operation, it may be necessary to place a bedding layer between the dielectric and the metallic screen. [1]

2 - 3 - Insulation and jacket shrinkages.

Shrinkage phenomena, which occur at cable ends, of both the insulation and the jacket have to be taken into account.

The shrinkages of the cable insulation may affect the insulation of joints. This is very effective in the case of taped joints ; with premolded joins, it is easy to design devices to prevent shrinkage of the cable insulation.

An excessive shrinkage of the jacket may lead to water ingress in the cable from the connection of the joint shell to the cable or the lower metal base plates of terminations.

3 . INSTALLATION CONDITIONS.

There are 2 fundamental installation designs, generally referred as « rigid » and « flexible » designs. [2,3]
In addition, as, in practical situations, a cable route may not be either rigid or flexible over the entire length, the transition points require special attention.

3 . 1 . Rigid design.

This method requires the cable to be rigidly supported and restrained from any movement due to thermal expansion or contraction caused by temperature changes.
When heated, the cable develops a thrust and the components of the cable circuit are subjected to a corresponding compressive force.

To ensure a satisfactory performance, the cable must not buckle under this force, giving rise to severe local sheath strains.

With direct burying or installation in troughs, the cables movements are naturally very reduced.

For installations in tunnels, cleating of cables is necessary. The required spacing between supports can be calculated using Euler's buckling theory :

$$L < 2.\pi.\sqrt{B/(kF)}$$

where :
* B is the total flexural rigidity of the cable,
* k is a safety factor (typically 4)
* F is the developed thrust of cable, according to Part 2.1.

3 . 2 . Flexible design.

This method allows the cable to move more or less freely as a result of its thermal expansion or contraction.
The cable is supported so that it can deflect laterally.
Because expansion is allowed to take place, this system does not develop the high values of thrust that occur in a rigid system.

Installation in ducts may be considered as a flexible design.
For installation in tunnels, in the most widely used technique - so called snaking - the cables are installed in a wave form, expansions and contractions being absorbed by the change in the snaking width.

In the French system, when cables are installed in tunnels, generally, a vertical snaking is adopted, with cleats at every 2 m.

3 . 3 . Transition areas.

A joint bay between a section where the cables are laid in ducts and a section where they are directly buried or in filled troughs is an example of transition area.

When conductor temperature increases, thrusts develop in the rigid section ; this can lead to core movement from the rigid towards the flexible section so that excessive strains may occur.

To face this situation, the thermal expansions are generally absorbed by offsets.[4]

4 . THERMO-MECHANICAL TESTS

To cope with thermo-mechanical aspects, tests have been carried out to achieve a mechanical characterization of cables and to check the shrinkage effects.

Moreover, to asses the correct behavior during operation (including overload or emergency operations), there is a need for tests involving thermo-mechanical stresses applied to cables and accessories.

4 . 1 . Mechanical characterization of cables.

4 . 1 . 1 . Cable sample preparation

To measure the elementary mechanical properties of cables, it has been chosen to evaluate it as a global system regardless whether it is constituted with different layers..
Several 6 metres long cable samples have been prepared by fixing the outer jacket and the metallic sheath with the insulation by inserting nails. The sample behaviour will then be closer to longer cable lengths.
In the following, test results which are given refer to a 1600 mm² Copper - XLPE - lead sheathed 400 kV cable.

4 . 1 . 2 . Evaluation of the cable longitudinal elongation

The experimental test bench is shown in figure 1. The cable is inserted in a stainless pipe with an inner diameter very close the cable one (air gap less than 3 mm). Lubricant has been added to ease the cable movements during the heating cycles.

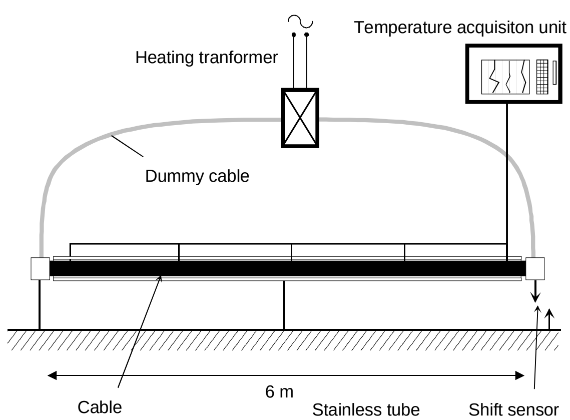

Figure 1 : Elongation test bench

The cable is connected to a dummy cable that goes through an current transformer for heating cycles.

Thermocouples have been installed every 15 cm through the pipe, the cable outer jacket, the metallic screen and the insulation, directly in the cable conductor. Holes in the metallic pipe allow the thermocouples to move during the test without any damage. The bench has been designed to have an equal temperature on all the cable length.

Elongation coefficient α can be calculated with the following formula :

$$\Delta l = l_0.\alpha.\Delta T \qquad (1)$$

with :

- Δl : measured cable elongation in m,

- l_0 : initial length of the cable (6 m)
- ΔT : conductor temperature elevation (°C.)

Figure 2 shows the result of the cable elongation with the temperature.

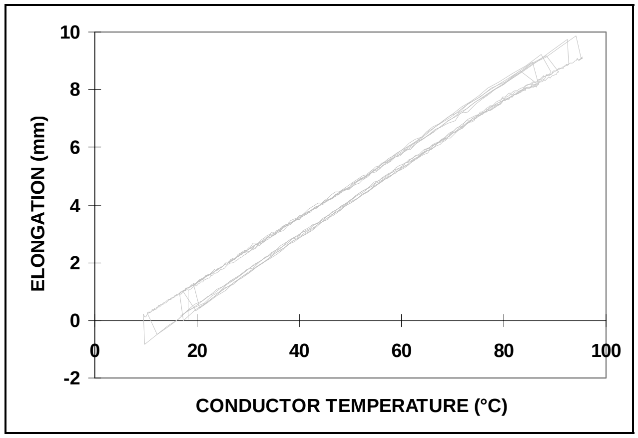

Figure 2 : Results of the cable elongation during heating cycles

Finally, the slope of the curve gives the elongation coefficient α : $\alpha = 21 \times 10^{-6}\ °C^{-1}$

which is a common value found in the literature [5].

4 - 1 - 3 - Evaluation of the longitudinal rigidity

The longitudinal rigidity is difficult to measure because high axial forces are originating from the cables. We therefore used the towers mechanical test facility for which the armed concrete platform can easily withstand such high forces.

The test bench is same than the one used previously, except that we simply added a special both-ways force sensor that has been chosen by using a formula found in literature to pre-evaluate maximum axial force F in daN [6] :

$$F = (A / 20 + 4).\Delta T \qquad (2)$$

with :

- A : core cross-section in mm²
- ΔT : conductor temperature elevation (°C.)

which gives an estimated maximal axial force of 6720 daN (15,107 lbs) for a temperature elevation of 80°C.

Figure 3 shows the test bench for the axial force measurements. In the background, one can notice the metallic fixation for the force sensor.

Figure 3 : Mechanical test bench for axial force measurement

The longitudinal rigidity E.A can be determined from the axial force F from the relationship :

$$F = E.A.\alpha.\Delta T \qquad (3)$$

with :

- α : elongation coefficient (°C^{-1})
- ΔT : conductor temperature elevation (°C.)
- E : Young's modulus of the cable
- A : core cross-section

The experimental results during ten daily thermal cycles are shown in figure 4.
One can notice a break in the curve at the inversion of the axial force. This may due to a mechanical gap in the force sensor or other mechanical parts of the bench. It may be evaluated with equation (1) around 0.7 mm.

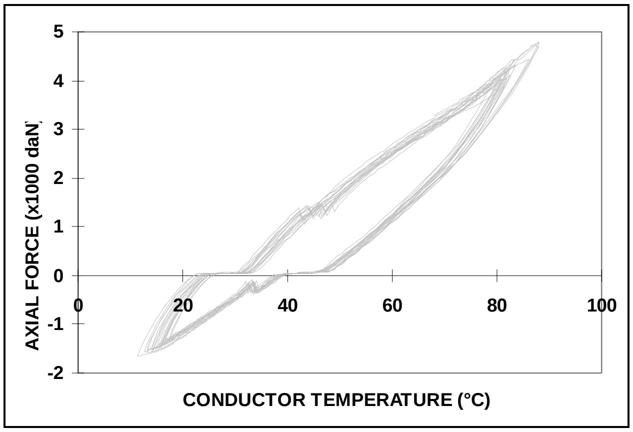

Figure 4 : Results of the axial forces measurements

We can also notice that equation (2) gives excellent results because we have measured a maximum axial force of 6600 daN at 100 °C, very close from 6720 daN.

With equation (3), we can calculate the average longitudinal rigidity :

$$E.A = 3.9 \times 10^6 \text{ daN}$$

4 - 1 - 4 - Evaluation of the flexural rigidity

The flexural rigidity is useful in the design of cleating systems and is also used by some utilities or cable manufacturers to design snakings in tunnels. [7]

Measurement of the flexural rigidity requires a completely different test bench. Figure 5 describes the chosen principle. An alternative movement is applied on the cable at a very low frequency (6 cycles an hour) to be representative enough of the actual cable daily speed. Because the cable has a limited movement inside the duct when installed in the system, the maximum movement of the cable has been limited to 60 mm.

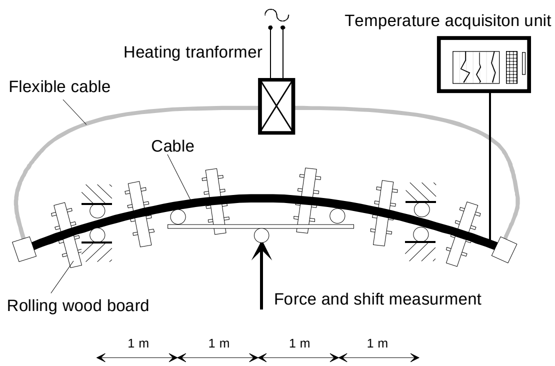

Figure 5 : Flexural rigidity test bench

Tests are carried out at different stabilized temperature, from ambient to 90°C. Tests are still underway at present time, but figure 6 displays the results of the flexural force at room temperature. The shift to the positive forces may be caused by a remaining deformation.

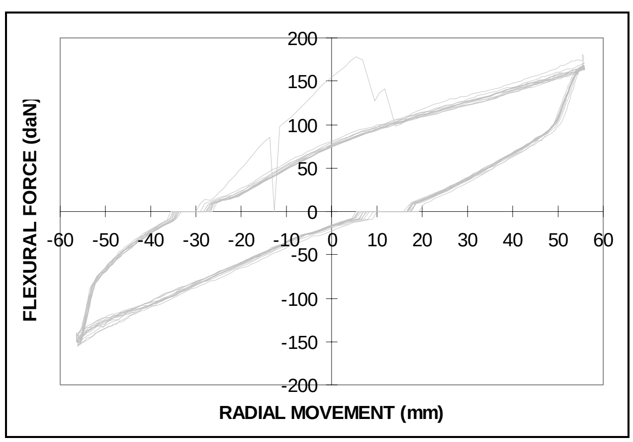

Figure 6 : Results of the flexural force at room temperature

The flexural rigidity B is derived from the formula :

$$B = \frac{F.L^3}{48.h}$$

Where :
F is the load applied.
L is the distance between supports.
h is the deflection of the cable.

