INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392 - I

SMR/169 - 10

WORKSHOP ON OPTICAL FIBER COMMUNICATION
(24 February - 21 March 1986)

OPTICAL CABLE DESIGN

presented by

C. TENCER
Pirelli S.A.
Companhia Industrial Brasileira
Av. Alexandre de Gusmao, 487
Santo Andre
Brazil

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1. OPTICAL CABLES

The use of optical fibres originated several modifications in the concepts used in the design and manufacturing of telecommunication cables. In metal conductor cables, the transmission properties were defined by the conductor and by the entire cable construction, besides being influenced by the insulating material used. However, due to the strength of the conductors, these cables were not much affected in their characteristics by the traction they were submitted to during manufacturing and installation.

The situation is different in the case of optical fibres: the transmission characteristics are intrinsic properties and their fragility is well known. Theirhigh sensitivity to mechanical stresses requires special efforts during the cable design and construction phases in order to assure the fibre a long life.

Studies were developed in order to know and evaluate the factors which may impair the good performance of the fibre, and based on this knowledge, a cable construction technology was created, to assure long useful life to the optical fibre after installation.

1.1 Some important concepts for the cable design

a) Sensitivity of the fibres to macrobends and microbends

The application of stress on the fibre introduces a considerable attenuation increase in case this stress causes a deformation along the fibre axis. This deformation is represented by bends of this axis, which may be classified as microbends and macrobends.
It may be said that although these phenomena are identical (microbends and macrobends), they will interfere differently in the cable design.

The macrobends, which cause part of the transmitted light energy to leave the fibre, cause local losses (punctual); they have curvature radii of a few millimeters. These losses occur due to the very small curvature radii.

This energy leaves the fibre, since part of the light impinging on the core-cladding interface has an angle larger than the limit propagation angle, and is thus transferred from the core to the cladding

and then lost. Theoretical studies result, for a quantitative evaluation of this problem, in formula (1):

$$\frac{\Delta P}{P} = C_1 e^{-C_2 R} \qquad (1)$$

where: $\frac{\Delta P}{P}$ is the power variation due to the microbend

C_1 and C_2 are constants which depend on the fibre type

R is the curvature radius

From the graph below we may see that a bend radius of about 60 mm, added to a safety margin, must be considered as a minimum limit for the cable design.

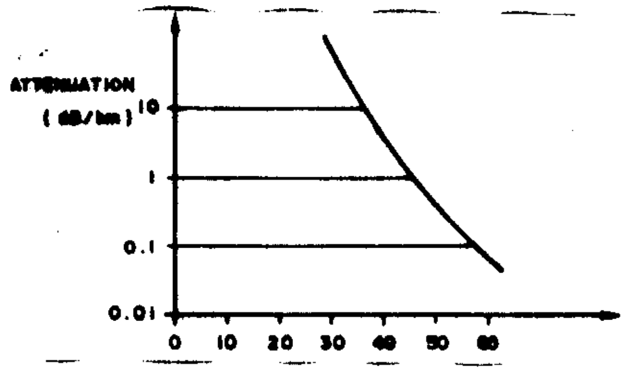


Fig. 7.1 - Attenuation increase as a function of the curvature radius

On the other hand, the microbend phenomenon, differently from the macrobends, is distributed and occurs when the fibre is submitted to a transverse pressure so as to compress it against a slightly rugged flat surface. These microbends "remove" light energy from the core due to the high order modes (external) becoming non-guided. Simultaneously, these modes are replaced by others due to the coupling among them, which, on their turn, are lost at the next bend.

The fibre susceptibility to losses caused by microbends is defined by equation (2):

$$\frac{\Delta P}{P} \alpha \frac{1}{(NA)^3} \quad \frac{D_n^{\ 4}}{D_c^{\ 4}} \qquad (2)$$

where: $\frac{\Delta P}{P}$ is the power variation due to the microbends

D_n is the core diameter

D_c is the cladding diameter

NA is the numerical aperture

Therefore, the losses due to microbends may be reduced with an increase of numerical aperture or a decrease of the ratio core dia./cladding dia. (D_n/D_c).

