PRACTICAL ASPECTS OF OPTICAL FIBRE CABLE DESIGN AND TESTING

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ABSTRACT

Principles of optical fibre cable design have been a secret art among cable manufacturers. Little is published regarding cable design and qualification test requirements with which cable manufacturers must comply.

The aim of this thesis is to describe the state-of-the-art in optical fibre and cable manufacture, including cable construction for particular applications.

The influence of mechanical and environmental conditions on cable design are presented together with test procedures. In addition, test methods and apparatus are described, and their limitations in practice are discussed. New approaches concerning fibre, cable design and construction, and manufacturing and testing technology are also discussed.

An example of an optical fibre cable with mechanical and environmental test report is presented in this thesis. This example demonstrates the development of a 2 - 30 optical fibre cable describing the practical aspects of cable design and analysis.

This thesis is the first comprehensive collection of material, to my knowledge, which covers the practical aspects of optical fibre cable design principles, analysis and testing from a manufacturer's perspective.

ACKNOWLEDGEMENTS

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I am grateful to my supervisor, Dr. Graham E. Town, for his guidance and advice during the final preparation of this thesis.

A special acknowledgement goes to my wife Irene Lia Yang for her patient and caring throughout the course of my study. Without her constant support and encouragement this work would not have been completed.

This thesis is dedicated to her.

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LIST OF ABBREVIATIONS

APD	Avalanche Photodiode
ASK	Amplitude Shift Keying
AVD	Axial Vapour Deposition
BER	Bit Error Rate
CSM	Central Strength Member
CVD	Chemical Vapour Deposition
dB	Decibel
dB/km	Decibel per Kilometre
E/O	Electro-Optic
FDM	Frequency Division Multiplexing
FPSL	Fibre Proof Strain Level
GRP	Glass Reinforced Plastic
HDPE	High Density Polyethylene
IVD	Inside Vapour Deposition
kg	Kilogram
km	Kilometre
LD	Laser Diode
LED	Light Emitting Diode
m	metre (SI Unit of length)
MCVD	Modified Chemical Vapour Deposition
mg	milligram
MHz.km	Megahertz Kilometre
mm	millimetre
MMOF	Multimode Optical Fibre

LIST OF ABBREVIATIONS (continued)

N	Newton
NA	Numerical Aperture
nm	Nanometre, being 1 x 10^{-9} metres
ns/km	Nanosecond per Kilometre
O/E	Optic-Electro
OTDR	Optical Time Domain Reflectometer
OVD	Outside Vapour Deposition
OVPO	Outside Vapour Phase Oxidation
PBT	Polybutylene Terephthalate
PE	Polyethylene
PIN	P-I-N Junction Photodiode
PMCVD	Plasma-Enhanced Modified Chemical Vapour Deposition
PP	Polypropylene
PVC	Polyvinyl Chloride
RMS	Root-Mean-Square
SFW	Strain Free Window
SMOF	Singlemode Optical Fibre
TDM	Time Division Multiplexing
UV	Ultraviolet
VAD	Vapour Axial Deposition
um	micrometre, being 1 x 10^{-6} metres
°C	Degree Celsius
%	Percentage

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CHAPTER ONE

INTRODUCTION

Optical fibres have become a centre of interest as transmission lines for telecommunication systems. In particular, the optical fibre cables offers a better alternative to traditional copper wire cables. These are mainly due to the successful fabrication of low loss silica-based optical fibres whose transmission losses are reduced as low as 0.2 dB/km. Hence, the low loss quality of silica-based optical fibres have enabled the construction of high bit-rate and long haul communication systems.

In this chapter, an overview of the history of optical communication and the major features of optical communication system are described. A brief description of the components in a basic optical communication system is presented. Finally, the contents of the remaining chapters and the author's contribution are outlined. This thesis will only deal with the transmission line of the system component, that is the fibre and cable properties, which are described in the later chapters.

1.1 Historical Background

The optical transmission of information is as old as mankind. The obvious desirability of communication over distances brought the development of smoke signals, semaphore, Aldis lamp and many other optical communication systems.

Today the principle behind optical transmission is the same as it was in the past. Information which is to be transmitted is transformed into a sequence of events visible as far as possible from the origin of transmission. At the point of reception, the observer sees and decodes the visible sequence of events, or passes on the signals in the same form.

Even at an early date, optical transmission occurred mainly in digital form, and considerable distances were bridged with high transmission quality. Natural sunlight or artificial light (fire for example) were employed as sources of light.

The optical fibre communication is based on the principle of light transmission through a glass fibre by total internal reflection (this principle will be discussed in Chapter 2). This phenomenon was demonstrated by John Tyndall at Royal Society of London in 1870. His famous demonstration consisted of illuminating the top surface of water in a vessel and when a stream of water was allowed to flow through a hole in the vessel, light was guided along the curved path of the stream.

Immense progress has been made since then, and thin glass fibre is now a viable means of transmission of light for communications.

In 1880 Alexander Graham Bell invented the Photophone, a light communication system. He used sunlight reflected from a thin voice-modulated mirror (a thin mirror of silvered mica, so that it would curve when sound struck it) to carry conversation. At the receiver, the modulated sunlight fell on a photo-conducting selenium cell (selenium - a metal whose resistance changes with light), which converted the message into electrical current. A telephone receiver completed the system. (See Figure 1)

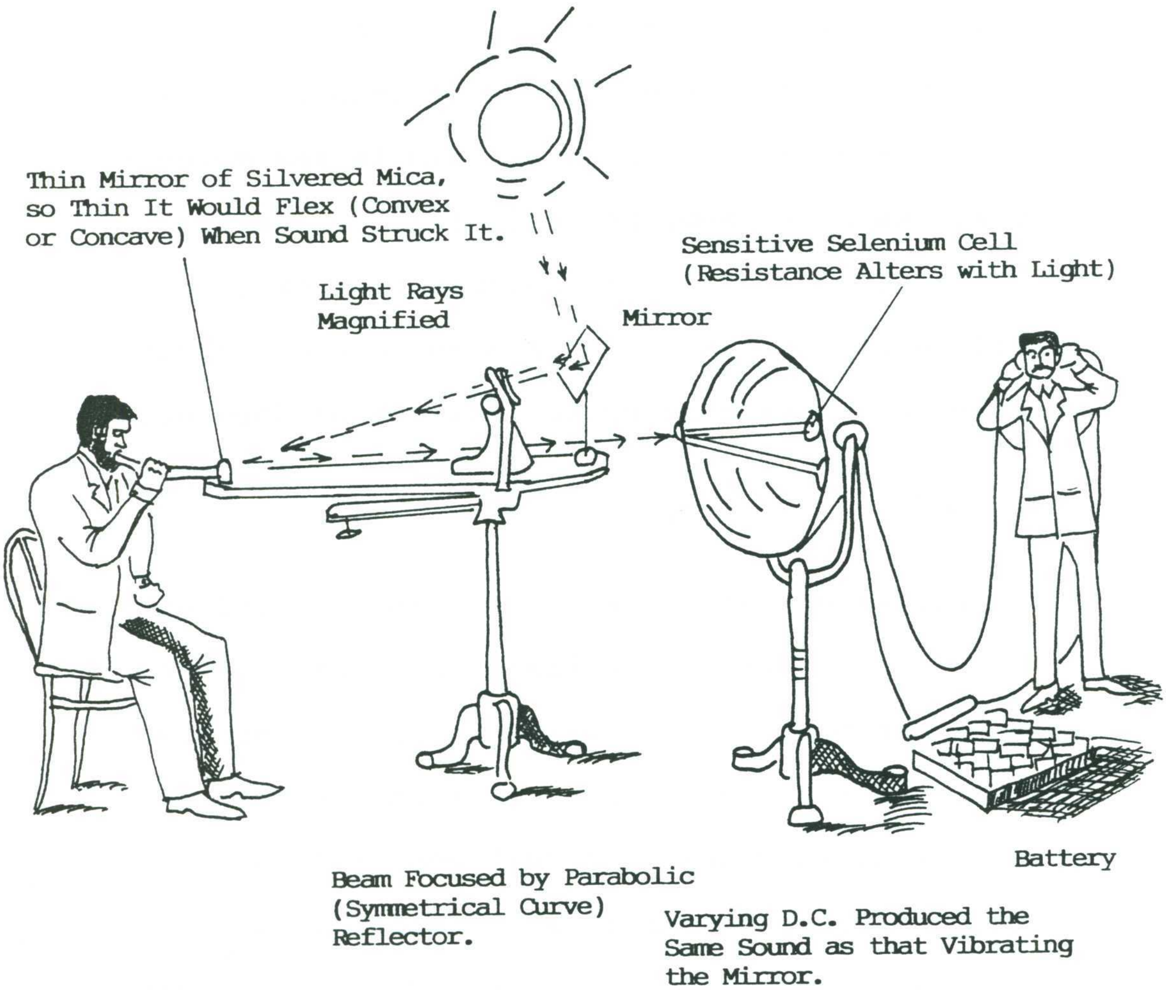


Figure 1 - Alexander Graham Bell's Photophone. [From Bell, 1880].

A major breakthrough that led to high capacity optical communications was the invention of the laser in 1960. The laser provided a narrow-band source of optical radiation which offered high enough power to be transmitted over significant distances. Due to very high effective carrier frequency (on the order of 10^{14} hertz), it would allow a very large amount of information (modulation bandwidth) to be transmitted.

However, the question of the transmission medium was still open. Free space as a transmission medium was eliminated because weather made it unreliable. Optical waveguides, such as glass fibre, were considered from the beginning. Materials available at the time attenuated light too much to consider using them as a transmission medium.

A solution came in 1966 when the theoretical works of Kao and Hockam of Standard Telecommunication Laboratories in England showed the attenuation in optical fibres can be reduced and used for long distance transmission. They pointed out that the attenuation found in glasses employed for optical fibres was not a basic properties of the material but was produced by the presence of impurities, mainly metallic ions. After that, many organisations started research programs in this field.

In 1970, the first truly low loss fibre was developed by Corning Glass Works in the USA, which showed an attenuation of less than 20 dB/km. The technique used in producing this fibre was outside chemical vapour deposition (OCVD). This process will be explained in detail in a later chapter.

Since then not only have other manufacturers been producing optical fibres, but attenuation has also decreased to around 0.2 dB/km. Research is continuing in this field to obtain ultra-low loss fibres (fluoride glass, singlemode, operating at 2500 nm wavelength, with attenuation less than 0.02 dB/km) and optical fibre amplifiers (already available on the market and can be used to increase transmitter power output, compensate in-line fibre attenuation or as preamplifier to improve receiver sensitivity).

Optical fibre cables, as well as all the other components for optical transmission systems, were developed and improved hand in hand with the development of optical fibres. This technology is moving at such a fast rate that the industrialised world already has a network of optical fibre cables connected to its major cities, and extending to customer access networks, with the aim of bringing them into homes.

This expansion has also spread to inter-continental optical fibre links replacing satellites.

Table 1 is a list of the historical events in optical communication.

TABLE 1. THE HISTORY OF OPTICAL COMMUNICATION

?	Hand signals, semaphore and smoke signals.
1870	John Tyndall, a British physicist, demonstrated the Royal Society that light can be guided along a curved stream of water.
1880	Alexander Graham Bell invented the Photophone, after he invented the telephone in 1876. Unfortunately it was almost 100 years ahead of its time. It main drawbacks were that it could only be used in daylight over short distances, smog, fog and smoke interfered with the signal and the transmitter and receiver had to be within line of sight.
1954	The invention of the cladded optical waveguide by Professor Van Heel.
1960	Ruby Laser - T.H. Maiman.
1966	Technology began to catch up with the Photophone when at the Standard Telecommunications Laboratories in Harlow, England, optical fibres were developed. Standard Telecommunication Laboratories in England published a famous paper on the possibility of transmitting light for communication purposes through a Silica Glass Rod. C. Kao and G. Hockham.
1970	The Corning Glass Works succeed in fabrication of first low attenuation optical fibre using outside chemical vapour deposition (OCVD) technique, with losses under 20 dB/km.
1971	Scientists at Australia's CSIRO and Telecom Australia experimented with a hollow glass fibre with a liquid core.
1973	Optical fibre using Modified Chemical Vapour Deposition (MCVD) technique, with losses under 1 dB/km - Bell System.
1975	A.W.A. began developing Solid Core Fibres for the P.M.G. Department.
1977	Optical fibre using Vapour Axial Deposition (VAD) technique, with losses under 0.4 dB/km - NTT and SEI.
1980	NEC Japan published results of an experimental system that could transmit 7000 conversations over a distance of 53 km using a single fibre without repeaters.

TABLE 1. THE HISTORY OF OPTICAL COMMUNICATION (continued)

1982	British Telecom Research Laboratories published results of experiments whereby 2000 conversations could be transmitted 100 km over a single fibre.
1984	Telecom Australia made a decision to install a 30 Fibre Single Mode Optical Fibre Cable between Sydney and Melbourne.
1986	Lasing Fibres- University of Southhampton.
1987	Sydney to Melbourne project completed.
1988	Optical Fibre Residential projects in Sydney and Melbourne commenced.
1989	The world longest point to point transmission system without repeaters. An 1.8 Gbit/s optical digital system transmitted over 270 km using Erbium-doped fibre amplifier - developed by Pirelli Cables.
1993	Telecom Australia launched a field trial in Wollongong, N.S.W. to extend optical fibre links closer to residential and small business premises. The services provided are telephony and ISDN, 2 Mbit/s that is integrated with the video services (20 channels) using Wavelength Division Multiplexing over the Passive Optical Network architecture.
?	Fluoride Glass Fibre < 0.02 dB/km ?

1.2 OPTICAL FIBRE COMMUNICATION SYSTEM

The main requirement for any communication system is a flexible, reliable, secure, low cost transmission medium with low attenuation and high bandwidth. Optical fibre systems have significant advantages over existing transmission systems such as :

- very high bandwidth, hence high transmission capacity.
- smaller size and weight, leading to efficient duct utilisation.
- lower material cost.
- lower system cost per channel kilometre.
- longer repeater spacing than for equivalent capacity metallic cable systems.
- negligible crosstalk and signal leakage.
- electrical isolation of input and output of data paths.
- high immunity to interference (electromagnetic and electrostatic fields).
- high security. It is practically impossible to tap information out of a fibre without detection, making it ideal for the transfer of sensitive data.

- metal free. It is possible to make cables completely non-metallic, making them safe to take to electricity sub-stations and other locations where earth potential rise could be a problem, such as lighting damage.

At the moment optical systems are generally more expensive than copper cable systems unless a very high capacity is required. Many trunk telephone networks around the world are rapidly being converted into optical systems as the fundamental requirements of very high capacity and reliability are desired. Also, future demands to bring fibres into homes for intelligent applications are becoming a reality.

The benefits of optical fibre systems over the metallic cable systems are sufficiently important to many users so much as to stimulate serious consideration of their installation. The cost and capacity advantages of optical fibre systems in comparison with metallic cable systems (twisted wire pairs and coaxial cables) will display a remarkable decrease in the future with respect to the system cost per channel kilometre of optical communication systems.

This will be made possible by substantially decreasing the cost at the system level, and will be accompanied by a comparable increase in the number of channels per system.

Table 2 shows the comparison of different cable types and their costs.

Optical fibres are most suitable for carrying information modulated onto optical carriers at wavelengths around 1 um. They have the potential to carry approximately one billion simultaneous two way voice channels. The current transmission capacity of optical fibre system has been demonstrated over 10 gigabits. In Australia, the current maximum capacity is 30720 voice frequency circuits per fibre, transmitted at 2.4 gigabits with a very low bit error rate (BER of 10^{-9}). [From Australian Standard Telecommunication Data Rates].

Low signal attenuation is another major feature of optical fibres. The singlemode fibre allows for a distance between repeaters of between 50 and 70 kilometres. Corning Glass (USA) has produced a Halide fibre which can theoretically allow distances between repeaters of up to 3,600 kilometres.

This is one of the reasons why the majority of the inter-continental optical fibre links will not be installed until the late 1990's. Underwater regeneration of the signal will not be necessary, but will simply be carried out at the various islands the cable passes through.

The structure of an optical fibre transmission system is similar to other systems in that it consists of a transmitter, a transmission line and a receiver. This is illustrated in Figure 2, which shows that the transmission line is an optical fibre cable. A brief description of each component of the system will be discussed here.

The transmitter is a light source whose output acts as the carrier wave. After adjustment for level and impedance, the electrical signal to be transmitted is directed to an optical transmitter (E/O converter). Semi-conductor light sources (LED, LD) are used as E/O converters. Although frequency division multiplexing (FDM) techniques are used in analogue broadcast systems, most optical communication systems use digital time division multiplexing (TDM) techniques.

The easiest way to modulate a carrier wave with digital signal is to turn it on and off, so called on-off keying, or amplitude shift keying (ASK). In optical systems this is achieved by varying the source drive current directly, so causing a proportional change in optical power.

The optical signal is guided from the transmitter via an optical fibre cable to the optical receiver (O/E converter). At the receiver, the optical signal is transformed back into an electrical signal. After adjustment for level and impedance, the original electrical signal is then available. The O/E converters are constructed using photodiodes (PIN, APD). The photodiode current is directly proportional to the incident optical power. Depending on the wavelength of operation, photodiodes can be made out of Silicon, Germanium or an alloy of Indium, Gallium and Arsenic.

In practice, the interface circuits, and the E/O and O/E converters, are offered as a single unit transmission terminal. Connections of fibres in optical transmission systems may be separable (optical plug connector), or spliced (bonding).

Ultimately, for a limited transmitter power and wide bandwidth channel, it is the receiver noise that limits the maximum transmission distance, and hence repeater spacing. This is of course without considering plug connectors, splices and fibre properties which represent an additional source of attenuation on the system.

Differences in fibre cross-section and numerical aperture, the ellipticity and eccentricity of fibre cores and error in adjustment all cause additional attenuation at coupling points. The properties of optical fibres which affect optical communication systems will be outlined in Section 2.4 of Chapter 2, with respect to fibre attenuation, dispersion and bandwidth.

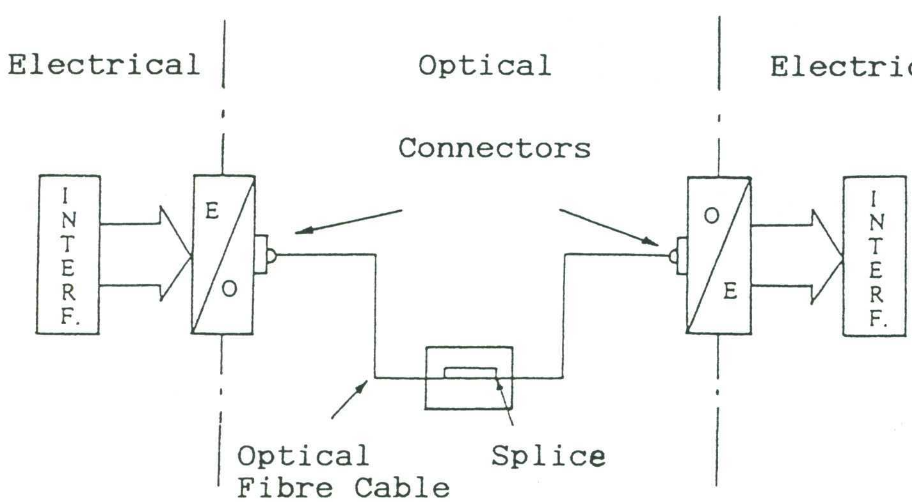


Figure 2 - Basic Optical Fibre transmission system.

TABLE 2. COMPARISON OF DIFFERENT CABLE TYPES

Characteristic	Twisted Pair	Coaxial Cable	Fibre optics cable
Length-bandwidth product MHz.km)	1	20	>10000
Spacing between repeaters (km)	1-2	1-2	>50
System cost	Low, slow increase in future	Medium now, slow increase in future	High now, steep decrease in future
System lifetime (years)	20-40	20-40	20-40
Crosstalk	High	Low	Negligible
Noise immunity	Low	Medium	High
Electrical input-output Insulation	No	No	Complete
Vibration tolerance	Good	Good	Good
Short circuit loading	Yes	Yes	No
Weight size	High	High	Low
Cable connections	Soldering, standard connectors	Soldering, standard connectors	Splicing, well-aligned connectors
Fabrication control requirements	Loose	Medium	Precise

1.3 Outline of Contents

Chapter 2 aims to present the physical principles underlying the guidance of light in optical fibre communication systems. This information provides the necessary background for an appreciation of the capabilities of optical systems and cables, as discussed in subsequent chapters.

After the mechanism which achieves the guidance of light in fibres is discussed, different types of optical fibre are described. This is followed by the causes of the fundamental propagation characteristics, loss and dispersion. At end of the chapter, description of different fibre fabrication processes are discussed .

Chapter 3 is concerned with the incorporation of the fibres discussed in the previous chapter into practical cables. The concept of cable design is thoroughly presented, such as cable components, cable construction, type of materials used, cable protection and design considerations with respect to mechanical, environmental and installation conditions.

In Section 3.2, different types of cable design are discussed, together with the design considerations for different applications. Mechanical and environmental characteristics that the cable may be exposed during manufacture, installation and operation are discussed in Section 3.3. This is followed by cable construction (Section 3.4), detailing cable components and their functions in the cable. Example of optical cable designs are given at the end of the chapter.

Chapter 4 has been devoted to the presentation of optical fibre and cable testing. Two sections are presented, the first section covers optical fibre tests and the second section optical cable tests. Optical transmission, mechanical and environmental tests are discussed. Test methods and test apparatus are briefly described, together with practical problems encountered and newly developed cable tests (ageing tests), to measure cable performance in high humidity conditions.

Chapter 5 deals with all the materials discussed in the previous chapters which are put into practical use. The development of a 2-30 fibre design optical cable is presented, practical aspects of cable design and analysis are demonstrated in this chapter with an example of mechanical and environmental test report.

The thesis concludes with Chapter 6, a review of the contents. The prospects for future developments are briefly discussed at the end of the chapter.

The author has contributed in the development and manufacture of optical fibre cable since 1987, when Pirelli Cables Australia established its optical cable facilities at Dee Why, New South Wales. Initially involved in prototype design in the Cable Design Department where development and manufacturing specifications are issued for production, later worked in the Quality Assurance Department where cable testing is conducted and at last in the Technology Department providing technical assistance to the factory, evaluation of new materials and conducting trials of new cable developments.

The chapters of this thesis are the first comprehensive collection of material, to my knowledge, which covers the practical aspects of optical fibre cable design principles, analysis and testing from a manufacturer's perspective.

CHAPTER TWO

OPTICAL FIBRE

2.1 Introduction

This chapter contains the principles of lightwave fundamentals in optical fibre communication systems. Different types of optical fibres and fibre characteristics are also discussed, together with the processes by which these fibres are manufactured.

The contents of this chapter provides the background knowledge necessary to be used in design and testing of optical fibre cables, as discussed in the subsequent chapters.

2.2 Lightwave Fundamentals

Optical fibre is used as a transmission medium in an optical fibre telecommunication system. The principle of optical transmission is to send information modulated onto a lightwave carrier through the fibre.

The optical fibre is a transparent, dielectric, long, flexible cylinder (solid) of small diameter, which guides light along its axis almost without loss, even when it is bent. The light carrier used is in the infrared region. Optical fibres (silica glass) are usually used to guide light at 850, 1300, or 1550 nanometres (nm).

The simplest way to understand transmission in optical fibres is to consider Snell's law of reflection.

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_2}{n_1}$$

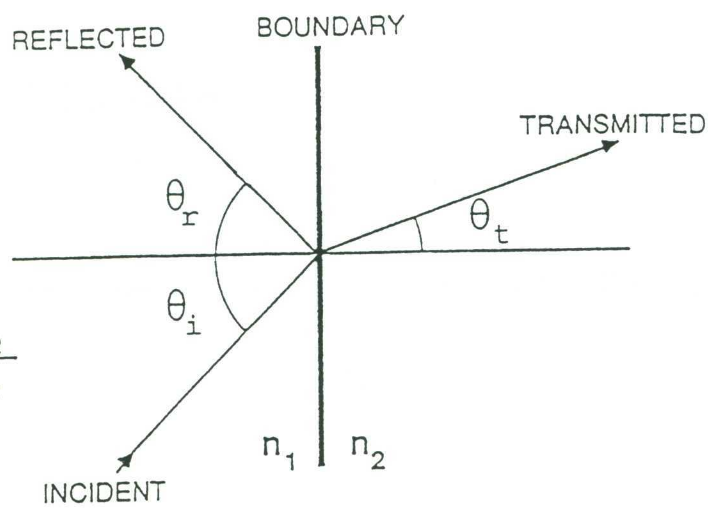


Figure 3 - Incident, reflected and transmitted rays at a boundary between two refractive index media. (After [1]).