Values of about 3200 daN.m² were found at room temperature, which corresponds to some values that can be found in the literature [8]

4 - 1 - 5 - Sidewall pressure test.

The lateral pressure at a bend can be calculated from the expression :

$$P = \frac{T.A}{R.C}.10^5$$

where :
P : lateral pressure (bars)
T : conductor thrust (Nm-2)
A : conductor area (m²)
C : conductor diameter (m)
R : radius of bend (m)

Permissible lateral pressure may be evaluated from a so-called sidewall pressure test.

The assembly consists essentially of a short length of cable core (150 mm) in which all but the outer layer of the conductor is replaced by a steel bar, the cable core being contained within a steel tube having an internal diameter equal to that of the cable at room temperature.
Axial expansion or deformation of the insulation is prevented by P.T.F.E. shims supported by metal plates.
Mechanical loading is applied to the conductor bar and its position relative to the steel tube measured.

If a limiting value of 10% of the insulation thickness is placed on the permissible conductor displacement for 225 - 275 kV of current design, the maximum allowable lateral pressure would be 14 bars at 90 °C, 5 bars at 105 °C.

With a normal minimum radius of 30 D where D is the cable diameter, it was found that up to 105 °C lateral conductor pressure does not impose a design limitation. [9]

4 - 2 - Shrinkage tests.

Several problems were encountered due to jacket shrinkage phenomenon.

In the French standards for HV and VHV cables, there are 2 shrinkage tests :
* a first one, performed on a short sample (about 250 mm) similar to IEC shrinkage test, as type and routine test.
* in addition, a second one, carried out on a long sample (approximately 5 m long), as type and sample test.

For the long sample test, a series of thermal cycles are performed, each comprising 6 hours heating (up to the overload temperature) and 6 hours cooling, until jacket and insulation shrinkages stabilize to within 1 % (or 0.1 mm corresponding to measurement accuracy). Heating is obtained from circulating current in the conductor.

The philosophy about shrinkage is the following :
* the manufacturer has to declare maximum values for both insulation and jacket.
* these values are checked during type testing.
* if the result of the long duration test is satisfactory, it is assumed that the design of accessories is correct for such values of the shrinkage.
* the purpose of routine and sample tests is to control that the amount of shrinkage remains similar.

4 - 3 - Long duration test.

To design this kind of test, several concerns have to be in mind :
* to deal with stresses during expansion and contraction phases, thermal cycles are necessary.
* to be representative of the normal temperature profile in the cable, heating of the cable has to be performed from conductor current.* the duration of the test has to be long enough to allow for shrinkage (which is a low-speed phenomenon) to fully develop.
* laying, fixing and bending of the cable in the test arrangement have to be designed according to the associated installation design conditions.
* accessories have to be installed to check the compatibility between cable and accessories designs and the correct design of joint chambers and terminations supports.

These features were considered when defining a long duration test, the purpose of which is not only to assess the dielectric long term performance of the system but also to demonstrate the efficiency of the solutions proposed to prevent the effects of thermo-mechanical stresses.

Test general specification.

The test is carried out on an experimental loop, approximately 200 m in length, incorporating 2 terminations and usually 4 joints (2 straight joints and 2 joints with screen interruption)

A voltage of 1.73 times the nominal voltage is applied on the main insulation and thermal cycles are carried out.

Installation
The test arrangement corresponds to the type of installation used in the system. (see figure 7)
* an ancillary loop is associated with the test loop. In this ancillary loop, using the same type of cable as the cable under test, a current equal to the current circulating in the test loop is induced. Such a way, the thermal environment is representative of effective installation. Moreover, this allows direct measurement of the temperature of the core (for the test loop, the core temperature has to be deduced from jacket temperature and circulation current).
* the cables are laid in a trefoil formation, at a depth of 1.3 m, partly in troughs and partly in ducts.
* the joints are installed in 2 system type joint chambers.

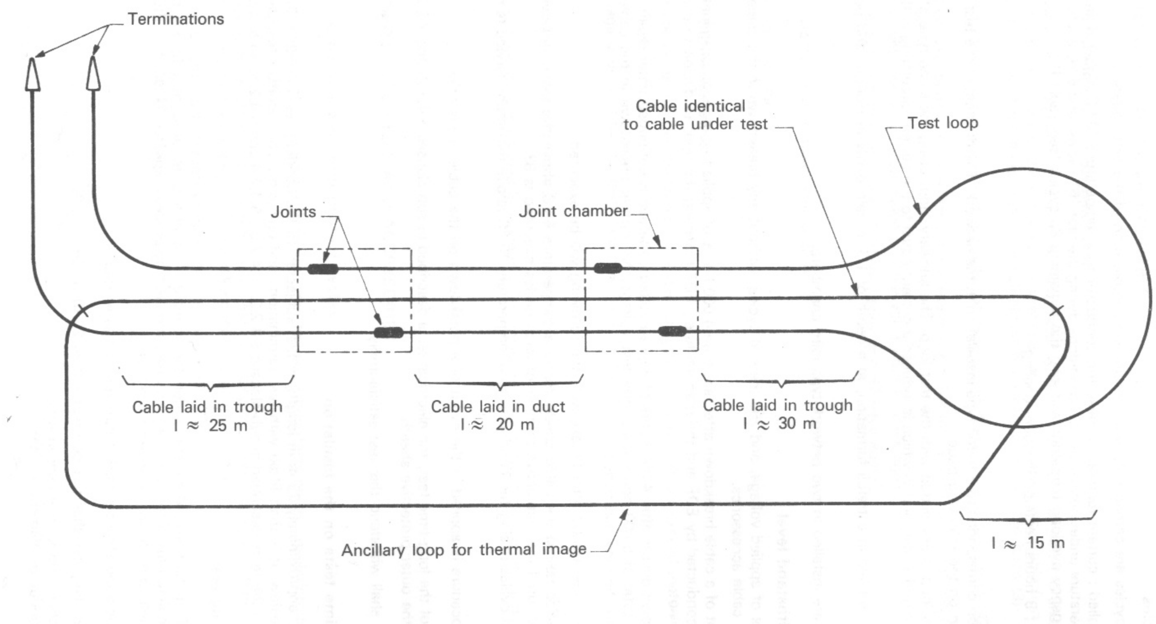

Figure 7 : Installation for long duration test

Thermal cycles.
250 thermal cycles are carried out with simultaneous application of the test voltage :
* the current applied is the current required to raise the conductor to a temperature 10 °C greater than maximum temperature under normal service conditions during the first 167 cycles and 5°C above maximum emergency overload temperature during the remaining 83 cycles,
* cycle time : 8 hours heating, 16 hours cooling.

Required withstand level.
* 6000 hours of applied voltage and 250 thermal cycles without any breakdown in the cable or in one of the cable accessories
* In the event of a cable breakdown, after less than 4000 hours of applied voltage, an examination is conjointly conducted by EDF and the manufacturer, EDF reserving the right to decide to continue the test or not.
* If a breakdown occurs after 4000 hours of applied voltage, the test is continued up to a cumulative total of 9000 hours under test voltage. No further breakdown shall occur during the new test period

During the new test period after breakdown, the following will be executed :
* thermal cycles raising the cable conductor to a temperature 5°C above the maximum overload temperature, until the cumulative number of such cycles is 83.
* 124 thermal cycles raising the conductor to a temperature 10°C above maximum service temperature.

The same procedure is applied in the event of a breakdown on the cable accessories.

Experience.

The experience gained with long duration tests may be illustrated by different examples :

* shrinkages of outer covering lead to the loss of water-tightness of terminations and joints (a shrinkage of 20 cm was noticed on the HDPE outer covering of a 225 kV cable).

* in some cases, joint breakdowns occurred. They affected joints located between a section where XLPE cables were laid in troughs and a section where they were laid in ducts.

To prevent the shrinkage of the jacket, an anchoring of the jacket to the joint protection has been engineered . A special device was designed, composed of aluminium sheets with rough spots (like a cheese grater), solidly connected to the jacket with rings. The numerous small rough spots penetrate into the jacket and allow anchoring of the embedding water-tight compound. Previously due to the shrinkage of the sheath (on the side where cables were laid in ducts and therefore were relatively free to move), the joint protection moved following the jacket shrink back. This produced excessive stresses on the insulation tapes.

* Dangerous buckling of cables and movements of joints were observed when the joints were not solidly bonded to a frame fixed in the ground of joint chamber.

* A 225 kV cable breakdown occurred due to overheating of the cable (core temperature larger than 130 °C) : the breakdown was located in a curve and a displacement of the core within the insulation was observed.

5 - RECOMMENDATIONS.

In the system, there is no experience of thermomechanical problem.

This may mean that the installation is properly designed to deal with themomechanical stresses.

But it is to be kept in mind that thermomechanical stresses in the system are generally much lower than during long duration test : this is due to the fact that cables are sized for an ampacity which is reached only a long time after installation and that, generally, full loading is observed only in case of problem in the system, links being normally operated at lower levels to make possible to ensure energy transmission even in case of a fault occurring on at least one element in the system

According to test and operating experience, following recommendations may be derived :

* shrinkage of both insulation and sheath has to be controlled.

* the permissible bending radius R is related to the cable overall diameter D according to : $R \geq 30.D$

* the joints have to be solidly bonded to a frame fixed in the ground of joint chamber to prevent from dangerous buckling of cables and movements of joints.

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PART 3

DESIGN OF CABLES AND ACCESSORIES

1 . INTRODUCTION.

In 1987, the CIGRE working group 21.09 carried out a detailed analysis on working electrical gradients adopted around the world for various types of extruded cables.[1]

The electrical gradients at power frequency are closely linked to the voltage level of the networks, ranging from 4 kV/mm for 33/66 kV cables up to 15 kV/mm for 400/500 kV cables.

This increase in gradient in relation to the network voltage obviously results from the need to limit the diameter of cables to take into account the production machinery's capabilities, to reduce the cost of materials and to facilitate handling of cables.

Some concerns to deal with when sizing cables' insulation are pointed out, such as the construction of cables (for instance whether or not a watertight metal sheath is used to protect against the penetration of water) or the type of jointing techniques in use.

The ability to withstand the specified lightning impulse test is also a limiting factor : as for a.c., the impulse stress value increases with the network voltage from about 30 kV/mm for 45 kV cables to about 90 kV/mm for 400 kV cables.