Since most of the fibres have a primary plastic resin protection, the above equation is then expanded considering this layer, and becomes:

$$\frac{\Delta P}{P} \alpha \frac{1}{(NA)^3} \cdot \frac{D_n}{D_c^{\ 4}} \cdot \frac{1}{D^2} \cdot \frac{E_R}{E_F} \qquad (3)$$

where: D is the outer diameter over the coating

E_R is the Young's modulus of the coating

E_F is the Young's modulus of the fibre

By analyzing the formula, we may note that the susceptibility to microbends may be reduced by using a soft coating (low Young's modulus). In the fibres produced nowadays, these materials are represented by acrylates and silicone rubbers, which are the primary coatings used most.

1.2 Fibre Mechanical Characteristics

The reliability of an optical system may depend partly on the fibre mechanical properties, i.e., on its mechanical strength and on its fatigue strength under different operation conditions. A summary of the most important characteristics affecting directly the cable design follows.

a) Mechanical Strength

The first impression we have regarding mechanical resistance of optical fibres is that they are extremely fragile.

This impression is soon changed if we consider the theoretical rupture value of a silicone fibre with 125 μm diameter over the cladding, which is of approximately 250N. It is true that in practice these values are not found due to the presence of microfissures at the fibre surface, which weaken its structure. Presently, in practice, values are obtained between 30 and 60N, such values tending to increase more due to the continuous evolution of the production methods. However, the level reached to date is more than sufficient for the manufacturing of mechanically reliable cables.

The analysis of the fibre rupture tests enables the obtention of a fault probability curve as a function of their distribution. A mathematical distribution of the curve is given by the following Weibull formula:

$$F(\sigma\ L) = 1 - \exp.\ (-L \times N(\sigma)) \qquad (4)$$

Where: $F(\sigma, L)$ is the accumulated probability of rupture of a fibre with length L when a stress σ or less is applied to it.

$N(\sigma)$ is the accumulated number of faults per length unit.

L is the sample length

The figure below enables to check the good adherence of this model to a practical distribution of rupture stresses.

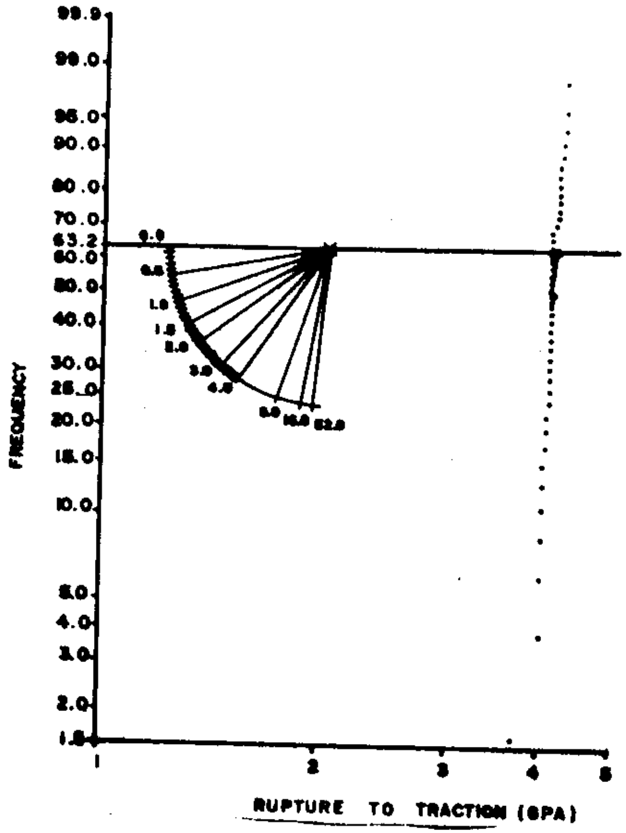


Fig. 7.2 - Rupture to traction of fibres with 50/125 microns

b) Ageing

The glass ageing caused by moist environments is the result of the propagation of surface fissures when a load is applied. The propagation of fissures also depends on temperature, accelerating rapidly at high temperatures and reducing with its decrease.

In order to check the influence of this phenomenon in the design of a cable, we may use the figure below as an example.