Where θ_t is the angle of transmission

θ_i is the angle of incidence

θ_r is the angle of reflection

and n_1 and n_2 are the refractive indices of the incident and transmission regions respectively.

The medium used in optical fibres is glass, when $n_1 > n_2$, the ray is bent away from the normal and towards the boundary surface. (See Figure 4)

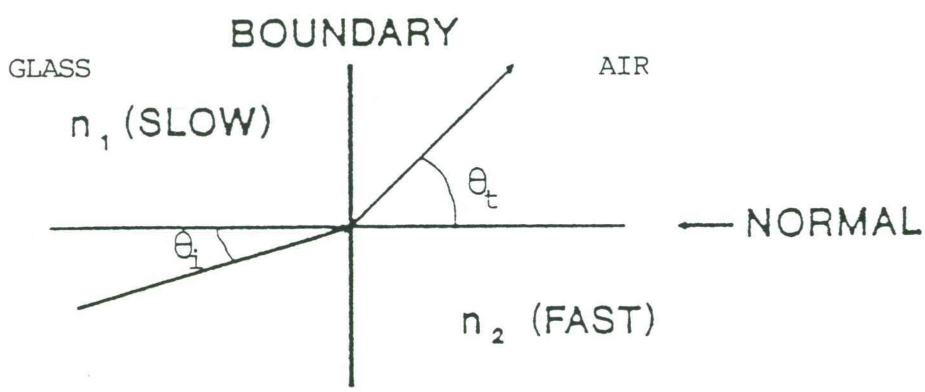


Figure 4 - Refraction from glass to air. (After [2]).

The glass used in optical fibre light guides is silica with a small amount of other oxides (used as dopants) added to modify the index of refraction and expansion coefficients of the glass.

The basic structure of a typical multimode step index fibre is shown in Figure 5.

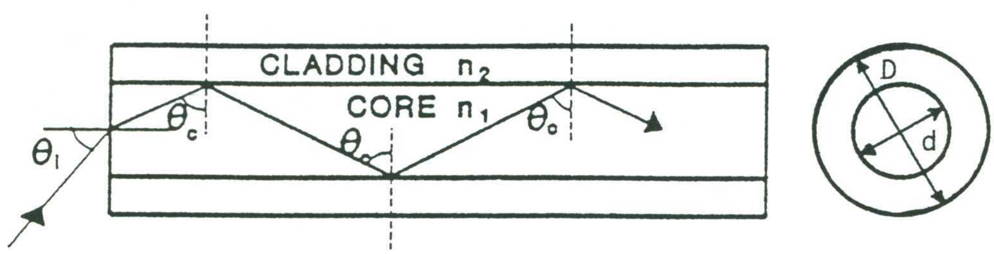


FIGURE 5 - Total internal reflection in a step index fibre. (After [2]).

The fibre consists of a core, with the diameter d and the index of refraction n_1, surrounded by a cladding of diameter D and index of refraction n_2, where n_2 is approximately 0.5 to 5 percent smaller than n_1, depending on the desired properties of the fibre.

This has the result that light entering the fibre within a certain solid angle (less than the critical angle θ_c) around the axis of the fibre undergoes total internal reflection at the core-cladding boundary, and therefore remains within the guiding path. As discussed in the last chapter, this fundamental principle was demonstrated in 1870 by John Tyndall who showed that light may be guided by a stream of water.

The light propagating in the core of the fibre at angles greater than a critical angle θ_c is refracted out of the fibre core. The critical angle for total internal reflection is expressed as:

$$\theta_c = \cos^{-1} (n_2/n_1)$$

As discussed earlier, the difference between n_1 and n_2 is small, that is $n_1 - n_2 << n_1$, so that the relative refractive index difference (Δ) can be defined by:

$$\Delta = \frac{n_1^2 - n_2^2}{2 n_1^2} \cong \frac{n_1 - n_2}{n_1}$$

Δ is usually expressed as percentage.

The parameter which described the maximum acceptance angle θ_o for guided light is the fibre numerical aperture (NA) and is defined as:

$$\begin{aligned} NA = \text{Sin } \theta_o &= \sqrt{(n_1^2 - n_2^2)} \\ &= n_1 \sin \theta_c \\ &= n_1 (2\Delta)^{1/2} \end{aligned}$$

The numerical aperture defines the solid angle over which the fibre can collect light and guide it to the other end.

A fundamental parameter used to describe optical fibres is the normalised frequency (V). This parameter V is given by:

$$V = \frac{2\pi a}{\lambda} (n_1^2 - n_2^2)^{½}$$

where a is the core radius of optical fibre, and;
λ is the free-space wavelength.

Multimode operation results when V > 2.405. In contrast, the optical fibre with a normalized frequency of less than 2.405 is called the singlemode optical fibre (typically V = 2.3).

2.3 Types of Optical Fibres

Optical fibres may be classified into singlemode fibres and multimode fibres according to the number of modes (or rays) that propagate in the fibre. A singlemode fibre is one in which only the fundamental mode (or approximately the axial ray) travels in the fibre. To achieve this the core diameter of the fibre has to be very small, in the order of 5 to 6 um. The advantage of a singlemode fibre is that it causes very little dispersion which in turn means that it offers a large information carrying capacity.

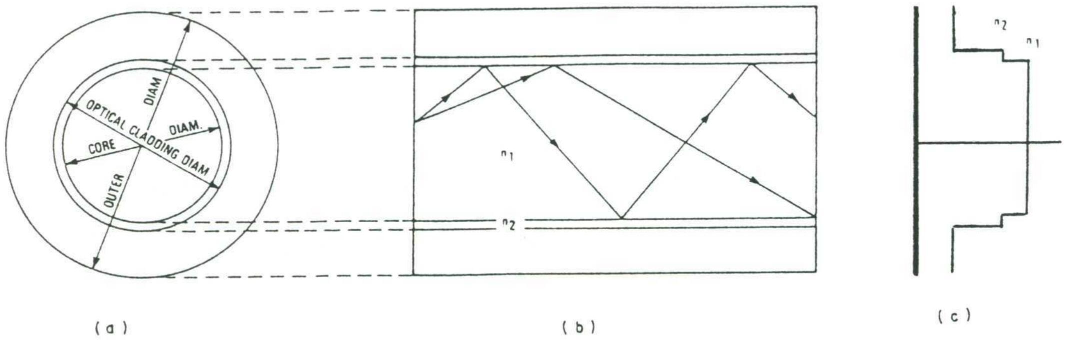
The multimode fibre is one in which a large number of modes (or rays) can propagate. Its core diameter is about 50 um while the overall fibre diameter is 125 um. The pulse propagating in this fibre broadens rapidly with distance due to modal dispersion, hence the information carrying capacity of a multimode fibre is much less than the singlemode fibre. On the other hand, more optical power is coupled from the source to the fibre.

Optical fibres may also be classified according to the shape of their refractive index profile. There are three main types used for telecommunications:

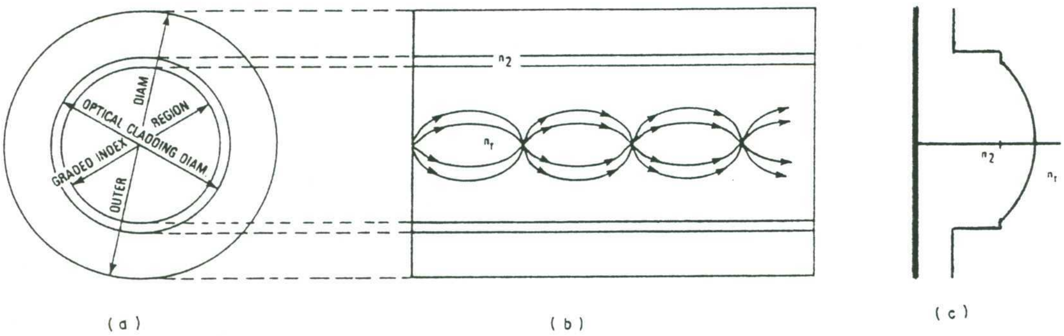
(1) step index fibres (singlemode and multimode);
(2) graded index fibres (multimode), and;
(3) dispersion shifted fibres (singlemode).

These typical optical fibre types are illustrated in Figure 6.

(1) Step index fibre (multimode)



(2) Graded index fibre (multimode)



(3) Dispersion shifted fibre (singlemode)

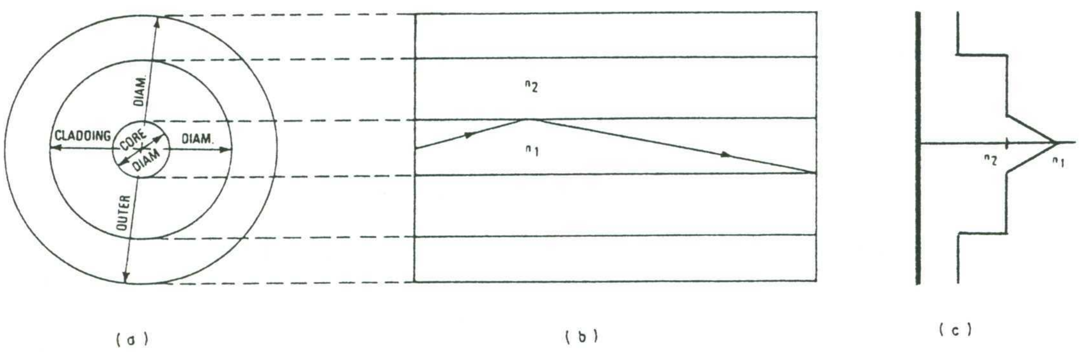


Figure 6 - Three typical optical fibre types.

(a) End view. (b) Cross-sectional side view.

(c) Refractive index profile.

(After [3]).

The selection of type of optical fibre to be used in an optical system will depends on the system requirements, that is, minimum loss, operating wavelength, bit rate, dispersion and device constraints (light source and receiver).

For low loss optical fibres used in telecommunications are optimised at wavelengths of 850, 1300 and 1550 nm. These are known as first, second and third window respectively.

The multimode fibre is normally optimised for operation at 850 nm and 1300 nm wavelengths. Typical applications are telephony, distribution and local networks; carrying data, voice and/or video services.

The singlemode fibre is optimised for operation at 1300 nm and with low induced bend loss at 1550 nm wavelength. It is designed for transmission systems requiring long distance between repeaters and/or high bit rates.

A singlemode dispersion-shifted fibre has the zero dispersion wavelength in the 1550 nm wavelength region, and it is designed to operate at 1550 nm wavelength. Applications for this fibre includes long haul telephony and submarine cables, where long spans without regeneration and high data rates are required.

2.4 Fibre Characteristics

The transmission properties are the main interest for telecommunications. The most important parameters describing the transmission characteristics of an optical fibre are attenuation and dispersion. These parameters will be discussed in this section.

2.4.1 Fibre Attenuation

Fibre attenuation is one of the most important properties of an optical fibre. Optical loss power in a fibre is caused by a combination of absorption, scattering of the light and bending effects.

a) <u>Absorption Loss</u>

Silica glass for optical fibre exhibits low loss of two main intrinsic absorption bands within the wavelength range 0.7 to 1.6 um. These intrinsic absorptions are natural properties of the silica glass.

Absorption bands occur at infrared wavelengths due to the interaction of photons with molecular vibrations within the glass such as the silicon-oxygen bond. Thermal energy causes the atoms to be moving constantly, so the SiO bond is continually stretching and contracting. This vibration has a resonant frequency in the infrared region. The absorption peaks for these bands are between 7 and 12 um, far from the region of interest.

The second intrinsic absorption is the fundamental absorption edge of the glass due to electronic and molecular transition bands. This type of absorption occurs very strong at short ultraviolet wavelengths and minimising as the visible region is approached.

The tails of both the infrared vibrational absorption peaks and the UV absorption edge can both extend into the wavelength ranges of interest, however, careful selection of both core and cladding composition can minimise these effects. Figure 7 illustrates the spectral loss for typical Germanium-doped silica glass fibre.

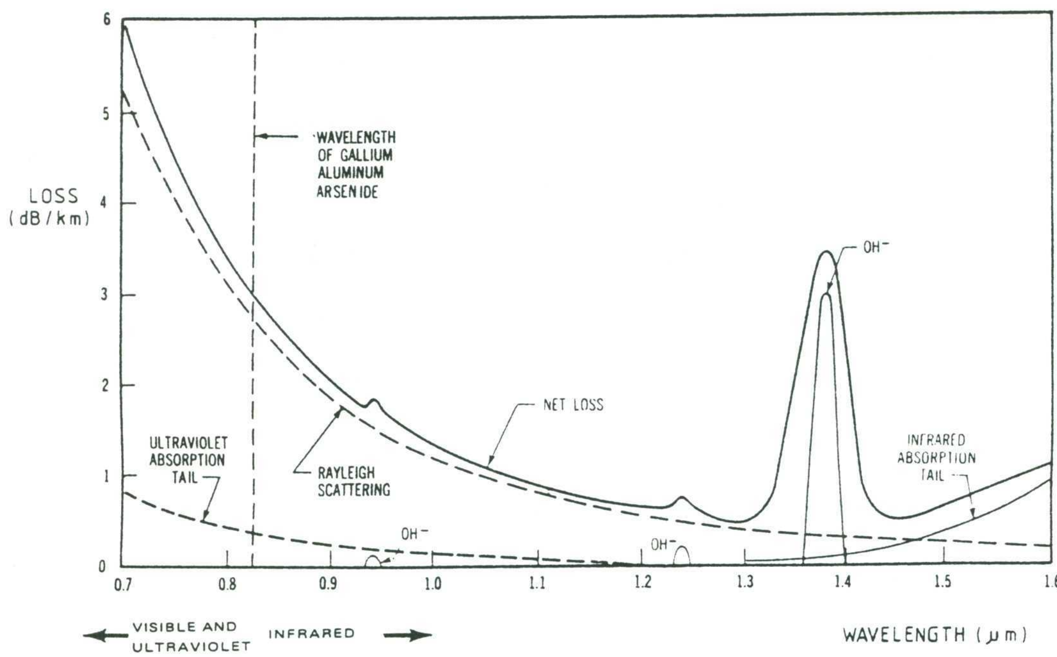


Figure 7. Spectral loss for typical doped silica glass fibre. (After [4])

The intrinsic losses are insignificant in the range of wavelengths used for communication systems. Impurities are the major source of loss in a optical fibre. At certain wavelengths, losses may be increased due to the presence of transition metal ions or hydroxyl (OH^-) ions within the silica.

Metal impurities such as Ti , V, Cr, Mn, Fe, Co, Ni and Cu (from the first series) are absorbed due to electronic transitions between the energy levels associated with the incompletely filled inner electron shell. This absorption must not exceed levels of a few parts per billion to obtain losses below 20 dB/km in the region of interest.

Current technology has advanced sufficiently such that the transition metal impurities no longer contribute significantly to the loss in high quality fibres suitable for telecommunications.

The hydroxyl ion, often referred to as the "water absorption loss", is the most significant and important impurity to minimise from the silica fibre point of view.

The loss mechanism for the hydroxyl ion is the stretching vibration, as for the absorption of the SiO bond. The oxygen and hydrogen atoms vibrate due to thermal motion. The fundamental occurs at 2.73 um with overtones and combination bands of this resonance at 0.95, 1.23 and 1.37 um.

Special precautions are taken during the fibre manufacture to ensure a low level of hydroxyl impurity to achieve the lowest loss in the wavelengths in which the optical fibre system operates.

b) Scattering Loss

The light energy passing through the optical fibre may be scattered and lost through two major scattering effects: Rayleigh scattering loss, and/or, defects in either the processing or the structure of the glass. Rayleigh scattering loss is an intrinsic property of the glass with a fundamental limit to fibre loss.

Rayleigh scattering arises from the variation in the refractive index which occurs within the glass over distances that are small compared with the wavelength of the scattered light. Such index variations are caused by local fluctuation in composition and density within the glass and are very dependent on the basic glass and its method of preparation.

A beam of light passing through such a structure will have some of its energy scattered by those fluctuations. Rayleigh scattering is proportional to λ^{-4}, so it becomes increasingly important as the wavelength diminishes. The Rayleigh scattered energy is both absorbed in the cladding and guided in the backward direction.

An important feature for the fibre is to reduce the impurity absorption loss to zero so that only the Rayleigh scattering loss is left.

Processing defects may be in the form of bubbles of gas trapped during cooling or released from the glass in a reboil effect, phase separated regions, devitrified sections or unreacted materials. These may be eliminated by careful handling of working compositions.

Structural defects are caused by material inhomogeneities introduced during fibre manufacture. Imperfect mixing and dissolution of chemicals, for example, can cause inhomogeneities within the core and imperfect processing can produce a variation in core-cladding interface.

The scattering objects in these instances are larger than the optic wavelengths. Unlike Rayleigh Scattering, the losses introduced by large objects are independent of wavelength. These losses can be controlled by proper manufacturing techniques.

c) <u>Bending Effects</u>

Forces applied externally to the fibre may result in bending, and depending on the radius of curvature, the attenuation will increase exponentially. There are two types of bends; macrobending and microbending.

Macrobending refers to large scale bending, such as handling of the fibre, winding on to a spool or pulling around a corner during installation. Bends of large radius (say 10 centimetre) do not result in significant impairment to optical transmission on a typical silica-based optical fibre.

The localised bending over small lengths (say 1 millimetre) which is subject to unequal axial oriented forces, is called microbending. One of the causes of excessive transmission loss in optical fibres is due to microbending, particularly at longer wavelengths (1550 nm).

From electromagnetic theory, optical fibres can be considered as open dieletric waveguides. A beam of light guide by the structure of the fibre, at any point where there is a bend, part of the light energy is radiated.

In the case of continuous curvature, the increased loss occurs due to radiation of higher order modes (which travel close to the critical angle). When bending occurs over a small distance (a few millimetres, mode coupling results in the conversion of power to radiation modes, hence resulting in an increase in fibre loss (microbending).

Microbending can be minimised by the design of appropriate protective fibre jacketing and cable structure to reduce the effect of externally induced forces.

2.4.2 Dispersion and Bandwidth

As light propagates in an optical fibre waveguide, its spectral components disperse as a function of the fibre length. An example is pulse broadening, which limits the bandwidth, and hence the information carrying capacity of the fibre. The total dispersion is the result of three effects: modal dispersion, material dispersion, and waveguide dispersion.

a) <u>Modal Dispersion</u>

Modal dispersion is due to the difference in group velocity of the different modes propagating in the fibre. This effect is eliminated in single mode fibres as only one mode is propagated.

In multimode optical fibre there are many modes carrying the power with each mode having its own wave propagation path and power distribution within the fibre.

In a step index fibre there is a maximum delay between the mode that takes the longest path and the mode exactly on axis. This results in the spreading of a laser pulse as it travels along the fibre (modal dispersion), hence the bandwidth for this type of fibre is restricted.

This effect can be substantially reduced by using a graded index fibre, as it compensates or equalises the time delay difference by varying the index of refraction across the radius of the core making it possible to widen the bandwidth.

b) <u>Material Dispersion</u>

Material dispersion is caused by the variation in the glass refractive index with the wavelength of the light source. Practical sources used in optical fibre transmission systems have a finite spectral width, and since the refractive index is different for the different wavelengths launched, there is a finite spread of group velocities resulting in the dispersion of propagating pulses.

The rms pulse spread per unit length due to material dispersion can be expressed as:

$$\tau_\lambda = M.\Delta\lambda . L$$

τ_λ is usually expressed as nanosecond per kilometre, ns/km.

where τ_λ is the material dispersion;
M is the material dispersion coefficient of the fibre;
$\Delta\lambda$ is the rms source spectral width, and;
L is the fibre length.

The material dispersion coefficient M is dependent on the type of dopant used to create the refractive index profile (such as Boron, Germanium or Phosphorus). Typically M is around 100 ps/nm/km at 850 nm wavelength.

Silica based optical fibre has a zero material dispersion near 1.3 um. This behaviour together with the low loss of fibre at wavelength around 1.3 um has provided aids in maximising the achievable bandwidth. Hence as far as pulse spreading due to material dispersion is concerned, it is desirable to design sources and receivers and operate optical fibre at a wavelength of 1.3 um.

In singlemode fibre, where modal dispersion is zero, the only significant limit on bandwidth is material dispersion. In multimode fibres operating other than 1.3 um wavelength, the effects of material dispersion may be partially compensated by choosing the optimum index of refraction profile.

c) <u>Waveguide Dispersion</u>

If it were possible to isolate modal dispersion and material dispersion completely in a fibre, a pulse launched into such fibre would still exhibit a broadering as result of a third dispersive mechanism known as waveguide dispersion.

This effect arises as result of the wavelength dependence of the group velocity in each mode, which causes the guided pulse to disperse in time. The magnitude of the waveguide dispersion is directly proportional to the spectral width of the light source.

The pulse spreading due to waveguide dispersion is usually negligible, but at longer wavelength where material dispersion is low, the waveguide dispersion is of the same order. Hence, this effect is more prominent in singlemode fibre than multimode fibre.

In singlemode fibres, since the material dispersion falls to zero and then changes sign after 1.27 um, the wavelength of zero total dispersion may be obtained when material and waveguide dispersion cancel at a wavelength slightly longer than 1.3 um, assuming no modal dispersion. In multimode fibre this effect is usually overcomed by the much larger modal dispersion.

As indicated earlier in the spectral loss plot of silica glass fibre, the lowest attenuation is at 1550 nm. Careful design of the fibre cross-section can allow the waveguide and material dispersion to cancel at this desired wavelength.

Fibres with this characteristic are known as dispersion shifted fibres. This has been accomplished by constructing a singlemode fibre with a triangular shaped refractive index variation rather than a step index or graded index variation. These types of fibres have a very high bandwidth, typically greater than 40 GHz.km [5].

d) <u>Bandwidth</u>

From the above discussions, the effective bandwidth of an optical fibre system is dependent not only on the basic fibre performance, but also, because of material dispersion, on the operating spectral width of the light source. Therefore, fibre bandwidth specifications must take into account the type of light source to be used in the system or vice versa.

Bandwidth describes the information carrying capacity of an optical fibre. It is used as measure for the dispersion properties of an optical fibre and normally expressed as the product of frequency and length (in relation to fibre transmission).

Typical bandwidths (ignoring the effect of material dispersion) achieved in good quality practical fibres are:

Step Index Multimode	20 - 50 MHz.km
Graded Index Multimode	0.4 - 5 GHz.km
Singlemode	10 - 200 GHz.km

These bandwidths are dependent on operating wavelength, core diameter and refractive index profile. System bandwidth are dependent on the spectral width of the light source, and transmitter and receiver bandwidths. These are normally considerably less than the intrinsic fibre bandwidth.

In order to determine the information carrying capacity of a fibre, either the fibre impulse response in the time domain (pulse spread per unit length, in ns/km) or the modulation transfer function in the frequency domain (cut-off frequency, in MHz.km) needs to be known. These will be further discussed in Chapter 4, Section 4.2.5.

The measurement of bandwidth is only applied to multimode fibres. The fibre bandwidth is expressed as the product of 3 dB optical bandwidth and length (generally in MHz.km). This is defined as that frequency (of modulation) where the optical power of a baseband modulated signal has dropped to half the value at zero frequency.

Since the output electrical power of an optical to electrical converter is proportional to the square of the incident optical power, the 3 dB optical bandwidth corresponds to 6 dB electrical bandwidth.

The bandwidth in singlemode fibres is determined by waveguide parameters and chromatic dispersion. The latter will be discussed in Chapter 4, Section 4.2.7.

2.5 Fibre Fabrication

The fabrication process consists of two stages. The first stage is the manufacture of a preform rod which contains core and surrounding cladding. Having prepared a preform, the next step is to draw a fibre from the preform with a protective coating. This protects the fibre from moisture and abrasion.

There are several techniques for producing preforms. All differ conceptually and economically depending on fabrication economy and quality of fibre properties required. The basic manufacturing techniques in practical use are described in following sections.

2.5.1 Rod-in-Tube Technique

This technique is the oldest and it does not allow the achievement of a low loss fibre. Hence, its use is limited to a few applications where high fibre quality is of secondary importance (for example plastic fibres). The fabrication of a step index fibre involves the preparation of a preform consisting of a higher index rod inserted in a lower index tube.

The preform is subsequently collapsed at an elevated temperature corresponding to the softening point of the glass and uniformly pulled down at the end of the preform on to a rotating drum. The fibre diameter depends upon the drawing speed and temperature. Figure 8 illustrates a diagram of the rod-in-tube technique.