For a given voltage level, the main factors which may limit the increase in operating stresses are the following ones :
* need in higher quality materials and stricter quality control procedures, possible higher breakdown rate in routine tests, which have a negative effect on the production cost.
* need for accessories offering better performances, but also more expensive.
* operating costs, linked to the cost of dielectric losses (a reduction in the insulation thickness leads to an increase in the cables capacitance and consequently of the dielectric losses) and to the expected failure rate in operation.

The working group states that, from the economic point of view, there appears to be an optimum insulation thickness and hence an optimum electrical gradient for each voltage level but it is very difficult to established an optimized design because the different factors will vary from case to case.

This part is split up into 4 paragraphs.
* specification of maximum operating electrical gradients in connection with the expected failure rate in operation.
* design criteria for lightning impulse stresses.
* influence of the technology of accessories.
* economical considerations.

2 . CABLE DESIGN WITH RESPECT OF A.C. STRESS.

2 . 1 . Principle.

The basic formula used to describe the breakdown statistics of cables, stated in part 1, may be re-written on the following more general form [2] :

$$P(t) = 1 - \exp\left[-\left(\frac{t}{t_0}\right)^a \left(\frac{G}{G_0}\right)^b \frac{L.r_1^2}{L_0.r_{10}^2} . \frac{\left[1-\left(\frac{r_1}{r_2}\right)^{b-2}\right]}{\left[1-\left(\frac{r_{10}}{r_{20}}\right)^{b-2}\right]} \right] \qquad (1)$$

where :

* p (t) is the cumulative probability of breakdown at time t, under a stress G, of a cable length L ; r_1 and r_2 being respectively the inner and outer radius of the insulation

* a and b are time and stress shape parameter of the Weibull's law.

* G_o is the stress in operation corresponding to a given fault rate in operation (1 breakdown at time t_0 on a length L_0 of a reference cable, with r_1 and r_2 respectively as inner and outer radius of the insulation).

When testing samples of a given cable with given length L_t and assuming a given time to breakdown tt, the nominal breakdown stress G_n - corresponding to a probability of breakdown of 63,2 % - which is determined from these tests fulfills the condition :

$$\left(\frac{t_t}{t_0}\right)^a \left(\frac{G_n}{G_0}\right)^b \frac{L_t}{L_0} = 1 \qquad (2)$$

Therefore, the allowable stress in operation may be derived from the measured nominal breakdown stress G_n. [3]

Unfortunately, it is not possible to perform a direct determination of G_n since, practically, the time to breakdown cannot be imposed.
G_n has to be estimated from a.c . breakdown tests leading to various breakdown stresses and times to breakdown.

The method usually applied to achieve this work is described in the following.

2 . 2 . Determination of a the nominal breakdown stress.

A.c. breakdown tests are carried out, using a step by step voltage rise (typically starting from a stress of 20 kV/mm and increasing in steps of 2,5 kV/mm every 10 min).

For each sample, the test result is expressed as an equivalent breakdown stress for a given time to breakdown.
This equivalent breakdown stress is derived according to the following procedure.

* first, the time to breakdown t_b for a constant stress equal to the breakdown stress G_m is deduced from the relationship :

$$G_m^b . t_b^a = \sum_{i=1}^{m} G_i^b . t_i^a$$

where G_i is the stress at step i and ti the duration of this step, or the time to breakdown (for the last step)

* then the breakdown stress G_b corresponding to a given time under voltage t_t is calculated as :

$$G_b^n . t_t = G_m^n . t_b$$

where : n=b/a

When tested samples have various lengths or conductor dimensions, corrective factors are introduced to get values relative to an identified reference sample.

$$G_r^b . L_r . r_r^2 . \left[1 - \left(\frac{r_{1r}}{r_{2r}} \right)^{b-2} \right] = G_k^b . L_k . r_k^2 . \left[1 - \left(\frac{r_{1k}}{r_{2k}} \right)^{b-2} \right]$$

where :

* G_k is the breakdown stress for a sample, L_k in length, with a conductor radius rk.
* G_r,L_r,r_r are corresponding items for a reference sample

From the relationship (2), the ratio of the nominal breakdown stress upon the allowable operation stress may be derived as :

$$\frac{G_n}{G_0} = \left(\frac{t_0}{t_t} \right)^{1/n} . \left(\frac{L_0}{L_t} \right)^{1/b}$$

2 . 3. Application.

Figure 1 is an example of such a curve.

Typical values of t0 and l0 are considered, leading to a fault rate of 0,2 fault per year and per 100 km 3-phase link :
* t_0 =8760 h
*L_0 =1 500 000 km

The length of samples is supposed to be 40 m and the time to breakdown is standardized as 1 h.

As the result of a.c. breakdown tests, the nominal breakdown stress was estimated around 54 kV/mm for a 1600 mm² 400 kV cable.

From the curve in figure 1, the allowable operating stress is given in Table 1, depending of the values of Weibull parameters. The first case corresponds to the values of Weibull parameters (b = 12 - n =17 - a = 0,7) usually considered by EDF. [4]

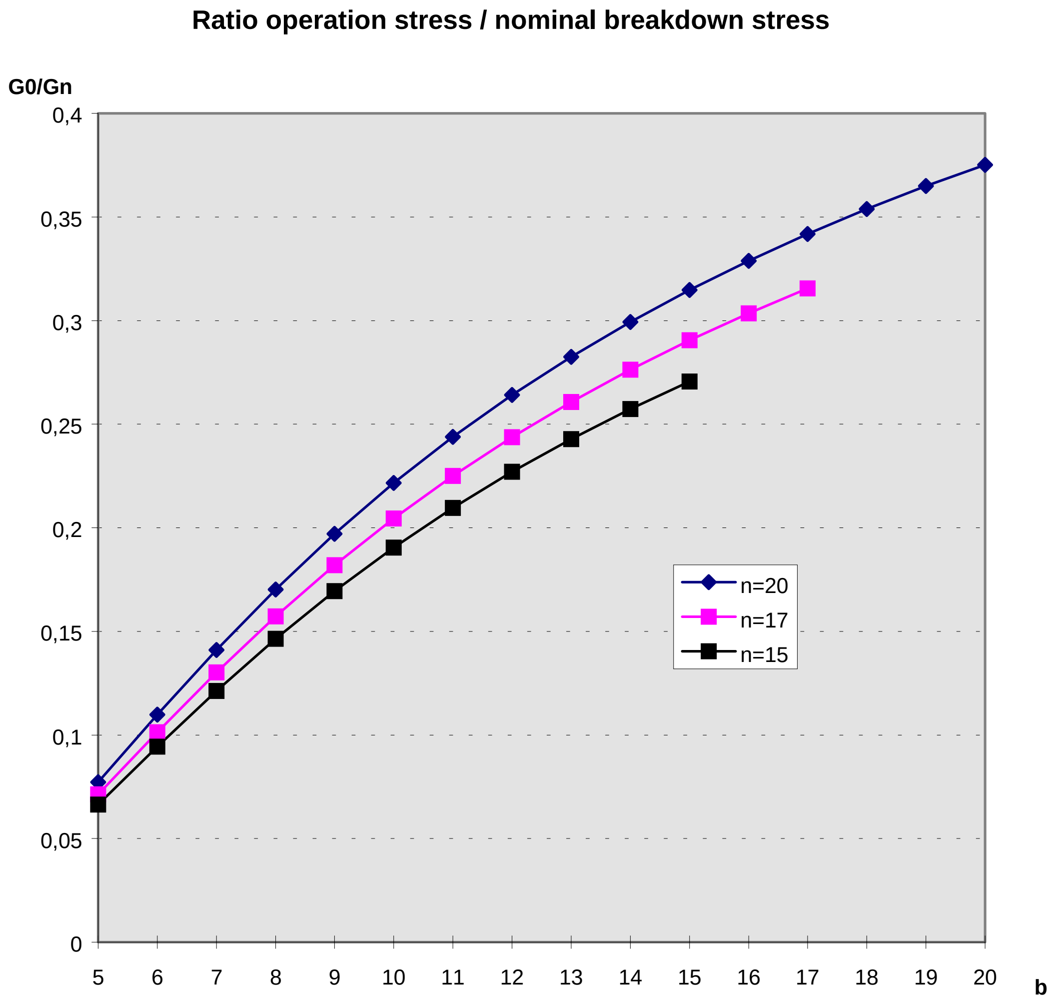

Figure 1 : ratio of the allowable operation stress upon the nominal breakdown stress

Operating stress for typical values of Weibull parameters			
Weibull parameters	b = 12 - n =17 - a = 0,7	b = 16 - n =20 - a = 0,8	b = 15 - n =15 - a = 1
Operating stress	13,1	17,7	14,5

Table 1 : Operating stress for typical values of Weibull parameters

Below (figure 2) are given the results of test performed on many 400 kV XLPE cables, with copper conductor, cross-section being either 1200 mm² or 1600 mm².
The stresses indicated are the stresses applied during long duration tests or the maximum stresses for short duration tests with voltage ramp.
Generally, the test was stopped before breakdown.

As a matter of fact, the Weibull parameter n cannot be deduced from these values, but a minimum value can be estimated.

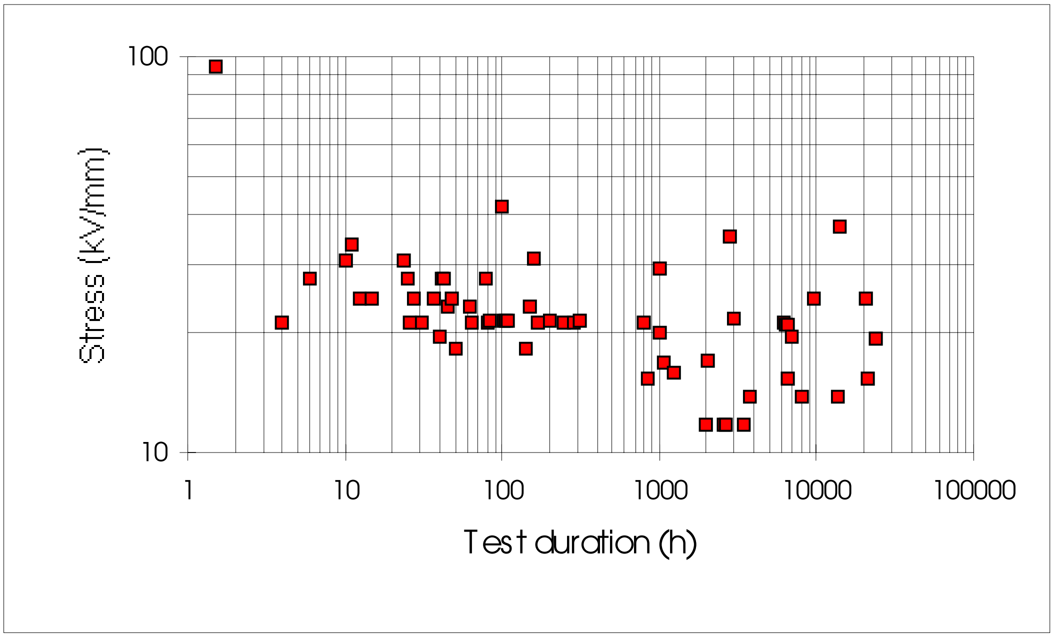

Figure 2 : a.c . withstand test results

3 . CABLE DESIGN WITH RESPECT OF IMPULSE STRESS.