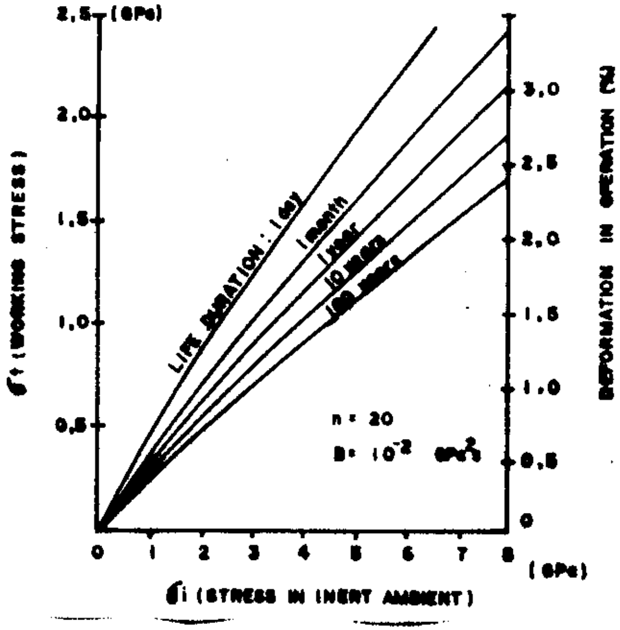


Fig. 7.3 - Life probability of the fibres X Operation stress

Figure 3 shows the relation between the operation stress (σ_t) and the rupture stress at an inert ambient (σ_i) for different life expectancies (Tv), using as an example the value of mechanical strength of a standard fibre.

In the graph, σ_i is the mechanical strength of the fibre total length, i.e., its worst value. For fibres with median quality, the value of σ_i for 1 km fibre will be of approximately one quarter of the value σ_i measured for 1 meter samples.

From the graph we may see that for values of σ_t lower than 20% of σ_i, the ageing effect may be disregarded. For our example, the ageing is negligible when operation is done with stresses not exceeding 5% of σ_i measured for samples with 1 meter length.

For fibres with σ_i = 40N the ageing effect is negligible for σ_t = 2N.

From the two items discussed before, the large importance of the cable design must be pointed out. Greatest care must be taken for the complete elimination of residual stresses in the cable, consequently obtaining a larger probability of a long service time for the cable, evidently considering the other factors influencing it as, e.g., the minimum curvature radii to which the fibre will be submitted.

1.3 Optical Cable Design

Although the optical fibre is initially protected by a primary coating, this does not normally have the required mechanical characteristics for the direct application of the fibre in the cable assembly. Therefore, it is necessary to protect the fibre with a secondary coating of extruded plastic material.

For this extruded plastic material, there are two different points of view:

- loose or non-adherent coating: in this type of structure, the fibre is not linked to the coating and thus the prior fibre characteristics are not changed if adequate techniques are used.

- tight or adherent coating: for this structure, the coating is applied directly on the fibre, thus forming a more compact structure which, however, is more susceptible to fibre attenuation variations due to the coating material behavior.

As seen before, in order to assure a high probability of long life for the optical cable, the fibre should not be submitted to high stresses.

For this purpose, tightener elements are used during the manufacturing of optical cables, aimed to absorb the mechanical stresses applied to the cable during the different installation phases. These elements are also very important in the cable manufacturing phases, assuring its dimensional stability.

In order to satisfactorily meet these requirements, the tightener elements should have the following main characteristics:

a) high Young's modulus

b) low weight per unit length

c) deformation stress higher than the one required for the cable

d) flexibility in order to assure good bending qualities to the cable.

A summary of the main mechanical characteristics of the materials meeting the above requirements is given in the following table:

Material	Specific gravity	Young's modulus (N/mm^2)	Yield stress (N/mm^2)	Elongation at yield (%)	Tensile strength (N/mm^2)	Elongation at rupture (%)
Steel wire	7.86	$20x10^4$	$4-15x10^2$	0,2 - 1	$5-30x10^2$	25 - 2
Nylon filaments	1.14	$0,6-1,3x10^4$	$8x10^2$	6	$10-15x10^2$	15 - 20
Terylene filaments	1.30	$0,6-1,3x10^4$	$6x10^2$	6	$10-15x10^2$	15 - 20
Kevlar 49 fibres	1.44	$13x10^4$	$30x10^2$	2	$30x10^2$	2
Kevlar 29 fibres	1.44	$6x10^4$	$7x10^2$	1,2	$30x10^2$	4
Glass fibre	2.48	$9x10^4$	$30x10^2$	-	$30x10^2$	3
Carbon fibres	1.5	$10-20x10^4$	$150-200x10^2$	-	$15-20x10^2$	15 - 1

1.4 Optical Cable Structures

Starting from the basic concepts, many cable types were developed. For a better analysis of the several types, this large family will be divided into two main groups: tight structures (adherent) and loose structures (non-adherent).