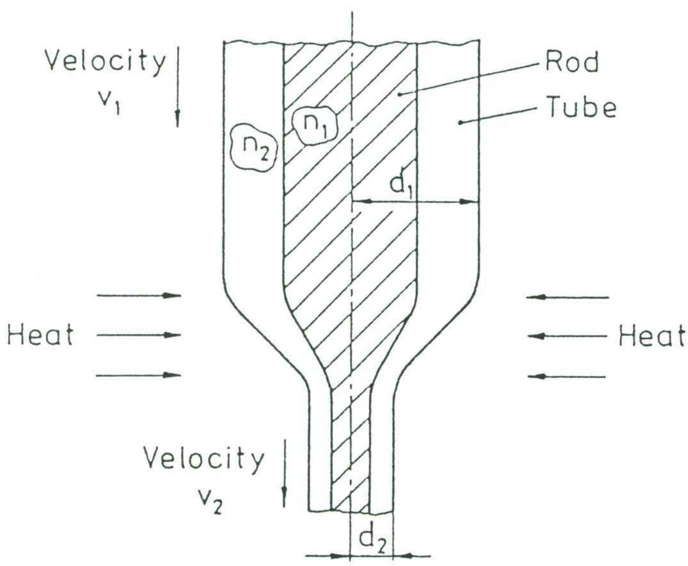


Figure 8. Simplified diagram of the Rod-in-Tube technique. (After [6]).

2.5.2 Double Crucible Technique

This technique is similar to the one described in 2.5.1, in that, instead of a preform, there are two concentric crucibles. The molten core-glass of the higher refractive index is placed in the inner vessel while the molten cladding glass of the lower refractive index occupies the outer vessel.

The crucibles are aligned vertically with the inner vessel being a few centimetres higher than the outer vessel. The two glasses come together at the base of the outer vessel, forming a glass-cladded core. This molten mixture is pulled into a fibre.

The double crucible technique can also be used for the fabrication of graded index fibres, by allowing ionic exchange (by diffusion) between core and cladding glasses. Diffusion causes a gradual change of the refractive index between that of the core and cladding glasses.

The main advantages of the double crucible technique are:

(i) the ease with which geometries can be altered;

(ii) the ease with which glass composition can be changed, and;

(iii) the potential for extending the process into a continuous one.

The disadvantages are:

(i) poor profile control;

(ii) risk of impurity contamination, and;

(iii) the inherent problem of crucibles that are neither attacked by molten glass, nor they themselves contaminate it.

The simplified diagram of the double crucible technique of fibre fabrication is illustrated in Figure 9.

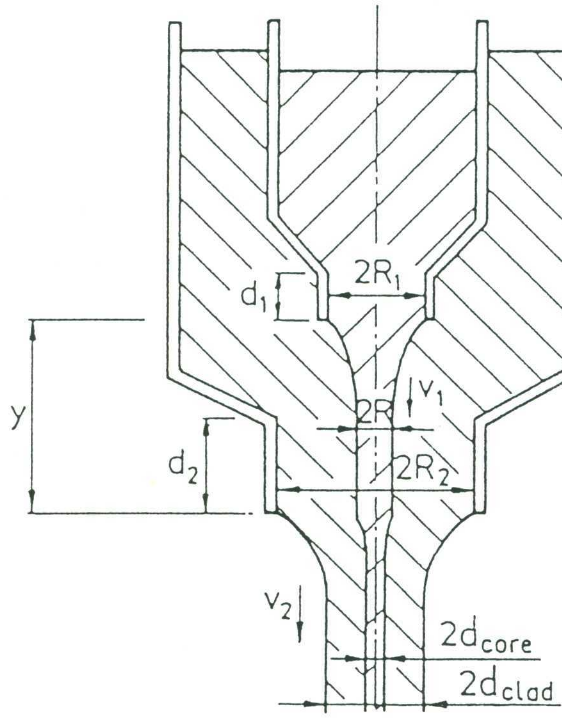


Figure 9. Simplified diagram of the Double Crucible Technique. (After [6]).

2.5.3 Vapour Phase Deposition

The process that yields the lowest attenuation losses and the most consistent performance is drawn from the preform fabricated by vapour phase deposition. There are a number of techniques using this type of process. Common to all vapour phase deposition techniques is the use of pure silica as a base, doped with other oxides (such as GeO_2, P_2O_5 and B_2O_3) to produce changes in the refractive index. The resulting cylindrical preform has the desired refractive index variation with its cross-sectional area being many times that of the finished fibre.

The chemical reactions may be written down as follows:

$SiCl_4+O_2 \rightarrow SiO_2+2Cl_2$ (1)

$GeCl_4+O_2 \rightarrow GeO_2Cl_2$ (2)

$4POCl_3+3O_2 \rightarrow 2P_2O_5+6Cl_2$ (3)

$4BCl_3+3O_2 \rightarrow 2B_2O_3+6Cl_2$ (4)

The reaction in (1) gives layers of pure silica, while the other reactions can be used to dope the silica to increase or decrease its refractive index. The reactions of (2) and (3) cause an increase while (4) causes a decrease. After deposition of the core-cladding boundary layers, subsequent layers are formed by increasing the amount of oxygen bubbled through, for example, the germanium tetrachloride ($GeCl_4$).

Singlemode, step index multimode and graded index multimode fibres can all made by the vapour phase deposition process. The vapour phase deposition techniques can be divided into three categories:

(1) external deposition;
(2) axial deposition, and;
(3) internal deposition.

2.5.3.1 External Deposition

External deposition by flame hydrolysis is referred to as external chemical vapour deposition (external CVD), outside vapour phase oxidation (OVPO) or outside vapour deposition (OVD). In this technique (used by Corning) the raw materials ($SiCl_4$ with oxygen) necessary for glass formation are injected via a burner onto a "bait" rod, producing a spray of ultra fine silica particles where they are deposited in soot form. The rod is simultaneously under rotation and translation. Layer by layer, a cylindrical porous glass preform is built up (typically 200 core layers).

After soot deposition is completed, the "bait" rod is removed by drilling. The soot preform is first dehydrated at high temperature in a chlorine atmosphere and then sintered in a furnace at a higher temperature to form a solid preform ready for fibre drawing. These steps are illustrated in Figure 10.

During the drawing process, the central hole of the sintered preform closes up.

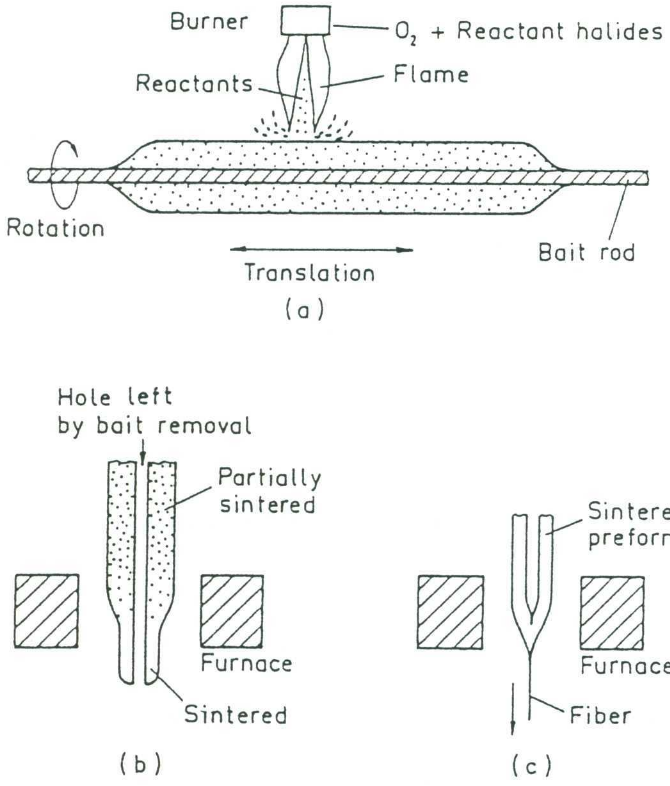


Figure 10. Outside Vapour Deposition Technique.

(a) Soot deposition.

(b) Preform sintering operation.

(c) Fibre drawing.

(After [6]).

The main advantages of the OVD technique are:

(i) the precise control of the refractive index profile, and;

(ii) the ease with which relatively large preforms can be manufactured (greater than 50 km fibre length have been produced by Corning).

The disadvantages are:

(i) the existence of the central hole after bait removal, and;

(ii) the higher attenuation peak in connection with the absorption of hydroxyl impurities (particularly at the longer wavelengths) compared with axial deposition technique.

2.5.3.2 Axial Deposition

An alternative technique, developed in Japan (by Sumitomo), produces extremely low loss fibres with negligible water contamination. This is known as vapour axial deposition (VAD) or axial vapour deposition (AVD), another form of external deposition.

In this case, the soot deposition occurs vertically at the end of the rotating bait which is being continuously pulled upwards and withdrawn as the preform builds up.

Gaseous raw materials, such a SiCl4, $GeCl_4$ and PCl_3, are fed into an oxy-hydrogen burner. The resulting stream of fine silica particles are produced into a flame hydrolysis and sprayed onto one end of the bait rod, where it is deposited in porous form. The doped core and a thin cladding region are formed by this process.

During its upward motion, the porous preform passes through a ring-like furnace where it is sintered. As in OVD technique, hydroxyl (OH) ions are removed (dry out the glass) by heat treatment in a thional chloride ($SOCl_2$) atmosphere before the sintering operation.

A very long core preform can be manufactured using this technique. This technique is illustrated in Figure 11.

Alternatively, a cladded fibre can be constructed by inserting the core preform inside a lower refractive index glass tube and pulling the fibre from the tube. This is similar to the rod-in-tube configuration.

The main advantages of the VAD technique are:

(i) the potential for the manufacture of large preforms.

(ii) complete avoidance of the central hole found in the OVD preform, and;

(iii) the attainment of low attenuation fibre when enclosed deposition is used.

The main disadvantage is:

(i) the difficulty of accurate profile control.

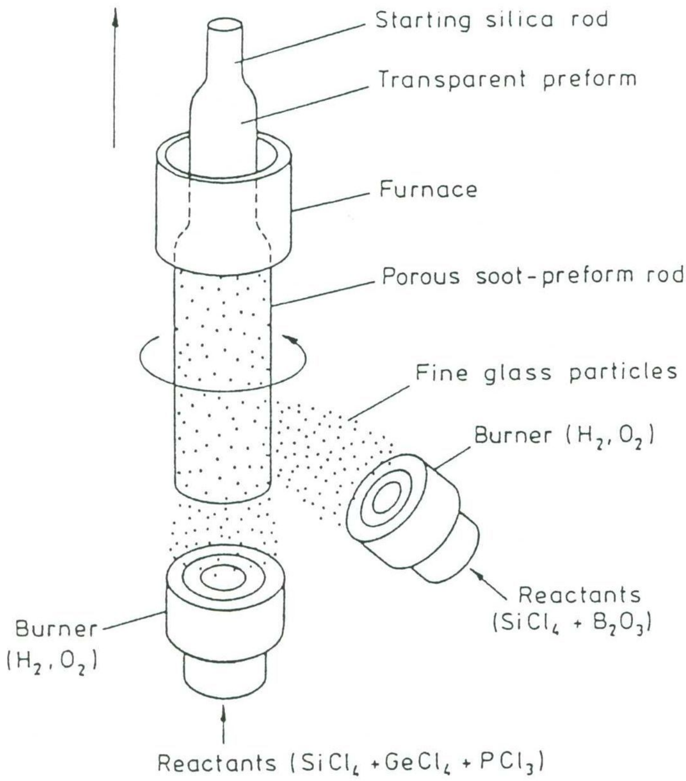


Figure 11. Vapour Axial Deposition Technique. (After [6]).

2.5.3.3 Internal Deposition

Internal deposition by flame hydrolysis is referred to as internal chemical vapour deposition (internal CVD), modified chemical vapour deposition (MCVD) or inside vapour deposition (IVD). In this technique, a fused silica tube is rotated in a glass lathe and heated externally with an oxy-hydrogen burner to thermally trigger vapour phase oxidation of the metal halide gases which are flowing inside and depositing silica soot on the tube wall. Ultimately, the tube becomes the outer part of the fibre cladding and the deposited soot becomes the fibre core.

The travelling oxy-hydrogen burner moves along the tube, fusing the deposited material to form a transparent glassy film. Layer upon layer (typically 50-100 layers) is deposited as the burner repeatedly traverses the length of the tube. By changing the concentration of dopants, the refractive index can be changed from layer to layer, creating a graded index profile.

After enough soot is deposited on the inside wall the metal halide vapour flow is then stopped and the flame intensity is increased so that as the burner traverses the tube it softens and collapses into a solid preform ready for fibre drawing.

The major advantage of the internal CVD (or MCVD) technique is:

(i) the high degree of purity that can be achieved by exploiting the enclosed nature of the deposition process.

(ii) many advanced fibre design can be produced, that is, low-birefringent fibres, high-birefringent fibres (linear, circular) and fibre lasers.

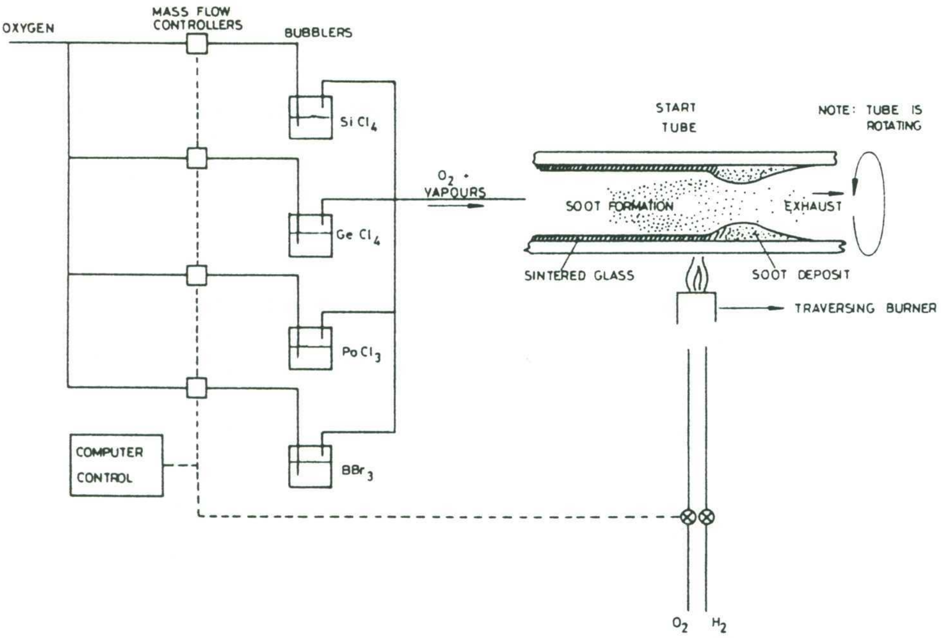
The main disadvantages are:

(i) the finite number of layers that can be practically deposited.

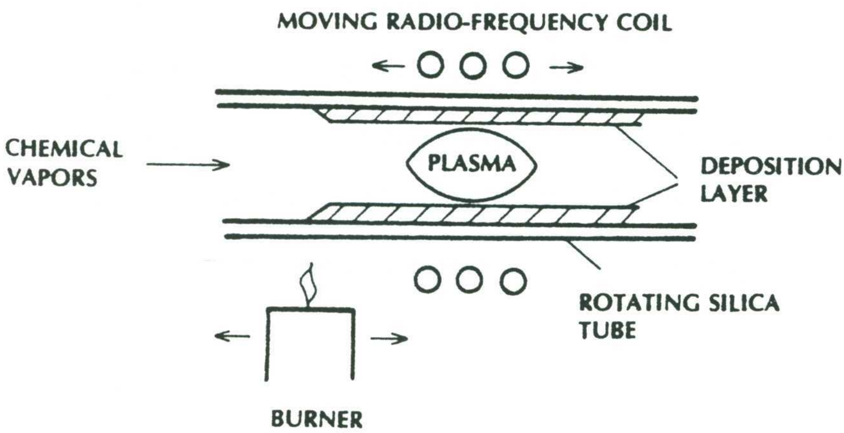
As a result, fibres made by this technique often have troublesome ripples in the refractive index at the centre of the core. This occurs during the collapse of the preform tube. When it is heated some of the deposited dopant material vaporises and is lost.

This difficulty is reduced in the Plasma-Enhanced Modified Chemical Vapour Deposition (PMCVD) technique developed at Philips Research Laboratory. This process is similar to the MCVD technique except that the deposition layer is also heated by a Radio Frequency (RF) coil. The RF heating coil and the burner independently traverse the tube.

The core is deposited into several thousand thin layers; hence the small amount of ripple is further smoothed by diffusion during the various heat treatment stages. This also contributes to the control of the refractive index profile with possibility of making very high bandwidth multimode fibres (greater than 2 GHz). Figure 12 illustrates the CVD and PMCVD techniques.



(a)



(b)

Figure 12. (a) Internal chemical vapour deposition, and; (After [7]).

(b) Plasma-enhanced modified chemical vapour deposition techniques. (After [1]).

2.5.4 Fibre Drawing

Once the preform is prepared it is placed in a fibre drawing apparatus, shown in Figure 13, capable of producing fibre with excellent diameter control and the ability to apply protective coatings which are necessary to minimise fibre attenuation and improve strength.

The preform rod is fed slowly into a furnace from which fibre is drawn onto a take-up spool via a capstan. The furnace is typically a carbon resistance or zirconia induction furnace, operating at 2000°C and stabilised within 1°C in order to reduce diameter fluctuations.

Fibre is drawn from the end of the hot preform and the diameter of the drawn fibre is measured on-line by a scanning laser monitor. A primary coating is applied to the fibre immediately after it has been drawn and measured. It then passes over a capstan drum where the speed is adjusted to maintain the correct fibre diameter.

The coating used is normally thermally cured silicone rubber, UV cured acrylate or polyurethane to protect the fibre from moisture and abrasion. A secondary coating may be added to give the fibre improved strength. The fibre is then ready for cabling.

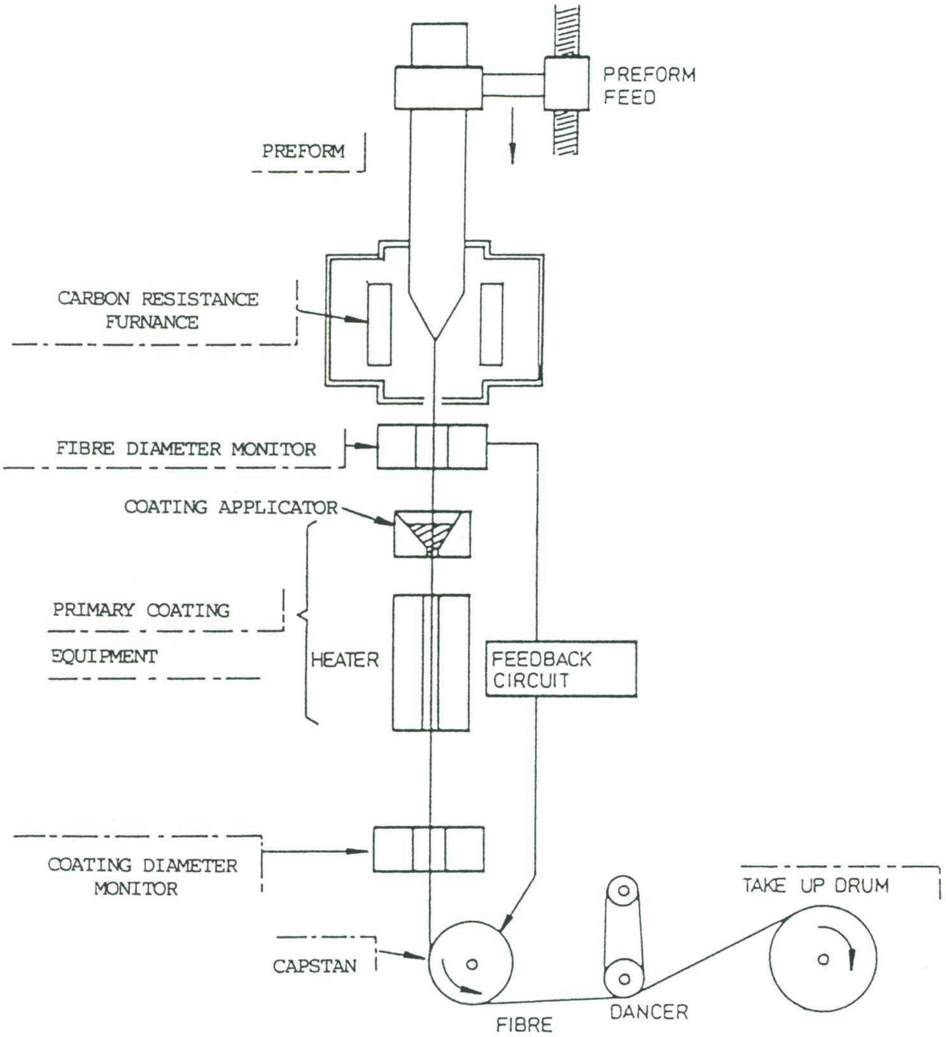


Figure 13. Fibre drawing apparatus.

CHAPTER THREE

OPTICAL FIBRE CABLE

3.1 Introduction

The basic principles of optical fibre cable construction are the same as the conventional metallic cables, that is, to design with materials which will maintain transmission and mechanical properties requirements during the cable manufacturing process, installation and operation.

The concept of cable design, from a cable manufacturer's perspective, will be thoroughly presented in this chapter. Different types of cable construction with their applications are discussed, particularly the transmission, mechanical and environmental characteristics that a cable design engineer must consider.

The contents of this chapter have been compiled based on the author's professional experience in cable design and manufacturing of optical fibre cables.

3.2 Cable Design

There are several types of cable design and construction that may be employed to suit different applications depending on the transmission system requirements and the installation conditions. Optical fibre cables may be used in all areas of telecommunication networks and they can be classified into three areas, based on the type of installation:

External cables

- trunk.
- junction.
- distribution.
- aerial link.

Internal cables

- customer premises.
- central office.

Submarine cables

- off-shore.
- underwater link.

The choice of fibre protection and cable construction involves many considerations, amongst which are the following:

- the number of fibres in the cable;
- "tight" or "loose" construction;
- the necessity or otherwise of pressurisation;
- absolute performance of the fibres and their behaviour at varying temperatures;
- the presence or absence of metallic elements;
- the type of installation and service to which the cable is to be applied;
- the type of external protection, and;
- mechanical characteristics of the cable (bending, with or without load, tensile strength, crush resistance, impact resistance, twisting, etc.).

Other design factors such as, environmental characteristics, long term reliability (normally 40 years), ease of installation and jointing, and network application need also to be taken into account.

The environmental conditions to be considered depend on the type of installation, such as aerial, buried, duct, tunnel, building and underwater. These are therefore exposed to severe natural conditions and required to be considered with care in order to determine the cable construction so that the desired characteristics are maintained.

3.3 Mechanical and Environmental Characteristics

It is important to consider in cable design the conditions that the cable may be exposed to during manufacture, installation and operation. The following are the constructional considerations for optical fibre cables under the mechanical and environmental conditions:

a) <u>Residual Fibre Strain</u>

Residual fibre strain may be caused by tension, twist and bending during cable manufacture, installation and operational environment. This reduces the life of the fibre due to weakening of the glass in the presence of environmental contaminants. The level of residual strain also affects the level of dynamic strain which the fibre can withstand before breaking.

Glass used for optical fibre behaves elastically up to a few percent elongation, then it fails in brittle tension. The strength of fibres is mainly governed by the size of flaws which are always present under the influence of stress and thus causes the glass fibre to weaken.

This weakening is accelerated if the stress is combined with moisture. When designing optical fibre cables, it is important to know the minimum strength of the fibres. For this reason, optical fibres are proof-tested to certain stress levels during manufacture (normally between 0.5 to 1 percent).

In instances where the cable is installed in a high moisture environment or aerial application with large thermal changes and strong winds, a larger proof-test strain may be required or the installation must compensate for the conditions.

The cable is normally designed to 50 percent of the fibre proof strain to minimise residual stress to fibres within the cable when subject to tension, torsion and bending during process, installation and operational environments.

b) <u>Impulsive Fibre Strain</u>

Impulsive fibre strain may be caused by impact, crush or excessive tension and bending during installation and the operational life of the cable. When the impulsive strain exceeds a certain magnitude, surface cracks will grow and reach a critical size causing breakage to occur in the optical fibre.

In cable design, the impulsive fibre strain is considered by employing a secondary protective layer over the optical fibre for the protection of these external lateral forces. Further protective layers are also employed over the optical cable core in forms of wrapping tapes and extruded sheath material.