There are a lot of discussions whether the design of cables should be based on the maximum or mean stress in the insulation to face lightning impulse constraints. [5]

Moreover, the value of the maximum stress to be considered may be fixed or depending on conductor size, according to Weibull statistics.

Design based on the mean stress

When the design is based on the mean stress in the insulation, the thickness t of the insulation is calculated from :

$$t = \frac{V}{E_m}$$

where :
* V is the impulse voltage supposed in the grid to be taken into account, depending on surge voltage limiters in use.
* Em is the withstand mean stress at impulse voltage.

Design based on the maximum stress

If the design is based on the maximum stress, then the insulation thickness is derived from :

$$t = r_1 . \left[Exp\left(\frac{V}{r_1 . E_i} \right) - 1 \right]$$

where :
* r_1 is the internal radius of the insulation.
* Ei is the withstand maximum stress at impulse voltage.

A fixed value of Ei is stated, supposed to be representative of the insulation material.

Design based on Weibull statistics.

In this case, the thickness of insulation ti is determined in the same way, but the maximum stress is depending on the inner radius of the insulation r1i.

$$t_i = r_{1i} . \left[Exp\left(\frac{V}{r_{1i} . E_i(r_{1i})} \right) - 1 \right]$$

According to Weibull statistics, to get the same breakdown probability of different cable sizes, the maximum stress to be taken into account depends on cable dimensions :

$$E_i(r_{1i}) = E_{i0} . \left(\frac{r_{10}^2 . h_0}{r_{1i}^2 . h_i} \right)^{1/b}$$

with :

$$h_i = 1 - \left(\frac{r_{1i}}{r_{1i} + t_i} \right)^{b-2}$$

where E_{i0} is the withstand maximum stress at impulse voltage of a reference cable (r_{10} being the internal radius of the insulation of this reference cable and t0 its insulation thickness)

Comparison of the 3 design methods.

The following figure presents a comparison of the three design methods.
*the 2 methods assuming fixed values of either the allowable mean stress or maximum stress.
* the method based on Weibull statistics and considering different values of the parameter b.

The insulation thickness to be specified is presented as a function of the conductor radius.

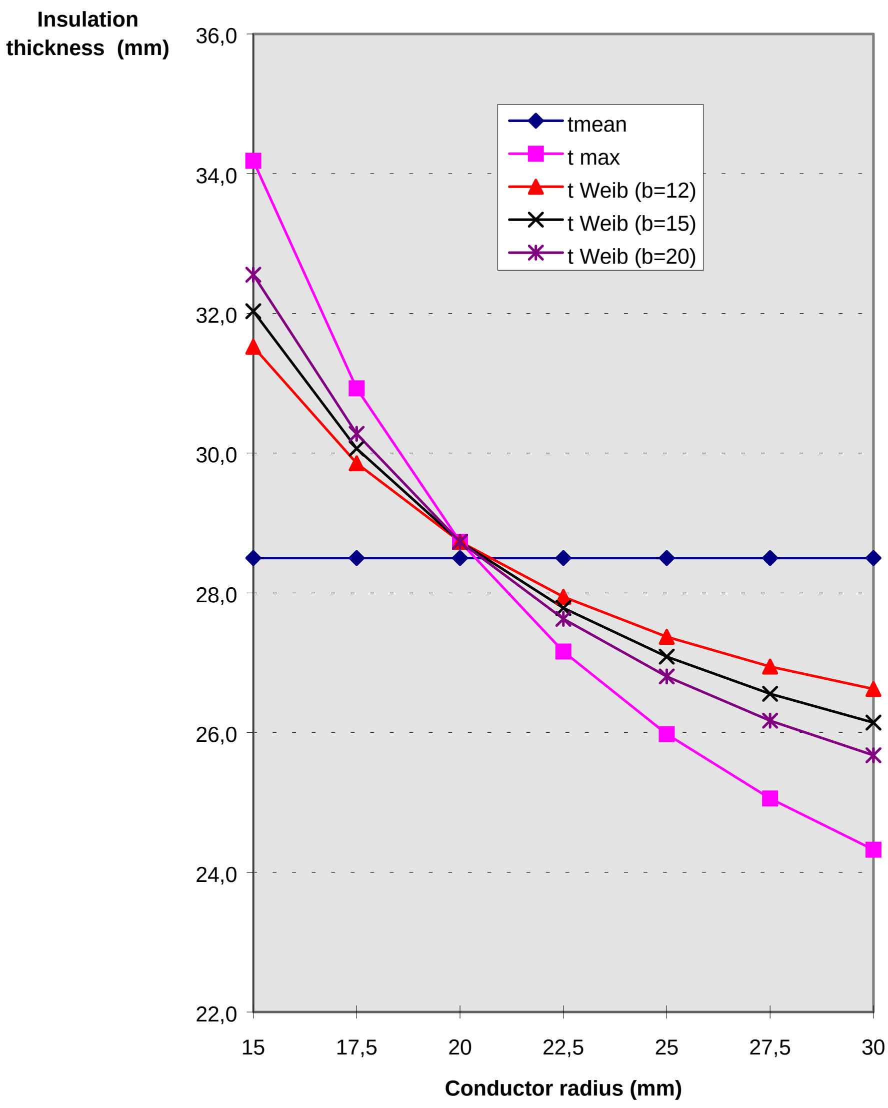

Figure 3 : Comparison of design methods.

The following values are assumed :
* protection level : 1425 kV
* mean stress : $E_m = 50$ kV/mm
* $E_{i0} = 80$ kV/mm for $r_{10} = 20$ mm

As the mean stress corresponding to a maximum stress of 80 kV/mm for the reference cable ($r_{10} = 20$ mm) is 49,6 kV/mm, the design is roughly the same as in the design based on a mean stress of 50 kV/mm.

Detailed analysis for various nominal voltages and core sizes show that, generally, significant differences do not appear among the three design approaches (only for extreme situations such as lower voltages - large conductors and higher voltages - smaller conductors).

The dimensions resulting from the statistical approach range between those obtained with the maximum and mean fixed stress designs, largely depending on the actual values of the parameter b.

Nevertheless, CIGRE working group considers that ,at impulse, extruded cables should be conceptually designed based on the maximum stress, using statistical approach.

4 . ACCESSORIES DESIGN.

4 . 1 . General

Some early failures were encountered on on-site molded terminations and joints, probably due to some contaminants introduced during molding, although a great care was given to the cleanliness of the process.

Some bad installations of taped joints also have been experienced.

According to many tests performed in EDF laboratories (including long duration tests), there seems to be a maximum outer gradient of 3,5 kV/mm for taped joints (CIGRE working group 21-09 indicates that taped joints limit the external gradient of cables around 3 kV/mm, while the on-site injection technique or prefabricated joints permit a value of around 5 kV/mm).

The introduction of pre-molded accessories is an effective progress in the achievement of higher reliability of underground links.
The "one piece pre-molded joint" has a dielectric block slipped over the cable insulation and is successively covered by a screen connection device and mechanical protection.

The dielectric performances of the joint, proven throughout long-term tests is supported by the concept of the block itself and by the interface between the cable and the joint insulation. [4]

The tangential stress is the main feature to be taken into account when designing the block profile. The reference to the radial stress on the insulation is not strictly correct when dealing with the withstand level of accessories, but it is a common and easier way to do since the determination of the tangential stress has to be computed. Moreover, generally, the block profiles from various manufacturers are not so different.
For a given profile, the withstanding of this interface is directly connected to the hoop pressure of the block on the insulation, which depends on the material used and on the manufacturing process.
In « simple » systems, the pre-molded block may be installed without special tools. For very high voltages, where high hoop pressures are needed, special devices are necessary to expand the block which on a pipe before installation.

4 . 2 . Influence of the hoop pressure.

The hoop pressure of the block on the insulation is the most important parameter concerning voltage withstanding of joints, as shown on figure 4 (this figure is the result of tests conducted to assess the performances of 400 kV pre-molded joints).

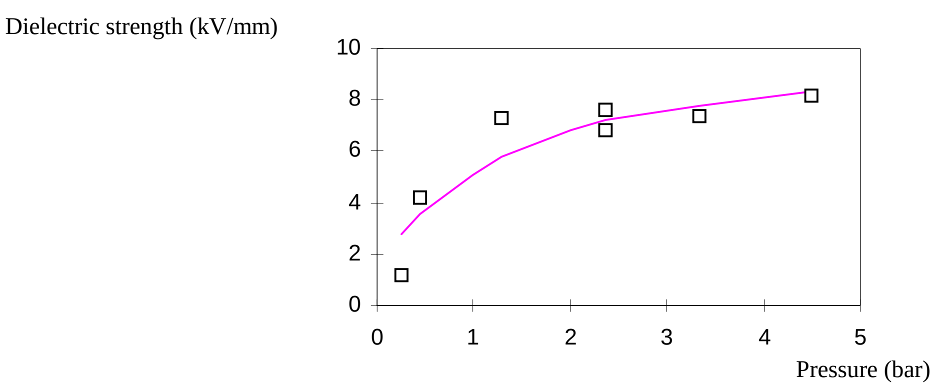

Figure 4 : Test on the dielectric strength of the interface (for given preparation and materials).

As the continous thermo-mechanical characteristics of the pre-molded block within thermal cycles are absolutely necessary to keep the pre-molded joints operating, the thermo-mechanical behavior of the joints has been investigated and compared to the predicted different behavior models. [6]

The most representative model regarding the trend of the pre-molded EPDM block properties, is the model of Thirion and Chasset as well from the point of view of the working hypothesis to the extend of adjustments to experimental points.

$$F(\lambda,t) = F(\lambda).\left(1+\left(\frac{\tau}{t}\right)^m\right)$$

where : F = hoop pressure λ = elongation τ = time constant t = duration m = characteristic exponent

The measures revealed a low influence of the elongation in the range of the experienced elongations The extrapolation (see figure 5) leading to prediction of values larger than 2 bars after 40 years validate the choices of the retained designs available for the development of pre-molded joints.

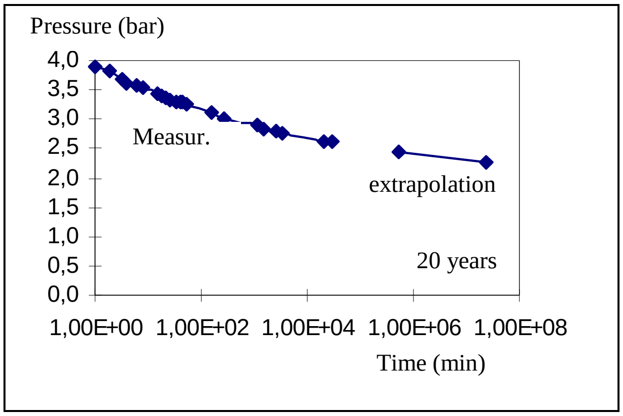

Figure 5 : Measurement and extrapolation, by means of Thirion and Chasset model, of the hoop pressure of the insulating interface on a period of 40 years, m = 0.1.