- Tight Structures

They are normally found in fibres protected by the adherent method and the cable assembly is done by bonding the fibres to the tightening elements. The most important structures are the following:

a) Tight stranded structures: in these structures, the fibres with primary coating (normally silicone rubber or acrylic resin) receive a secondary coating (normally Nylon) prior to being stranded over a tightening element in the form of groups or crowns.

The figure below shows two typical examples.

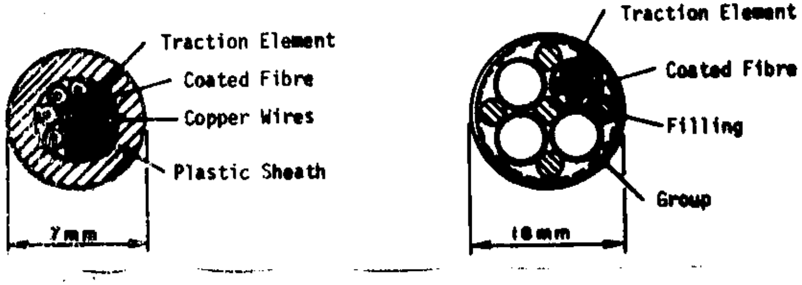


Fig. 7.4 - Examples of Tight Structures

b) Tight tape structures: these are structures where the fibres, only with primary coating, are assembled compactly in tapes. With this structure type, it is possible to increase considerably the fibre density in the cable. Fig. 7.5 shows a structure with 144 fibres, with 12 tapes, each containing 12 fibres.

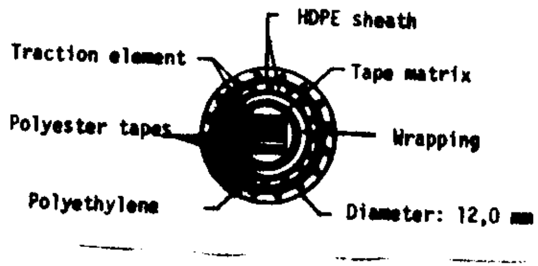


Fig. 7.5 - Tight Tape Structure

These structures have as main advantage their reduced dimensions, enabling the placement of a large number of fibres in small diameter cables. However, these cables present stricter requirements regarding the materials used, in order to avoid an increase of the fibre attenuation, besides not being very resistant to side compression.

- Loose Structures

These are normally formed by fibres protected adherently or not, and the cable assembly is done without bonding the fibres to the tightening elements.

a) Loose tubular structure: the fibres with primary coating are only placed within a plastic extruded tube and these tubes are then stranded around a central tightening element. Starting from this initial structure, other similar structures have appeared, using fibres with secondary coating placed in extruded plastic tubes or in metal tubes. In the case of metal tubes, these dispense with the use of additional tightening elements.
Fig. 7.6 shows several types of tubular structures.