If the cable is subject to impulsive strain and dynamic stress from cable tension and bending during installation and the operational life of the cable, the strength elements in the cable must be selected to accommodate these combined strains. These include armouring, extra thickness of protective layers or metal tape/sheath.

c) Fibre Macrobending

Macrobending of an optical fibre may be caused through bending of the fibre during cable manufacture (cable stranding, bending around pulleys, winding onto a spool) or pulling around a corner during installation. This may result in an increase of attenuation.

The cable construction must be selected to ensure that the fibre cannot be bent to a radius where increased optical losses occur due to macrobending. Also, care needs to be considered when selecting pulley diameter size (during cable manufacture or installation), and minimum barrel diameter of the spool that the cable is wound onto.

d) Fibre Microbending

Microbending of an optical fibre may be caused by localised lateral forces. These may be caused by manufacturing and installation strains, as well as dimensional variations in the cable materials due to temperature changes.

The effect of fibre microbending is to increase the radiation losses (scattering) in the fibre. Sensitivity to microbending is a function of the difference of refractive index of the core and the cladding, and of the diameters of the core and cladding.

Therefore, the smaller the mode field diameter (singlemode) or larger numerical aperture (multimode) would reduce the susceptibility to microbending.

The design of appropriate protective fibre jacketing and cable structure can minimise the effect of microbending. It is important to select cable components which prevent lateral forces (compression and expansion) on the fibre due to temperature changes or external mechanical forces, that is, allowing enough fibre excess length in the cable.

e) <u>Water and Moisture</u>

The presence of water or moisture reduces the tensile strength and the lifetime of the fibre. Optical loss may also increase due to the generation of hydrogen when water is present in the cable structure, particularly when cable construction incorporates metallic elements.

Water may penetrate along the cable core or between sheath layers, if inadequate cable construction or sheath damage is made to the optical cable. Water blocking materials (such as jelly compounds) are applied during cable process to prevent or minimise water penetration through the cable core. For unfilled cable, dry air pressurisation during installation and operation is used.

Moisture may permeate into optical cables through diffusion, as most of the materials used in optical cable are not impervious to moisture, hence the moisture content in the cable will rise with time. Permeation is minimised by longitudinal overlapped and bonded metallic tape and the use of water blocking material.

A complete prevention in permeation can be achieved by using a soldered metallic tape or an extruded metal sheath (see Section 3.4.7). These constructions are generally recommended for unfilled cables due to problems associated with trapped hydrogen.

f) <u>Hydrogen</u>

Hydrogen in the fibre core will increase the optical loss caused by the formation of OH ions in the glass.

Hydrogen gas concentration may build up within a cable from:

(i) hydrogen released from cable components;

(ii) electrolytic effects between two different metallic elements in the presence of moisture;

(iii) hydrogen contained in pressurised air pumped into the cable, or;

(iv) corrosive reaction of the metallic elements in the presence of moisture.

Materials used in the cable construction are selected so that the concentration of hydrogen within the cable is low enough to ensure the long term increase of optical loss is acceptable. Alternatively, hydrogen absorbing materials (normally in jelly form) or dynamic gas pressurisation can be used to eliminate or reduce the added loss due to hydrogen within the cable core.

g) <u>Lightning</u>

Optical cables containing metallic elements have a greater susceptibility to be struck by lightning. Metallic elements, such as conventional copper pairs, metallic sheath and/or metallic strength member, when struck by lightning, will cause a current to flow in the cable.

The mechanical impact and energy dissipated from the lightning strike may damage the sheath and the fibre in the cables. In order to avoid lightning strikes the cable is constructed with non-metallic elements (dielectric).

h) <u>Nuclear Radiation</u>

Fibres are insensitive to electrical interference but they are sensitive to nuclear radiation. Exposure to nuclear radiation such as gamma rays, electrons, protons, heavy ions and neutrons causes increased optical loss.

Fibres used in weapon systems and space systems can be exposed to radiation in space (such as Van Allen Belt protons), as can fibres employed in systems that monitor and detect radiation at nuclear waste sites, fission and fusion reactors.

Radiation can interact with atomic nuclei in the fibre material, displacing nuclei from their normal position in the crystal lattice. This displacement causes an interstitial defect. Defects within a fibre may cause light absorption at undesirable energies within the wavelength range used for sensing or communication links (600 - 1600 nm), so the information carrying light photon is absorbed before it can be detected and de-coded.

The longer wavelengths (greater than 1300 nm) are most popular for optical communications because of the lower the intrinsic fibre attenuation. The radiation induced effects are also less severe at these long wavelengths.

This is because more energetic light is needed to raise an electron into an allowed state in the conduction band.

The induced losses are reversible over a period of time depending on the initial and final attenuation, and on a recovery lifetime factor (dependant of dopant levels in the cladding of silica fibre). To prevent or minimise nuclear radiation in optical cables, a radiation resistant optical fibre is used in this application.

Radiation resistance can be achieved by varying manufacturing processes such as drawing parameters, doping and temperature. For example, Germanium-doped fibres are suitable as radiation resistance fibres because radiation induced attenuation is less severe compared with phosphorus-doped fibres.

3.4 Cable Construction

As discussed earlier, there are several types of cable construction that may be employed to suit different applications. In this section, we will describe the construction of an optical fibre cable from the basic element (optical fibre) and build it up in layers to its outer protection (sheath).

Design features will be discussed including information on materials used in cable and manufacturing equipment.

3.4.1 Optical Fibre

There are two types of fibres commonly used in optical fibre cable. These are multimode fibres, and singlemode silica glass fibres. The size and transmission characteristics of the optical fibres used comply with one of the following International Standards in order to guarantee the compatibility of fibres of different manufacturers:

a) IEC (International Electrotechnical Commission) Standards [8]:

- IEC 793-1 Optical Fibres Part 1: Generic Specification.

- IEC 793-2 Optical Fibres Part 2: Product Specification.

b) CCITT (International Telegraph and Telephone Consultative Committee) Recommendations [9]:

- G.651 Characteristics of a 50/125 um Multimode Graded Index Optical Fibre Cable.

- G.652 Characteristics of a Singlemode Optical Fibre Cable.

- G.653 Characteristics of a Dispersion Shifted Singlemode Optical Fibre Cable.

- G.654 Characteristics of a 1550 nm Wavelength Loss Minimised Singlemode Optical Fibre Cable.

The primary coating of the fibre, normally a layer of ultraviolet cured acrylate with a outer diameter of 250 um, must meet the following requirements:

- withstand physical handling of the fibre during cable manufacture and installation;
- the primary coating materials must be selected to ensure stability over the range of temperature that the cable is designed and in the presence of moisture;
- the coating should be removed easily with fibre stripping tools for splicing purposes without damage to the fibre;
- the coating material should have a slightly higher refractive index than the fibre cladding and absorption loss to prevent the propagation of undesirable modes;
- the primary coated fibre should be proof-tested to a selected level in order to be able to predict the fibre life for the installation and expected environmental conditions.

If the primary coating surface needs to be coloured for fibre identification, the ink used and the colouring process should ensure compatibility with other materials used in the cable and be stable during the lifetime of the cable without affecting any transmission characteristics.

There are two techniques to colour an optical fibre. One utilises ultra-violet (UV) light and other uses thermal heat ovens to cure (dry) the ink applied over the fibre coating.

The UV curing process is most commonly used, as the equipment requires much less floor area for installation and the colouring speed is higher than thermally cured process (up to 1000 m/min can be achieved, three times faster than oven curing).

Both processes are equally good technically; however, the thermal cured process has an advantage on costs, that is, one third of the ink cost and half the operation cost compared with UV process, but the UV technique produces a much higher output.

3.4.2 Secondary Protection

Primary coated fibres may be protected by a number of methods. This selection is guided by design preference or by taking into account the optical fibre construction. Its main purpose is to improve the tensile strength of the fibre and to provide radial reinforcement.

The secondary protection can be classified into the following categories:

- loose construction within a tube or groove;
- tight polymer coating/jacketing, and;
- ribbon construction.

3.4.2.1 Loose Tube Construction

The primary coated fibre lies in a plastic tube, having an inner diameter considerably larger than the fibre diameter. Filling compound may be used within the protective tube as a means of protecting the fibre from the ingress of water or moisture. Loose tube construction permits the intrinsic fibre to move freely in all directions and maintain transmission characteristics of the fibre practically unchanged after cabling.

The material used for loose tube is a thermoplastic polyester or PBT (Polybutylene Terephthalate). They are extruded in the Buffering line (loose tube extrusion line) to a speed up to 150 m/min, where the filling compound is also injected (if required) inside the tube concurrently in this process. The line speed is dependable on the size of the tube, that is, the wall thickness and tube diameter.

The advantages of loose tube construction are:

(i) flexibility (lower minimum bending radius);

(ii) easy installation (fibres are contained within a tube, hence easy handling and the tube can be taken to the termination point without exposing the fibres), and;

(iii) higher fibre excess (length) in the cable allowing better tensile performance.

The disadvantages are:

(i) lower impact tolerance, and;

(ii) lower crush resistance compared with slotted core construction.

Figure 14 illustrates primary coated fibres protected by a loose tube.

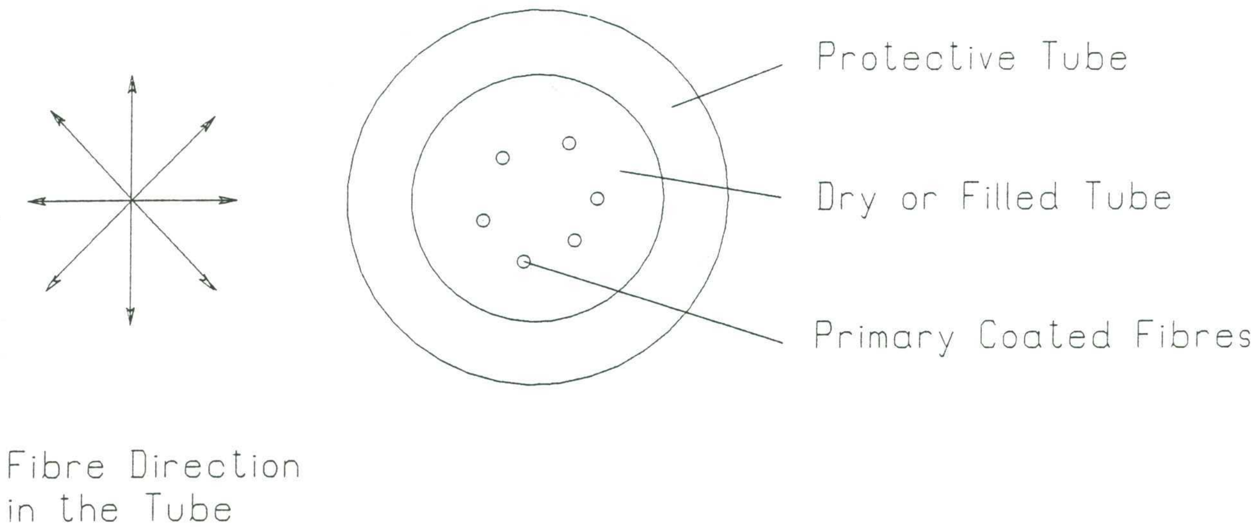


Figure 14. Loose tube construction.

3.4.2.2 Slotted Core or Groove Construction

The cabling element (slotted core) consists of a V-grooved plastic core extruded around a central strength member with the slots helically or reversally laid (S-Z or sinusoidal) along the slotted core. This provides the element with enhanced mechanical and thermal qualities. The primary coated fibre lies in each groove without tension and with a slight fibre excess length. See Figure 15.

The material used in slotted core is made of either high density polyethylene (HDPE) or polypropylene (PP). The extrusion line speed is quite slow compared with loose tube process, around 15 m/min, as there is much more extruded material and the process includes a rotational head to make the V-groove.

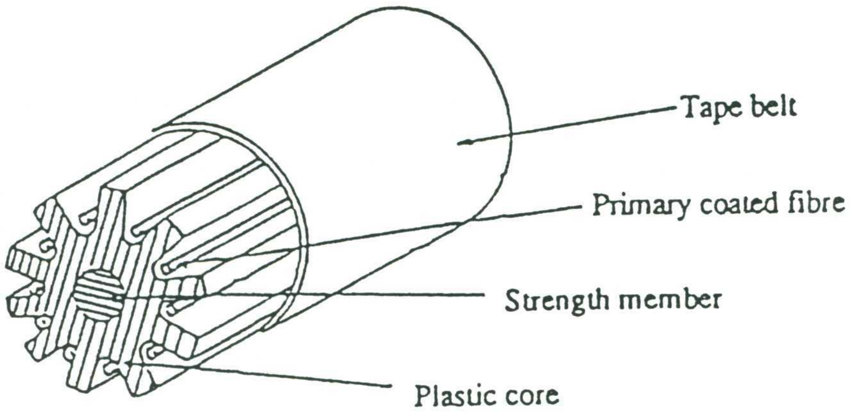


Figure 15. Slotted core construction.
(After [10]).

The advantages of slotted core construction are:

(i) high impact, and;
(ii) high crush resistance.

The disadvantages are:

(i) low flexibility, and;

(ii) lower fibre excess length compared with loose tube.

3.4.2.3 Tight Polymer Coating / Jacketing

A multiple layer tight coating consists of a composite primary layer, an optional buffer layer and a polymer secondary coating. The buffer layer improves the stability of the optical loss when the fibre is subjected to radial pressure. This layer of material has a low modulus of elasticity (normally silicon rubber built up to 0.4 mm diameter), and acts as a buffer to absorb non-homogeneities in the outer extruded secondary coating. The secondary coating of polymer (normally Nylon 12 with overall diameter of 0.9 mm) improves the compressive load characteristics and handling properties of the fibre.

Alternatively, tight jacketing can be also constructed by using a "build-up" fibre (buffered layer of a mechanical strippable acrylate coating with a 500 um nominal outside diameter), and PVC as secondary coating with 0.90 mm overall diameter. The advantage of this process is that the line speed can be doubled compared with nylon secondary coating processed in tandem with silicon rubber application.

Figure 16 shows an example of a multi-layer tight coated fibre, where the soft buffer coating/layer can be either of the material discussed depending on the construction chosen.

This type of construction is particularly suitable as an equipment tail cable when it is encapsulated in a sheath reinforced with aramid yarn strength members or laid up around a central strength member (normally aramid yarns with plastic cover) to form a multi-fibre cable construction. Example of these cables will be described in Section 3.5.

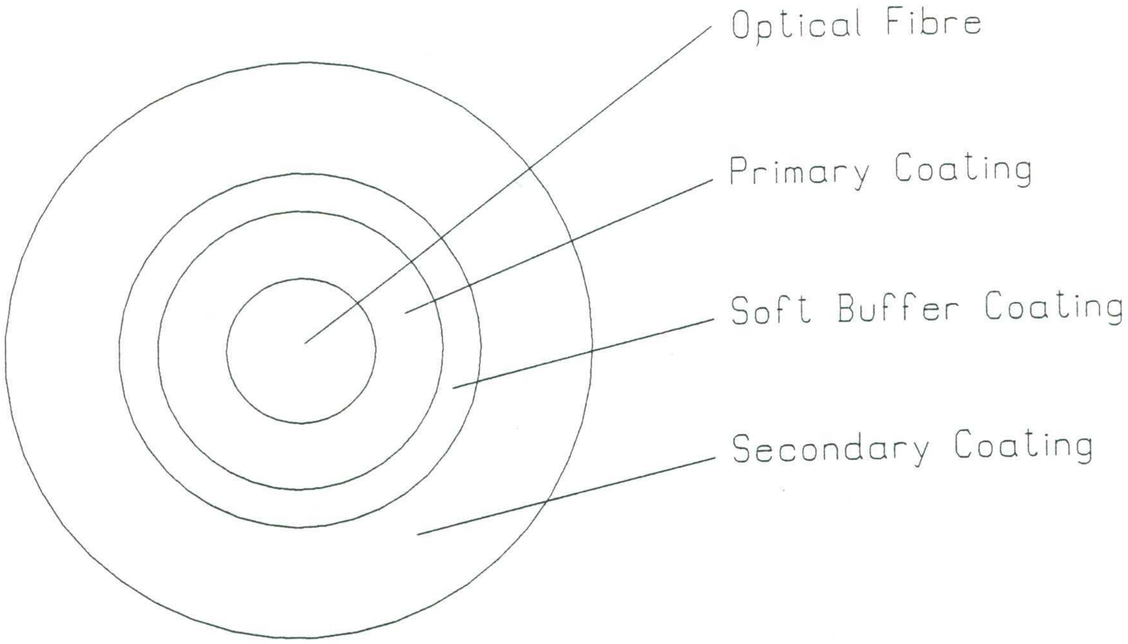


Figure 16. Example of a multi-layer tight coated fibre.

3.4.2.4 Ribbon Construction

Ribbon cables contain a linear array of fibres assembled by one of two typical methods. The first method involves a secondary ribbon coating using an ultraviolet cured acrylate material for fixing fibres in a linear array and the second method involves using adhesive tapes.

The UV cured acrylate coating is the most commonly used method. There are two types of ribbon structure using this method, the encapsulated fibre ribbon and the edge bonded fibre ribbon. See Figure 17.

This construction is developed for the telephone system in which large numbers of channels need to be transmitted along a common path between interchanges. The latest ribbon technology allows up to 16 fibres in each ribbon (using UV cured acrylate material) with the capacity of the process line speed up to 300 m/min.

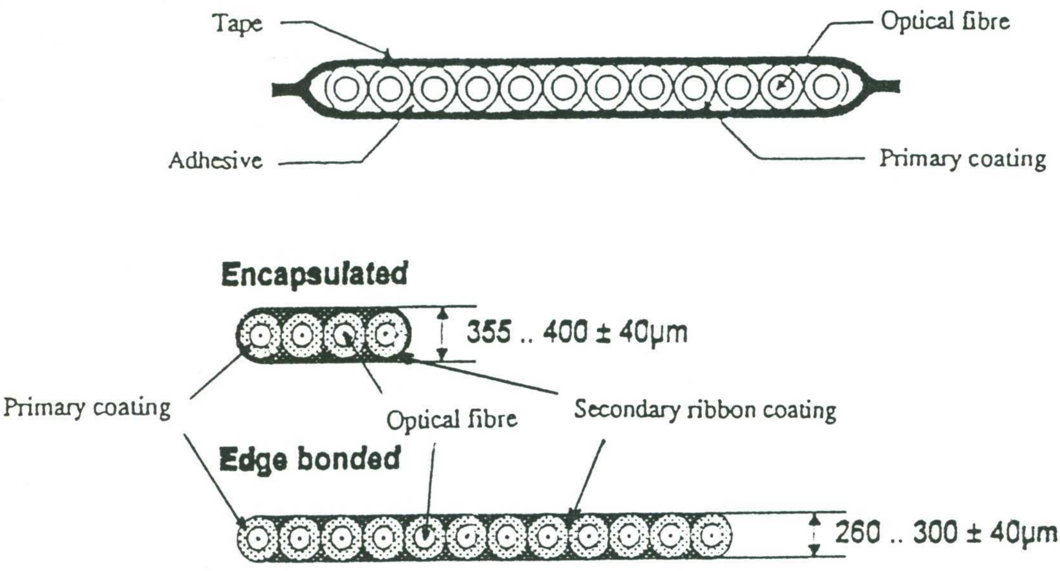


Figure 17. Examples of ribbon constructions.

3.4.3 Strength Member

A strength member is a cable component which provides sufficient strength to the cable during handling of the cable at manufacture and installation. The strength member must be selected to ensure the fibres are not strained beyond their permissible limit taking into account the dynamic strain introduced under these conditions.

The main requirements of the strength member are:

- high Young's modulus;
- strain at yield greater than the maximum designed cable strain;
- low weight, per unit length, and;
- flexibility to ensure good bending capacity of the cable.

Prior to selecting the strength member's tensile load requirements, it is necessary to take into account the cable weight, the cable design (construction, tensile strength and the use of non-metallic strength components), the range of environmental temperatures, and the conditions of installation (whether the cable is installed in air, ducts, buried or subject to bends).

Under the maximum loading of the cable, the strength member should remain elastic to ensure that when the cable is relaxed the fibres are maintained below their permissible long term residual strain (50 percent of the fibre proof strain).

There are five main types of materials employed for the construction of the strength member:

a) steel wires;
b) plastic mono-filaments (special processed polyester filament;
c) glass fibres/glass reinforced plastic (GRP);
d) multiple textile fibres (aramid yarns, polyethylene terephthalate or polypropylene yarns), and;
e) carbon fibres.

The strength member can be employed at the centre or at the periphery of the cable. It can also be used in both places, depending on the tensile requirements. The ultimate selection of material for the strength member depends upon the relative importance of cost, mechanical properties and the acceptability of a metallic component.

The most commonly used strength members are glass reinforced plastic rod and aramid yarns for dielectric cables, and high tensile steel wire where metallic components are allowed in the cable.

3.4.4 Optical Cable Core

The core of the optical fibre cable is constructed by using one or more optical fibre units. An optical fibre unit is defined as the structure selected according to the type of secondary protection of the primary coated fibres. For ribbon construction, the optical cable unit structure is in the form of either multiple fibre ribbons tightly stranded around a slotted core or multiple fibre ribbons stacked and twisted in a single tube.

In order to determine the cable core construction, it is important to consider cable installation and fibre jointing requirements. The required number of fibres in the cable and the application of the cable will also determine the selection of the core structure.

Optical cable core construction can be classified into two categories:

- single element cable, and;
- multiple element cable.

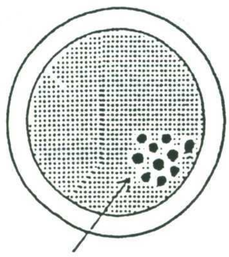
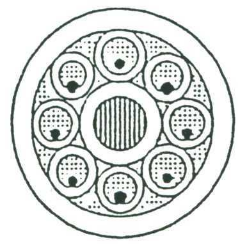
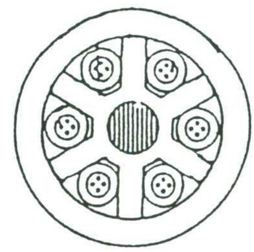
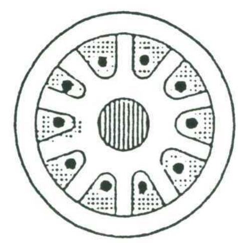
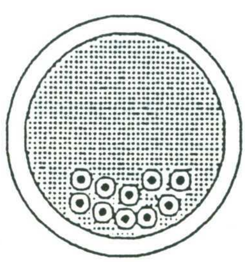
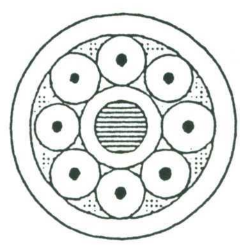
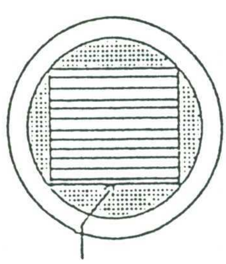
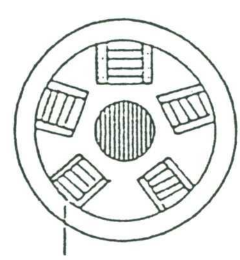
3.4.4.1 Single Element Cable

Cable core construction is based on a single optical fibre unit. This construction can be a single fibre or multi-fibre cable depending on the type of secondary protection of the primary coated fibre selected.

Examples of single element cable constructions are given in Table 3.

Other components used in optical cables as single element are insulated conductors and fillers. Insulated copper conductors (normally in quad formation, 4 wires) may be incorporated in the core assembly for power feeding of repeaters or system supervision (voice communication or alarm system). The presence of conductors in the optical cable may present a hazard in areas where power co-ordination or lighting problems exist (as discussed earlier). They also increase the cable weight.

TABLE 3. EXAMPLES OF SINGLE ELEMENT CABLE CONSTRUCTIONS (After [10]).

Protections		Structures of optical fibre units		
		Single tube strucrure	Layer structure	Slotted rod structure
Loose packaging	within a tube	 Fibre bundle		
	within a groove	——	——	
Tight secondary coating				——
Ribbon construction		 Fibre ribbon	——	 Fibre ribbon

• : Primary coated fibre(s) [one or more]

 : Strength member

 : Tight secondary protected fibre

 : Water-blocking material

The materials used as fillers are chosen on the basis of the function of the filler, that is, whether it is required for geometrical reasons or to "fill" a gap. Solid fillers are typically used for geometrical circumstances (circular PVC or polyethylene fillers) and textile fillers are used to fill the gap (polyethylene terephthalate yarns are normally used).