4 . 3 . Conclusion.

Figure 6 displays withstand tests results obtained on 400 kV joints (the stress indicated is the electrical stress on the conductor of cables, mainly 1600 mm²).

The result of the tests performed on pre-molded joints for HV and VHV systems is that a maximum outer gradient of about 7 kV/mm is possible for the 400 kV system. For 63 and 90 kV cables, the new issue of the French standard for HV cables recently published specifies a limit of outer gradient of 4 kV/mm.

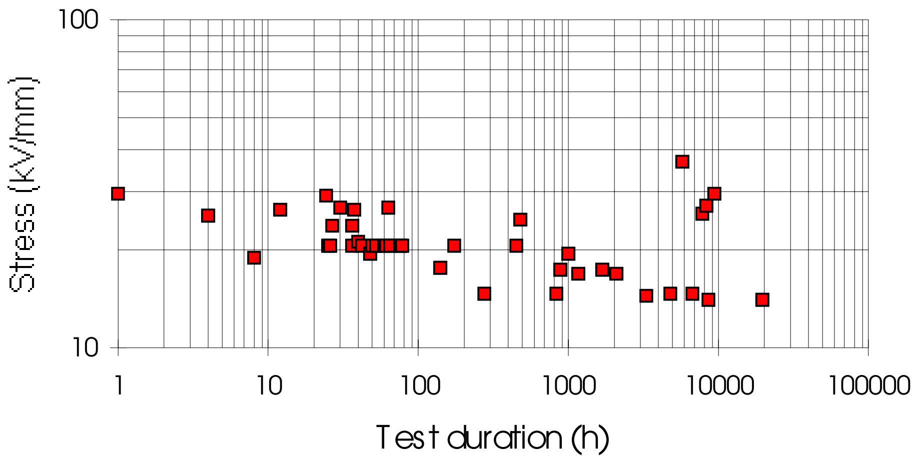

Figure 6 : joints a.c . withstand test results

5 . ECONOMICAL CONSIDERATIONS.

5 . 1 . Principles.

The thickness of the insulation affects both the cost and the reliability of cables.

Increasing insulation thickness increases the cost of cables (greater quantities of materials and more expensive production machinery being necessary) on one hand, but, on the other hand, leads to lower electrical stresses, and therefore, to a better reliability.

The effect of the reliability on the operating cost is not only due to repairing costs but, also, to the cost due to possible power supply outages.

Grids are normally designed to face a fault on one element of the grid, but, generally, they are not supposed to be able to face 2 simultaneous faults. In the case of underground links, repairing duration is generally much longer than for overhead lines, so that the probability of facing a fault on a transmission cable while one another is not available for repairing is not negligible.

If the global cost of a link is concerned, with increased insulation thickness, investment costs are higher but operating costs are lower.
So, there exists an optimum thickness of insulation which minimizes the global cost of underground links.

As it is possible to express the cost of cables and the reliability of underground links as functions of the wall thickness, the optimum thickness may be theoretically determined.

As a matter of fact, a general optimization is not really possible because the outage probability in case of simultaneous fault strongly depends on the grid structure.

Nevertheless, such calculations for identified situations allow to stress upon some interesting general trends.

5 . 2 . EDF studies

Studies performed by EDF some years ago (which are to be updated in next future) concerned a situation where, in every point, the power supply is supposed to be ensured by a single feeder, composed of 2 underground links.

The cost of underground links is approximated by : $C_i = \left[A.\left(e - e_0\right) + B\right].L + C$

* e is the insulation thickness of cables.
* e0 is the insulation thickness of a reference cable.
* A is the increase in cost related to the insulation thickness
* B is the cost of the reference cable par unit length.
* C is the cost of terminations.
* L is the length of the link.

The cost of outages is : $C_f = K.p.W$

* K being the cost of « not supplied » energy (which, in France is a function of the outage duration) .
* W being the « not supplied » energy due to outage (depending on the load to be supplied).
* p being the probability of 2 simultaneous faults :

$$p = \left(\frac{\tau.h.L}{8760} \right)^2$$

where :
* h is the mean duration (expressed in hours) of repairing.

* τ is the average fault rate (mean number of faults per year and per 100 km of 3-phase links) which may be found on the following form :

$$\tau \approx \frac{K}{\left[Ln\left(1 + \frac{e}{r_1} \right) \right]^b}$$

r1 being the inner radius of the insulation.

The influence of the insulation thickness is shown on the following figure 7.
The cost per unit length of the underground supply (arbitrary unit) is displayed as a function of the insulation thickness.
This study concerned 1200 mm² copper conductor LDPE 225 kV cables.
A fault rate of 0,2 fault per year and per 100 km of 3-phase link was assumed for a wall thickness of 22 mm.
The Weibull parameters were supposed to be a=1 and b=17,5.

5 . 3 . Main conclusions.

It is worth noting that :
* the total cost is increasing very rapidly when the insulation thickness decreases under the optimum value (due to the high cost of outages), while it increases rather slowly when the insulation thickness increases (due to the relatively low dependence of the cable cost on the wall thickness).
* the repairing duration has a very sensitive effect on the economics.
* for repairing durations of 300 h, the thickness in use is very close to the optimum thickness.

This situation was relative to economical parameters in force in 80’s but these general conclusions still remain valid for the today situation and XLPE cables.

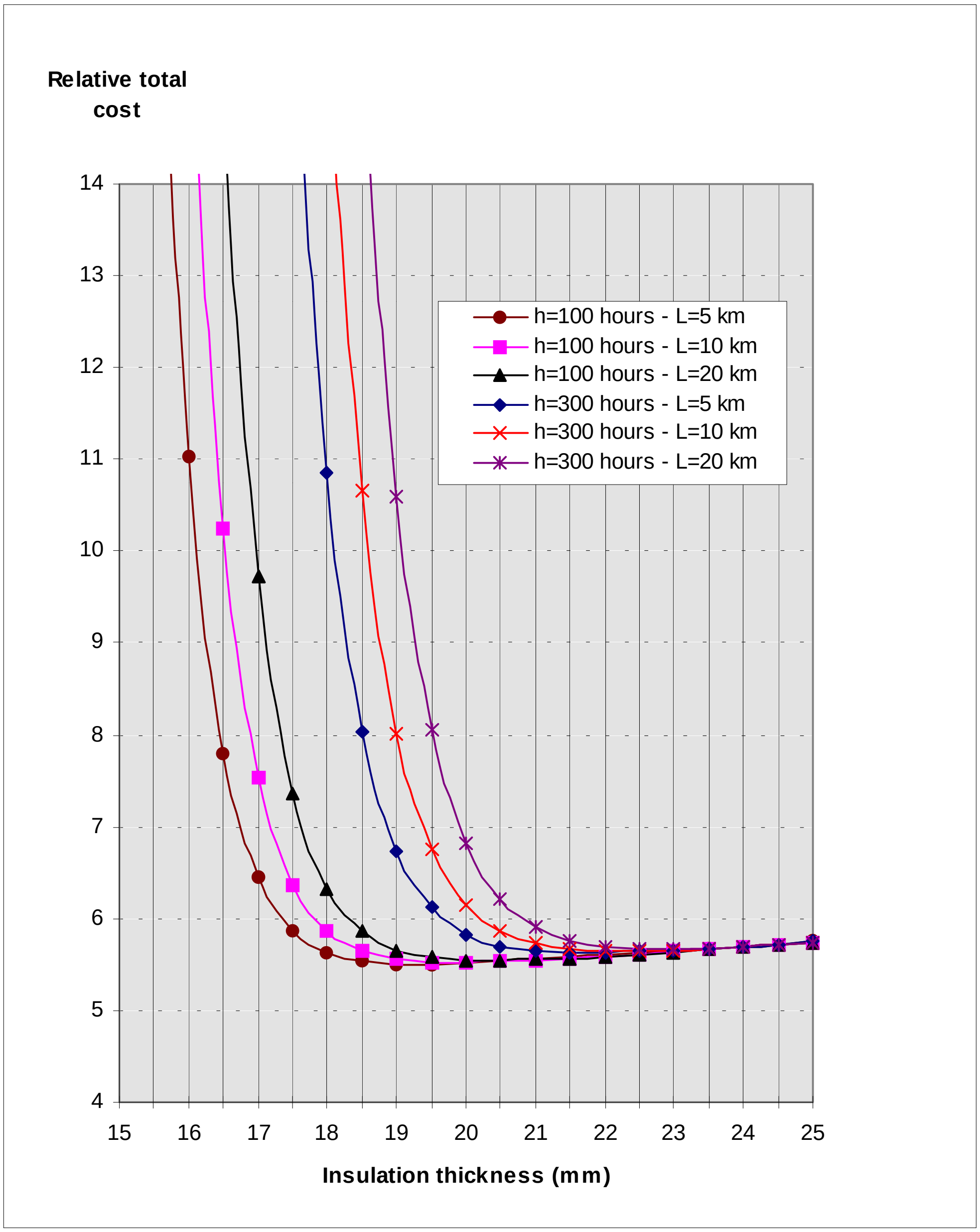

Figure 7 : Total cost of underground 225 kV transmission as a function of insulation thickness of cables.

6 . CONCLUSION

The satisfactory service experience gained with extruded dielectric cables, higher reliability of production technology and more comprehensive quality control performed during and after production resulted in a gradual increase in operating stress levels.

Recently developed prefabricated accessories allow factory testing and thanks to their ease of assembly limit the risk of jointing errors. This enables an increase of the allowable electric stress on the insulation which is a very sensitive parameter in the design of cables.

In France, an EDF standard for 63 - 90 kV has been established in 80s with a maximum gradient on the conductor of 6 kV/mm and over the insulation of 3 kV/mm leading to a reduction of insulation thickness of about 3 mm (from 17 to 14 mm for 90 kV). The new issue of this standard - recently published - specifies limits of inner and outer gradient of 7 and 4 kV/mm respectively. These new levels are acceptable with prefabricated accessories which are now in use.

For high voltage systems, the maximum stress over the insulation allowable for the accessories remains a limiting factor.
For the 225 kV system, a reduction of the insulation thickness from about 22 mm to 17 mm is foreseen in near future. The impulse withstand stress as the limiting factor will be a maximum value of 80 kV/mm.
For the 400 kV system, both the a.c. stress allowable for accessories and the impulse withstand level are limiting factors, as illustrated in the table below

Comparison of some designs				
Voltage level (kV)	90	225	400	
Impulse level (kVc)	450	1050	1425	
Insulation thickness (mm)	11	17	25	24,5
A.C. Inner electrical stress (kV/mm)	5.6	10.0	13.0	13.4
A.C Outer electrical stress (kV/mm)	**4.0**	6.0	6.7	**7.0**
Impulse Inner electrical stress (kVc/mm)	49	**80**	**80**	86

Table 2 : Comparison of some designs (1600 mm² cables)

Finding an optimum between production costs and operating costs may lead to the concept of economic stress levels, depending on the grid structures and energy costs. Obviously these parameters can be differing from one country to another.