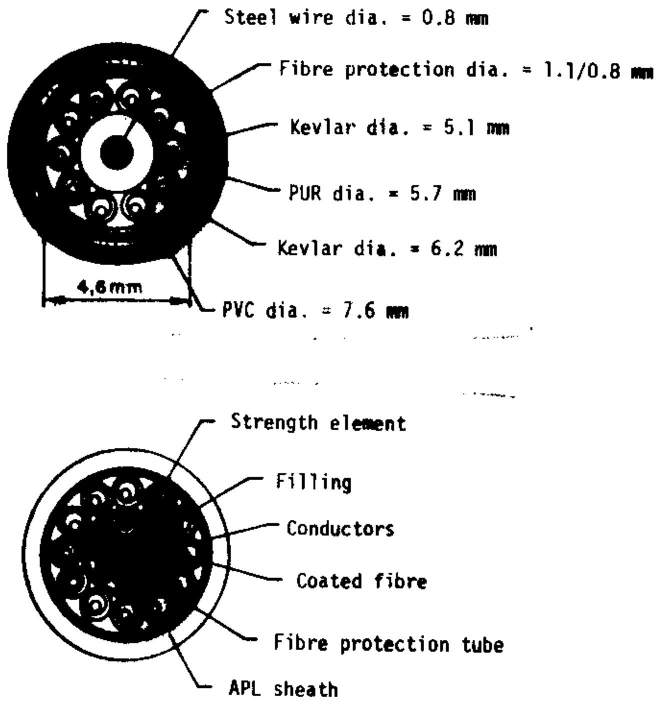
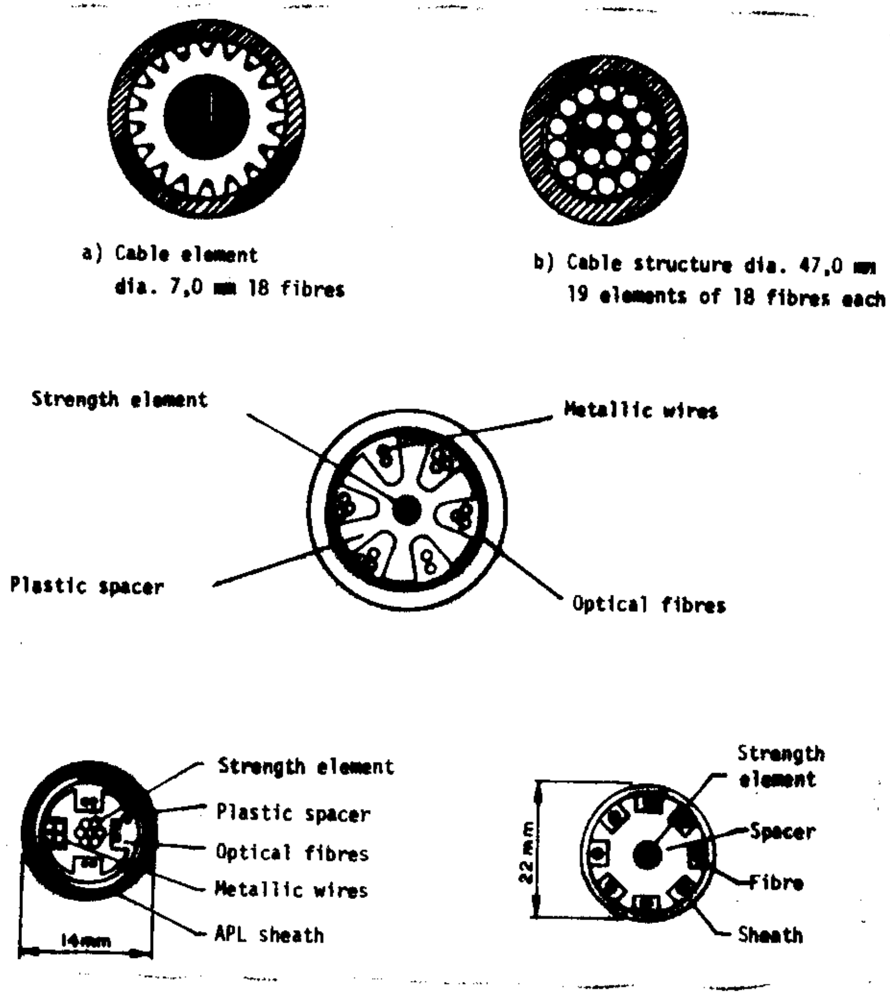


Fig. 7.6 - Loose tubular structures

b) <u>Star-shaped structure</u>: the cable base element is a grooved core in whose channels one or more fibres are deposited by the non-adherent method. The cable tightening element is normally placed at the center of the grooved core, which may be metallic or dielectric.



<u>Fig. 7.7</u> - Cables with star-shaped structure

c) Loose tape structure: this cable structure is similar to the one already described for adherent structures, i.e., the cable is composed of several tapes assembled and twisted together in order to form the cable core. The large difference is in the tape structure, which is not adherent to the fibre, forming a beehive, as shown in the example of Fig. 7.8.