3.4.4.2 Multiple element cable

Cable core construction is based on multiple optical fibre units. In this construction, the multiple optical fibre units are stranded together around a central strength member with fillers, if required for geometric reasons, and held in place by helically applied tapes. The stranding process can be helically applied or reversally laid (S-Z or sinusoidal). If a second layer is required the process is performed twice with binder tapes applied between the layers.

Another type of cable core construction can be made by placing multiple single element cable or multiple element cable units loosely in binder groups stranded around a central strength member. Examples of multiple element core constructions are given in Figure 18.

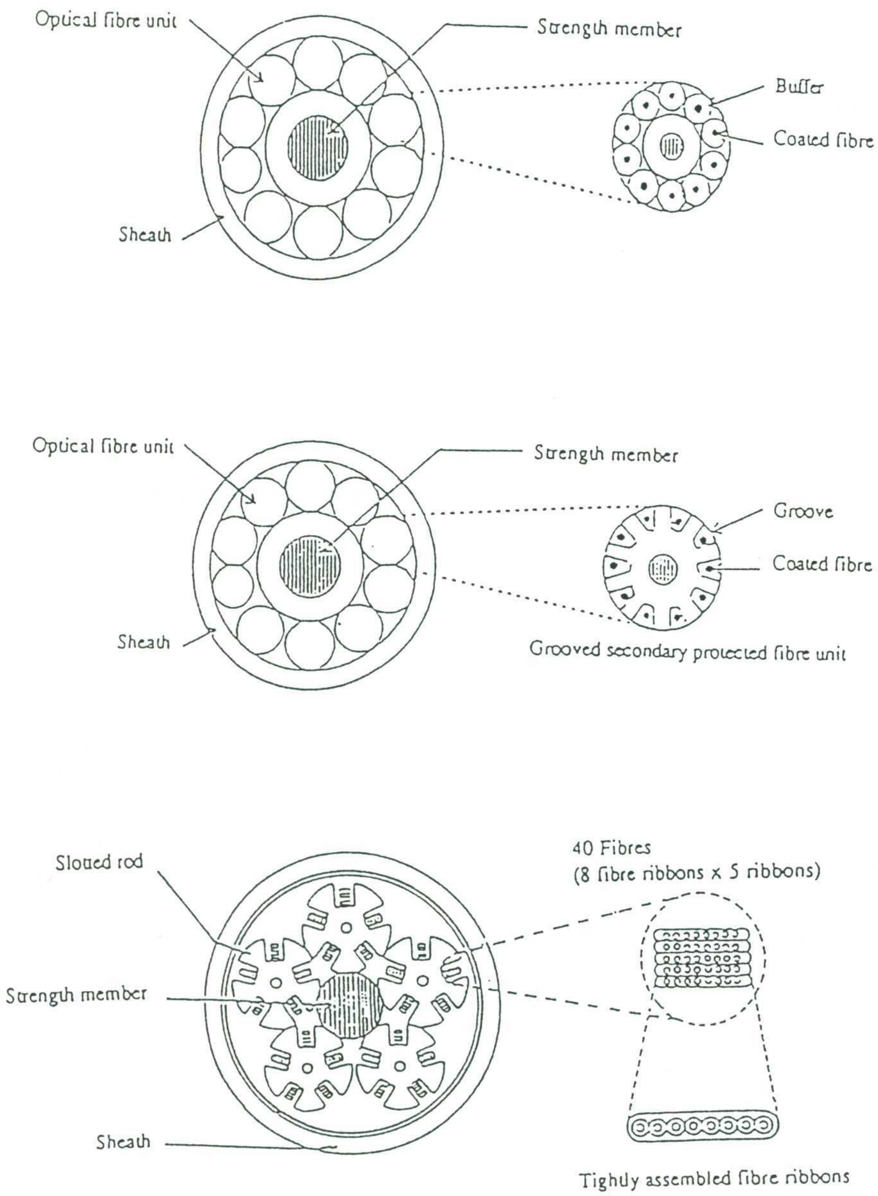


Figure 18. Examples of multiple element core constructions. (After [10]).

Once the core elements are laid-up (stranded), core wraps are used to maintain geometric uniformity of the core elements, and to provide head barriers during extrusion of the external sheath. Usually, polyethylene terephthalate tapes (25 to 50 um) is employed.

3.4.5 Water Blocking Materials

Water blocking material is one means of protecting fibres from the ingress of water or moisture. A filling compound, swelling tape, swelling powder or a combination of these materials, may be used for this purpose. The filling compound or swelling powder is applied between the interstices of the optical cable core where the swelling tape is wrapped around it. The filling compound can also be used as a filler in a tube or groove.

The main requirements for the filling compound, swelling tape or powder in optical fibre cables are as follows:

- fibre movement should not be constrained by viscosity of the filling compound;
- compatibility with primary coating or colouring materials;
- compatibility with secondary protection and sheathing materials;
- no change in the optical performance with activation of the water blocking material;
- no change in optical performance with temperature variation;
- no compound flow (drip) for filling compound under required temperature, and;
- easy removal of water blocking material for cable installation and fibre splicing.

If the cable design chosen should have an unacceptably high concentration of hydrogen predicted during its lifetime, then hydrogen absorbing chemicals may be introduced into the filling compound applied to the interstices of the cable core, or smeared between binding tapes.

The filling compound used in loose tube and slotted core is of soft thixotropic type, that is, the viscosity of the jelly is reduced under shearing action with the subsequent regeneration to original viscosity when the shear is removed. The filling compound used for interstitial filling is of a petroleum coarsed jelly consisting of a microcrystalline paraffin wax and mineral oils.

3.4.6 Pressurisation

Dry air pressurisation is normally employed to protect against water ingress on unfilled optical cable. The pneumatic system is used for cable maintenance in order to detect the ingress of water or moisture when the sheath is perforated. The optical cable core must be selected taking into account the pneumatic resistance and the cable diameter which will satisfy the installation environment.

A small core diameter in optical cable (up to 10 mm) used as single or multiple element cable, may have high pneumatic resistance from the small interstitial gaps within the cable core. In this case, gas pressurisation may be required and special low pneumatic resistance material may be introduced in cable design.

3.4.7 Cable Sheath

The cable sheath protects the cable core from mechanical and environmental damage. The sheath material is applied by an extrusion process covering the cable core with a smooth and close fit sheath, which is uniform and free of pin holes at the required sheath thickness.

The following sheath properties should be considered in cable design:

- mechanical characteristics (tensile and elongation);
- environmental performance;
- air tightness;
- moisture resistance;
- chemical resistance;

- fire retardant/resistance;
- rodent resistance;
- flexibility, and;
- mechanical stability (bending, torsion, tension, abrasion, impact and crush).

The cable sheath can be plastic, a combination of metal and plastic with metallic tape, or pure metallic layer. With the exception of plastic sheath only, these cable sheaths are used as moisture barriers. Both forms of the metallic component can be corrugated to improve the flexibility and crushing strength of the cable. The following are some examples of these types of cable sheath construction:

- PVC (polyvinyl chloride) or PE (polyethylene) plastic sheath;
- metal/plastic bonded sheath with coated aluminium or steel tape;
- metal/plastic sheath with a welded steel tape;
- metal/plastic sheath with an extruded lead or aluminium sheath, and;
- aluminium or lead extruded metal sheath.

The last three types of sheath construction form an impervious barrier against moisture.

The selection of cable sheath type depends on the mechanical and environmental conditions. A lead oversheath may be used in areas of severe or extensive exposure to petrochemicals. As a protection against rodents, a metal plastic bonded sheath with a corrugated steel tape can be used. An example of a rodent proof cable is given in Section 3.5.

3.4.8 Armour or Metallic Tape

Armour wire or metallic tape is used for added protection to the optical fibre cable to meet particular mechanical and environmental conditions. Both materials are applied helically over a cable sheath, often called bedding sheath. If a second layer is required, the process is performed twice.

The following are some examples where additional protection is applied to the cable sheath:

- submarine, lake and river crossing cables (to resist water currents and snagging, it also acts as an extra mechanical strength to the cable);

- when the optical cable is installed in marshland areas where there is a danger of damage to the cable by cattle, vehicles or rocky ground where adequate cover cannot readily be provided;
- where the optical cable is in danger of excavation;
- where the optical cable needs protection against rodents or teredo (also known as shipworm), and;
- self-supporting aerial optical fibre cable, where there is a danger of gun shot damage to the cable.

For high mechanical strength with impact or crush resistance, galvanised steel or stainless steel wires/tapes are generally used. As protection against rodents, stainless steel tape coated on both sides may be used. A copper tape may be used as anti-teredo protection.

3.4.9 Protective Jacket/Sheath

A protective jacket/sheath is applied over the cable sheath when a special purpose is required or when it acts as a sacrificial sheath to protect the under layer sheath/jacket that may be damaged during installation. An example where a protective jacket is applied to the optical cable is for insect resistance. The smooth, glossy, relatively hard surface of a polyamide (Nylon 12) jacket makes it difficult for an insect or termite to obtain a grip with its mandible.

If there is a danger of damage to the protective jacket during installation, then a sacrificial sheath is applied over the nylon jacket for protection.

In Australia, all optical fibre cables are manufactured with black polyethylene sheath and blue nylon 12 outer jacket. The outer jacket has three functions:

(a) to act as termite resistance, direct buried (normally in the Northern areas of Australia).

(b) ease duct installation, due to its low coefficient of friction the cable can be easily hauled into the duct. It is used within central distributed areas.

(c) to identify as an optical fibre cable, the blue nylon jacket signifies that it is an optical fibre cable within Telecom networks.

3.5 Example of Optical Fibre Cables

This section we will illustrate examples of different types of optical fibre cables together with a brief description of their use in the field.

Table 4 gives a summary of the features of each cable type that will be discussed in this section.

TABLE 4. SUMMARY OF DIFFERENT CABLE PROPERTIES

	PATCH CORD	*RISER*	*LOOSE TUBE*	*SLOTTED CORE*	*RIBBON*
Size Range * (No. Fibres)	1 - 12	6 - 24	2 - 216	2 - 72	60 - 1000
Strength Member	Aramid Yarns	Aramid Yarns	GRP/Aramid Yarns	GRP/Aramid Yarns	GRP/Aramid Yarns
Water Resistance	Poor-unfilled	Poor-unfilled	Good	Good	Good
Sheath	PVC	LSOH	PE/Nylon	PE/Nylon	PE
Flexibility	Very Good	Very Good	Good	Poor	Poor
Crush Resistance	Medium Good	Medium Good	Good	Very Good	Very Good
Tensile Strength	Poor-Good	Good	Very Good	Good	Good
Options	- GRP strength member - LSOH Sheath		- Steel CSM for added strength - Cu pairs - LSOH sheath - Aerial	- Steel CSM for added strength - LSOH sheath	
Benefits	- Unit construction - Direct connectorization	- Lightweight - Direct connectorization - Small diameter	- Industry standard - Easy splicing - Modular construction	- Small diameter - Very good crush	- High capacity
Disavantages	- Indoor only - Expensive	- Indoor only		- Difficult to handle - Low fibre excess	- Specialised
Uses	- Patching - Office distribution	- Vertical risers	- General - Long distance	- General - Long distance	- Data highways - CBD

* Common fibre range size

KEY

GRP - Glass Reinforced Plastics (CSM)

CSM - Central Strength Member

LSOH - Low Smoke Zero Halogen

CBD - Central Business District

3.5.1 Cord Cable

This cable is available as single cord (Simplex), two cords (Duplex) or multicord. Refer to Figures 19 and 20.

The basic cord construction consists of a tight jacketed fibre 0.9 mm in diameter around which is laid some aramid yarns and an overall jacket of PVC or LSOH. The necessary number of cords are taken to build up a cable as required.

The primary use for this cable is when it is desired to fit connectors directly to the cable for patching. The diameter of a single cord is designed to fit the connector and a locking device is incorporated to trap the aramid yarns giving strength.

There is no protection against the ingress of moisture, so the cord cable is normally restricted to indoor usage. Since the cable is very expensive it is used only for point to point patching over short distances.

3.5.2 Riser Cable

This is a relatively new development aimed to satisfy the needs of optical fibre backbones in data networks which are usually installed in riser shafts of buildings. Refer Figure 21.

Fibres are protected by tight jackets suitable to fit connectors, but due to the absence of aramid yarns and outer jacket around each fibre it will not withstand the rigours of constant patching.

The cable is lightweight, very flexible and quite strong. Usage is expected to increase as office automation becomes progressively more integrated.

3.5.3 Loose Tube Cable

This is the design developed and patented by Pirelli and pioneered in Australia to become the favoured design by Telecom, Railways and other major users. Refer Figures 22, 23, 24, and 25.

Fibres are protected by loose tubes and have some excess length such that any strain applied to the cable will not be transferred directly to the fibres. Tubes contain from 2 to 12 fibres depending on the size of the cable. The required number of tubes are laid around a central strength member (CSM) with a short oscillating lay.

The design is very flexible in that tubes may be tee'd off if required and there are a number of options available for installation in different environments. Standard cables are suited to duct and direct burial, options are available for special purpose such as, aerial installation or rodent proof. Also, if required one or more tubes may be substituted with copper pairs or quads.

A nylon jacket can be applied over the cable for protection against termites and to reduce friction when hauling into ducts.

The aspects of cable design and testing of a Loose Tube Cable will be presented in Chapter 5, where a comprehensive design criteria and construction will be discussed together with the mechanical and environmental test report.

3.5.4 Slotted Core Cable

Applications of slotted core cable are similar to loose tube cable. The slotted core consists of a V-grooved plastic core extruded around a central strength member with the slots helically or reversally laid (S-Z or sinusoidal). This provides the element with enhanced mechanical and thermal qualities. The primary coated fibre lies in each groove without tension and with a slight fibre excess length. See Figure 26.

This cable is much less flexible than loose tube design. The tensile strength is also lower (for the same amount of strength members) as it has lower fibre excess length. During installation you cannot tee-off the fibre making fibre jointing more difficult.

However, the slotted core cable provides very good crush and impact resistance, also good in thermal stability over a temperature range.

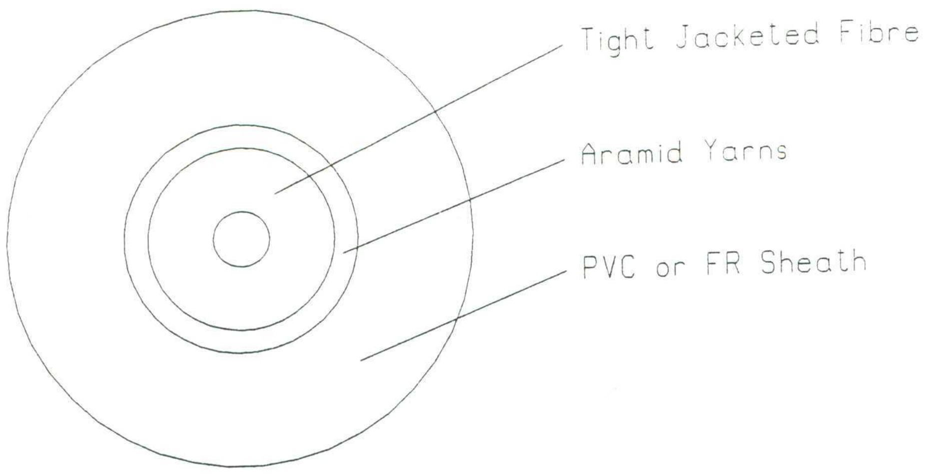
3.5.5 Ribbon Cable

The technology behind ribbon cables is the latest evolution in the cable-making. Ribbon construction contains a linear array of fibres assembled into two typical methods. The first method involves a secondary ribbon coating using an ultraviolet cured acrylate material for fixing fibres in a linear array and the second method involves using adhesive tapes, as discussed earlier.

The diagram in Figure 27 shows a cable manufactured by Pirelli Italy using 4 fibre ribbons. The ultimate design will be 12 fibre ribbons which allows efficient mass fusion splicing (current limitation on fussion splicer, although the ribbon manufacture equipment allows a maximum of 16 fibres in each ribbon). You will note that the cable shown is of slotted core design, loose tube version is also available in the market.

Usage is likely to be restricted to large administrations who require very high fibre counts.

Simplex Cord



DUPLEX CORD

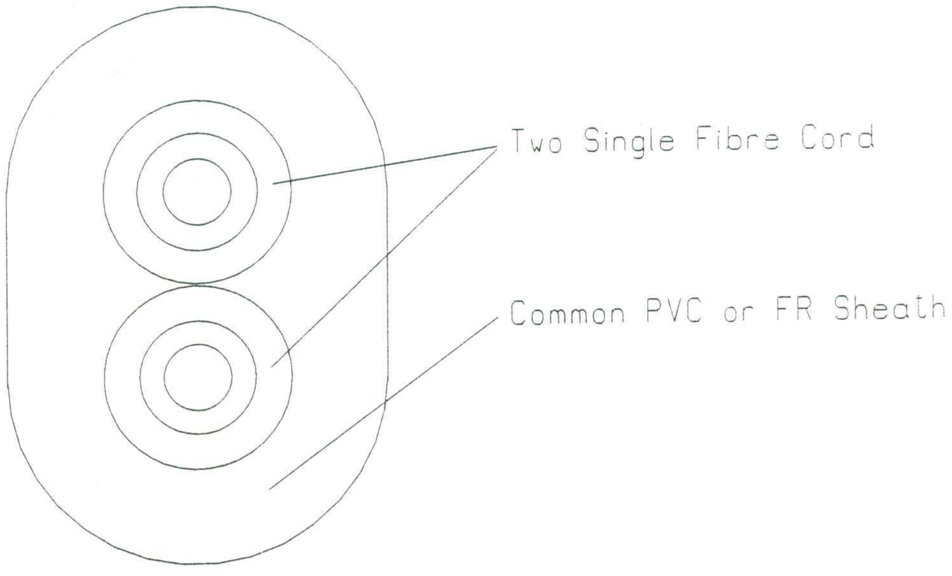


Figure 19 - Patch Cord Cables.

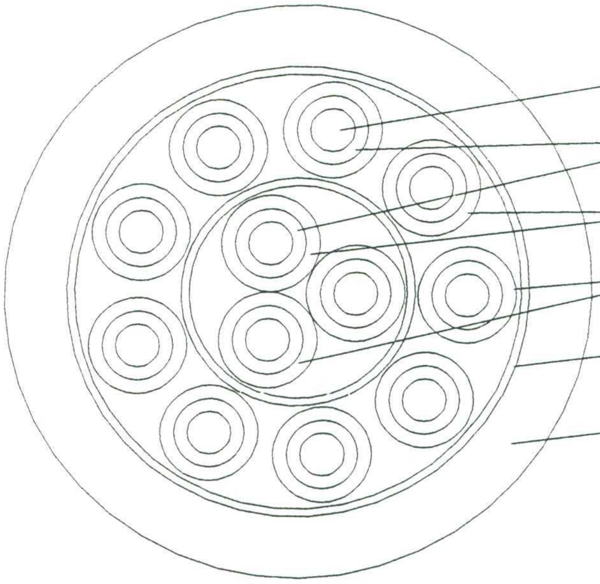


Figure 20 - Example of Multicord Cable.

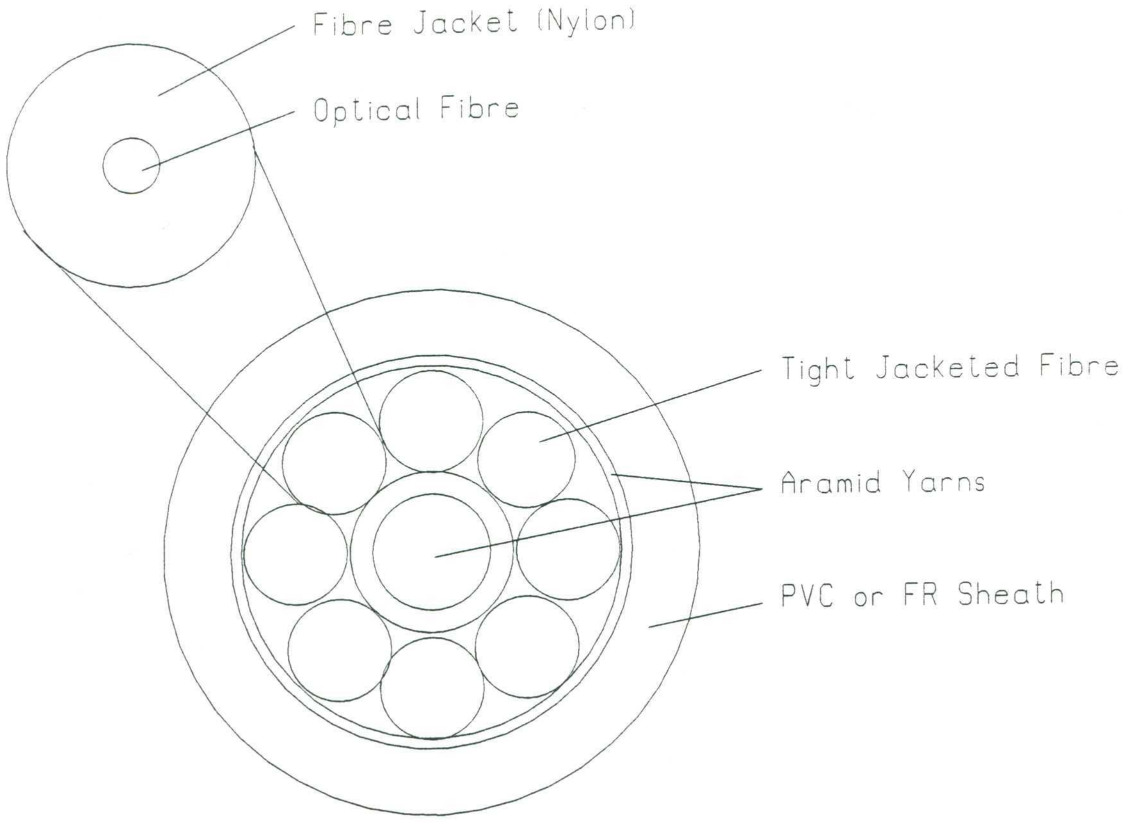


Figure 21 - Example of Riser Cable.

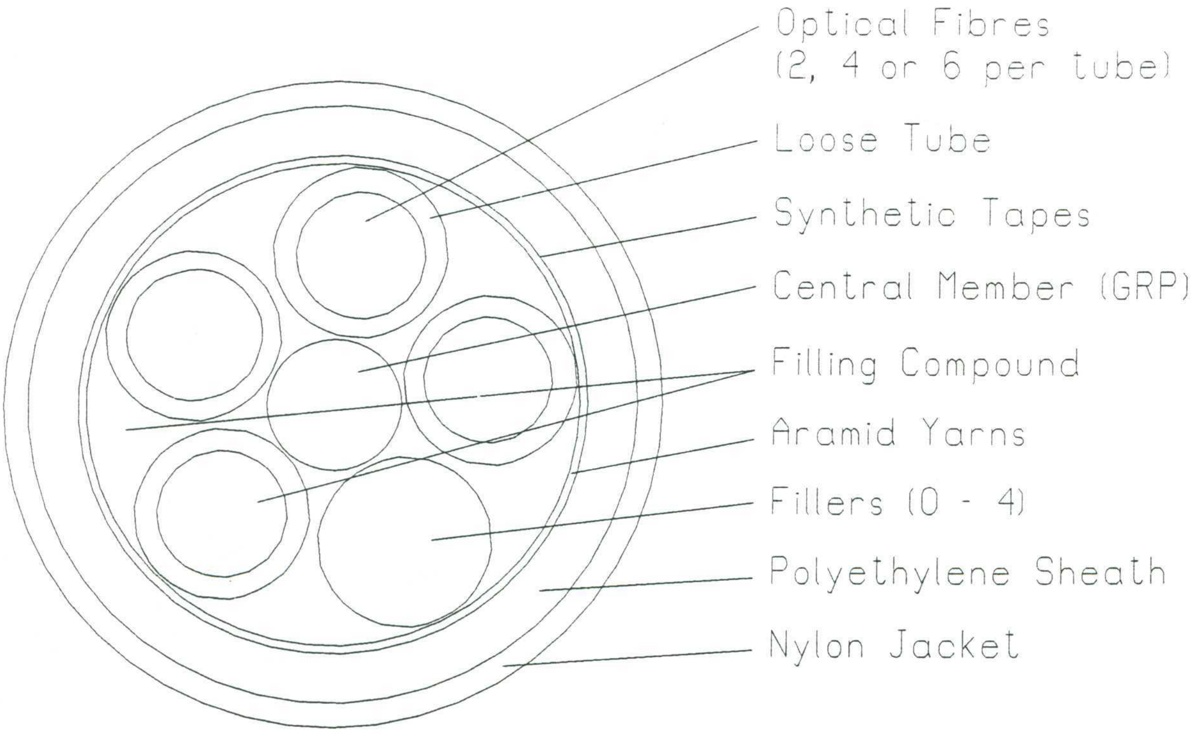


Figure 22 - Example of Loose Tube Cable.