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PART 4

1 . GENERAL

Both the grid service experience, from France and other countries, and laboratory tests demonstrate that the water-tightness of synthetic cables is an important feature to achieve high reliability of underground links.

The lead sheath is a proven and easily manufactured technology for metallic sheaths of cables, which has many advantages : the water tightness is perfectly ensured and the withstand to corrosion in the ground is quite good. The main drawback is due to the resulting weight of the cable, due to the high weight of lead.

Among alternative solutions, aluminum laminate screens were selected.

To design such a technology, many development tests were carried out, first for medium voltage cables, then for high and very high voltage cables.

To check the design quality, type tests were set up and are now part of cables French standards : mainly tests to control the mechanical performances of the complete cable and its ability to withstand mechanical damage, and a test to check the water-tightness and absence of corrosion over long service periods, even in aggressive soils.

This part is split up into parts :
* effect of water ingress in cables on their life expectancy, from the grid service experience and laboratory tests.
* design of laminate screens.
* type tests specific to laminate screens.

2 . EFFECT OF WATER INGRESS ON CABLES LIFE EXPECTANCY.

As already mentioned in Part 1, the service experience gained on the French grid demonstrates that the life expectancy of polyethylene insulated cables is significantly reduced in case of water ingress in the cable.

The dielectric withstand level of polymeric insulations is strongly affected by moisture : water degrades the organic insulating material under electrical stresses, which is called the water-treeing phenomenon..

The inception voltage and growth speed of water-trees, generally starting from contaminants or surface defects on the interface between insulation and semi-conductive layers, depend upon many parameters, such as electrical stress, temperature or frequency. According to field records water trees lead to the cable breakdown within a period of 5 to 20 years.

As a matter of fact, many breakdowns occurred on high voltage cables (63and 90 kV) without moisture barrier (copper tapes being used according to the specification in use between 1962 and 1967) but only very few breakdowns were recorded on cables with lead sheath.

Examinations of faulted cables pointed out the problem of water-treeing : some examples are reported in paragraph 2.1

From a.c. withstand tests performed by EDF, XLPE is shown to be less sensitive to water treeing than LDPE or HDPE. Nevertheless, even for XLPE, aging in presence of water leads to a decrease of the dielectric withstand level of the cables.

Consequently, in EDF, it is considered that a metallic water barrier is necessary whatever insulation materials are used in extruded dielectric cables.

2.1. Examinations of faulted cables (63 kV with copper tapes as metallic screen)

Over a period of 28 years (from 1974), about 130 breakdowns have been recorded in the French High Voltage grid, affecting 63 kV cables with copper tapes as metallic screen.

During examination of faulted cables, generally, water-trees are observed and high moisture level are measured both in the insulation and in the semi-conductive layers (measurements are carried out, using Karl Fischer method).
Typical value of insulation moisture content for new cables is 15 ppm ; on faulted cables values up to 1000 ppm may be measured.
The water penetration is due to diffusion through the PVC outer jacket.
In many cases, several breakdowns occurred on the same link.

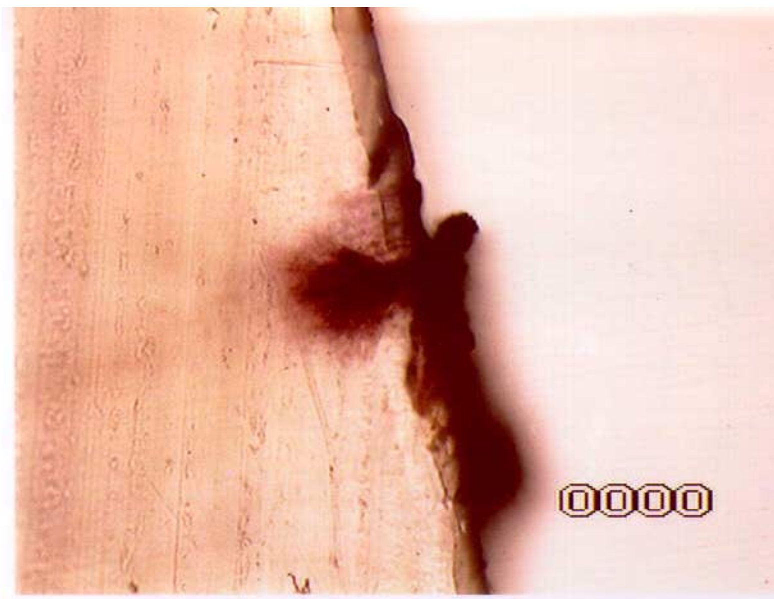
2.1.1. Example 1 - Landernau cable

3 successive breakdowns happened in the same link in Landernau (West in France) in 1993.
The cable - 400 mm² Al 63 kV LDPE insulated with copper tapes - has been manufactured in 1967.

Insulation wafers, 200 µm thick, were cut with a microtome at about 30 cm from the breakdown location.
Microscopic examination was performed with a magnification ranging from 80 to 150.

Many water-trees were detected, some of them up to 150 µm in length. In Figure 1, a water-tree can be observed, starting at the interface between the insulation and the outer semi-conductive layer and directed towards the conductor.

Figure 1 : water-tree in the insulation of a cable without water-tightness



2.1.2. Example 2 - Toulouse cable.

3 breakdowns occurred, in 1980, then 1985,and 1986 in a link feeding a HV/MV substation, near the town Toulouse (South of France).

The faulted cable - 63 kV 240 mm² Al LDPE insulated with screen copper tapes has been manufactured in 1965.

During examination of the faulted cables, oxidation of copper tapes was noticed.
Microscopic examination (magnifying power 80) was carried out on 100 µm thick insulation wafers. The wafers had been first stained in an iodine solution at 60 °C for at least one hour.
A lot of bow-tie trees were observed, sizes ranging from 30 to 60 µm, with a density of about 2/mm² close to the fault location.

2 . 2 . Tests on dielectric performances of XLPE insulation in the presence of water.

XLPE is less sensitive to water treeing than LDPE or HDPE.
Nevertheless, even for XLPE, aging in presence of water leads to a decrease of the dielectric withstand level of the cables. [1]

Many tests were carried out on a lot of samples, some of them with calibrated voids or contaminants (such as particles of polyethylene partly cross-linked before extrusion) or with defects of the interface between insulation and semi-conductive layers. Tree-retardant compounds were also investigated.

Test voltage level ranged from 2 times the nominal voltage up to 5 times.
Some tests were carried out at ambient temperature, some others with a temperature of 75 °C on the conductor and in some cases thermal cycles were performed.

The main test results are shown on the figure 2.

The general conclusions may be summed up as follows :
* the voltage withstand level of cables trends to decrease when aging in presence of moisture.
* the decrease rate is higher when contaminants or surface defects affect the insulation.

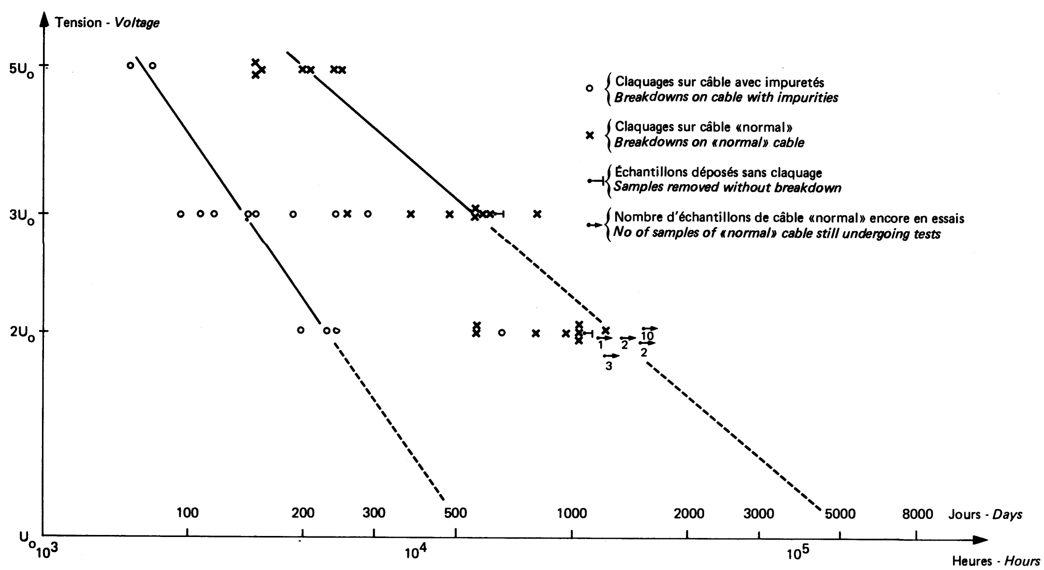


Figure 2 : Lifetime of cables with water in the conductor.

3 . DESIGN OF LAMINATE SCREENS.

During the seventies first attempts were made to find water-tight constructions for Medium Voltage cables as alternatives to the lead sheaths.

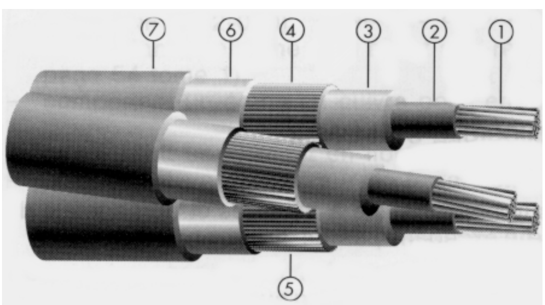
The experience gained with aluminum laminate for MV cables was very useful when considering, later, High Voltage cables.

3.1. Medium voltage cables screen design.

Up to seventies, the French Medium Voltage underground links used mass impregnated cables with a lead sheath. Today , they still represent about one third of the total installed length (around 570 000 km).

The cable now installed is a XLPE insulated cable with aluminum laminate screen, the 3 cores being twisted in one assembly (see figure 3).

This design results from many studies (about 30 options were tested) and tests carried out to ensure that the cable meets the EDF requirements [2] :
* cheaper.
* water-tight.
* light, to be adapted to mechanical laying .
* suitable for direct burying.
* allowing short bending radius.



1 - stranded core 95, 150 and 240 mm²
2 - semi-conductive layer
3 - XLPE insulation
4 - strippable semi-conductive layer with grooves
5 - hygroscopic powder
6 - laminate aluminium 0.2 mm
7 - PVC outer jacket 3 mm

Figure 3 : MV Cable Design

A laminated aluminum foil bonded to a PVC outer jacket ensures the radial water-tightness of the cable.