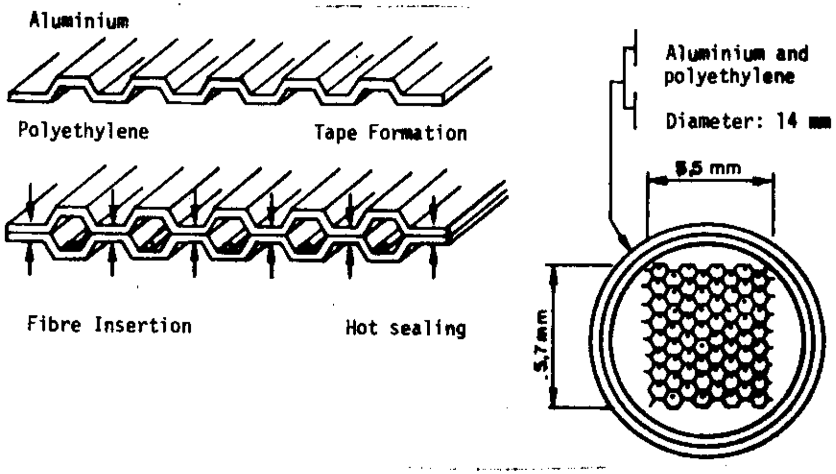


Fig. 7.8 - Example of loose tape structure

The loose structures result in less compact cables than the tight structures, however with other interesting advantages, such as non-bonding of the fibre to the cable structure and large strength to side stresses applied to the cable. The non-bonding of the fibre to the structure, and consequently to the tightening elements enables the cable to be installed with minimum load on the fibres.

1.5 Outer Protections

The large variety of foreseen applications justifies the attempt to develop appropriate structures with different types of sheaths.

Initially, two groups of sheaths may be identified: one for totally dielectric cables and the other for cables which allow the use of metallic protections.

The dielectric sheaths are normally made of plastics reinforced by synthetic threads with high elastic modulus and breaking load. The synthetic threads used most frequently are glass fibres and Kevlar. For cables which do not need to be totally dielectric, several metallic protections may be used. The most common solutions are the APL sheath, extruded aluminium sheath with plastic protection, steel tapes and plastic sheath, steel wire armour and plastic sheath, etc.

Therefore, the selection of the protection type to be used in a cable depends mainly on its core type and the installation conditions for which it is being sized.

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LEGENDAS DAS FIGURAS (cont.)

Fig. 7.6

1 Fibre protection dia. 1.1/0.8 mm
2 Steel wire dia. = 0.8 mm
3 Kevlar dia. = 5.1 mm
4 PUR dia. = 5.7 mm
5 Kevlar dia. = 6.2 mm
6 PVC dia. = 7.6 mm
7 DIA. 4.6 mm
8 Tightening element
9 Unit with 6 fibres,
10 Mechanical protection and
11 Tightening element
12 Filling
13 APL sheath
14 dia. 0.85 fibre + polyamide
15 *ao invés de Ø colocar* dia.
16 Aluminium dia. 20
17 Polyethylene dia. 22
18 Coated fibre
19 Tightening
20 Filling
21 Conductors
22 APL sheath
23 Fibre protection tube
24 Tightening element
25 Coated fibre
26 Wrapping
27 Metallic wires
28 Aluminium tube
29 Fibre protection tube
30 Tightening element
31 Plastic sheath
32 Corrugated metallic tube
33 Wrapping
34 Filling
35 Fibre group
35 Metallic tube

LEGENDAS DAS FIGURAS (cont.)

Fig. 7.7

1 a) Cable element
dia.: 7 mm 18 fibres
2 b) Cable structure dia. = 47 mm
19 elements of 18 fibres each
3 Tightening element
4 Metallic wires
5 Plastic spacer
6 Optical fibres
7 Tightening element
8 Plastic spacer
9 Optical fibres
10 Metallic wires
11 APL sheath
12 Spacer
13 Sheath
14 Element
15 Tightening element
16 Fibre

Fig. 7.8

1 ALUMINIUM
2 POLYETHYLENE
3 TAPE FORMATION
4 Fibre insertion
5 Hot sealing
6 Aluminium and polyethylene
7 Diameter: 14 mm

LEGENDAS DAS FIGURAS

Fig. 7.1

1 Attenuation (dB/km)

Fig. 7.2

1 OPTICAL FIBRE MECHANICAL STRENGTH
F. PB024/0 NYLON

2 Frequency

3 Rupture to traction (? - ilegível)

Fig. 7.3

1 σ_t (working stress)

2 Life duration: 1 day

3 1 month

4 1 year

5 10 years

6 100 years

7 Deformation in operation (%)

8 σ_i (stress in inert ambient)

Fig. 7.4

1 Plastic sheath

2 Traction element

3 Coated fibre

4 Copper wires

5 Coated fibre

6 Filling

7 Group

8 Traction element

Fig. 7.5

1 Traction element

2 Polyester tapes

3 Polyethylene

4 HDPE sheath

5 Tape matrix

6 Wrapping

7 Diameter: 12 mm