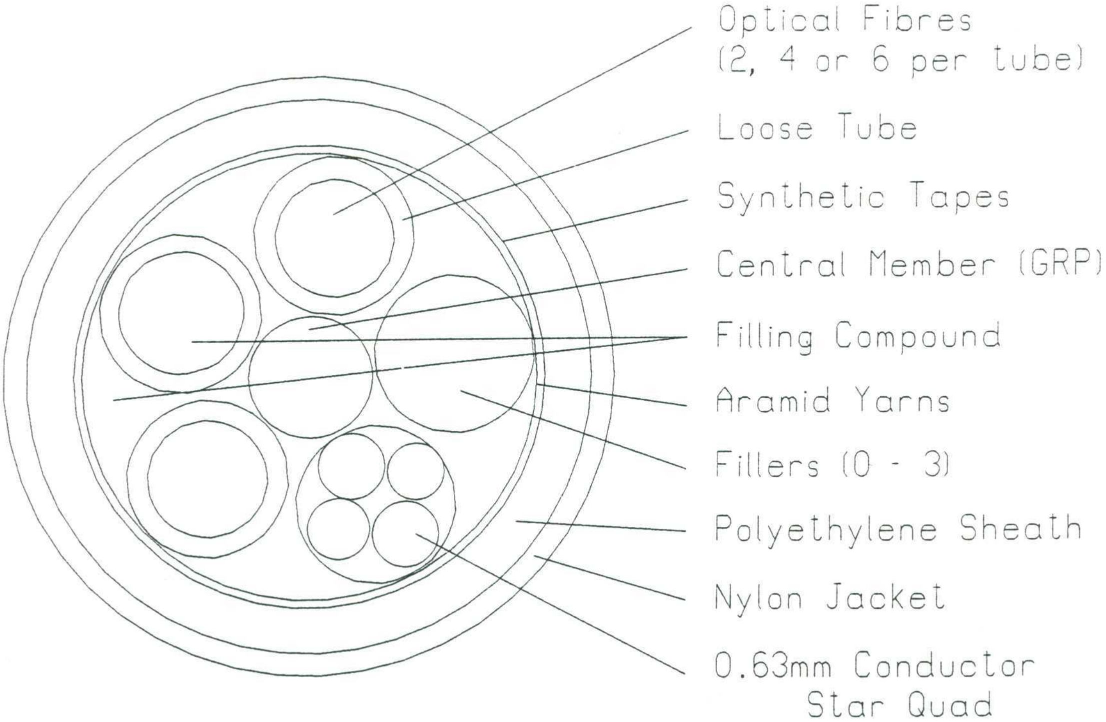


Figure 23 - Example of Loose Tube Composite Cable.

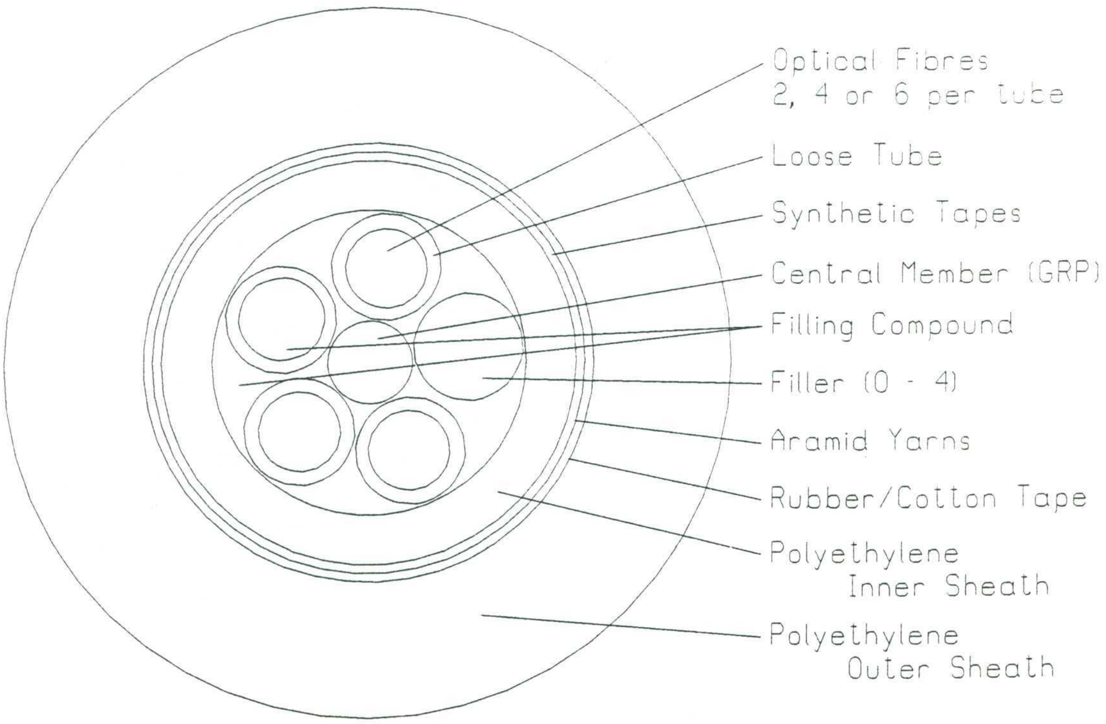


Figure 24 - Example of Loose Tube Aerial Cable.

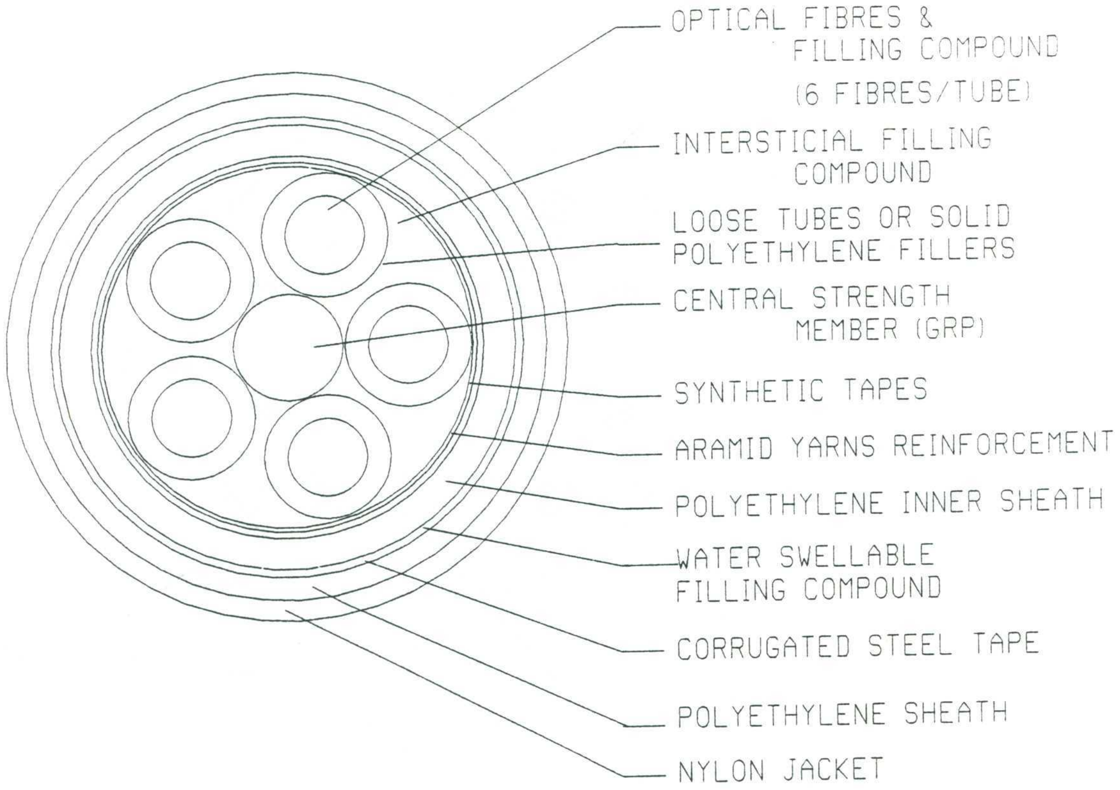


Figure 25 - Example of Loose Tube Rodent Proof Cable.

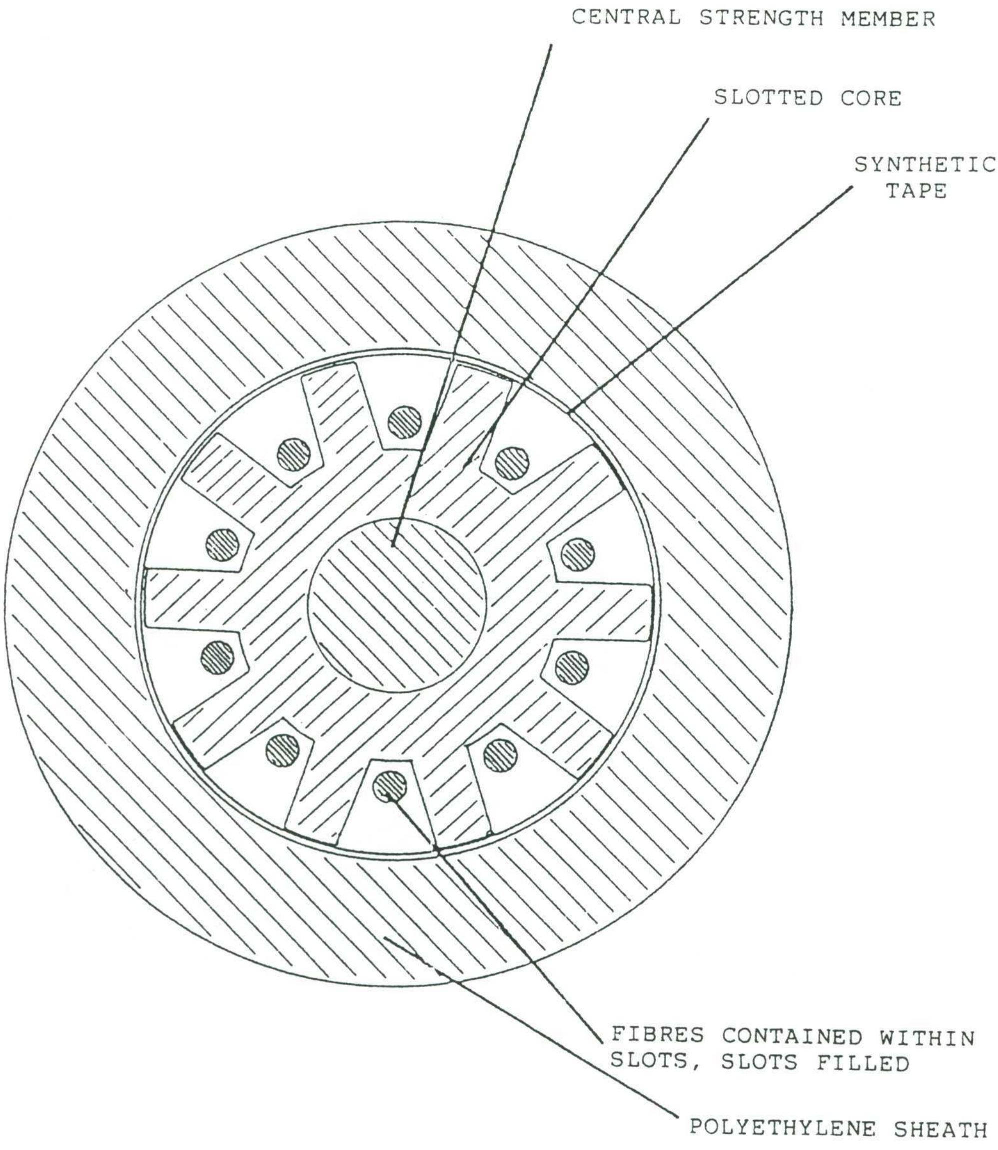


Figure 26 - Example of Slotted Core Cable.

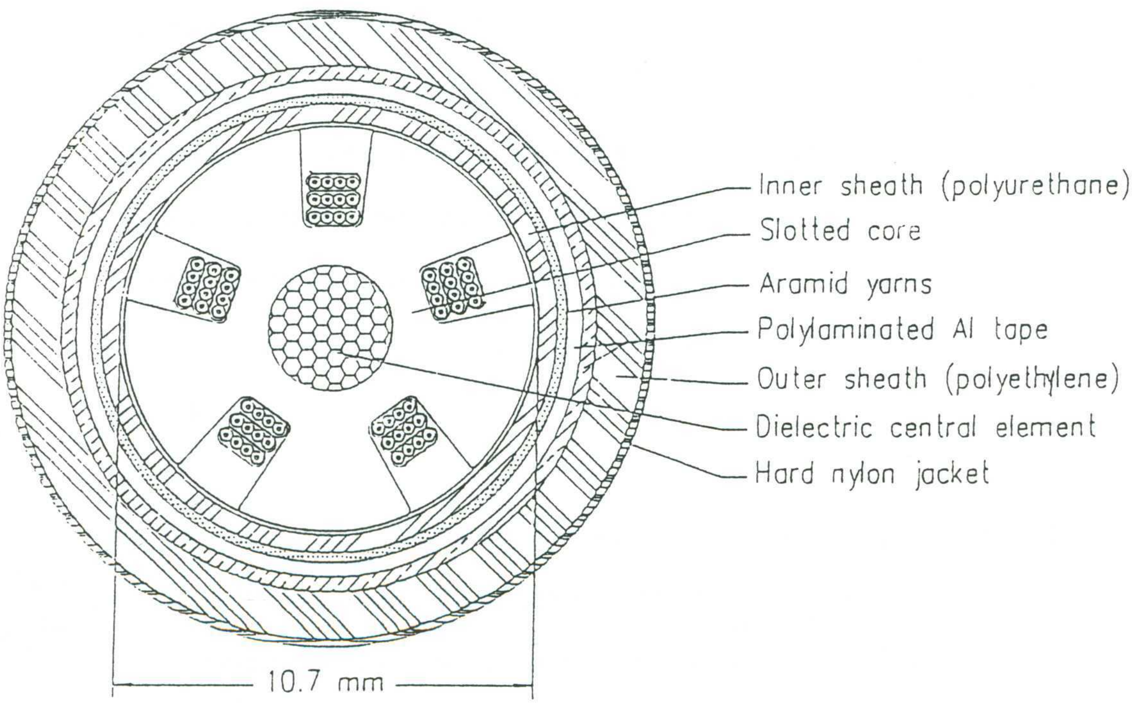


Figure 27 - Example of Ribbon Cable.

CHAPTER FOUR

OPTICAL FIBRE AND CABLE TESTS

4.1 Introduction

This chapter contains the test requirements for optical fibres and cables. Optical transmission, mechanical and environmental tests will be considered. Two sections are presented; the first section deals with the optical fibre tests, and the second section covers optical cable tests.

In Section 4.2, the optical fibre tests performed by the fibre manufacturer are summarised. The test methods and equipment/apparatus are briefly described, however, reference documents are given for further information, as these test procedures are well defined and in compliance with the International Standards.

In Section 4.3, the optical cable tests performed by the cable manufacture are described. They are categorised into three parts, mechanical tests, environmental tests, and transmission and optical tests.

Cable specification normally contains both the basic transmission performance required, and the stability of these parameters under various mechanical and environmental conditions that the cable may endure during its lifetime.

The test procedures are designed to reflect these conditions into laboratory environment, by using special apparatus, these parameters are measured against the designed criterion to determine the integrity of the optical cable.

4.2 Optical Fibre Tests

The determination of transmission and geometrical characteristics of optical fibre is an important requirements, particularly in relation to:

- experimental investigation;
- fibre manufacturing;
- cable manufacturing;
- installation performance;
- joint losses;
- system design, and;
- fault location.

Therefore, the optical fibre is tested to ensure its designed characteristics.

The optical fibre characteristics will depend on the type of fibre. In multimode fibres, the parameters of importance are physical dimensions, attenuation, bandwidth, and numerical aperture. For singlemode fibres other parameters such as cut-off wavelength, chromatic dispersion and mode field diameter are also important.

Table 5 summarises tests performed by the fibre manufacturer. These tests are discussed in following sections.

TABLE 5. TESTS PERFORMED BY FIBRE MANUFACTURER

TEST PERFORMED	FIBRE TYPE SINGLEMODE	FIBRE TYPE MULTIMODE
DIMENSION - core and cladding diameters - core and cladding non-circularities - concentricity error	YES	YES
ATTENUATION - OTDR: check length, uniformity and loss measurement - cutback - spectral attenuation: measures loss versus wavelength	YES	YES
BANDWIDTH - measures F_{3dBopt} of multimode fibre	NO	YES
CHROMATIC DISPERSION - measures dispersion versus wavelength of a singlemode fibre	YES	NO
CUT-OFF WAVELENGTH - measures cut-off wavelength of the second mode of a singlemode fibre	YES	NO
MODE FIELD DIAMETER - measures diameter of the Gaussian beam emerging from a singlemode fibre - mode field concentricity error	YES	NO
NUMERICAL APERTURE - measures emergence angle of light from a multimode fibre	NO	YES
REFRACTIVE INDEX PROFILE	YES	YES
PROOF TEST	YES	YES

4.2.1 Fibre Geometrical Characteristics

The physical dimensions of an optical fibre are measured across the circular cross-section of the fibre to control and ensure uniform geometrical properties. This is to keep coupling losses at a minimum.

The following geometrical parameters are measured on optical fibres:

- core diameter (multimode fibres);
- core non-circularity (multimode fibres);
- core/cladding concentricity error (multimode fibres);
- mode field non-circularity (singlemode fibres);
- mode field/cladding concentricity error (singlemode fibres);
- cladding diameter;
- cladding non-circularity, and;
- coating diameter.

For multimode fibres the core diameter plays an important part in determining the fibre characteristics. It determines properties such as the number of modes carried in the waveguide, power confinement and modal dispersion. These have already been discussed in Chapter 2.

For singlemode fibres, the mode field diameter is measured. It is a measure of the spot size or beam width of light propagating in the fibre. Mode field diameter is a function of source wavelength, fibre core radius and fibre refractive index profile. Mismatches in mode field diameter will affect splice loss, and fibre with varying mode field diameter also affects microbending and macrobending losses. The test method will be discussed in Section 4.2.2.

The core/mode field - cladding diameter ratio has a critical effect on microbending loss. The other parameters mentioned affect splice losses.

The geometrical measurements are made by mounting a short piece of fibre sample under the objective lens of a microscope. The core region is illuminated from beneath and the cladding region by top lighting. The fibre dimensions are measured with the assistance of a transparent templates.

The core diameter and the cladding diameter, as well as the core and cladding centre, can be determined from this measurement by taking an adequate number of points suitably distributed on the core/cladding and the cladding boundaries respectively. The concentricity error can be evaluated from the distance between the core and cladding centres. Core and cladding non-circularities can be determined from the tolerance field.

The output field of the microscope is processed normally with a digital video analyser controlled by a computer, such as a scanning vidicon, the completed image is monitored and processed. The boundaries are found by contrast level of the image to give the geometrical parameters to be measured.

The test method and test apparatus are described in CCITT Recommendation G.651 for multimode fibres and G.652 for singlemode fibres. Section 2 of IEC Publication 793-1 also describes these measuring methods for dimensions.

4.2.2 Mode Field Diameter

The mode field diameter $2w$ can be measured by applying one of the following definitions:

(i) Far-Field Domain: (Three methods of measurement are possible.)

(a) far-field scan. The far-field intensity distribution $F^2(q)$ is measured as a function of the far-field angle θ , and the mode field diameter at the wavelength λ is calculated from:

$$2w = \frac{2}{\pi}\left[2\,\frac{\int_0^\infty q^3F^2(q)dq}{\int_0^\infty qF^2(q)dq}\right]^{-1/2}, \text{ where } q = \frac{1}{\lambda}\sin\theta$$

(b) knife-edge scan. The knife-edge power transmission function $K(x)$ is measured as a function of knife-edge lateral offset position, x . The plane of the knife-edge is separated by a distance D from the fibre. This function $K(x)$ is differentiated and the mode field diameter is found from:

$$2w = \frac{2}{\pi}\left[4\,\frac{\int_0^\infty K'(x)q^2dq}{\int_0^\infty K'(x)dq}\right]^{-1/2}, \text{ where } x = D\tan\theta,\ K'(x) = \frac{dK(x)}{dx} \text{ and } q = \frac{1}{\lambda}\sin\theta$$

(c) variable aperture technique. The power transmitted by variable aperture device is measured for each aperture, $P(x)$. The complementary aperture transmission function, $a(x)$, is found as:

$$a(x) = 1 - \frac{P(x)}{P_{max}}$$

where P_{max} is the power transmitted by the largest aperture and x is the aperture radius with the plane of aperture separated by a distance from the fibre. The mode field diameter is calculated from:

$$2w = \frac{2}{\pi}\left[4\int_0^\infty a(x)qdq\right]^{-1/2}, \text{ where } x = D\tan\theta \text{ and } q = \frac{1}{\lambda}\sin\theta$$

(ii) Offset Joint Domain:

The power transmission coefficient $T(\delta)$ is measured as a function of the transverse offset δ . The field diameter is calculated from:

$$2w = 2\left[-2\frac{T(0)}{\left[\frac{d^2T}{d\delta^2}\right]_{\delta=0}}\right]^{1/2}$$

(iii) Near-Field Domain:

The near field intensity distribution $f^2(r)$ is measured as a function of the radial coordinate r . The mode field diameter is calculated from:

$$2w = 2\left[2\frac{\int_0^\infty rf^2(r)dr}{\int_0^\infty r\left[\frac{df(r)}{dr}\right]^2 dr}\right]^{1/2}$$

From the measurement point of view, all three techniques can be considered equivalent as regards to the test time and preparation of fibre ends. However, the offset joint technique provides more repeatable results but requires a more sophisticated test apparatus with high precision and accuracy of the offset mechanism (a resolution of 0.1 um is needed). This technique can also be used for the measurement of the cut-off wavelength, this will be discussed in Section 4.2.6.

The near-field and far-field techniques require a greater dynamic range (particularly the far-field in order of 50 dB) to avoid errors in the best fitting procedure. The far-field technique is used extensively because the measurement setup is easy to conduct.

The test method and test apparatus are described in CCITT Recommendation G.651 for multimode fibres and G.652 for singlemode fibres. IEC Publication 793-1 also describes these measuring methods for the mode field diameter (IEC 793-1-C9A to C9D).

4.2.3 Numerical Aperture

The numerical aperture (NA) of a multimode fibre is an important parameter as it affects properties such as light acceptance efficiency, pulse distortion, microbending loss and curvature loss. It is defined as the sine of the maximum half angle of the cone of rays that can enter or leave the core of an optical fibre.

The measurement of numerical aperture can be made by the far-field distribution technique. A fibre sample of 2 metres is taken and the angular intensity distribution of the far-field pattern is determined. The numerical aperture is then calculated as the sine of the half angle at which the intensity drops by 5 percent of the maximum value. This technique is used for a fibre which has a near parabolic refractive index profile, that is, a graded index multimode fibre.

An alternative test method is the refracted near-field technique (used for geometrical parameters). This technique is not as accurate as the far-field distribution technique. The numerical aperture determined using the near-field technique has higher NA, typically 5 percent, than the numerical aperture determined by the far-field distribution technique.

For step index multimode fibres, the numerical aperture is calculated from the measured value of Δ , the fractional difference between peak refractive index of the core and that of the cladding.

The test method and test apparatus are described in CCITT Recommendation G.651 and IEC Publication 793-1-C6 (Far-field distribution).

4.2.4 Attenuation

The measurement of attenuation, or power loss, is one of the most important parameters of an optical fibre. Attenuation is the result of the cumulative effect of the absorption, scattering and bending effects. These have been discussed in Chapter 2. The total loss value is the relevant parameter for the measurement. As the attenuation is wavelength dependent, the measurement is conducted either at a single wavelength or over a wide range of wavelengths (typically between 1000 nm and 1600 nm).

In an optical fibre, the attenuation is expressed per unit length (typically dB/km) or by the term "the attenuation coefficient". The attenuation $A(\lambda)$ at wavelength λ between two points 1 and 2 separated by distance L of a fibre is defined as:

$$A(\lambda) = 10 \log \frac{P_1(\lambda)}{P_2(\lambda)} \quad \text{(dB)}$$

Where $P_1(\lambda)$ is the optical power traversing the point 1 and $P_2(\lambda)$ is the optical power traversing the point 2 at the wavelength λ.