The aluminum foil is 0.2 mm thick (to meet short-circuits requirements) and has a corrosion protective coating. The overlap is sealed with an adhesive.

The fault rate of MV XLPE cables due to intrinsic breakdown is very low and the tests performed on some lengths of cables, removed from the grid after about 15 years in operation, generally, do not indicate significant aging.

3.2. High and very high voltage cables screen design.

For High Voltage and Very High Voltage cables, the design is more or less the same as for Medium Voltage cables. Of course, due to higher short-circuit currents, the thickness of the laminate foil has to be thicker.

In the nineties, a new type of high voltage cable has been defined according to French Standard NFC 33-252 in order to reduce the cables weight and consequently facilitate their installation and reduce their cost. [3]

Two major directions have been developed [4] :
- increase of the operating electrical gradients (see Part 3)
- weight reduction.

The replacement of the lead sheath with an aluminum laminate satisfies this request. This choice requires that the design of the screen/sheath complex is conducted in a global manner, to take into account:

- the electrical constraints (Icc=10.3 kA - t=1.7s),
- the mechanical constraints,
- the constraints linked to resistance to corrosion,

imposed by the standard, while integrating techno-economic, thermo-mechanical constraints, implementation constraints, and compatibility with the accessories.

The technological solution chosen (see Figure 4) is the longitudinal application of a 0.5-0.7 mm thick aluminum tape adhering to the outer jacket to avoid any risk of corrosion. The application of an adhesive in the overlap ensures water-tightness of the aluminum screen.

With this technological choice, the expansion of the insulation during heating and cooling cycles must be taken into consideration. Indeed, for an insulation thickness of 11 mm, the increase of the insulation diameter is on the order of 2 mm when the temperature rises from 20°C to 90°C.

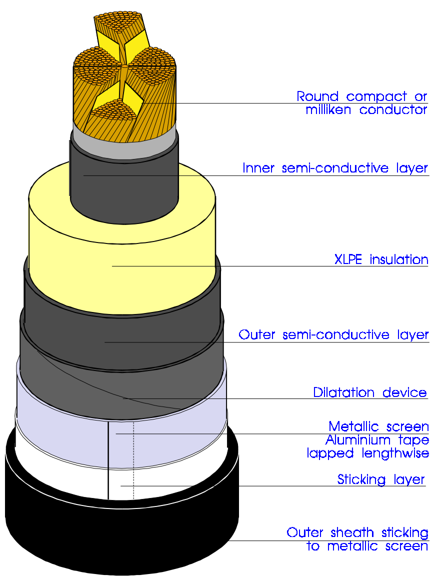


Figure 4 : New technical step of 90 kV cable

This technology using a laminate foil adhering to the external sheath has technical advantages towards the technology using a thick corrugated sheath : the eddy current losses and the internal thermal resistance are lower. The carrying capacity is significantly higher. This is confirmed by different test results presented in JICABLE [5].
Technologies with a copper screen were not considered because these solutions were too expensive.

Development tests have been carried out on prototypes with various designs of the laminate screen, mainly to select suitable adhesives and to determine the jacket material and the jacket thickness.

This new technology, validated by the tests of the NFC 33-252 standard, allows today a reduction in cable weight of up to 50%, and a decrease in the external diameters of the order of 5 mm. This opens the possibility to deliver unit lengths twice as long to installation sites, and therefore to better profit from mechanized laying and to reduce the number of joints.

For 400 kV cables, some designs use aluminum or copper wires, under the aluminum laminate foil to meet short-circuit requirements.
As thicker foils are used, welding processes are possible, possibly without overlapping,.

3.3. Integration of moisture barrier in accessories

The radial water-tightness of joints is provided either by the use of a metallic tube covered with heat shrinkable sheaths or by self amalgamating mastic tapes and adhesive aluminum tapes which are integrated in the outer protection of the joint.

The longitudinal water-tightness of joints is provided by self amalgamating mastic tapes, set at the interruption of the metallic screen of the cable.

A technique to connect the aluminum laminate to ground consists of a metal clip clamped between the bottom and top of the composite aluminum laminate jacket. The bottom half provides the electric contact to the aluminum while the top part is necessary to exert the mechanical force. The ground connection is bolted to the bottom half of the clamp.

4 . TESTS OF LAMINATE SCREENS.

Many development tests were carried out to design laminate screens and to check their performances.

Today, EDF standards include specific tests to be performed as type tests on cables with laminate screens, to check the mechanical performances and the thermo-mechanical behavior of the cables, and to demonstrate long-term water-tightness of the construction.

In the following these tests are presented and some results are displayed.

These tests are described in French standards NFC 33-252 and C 33-253. [6]

4.1 Mechanical tests

Tests shall be undertaken at an ambient temperature of 20 (± 5) °C.

4 . 1 . 1 . Impact test .

a) Principle

The impact test shall be performed using a weighted metal wedge falling onto a cable sample at least 1 m in length. The cable is installed on a rigid metallic base (see Figure 5).

The 90° wedge shall have a 1 mm radius of curvature at the point of impact and its axis shall be perpendicular to that of the cable.

The test apparatus is shown hereafter.

b) Definition of the impact

- total mass of the assembly :	(27 ± 1) kg
- falling height :	(27 ± 1) cm

c) Test

Series of impacts are performed along the sample : one impact at point Al, two impacts at point A2, and four impacts at point A4.

For longitudinally applied tape screens (laminates) or for longitudinally welded aluminum sheaths, the impacts are performed on the screen overlap, or on the welding of the sheath (impacts A), and on the opposed line (impacts B). For lead sheaths, the impacts are performed on one line only.

On one line, the distance between two impacts shall be 150 mm. On the two opposite lines, the impacts are staggered by 75 mm (see Figure 6).

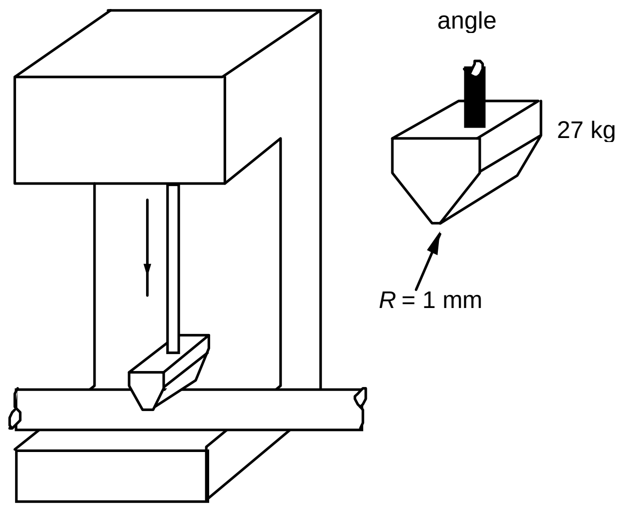


Figure 5 : Impact test

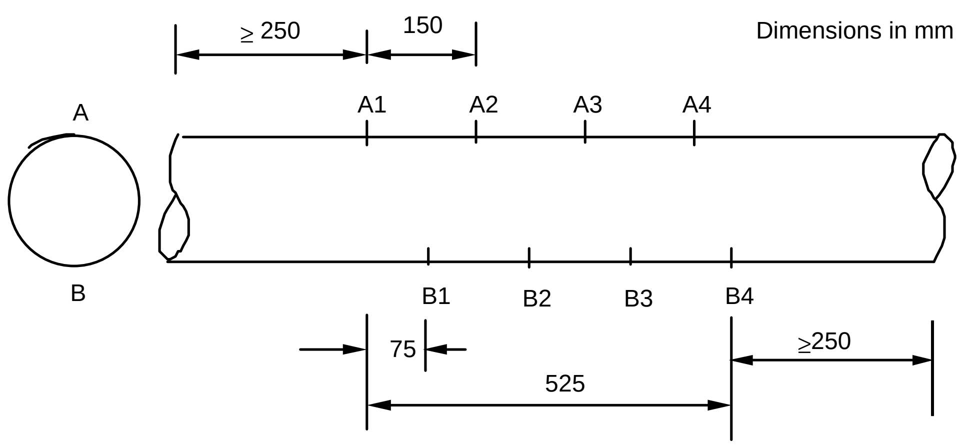
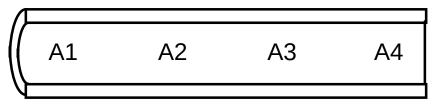


Figure 6 : Impact positions

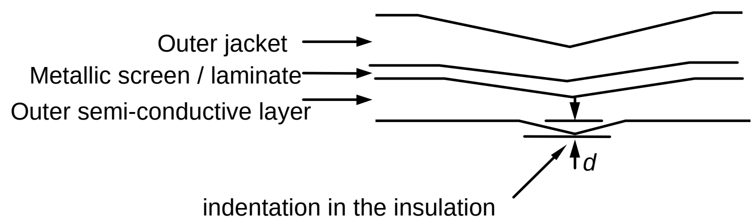
d) Requirements

After completion of the impacts, the sample is then cut longitudinally along two opposite lines, perpendicularly to the impacts. The internal face of the screen or jacket is then visually inspected at the places of impact (see figure 7 a) :

- there shall be no puncture of the metallic screen/jacket at points Ai and Bi ;
- the deformation (d) of the insulation screen, measured on a longitudinal cut at impact points M and B4 shall not exceed 1 mm nor show any sharp indentation into the insulation (see figure 7b).



(7a)



(7b)

Figures 7 : Final Examination.

4.1.2 Abrasion test

The sample shall be installed firmly on a rigid metallic base.

A cone-shaped metal tool, with a 90° cone angle, a radius of curvature of 1 mm at the tip and a mass of (48 ± 2) kg shall be applied on the upper surface of the cable. The cone surface shall not have protrusions.
The cone shaped tool shall be dragged over the cable sample between marks A and B (see figure 8) at a constant speed.

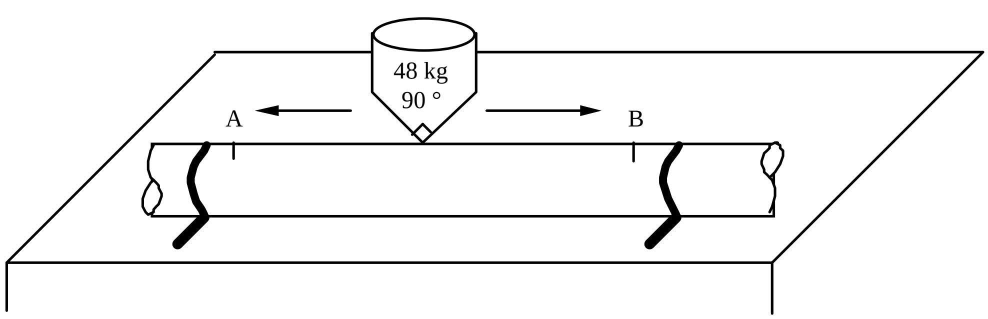


Figure 8 : Abrasion test - principle

Details of the test shall be as follows :

- distance between A and B : (50 ± 10) cm
- moving speed between A and B : 0,3 m/s (±15 %)
- the tool is passed over the cable 8 times (4 movements in each direction).