In a steady state propagation condition, the attenuation can be calculated per unit length, or the attenuation coefficient $\alpha(\lambda)$ according to:

$$\alpha(\lambda) = \frac{A(\lambda)}{L} \quad \text{(dB/unit length)}$$

Three test methods are used for attenuation measurements: the cut-back technique, the insertion loss technique, and the backscattering technique.

4.2.4.1 Cut-Back Technique

The cut-back technique is a destructive measurement. This method consists of measuring the optical power levels at two points along the fibre. The power level P_2 is measured from the emerging end of the fibre and P_1 is measured from a point near the input after cutting 2 metres of the fibre. The apparatus used consists of a multi-wavelength optical source with a high power tungsten halogen lamp (or xenon arc lamp) and a monochromator (or a filter set) as the transmitter and a photodiode connected to a lock-in amplifier as the receiver.

A schematic diagram is illustrated in Figure 28.

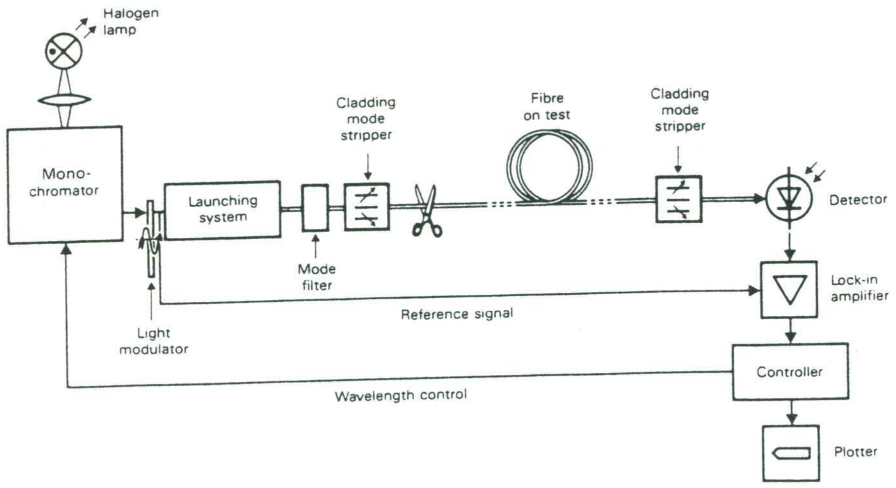


Figure 28. The cut-back technique. (After [9]).

This method has the advantage of leaving the launching conditions fixed thus enhancing the accuracy of the measurement (better than 0.1 dB). The dynamic range of this measuring apparatus is around 20 dB in the range of 1000 to 1600 nm wavelengths. A suitable laser source or LED at the nominal wavelength can be used as the transmitter to increase the dynamic range.

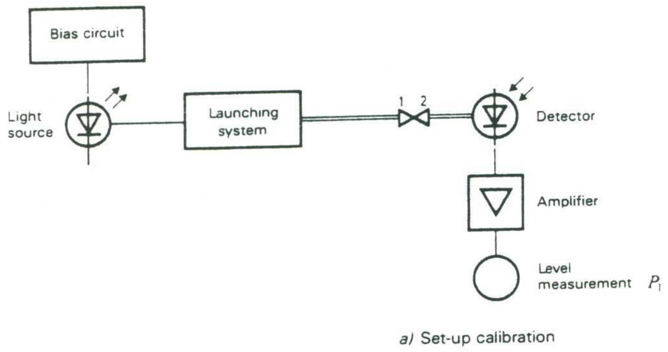
The cut-back technique is recognised as the reference test method for attenuation measurement. Its destructive nature and the nature of the test condition (laboratory set-up) are considered to be disadvantages.

The test method and test apparatus are described in CCITT Recommendation G.651 Annex B - Section II.

4.2.4.2 Insertion Loss Technique

The insertion loss technique is a non-destructive measurement. This method consists of measuring the attenuation on the inserted fibre between the transmitter and the receiver. The power level P_1 is measured from the output of the launching system and P_2 is measured from the emerging end of the fibre. The measured attenuation is the sum of the attenuation of the inserted length of fibre and the attenuation caused by the connection between the launching system and the fibre under test.

This method requires calibration of the set up apparatus to ascertain the amount of coupled power and to ensure its stability. A schematic diagram is illustrated in Figure 29.



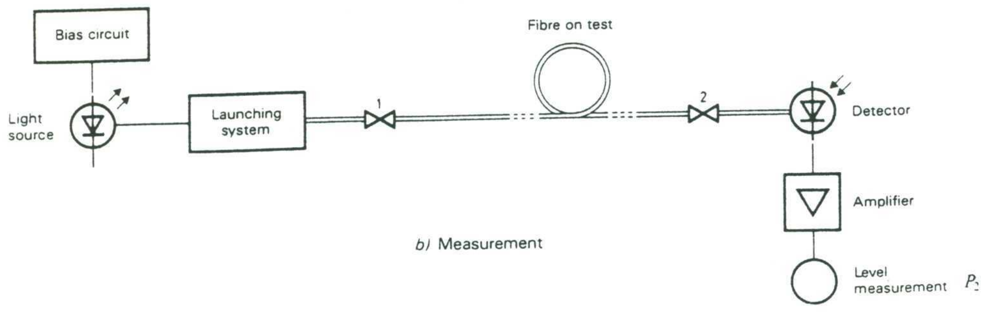


Figure 29. The insertion loss technique. (After [9]).

This method has an inherently lower accuracy than the cut-back technique, however the insertion loss technique avoids cutting a part of the fibre thereby making it a more practical in the field measurement.

The test method and test apparatus are described in CCITT Recommendation G.651 Annex B - Section II.

4.2.4.3 Backscattering Technique

The backscattering technique is another non-destructive measurement. This method consists of injecting a short, high power pulse into a fibre end, then measuring from the same end the backscattering power traversing two points of the fibre.

The test apparatus consists of a stable high power optical source of a nominal wavelength, an optical detector to receive the backscattered power, a signal processing is used to improve the signal-to-noise ratio and a data acquisition / display system.

A schematic diagram is illustrated in Figure 30.

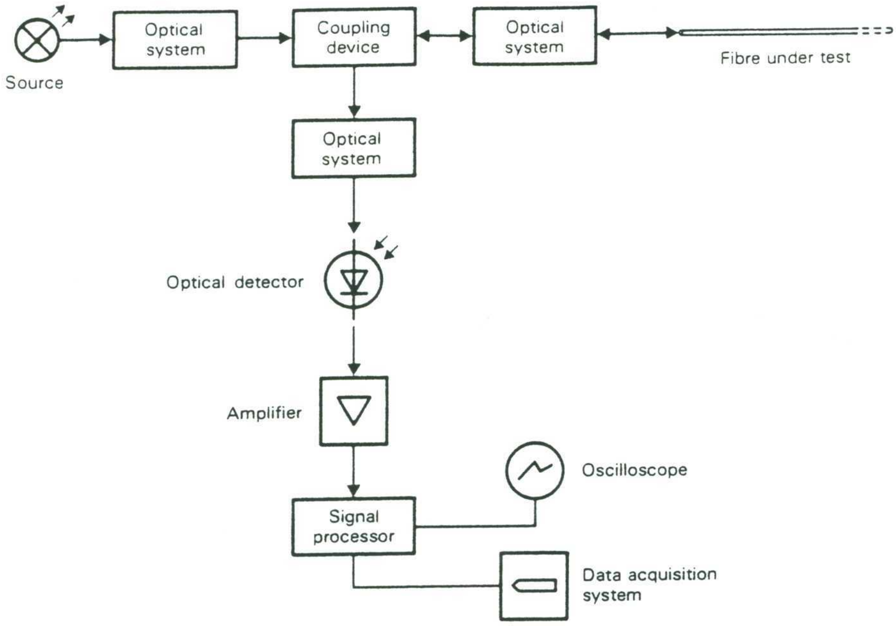


Figure 30. The backscattering technique. (After [9]).

The fibre under test is aligned to the coupling device and the backscattered power is analysed by the signal processor and recorded in logarithmic scale. Figure 31 shows such a typical curve.

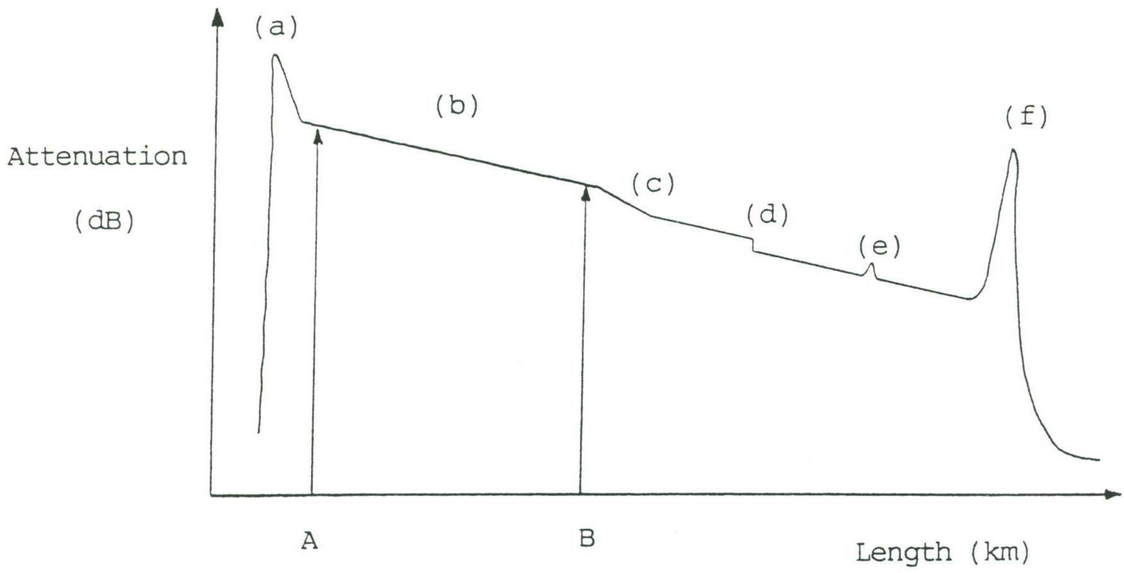


Figure 31. Example of a backscattered power curve.

The backscattered power curve shows a typical display of a backscattered measurement. The spike at the beginning and end of the fibre, points (a) and (f), are caused by the Fresnel reflections. The constant slope between two points A and B corresponds to the power loss for that length, point (b). The points (c), (d) and (e) correspond to discontinuities of the fibre, namely, slope change (continuous loss within two points), step (localised point loss), and splice respectively.

OTDR (Optical time domain reflectometer) equipment is normally used for this measurement.

The advantages of the backscattering technique are:

- a single ended measurement;
- a non-destructive method;
- ability to check optical continuity, physical defects, splice loss, backscattered light of optical cables and the length of the fibre;
- excellent repeatability, and;
- its ease of use in the field/factory measurement.

The disadvantages of the technique are:

- the inability to perform spectral measurements;
- inability to control the mode distribution of the backscattered light, and;
- sensitivity to fibre non-uniformities.

The last two disadvantages can be partially overcome by measuring the signals from both ends of the fibre and calculating the average attenuation.

The test method and test apparatus are described on CCITT Recommendation G.651 Annex B - Section II.

4.2.5 Bandwidth

Various causes of dispersion are present in an optical fibre (as discussed in chapter 2). The dispersion determines the bandwidth, and hence the information carrying capacity of a fibre. The bandwidth can be measured by two methods. The first method measures the baseband response in the time domain (impulse response, $g(t)$) and the second method in the frequency domain (frequency response, $G(f)$).

The bandwidth in the frequency and time domain of a linear system are related by:

$$G(f) = \int_{-\infty}^{+\infty} g(t) \exp(-j2\pi ft) \, dt$$

The amplitude and phase responses are the absolute value and the argument of $G(f)$ respectively.

The bandwidth is presented in the frequency domain and it is given by the frequency range from zero to the frequency at which the attenuation is down to 3 $dB_{optical}$.

4.2.5.1 Impulse Response Method (Time Domain)

The impulse response is measured by comparing input and output pulses of the fibre under test. A diagram of test apparatus is given in Figure 32. The fibre under test is aligned to the axis of the launch system which is connected to the optical source of known wavelength and spectral width.

The output end of the fibre is aligned to the detector surface, such that all of the emitted radiation is received by the detector. At the fibre, the input and output pulses are recorded and bandwidth $G(f)$ is calculated.

The launching conditions are important for this measurement and an equilibrium mode distribution to be achieved at the fibre launch to give the best reproducibility and accuracy.

A mode scrambler is normally used for this measurement, the net effect of the mode scrambler is to produce a uniform irradiance across the fibre core, with launch NA exceeding the fibre NA.

A laser source is also used, as the optical source must be stable in intensity, wavelength and spectral width for the duration of the test. A high speed photodiode detector is used to intercept the full mode volume of the fibre output.

After the output is measured and recorded, the fibre is then cut back (similar technique to that of attenuation measurement in Section 4.2.4) to remove the effect of detector electronics risetimes.

The system bandwidth can then be calculated by taking into account the reference pulses. This test method is mostly used for bandwidth measurement of multimode fibres.

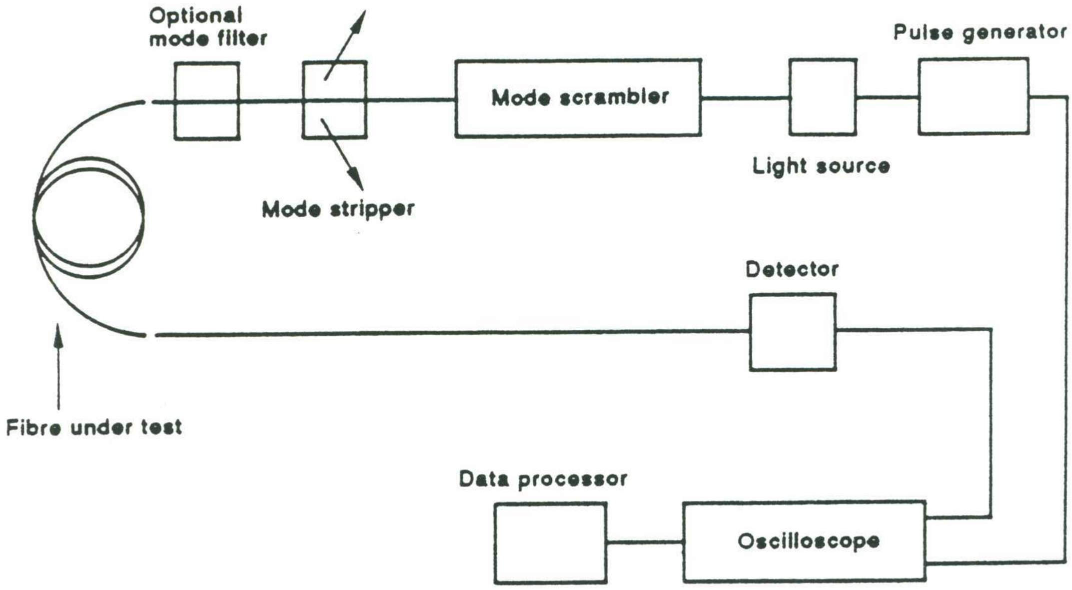


Figure 32. Example of impulse response measurement. (After [8]).

The test method and test apparatus are described in CCITT Recommendation G.651 and IEC Publication 793-1-C2A.

4.2.5.2 Frequency Response Method (Frequency Domain)

In the frequency response, the amplitude is measured as a function of the frequency:

(1) by means of spectral analysis of the output signal from the fibre when excited with an input pulse, or;

(2) by output analysis of swept frequency or sinusoidal input signals.

A diagram of test apparatus is given in Figure 33. The fibre under test is aligned to the axis of the launch system and the output end of the fibre is aligned to the detector surface, similar to the impulse response method. The sets of frequency domain amplitude data corresponding to the output signal from the fibre under test are used to calculate the bandwidth $G(f)$.

The optical source and detector used are the same as in the impulse response method and care must be taken for launching conditions. The network analyser provides additional information such as the phase of the transfer function. This phase can be used to find the length of the fibre under test by means of the group time delay. This time delay is the time required by an optical signal to traverse the fibre over a length L such that:

$$L = \frac{c\tau}{n_1}$$

where n_1 is the refractive index of the fibre core;

c is the velocity of light in free space, and;

τ is the group time delay which is expressed as $1 / \Delta f$, Δf being the increased amount of the signal frequency.

The frequency domain representation is more suitable than the time domain for system engineers involved in the design of equalisers and receivers in an optical system.

The test method and test apparatus are described in IEC Publication 793-1-C2B and CCITT Recommendation G.651, Annex B - Section III.

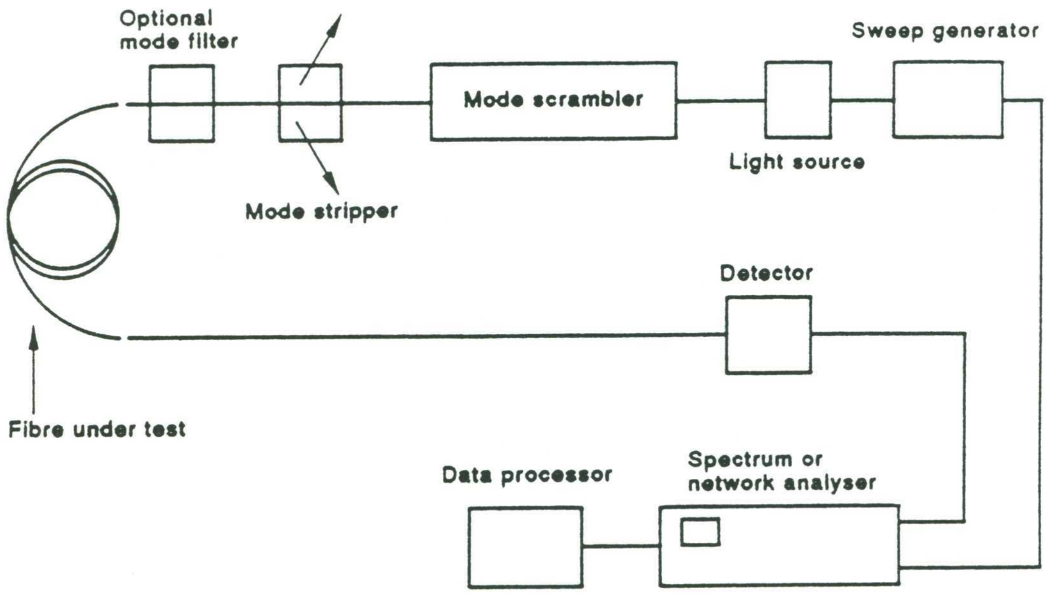


Figure 33. Example of frequency response measurement. (After [8]).

4.2.6 Cut-Off Wavelength

The cut-off wavelength for a singlemode fibre is defined as the wavelength greater than which the first higher order mode (LP_{11}) ceases to propagate. The measurement of the cut-off wavelength is highly dependent on the fibre sample length and bending radius of the fibre. The test method is therefore standardised on a bend radius of 140 mm and the fibre sample length of 2 metres.

Two types of cut-off wavelengths can be distinguished in an optical fibre cable:

(a) The cut-off wavelength λ_c measured in a short length of uncabled primary coated fibre, and;

(b) the cut-off wavelength λ_{cc} measured in a cabled fibre in a deployment condition.

The correlation of the measured value of λ_c and λ_{cc} is generally $\lambda_{cc} < \lambda_c$.

There are two main approaches to measure the cut-off wavelength λ_c of the primary coated fibre:

(a) plotting the power transmission against wavelength (the transmitted power method), and;

(b) plotting the mode field (spot size) variation against wavelength (the spot size variation method).

The transmitted power method is performed on a 2 metre fibre sample. The fibre sample is inserted into the test apparatus and bent to form a single loop with 140 mm radius. The transmitted power through the fibre is measured as a function of the wavelength (P_1), and compared to a reference transmitted power (P_2).

Two techniques can be used to obtain this reference power, one is to measure the output power over the same wavelength range with a loop of smaller radius in the test fibre to filter the LP_{11} mode (a typical value for the radius is 30 mm). The other technique is to measure the output power over the same wavelength range with a short (1 to 2 metre) length of multimode fibre.

The logarithmic ratio $R(\lambda)$ between transmitted powers is then calculated as:

$$R(\lambda) = 10 \log [P_1(\lambda) / P_2(\lambda)]$$

where $P_1(\lambda)$ is the transmitted power, and;
$P_2(\lambda)$ is the reference output power.

A typical cut-off wavelength plot using the transmitted power method is shown in Figure 34.

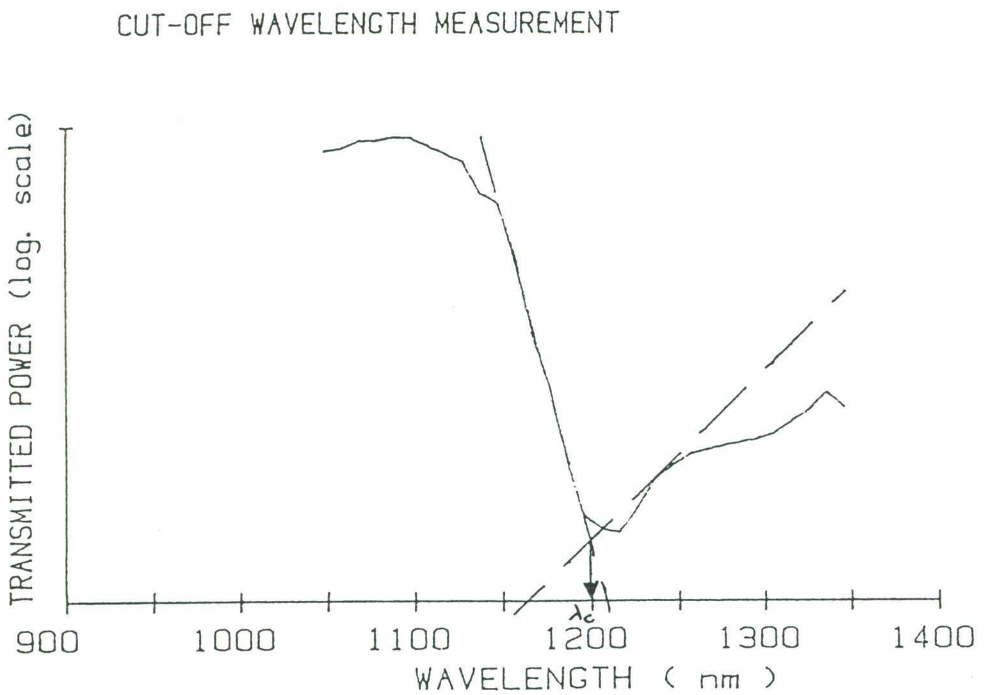


Figure 34. Plot of the transmitted power versus wavelength.

A similar result is obtained with the spot size variation method. This method is based on the sharp decrease of the spot size value as a function of the wavelength. A typical cut-off wavelength plot using the spot size variation method is shown in Figure 35.

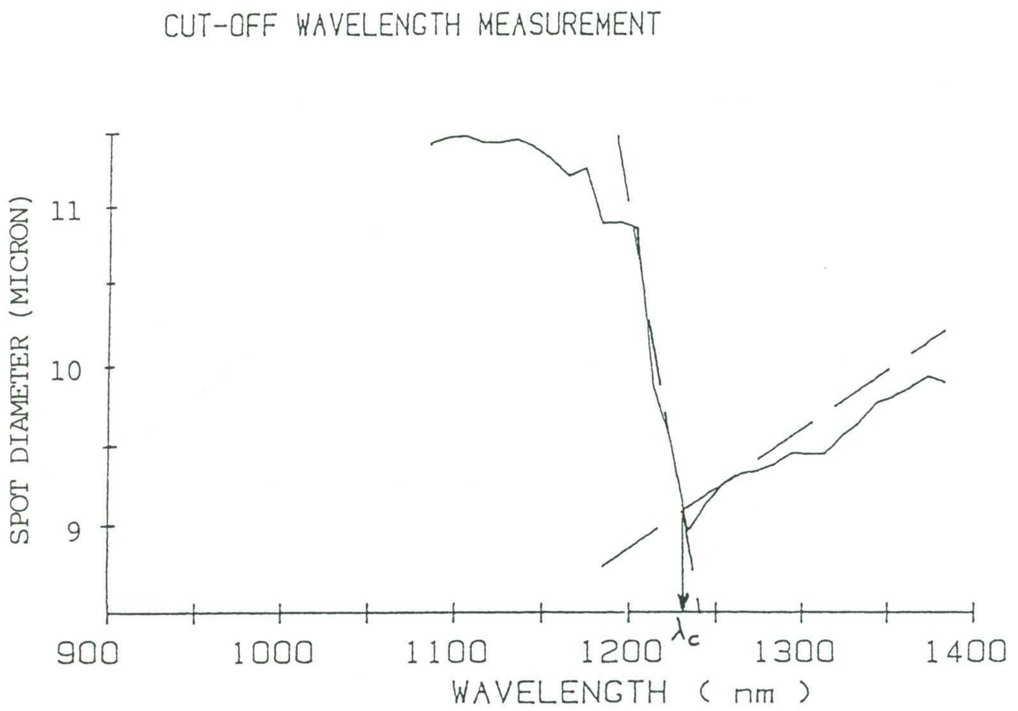


Figure 35. Plot of the spot size.