After completion of the test, the metallic screen/jacket between marks A and B shall not be visible when examined with normal or corrected vision without magnification.

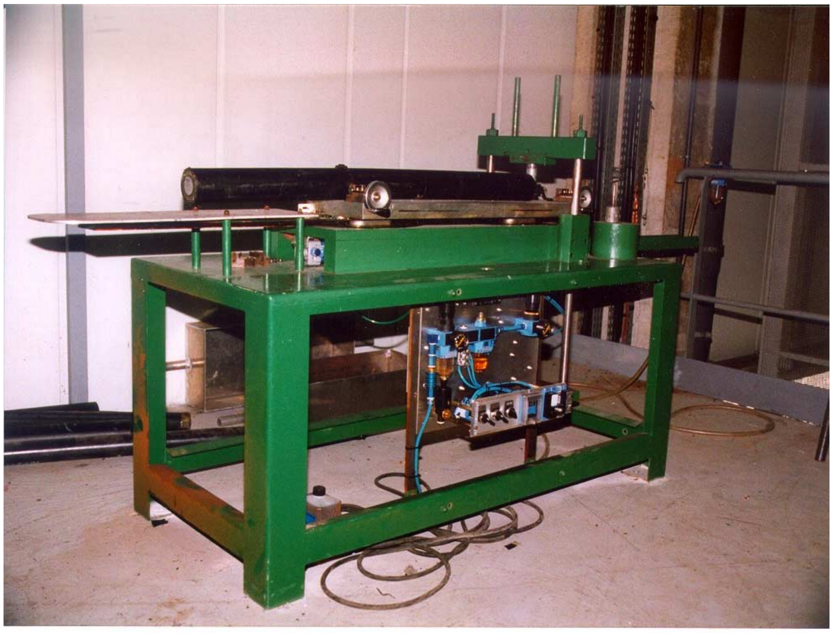


Figure 9 : Abrasion test apparatus

4.1.3 Bending test

The following bending test shall be carried out on a cable sample of at least 3 m in length.

The length shall be bent around a mandrel 25 $(D + d) \pm 5\ \%$ *in* diameter, D being the external cable diameter and d the conductor diameter. The length is then unwound, straightened and wound again around the mandrel after having first rotated the cable 180° around its longitudinal axis. This complete sequence shall be repeated three times.

After the test, the sample shall be submitted to a visual inspection. The components shall show no cracks, tears, punctures or discontinuities. In particular, the metallic screen/jacket shall show no annular wrinkles ; however, a few longitudinal wrinkles may be tolerated.

4.2 Short-circuit test

Two identical cable samples, whose length shall be at least 2 m, shall be submitted to the test, each sample being equipped with a screen tap at both ends.

Transient temperature measurements shall be made using devices that have a response time less than 200 ms (thin thermocouples, infrared camera, ...).

Depending on the type of insulation, the initial temperature of the cable metallic screen/jacket before each short-circuit shot shall be :

- (60 ± 5) °C for LDPE
- (70 ± 5) °C for HDPE
- (80 ± 5) °C for XLPE.

Each sample shall undergo five short-circuits.

- on the first sample, the screen/jacket temperatures shall be noted after each short-circuit, especially the temperature on the longitudinally applied metallic screen overlap (for laminated screens) and screen connections. The maximum temperature of the screen taps shall be less than that of the screen measured away from and on the overlap.

-on the second sample, a radial watertightness and corrosion test shali then be performed, as described in clause 4.3 below.

4 . 3 . Radial water-tightness and corrosion test

This test (see Figure 10) shall verify :
- the resistance to corrosion
- the cable longitudinal water-tightness following various stresses (mechanical, short-circuit ....).

The test shall be undertaken on three samples having first withstood :
- sample one, mechanical tests ;
- sample two, a short-circuit test ;
- sample three, a shrinkage test.

These tests are described below, in sub-clauses 4.3.1, 4.3.2 and 4.3.3 respectively.

4.3.1 Preliminary mechanical tests on the first sample

The sample is made of two test pieces, each of them consisting of a length of cable at least 1,5 m, on which the following tests are performed in sequence :

a) Bending test :
The sample is bent around a mandrel 25 (D + d) ± 5 % in diameter, where *D* is the external cable diameter and d the conductor diameter. The sample is then unwound, straightened and wound again around the mandrel after having first rotated the cable 180° around its longitudinal axis. This complete sequence shall be repeated three times.

b) Impact test :
The sequence of impacts is stated in sub-clause 4.1.1.
However, series of four impacts at 10 different places shall be carried on two opposite lines : five on one line, and five on the other.

c) Bending test :
As in a) above.

d) Abrasion test :
The test described in sub-clause 4.1.2 shall be undertaken along a line on the cable surface at 90° in relation to the lines used for the impact test in b) above.

On completion of the sequence of mechanical tests, one of the samples shall be submitted to a visual inspection. The components shall show no cracks, tears, punctures or discontinuities. In particular, the metallic screen/jacket shall show no annular wrinkles.

If the result of this inspection is satisfactory, the second sample is subjected to the radial water-tightness and corrosion test of sub-clause 4.3.4. Otherwise, the cable is deemed not complying with the requirements and the tests are stopped at this point.

4.3.2 Preliminary short-circuit test on the second sample

The second sample shall be one of the two samples which has undergone the short-circuit test defined in clause 4.2 and been put aside to undergo the water-tightness and corrosion test.

4.3.3 Preliminary shrinkage test on the third sample

The third sample consists of a cable length of 1.5 m taken on completion of the shrinkage test

4.3.4 Radial water-tightness and corrosion test

After undergoing the tests described in sub-clauses 4.3.1, 4.3.2 and 4.3.3 above, the three samples are subjected to a long-term immersion under the following conditions :

- NaCI concentration : 10 g/l
- Na2SO4 concentration : 10 g/1
- pH of solution to be adjusted by addition of NaOH : 8,5
- temperature of the solution : (80 ± 2)°C
- test duration : 3 000 h

Figure 10 : Photo of corrosion test

4.3.5 Requirements for the radial water-tightness and corrosion test

On completion of the test, a visual inspection is carried out on the three samples. Two longitudinal opposite cuts are made in the oversheath, perpendicular to the overlap for longitudinally applied tape screens (laminates) or to the welding for longitudinally welded sheaths.

No evidence of corrosion of the metallic screen/jacket, and no presence of water under the metallic screen/jacket shall be observed when the three samples are examined with normal or corrected vision, without magnification. The radial water-tightness of the cable shall be maintained.

When the screen is bonded to the oversheath (laminates), no loss of adhesion of these two components or at the overlap shall be noted.

4 . 4 . Aging test of metallic screen longitudinal overlap seal (for laminated shields)

The test shall be carried out on metallic screen samples as shown in the figure below :

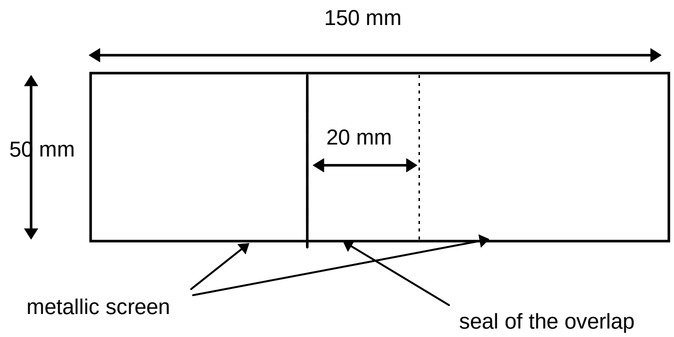


Figure 11 : overlap seal test

The seal shall have the same composition as that used on the cable on the longitudinal overlap.

The test is performed by tensile testing using a dynamometer (20 mm/min) at ambient temperature (20 ± 5)°C and measuring the shear force necessary to separate the two layers of the metallic screen.

Ten samples shall be tested :
- five unaged samples
- five samples aged in a dry oven at (100 ± 2) °C for 20 days. During the ageing phase, the samples shall be laid in a horizontal position.

The mean shear force shall be calculated from the five measurements.

The average shear force after ageing shall be at least 80 % of that in the unaged state. Should the metallic screen break outside the overlap, it shall be regarded as having passed the test.

4 . 5 . Long-term test

After completion of the long-term test, samples shall be taken from all parts of the test loop (between 5 and 10 samples) (including cable from bends and parts of the loop subjected to the highest mechanical or thermal stresses, from joints, etc.).

No evidence of corrosion of the metallic screen/jacket or trace of humidity under or on the screen/sheath shall be observed when examined with normal or corrected vision without magnification.

When the screen is bonded to the oversheath (laminates), no loss of adhesion of these two components or at the overlap shall be noted.

4 . 6 . Some results of development tests.

The examinations carried out on some prototype samples, after completion of the corrosion test, showed detachments between the outer jacket and the aluminum foil (see figure 12) or on the overlap (see figure 13).

After completion of the long duration test, some corrosion marks were observed on the aluminum foil, due to moisture migration through the outer jacket (see figure 14).

The results of such tests lead to improvements in the bonding between the aluminum foil and the outer jacket and on the overlap.


Figure 12 : Detachment screen / outer jacket

Figure 13 : Overlap detachment

Figure 14 : Screen Corrosion

4 . 7 . Conclusion

Developments tests revealed that many efforts have to be made to reach a satisfactory design and select reliable manufacturing processes.

So, there is a need for specific tests to check the performances of laminate screens.

CIGRE Working Group 21-14 published some guidelines which are in accordance with the EDF practice. [7]

Type tests performed by EDF - including long duration tests with thermo-mechanical stresses - and EDF's service experience provided cables with reliable metal-laminate jackets.
One hundred circuit kilometers of three-phase of 90 kV cable (with aluminum laminate sheath) have been installed now on the French grid with satisfactory performance.

5. RECOMMENDATIONS

The service experience, gained from the French grid operations, demonstrates that extruded cable designs with a metallic water-tight barrier achieve high reliability of underground links.

Many failures were encountered with HV LDPE and MV XLPE cables without water-tight barrier (with copper tapes), due to the water-treeing phenomenon.

Screen designs using laminate aluminum foils are an interesting alternative to conventional lead sheath.
They lead to lighter weight cables and facilitate handling and installation (including mechanical laying).

To check the proper design of laminate screens, a sequence of specific type tests is necessary.

The various tests specified in the French standards (in accordance with international recommendations) make it possible to assess the satisfactory performance of cables facing different stresses when installed in the grid (mechanical shocks, thermo-mechanical constraints, short-circuit...).
Maybe the most important test is the water-tightness-corrosion test, the purpose of which is to check the effectiveness of the screen as moisture barrier for long term operation.

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