The two test methods described have the same performance as regards repeatability of the results. The spot size variation method requires a longer measuring time.

The transmitted power method is most commonly used and preferred as a reference test. However the spot size variation method allows the cut-off wavelength and the spot size at the nominal wavelength to be determined concurrently, by measuring with any technique outlined previously in Section 4.2.2.

The test method for the cut-off wavelength λ_{cc} of the cabled fibre using the transmitted power technique is described as follows:

The measurement is performed on a 22 metre length of cable. One metre of fibre at each end of the cable is exposed with the remaining 20 metre cables portion laid in such a way that it does not introduce any changes to the measurement. One loop of 38 mm radius is applied to each uncabled fibre length (See Figure 36). The output power is recorded as a function of the wavelength and compared to a reference transmitted power.

As in the uncabled fibre, there are two possible ways to obtain this reference power. First method, the output power is measured over the range of wavelength on the cabled test fibre with a loop of 30 mm radius. The second method is to use a short length (1 to 2 metre) length of multimode fibre. The logarithmic ratio between the transmitted powers is calculated as per uncabled fibre.

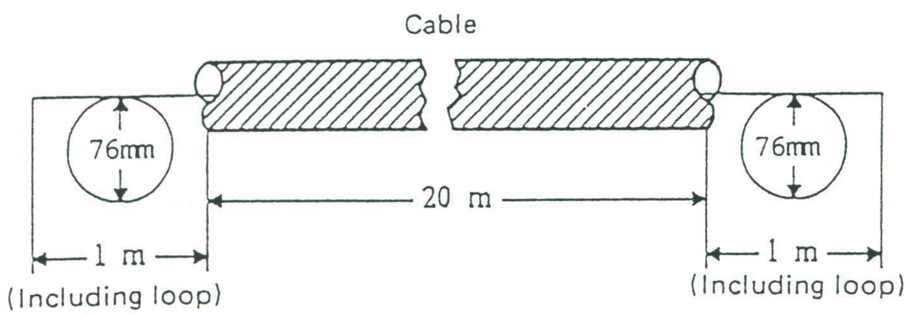


Figure 36. Deployment condition for measurement of the cabled fibre cut-off wavelength.

The test method and test apparatus for the transmitted power technique (for both λ_c and λ_{cc}) are described in CCITT Recommendation G.652 Annex B - Section III.

4.2.7 Chromatic Dispersion

The bandwidth in singlemode fibres is determined by chromatic dispersion. Chromatic dispersion is defined as the derivative of the group delay with respect to wavelength and crosses zero at the wavelength corresponding to minimum delay. The measurement of the chromatic dispersion can be performed by several techniques, four of these test methods will be discussed.

The first method (Raman fibre method or the time domain method) consists in sending short light pulses at different wavelengths. The time delay versus operating wavelength is measured, an analytical curve is fitted through the data and the chromatic dispersion is calculated.

The set up for this measurement uses a high power pulsed YAG laser, emitting at 1.06 um. This induces a non linear effect in an optical fibre which gives rise to a wide spectral emission in the wavelength range from 1.1 um to 1.8 um due to Raman scattering. The pulse delay variations are measured using a low jitter delay line and a sampling oscilloscope connected to the receiver.

The resolution of the system is around 50 ps and the dynamic range of 20 dB. A Raman laser is very good in a laboratory environment, because of its size, it is not practical for field use.

Multiple (three or more) laser diodes can be used as an alternative light source for this test method. The spectral width of the source, as measured in the test fibre, must be less than or equal to 10 nm at 50 percent power points.

The second technique, which provides high accuracy, comparatively simple and less expensive apparatus is the LED method or the frequency domain method. In this method, the emitted optical power from a sinusoidal modulated LED is filtered by a monochromator and launched into the fibre to be measured. The fibre output end is connected to an optical receiver and a vector voltmeter which determines as a function of the wavelength the phase variation with reference to the modulating signal. The time delay versus operating wavelength is measured and the chromatic dispersion calculated.

The resolution of this method is around 20 ps and the dynamic range of 15 dB. Multiple laser diodes can also be used in this technique replacing the LED, the centre wavelength and modulated output phase of each source need to be stable over the measurement time period at the bias current, modulation frequency and diode temperature range encountered.

This test method can be applied to laboratory, factory and field measurements.

A third technique, based on the differential phase shift method. The chromatic dispersion at particular wavelength is determined from the differential group delay between two closely spaced wavelengths.

A modulated light source (multiple laser diode or filtered LED) is coupled into the fibre under test, and the phase of the light exiting the fibre at first wavelength is compared with the phase of the light exiting at a second wavelength. The average chromatic dispersion over the interval between the two wavelengths is determined from differential phase shift, wavelength interval and fibre length.

There are different methods in recording and processing the differential phase shift, such as, by dual wavelength method and double demodulation method. These methods will not be described, as references will be given at the end of this section.

The last technique to be discussed is the interferometric test method. This method allows the chromatic dispersion to be measured using a short piece of fibre (couple metres). According to the interferometric measuring principle, the wavelength dependent time delay between the test fibre and the reference path is measured by a Mach-Zehnder interferometer. The reference path can be air or another piece of singlemode fibre with known dispersion characteristics.

The advantage of this method is that the measurement resolution can be as high as 0.1 ps. The disadvantage of this method id that the path difference between the fibre and the reference must be within the coherence length of the light source.

A schematic diagram of the chromatic dispersion measurement is illustrated in Figure 37(a) and the interferometric test method is illustrated in Figure 37(b).

The test method and test apparatus are described in CCITT Recommendation G.652 Annex B - Section V and IEC Publication 793-1-C5A to C5C.

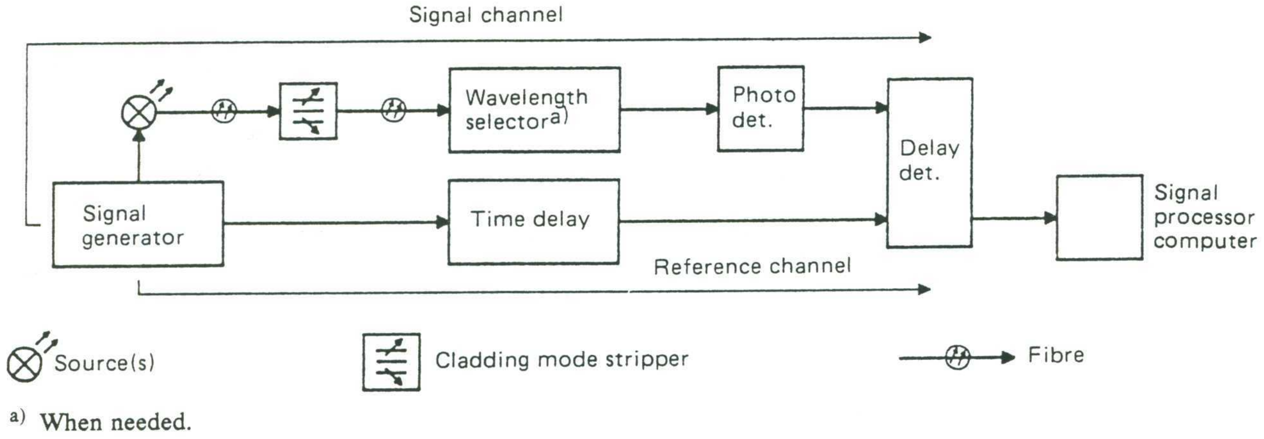


Figure 37(a). Chromatic Dispersion Measurement. (After [9]).

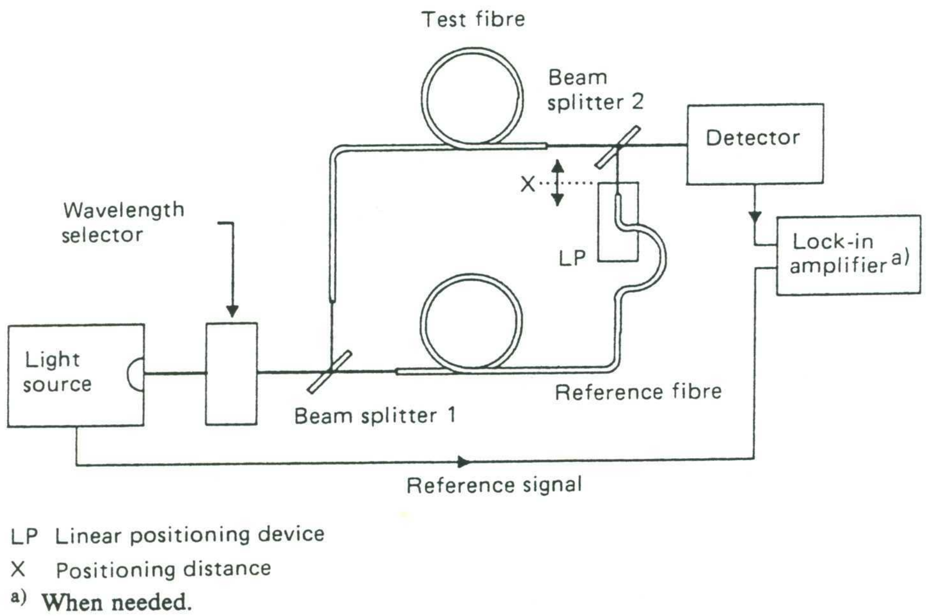


Figure 37(b). Chromatic Dispersion Measurement - Interferometric method with reference fibre.
(After [9]).

4.2.8 Proof Test

The purpose of a proof test on the optical fibre is to ensure long lengths of fibres manufactured have a certain minimum strength and a certain minimum static fatigue under service conditions.

The proof test is normally performed in the last stage of fibre drawing process or performed by an off-line screening apparatus. This test involves subjecting the fibre to a nominal tensile screening stress (typically to a strain of 0.7 percent or 1 percent elongation) continuously throughout the entire length of fibre. This eliminates any fibre having flaws above a certain (critical size), which may result in product failure at stresses below the proof test level.

The proof test is also used by fibre manufacturers to guarantee the minimum static fatigue lifetimes in particular environments by means of failure probability. A logarithm plot of lifetime versus service strain can be made.

As discussed earlier, the proof test measurement can be performed as with on-line or off-line screening. The off-line technique will be discussed here.

The optical fibre is pay-off from a spool mounted on a drive shaft. The fibre travels through a series of capstans where an adjustable dead weight is placed on the central capstan that is free to move vertically. The other capstans remain in fixed positions with the capstan belts maintaining a constant tension on the fibre throughout the duration of the test. The fibre is then wound on to a take-up spool mounted on a drive shaft. This is illustrated in Figure 38.

Another off-line technique is used for the proof test of the optical fibre. The set up is practically the same as described previously except in lieu of an adjustable dead weight placed on the central capstan, it is fixed with a step capstan wheel with two different diameters. See Figure 39. Therefore, for a fibre of 250 um diameter with a strain of 1 percent elongation, this capstan has the dimensions of 250.0 mm and 252.5 mm in diameter.

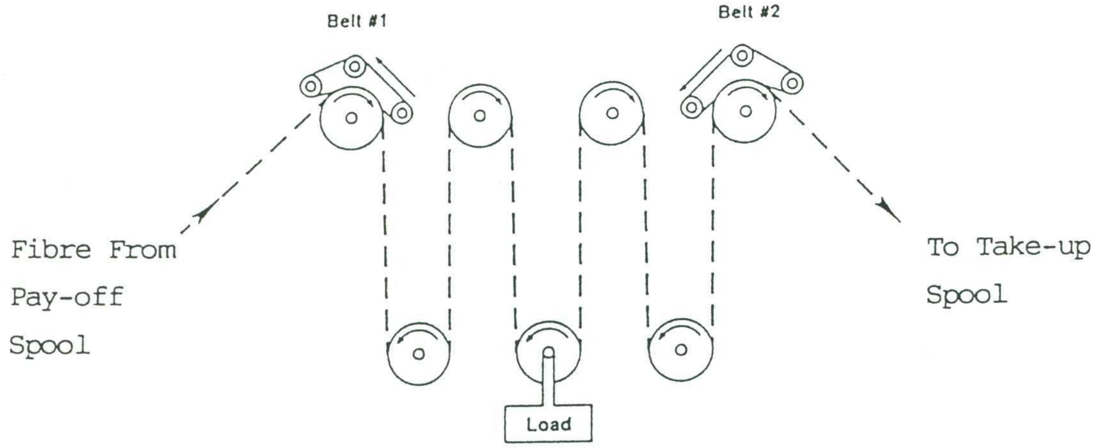
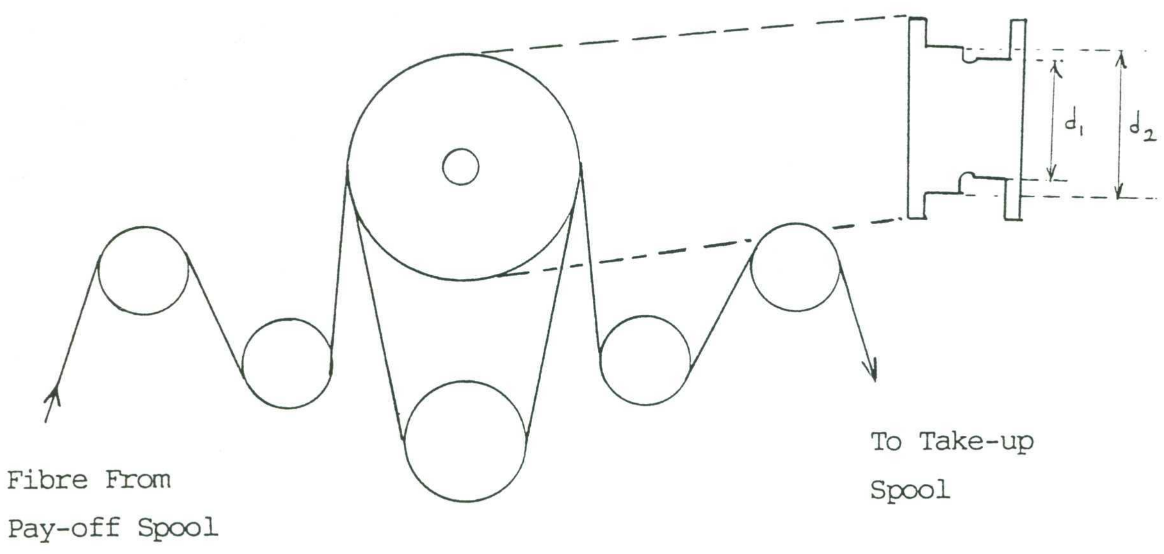


Figure 38. Example of a proof test apparatus.



For 1% Elongation d_1 = 250.0mm

d_2 = 252.5mm

Figure 39. Step capstan wheel technique.

4.3 Optical Cable Tests

The optical cable is designed and manufactured to improve the mechanical and environmental characteristics of a fibre without impairment to its transmission properties. During manufacture a number of tests are performed to ensure compliance to cable specification.

The cable specification normally includes both the transmission performance required and the stability of optical characteristics under various mechanical and environmental conditions. Hence the finished cable must meet the Qualification (Type) Tests in accordance with the methods and procedures specified in the cable specification.

The common tests which form part of the cable specification will be discussed in this section. They are described in three parts, mechanical tests, environmental tests, and transmission and optical tests. These test methods reflect the Australian requirements, as cable specification varies with different countries, although the equipment used are practically identical.

An example of the Qualification Tests will be presented in Chapter 5. Reference documents are provided for further information, these test procedures are defined in the International Standards.

4.3.1 Mechanical Tests

The purpose of mechanical tests is to estimate the stress to which the optical cable can be subjected without affecting the transmission characteristics of the fibres.

The types of mechanical tests performed on an optical cable length are tensile strength, bending, crush resistance, impact resistance, and torsion. The last five tests are normally performed together, as the cable sample required is short (around a metre) and the test apparatus can be fitted into a small floor area.

A cable length of around 10 metres is cut from a factory drum, it is then passed through each apparatus so that all the tests may be performed with a single set-up.

4.3.1.1 Tensile Strength

The purpose of this test is to determine the maximum tensile strength that can be applied to a cable which may occur during installation. It is usually specified as a function of allowable fibre strain at tensile rating which is some fraction of the fibre proof strain (typically around 50 percent).

An example of maximum permissible fibre strain during installation versus fibre proof test level are given below:

Fibre Proof Test Level (%)	Fibre Strain (%)	Fibre Strain as % of Proof Test Level
0.7	0.38	54.2
1.0	0.53	53.0
1.5	0.77	51.3
2.0	1.00	50.0

This method is intended to be non-destructive, that is, the tension applied is within the operational values. The behaviours of the attenuation as a function of the load on a cable can be examined. Figure 40 shows schematically an apparatus for tensile strength measurement.

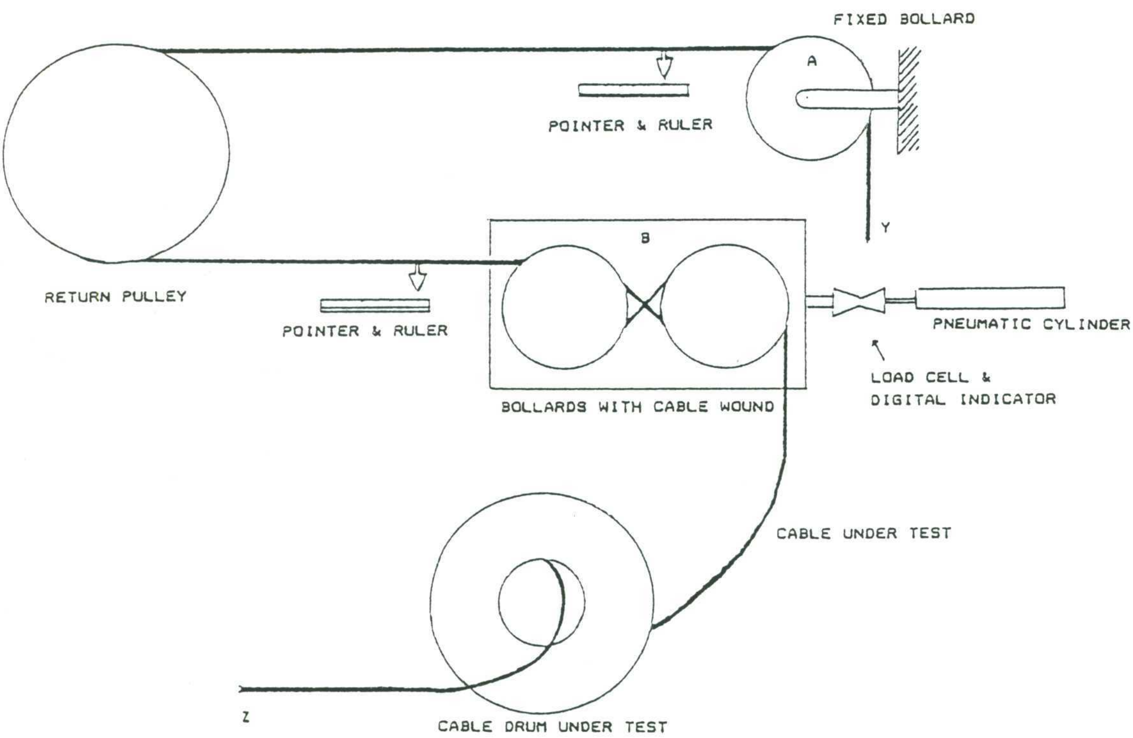


Figure 40. Example of a tensile strength measuring apparatus. (After [13]).

The attenuation measuring apparatus for the determination of attenuation change is connected over the measurement time period (reading is taken at least 30 minutes after tensile strength is achieved).

Normally, an Optical Time Domain Reflectometer (OTDR) is used for continuity and loss detection. Alternatively, a light source (1550 nm wavelength for singlemode optical fibre - SMOF and 1310 nm wavelength for multimode optical fibre - MMOF) and power meter can be used, however, only attenuation change can be detected using this set-up.

The test criteria for attenuation increase is:

a) If using an OTDR, less than 0.05 dB/km at 1550 nm for SMOF or less than 0.05 dB/km at 1310 nm for MMOF.

b) If using a light source and power meter, less than 0.10 dB at 1550 nm for SMOF or less than 0.20 dB at 1310 nm for MMOF.

The test method and the measuring apparatus are described in IEC Publication 794-1-E1.

4.3.1.2 Bending

The purpose of this test is to determine the minimum bending radius of the cable so that the optical fibre cable is able to withstand bending during the installation process. This test involves both the physical behaviour of the sheath and the transmission performance of fibres.

The cable sample to be tested is connected to an optical attenuation measuring apparatus. A section of this cable is wrapped in a close helix around mandels of different diameters. Sufficient tension is applied to ensure that the cable contours the mandel.

The cable bending radius is reduced by decreasing the mandel diameter step by step until there is a point where attenuation increases. The minimum bending radius is defined by either where the attenuation starts to change or by the flattening or wrinkling of the sheath.

On completion of the test, the condition of the cable sheath is examined for damage. The sheath is then stripped, the core and fibres are examined and recorded for any damage (tube kinked, fibre broken, etc.). Figure 41 shows schematically a cable under bend test.

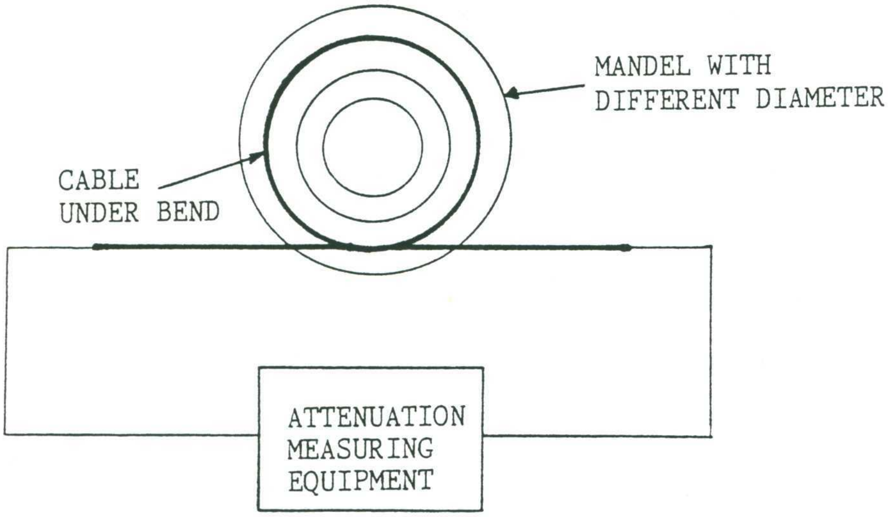


Figure 41. Cable under bending test.

The attenuation measuring apparatus for the determination of attenuation change is a light source (1550 nm for SMOF or 1310 nm for MMOF) and power meter. The criteria of acceptance is less than 0.10 dB at 1550 nm for SMOF or less than 0.20 dB at 1310 nm for MMOF.

The test method is described in IEC Publication 794-1-E11.

4.3.1.3 Bending Under Tension

The purpose of this test is to determine the ability of the optical fibre cable to withstand bending while under tension during installation. This test is normally performed in conjunction with the tensile test.

The test requirements are a combination of tensile and bend tests, that is, the radius of the loop or test mandel and applied tensile loads are provided together with each measured attenuation change.
Likewise, in the bend test the sheath is examined for damage.

The test apparatus consists of a attenuation measuring apparatus for the determination of attenuation change, test mandels of appropriate radii and tensile strength measuring apparatus.

The test method is the same as the tensile strength except that the test mandels are incorporated into the apparatus.

4.3.1.4 Crush Resistance

The purpose of this test is to determine the ability of the optical fibre cable to withstand crush or compression. The crush resistance of a cable is important in relation to cable hauling and in some service conditions. This test establishes the crush or compression force required to produce attenuation increase.

The cable sample to be tested is connected to an optical attenuation measuring apparatus. A section of this cable is crushed between a flat steel base plate and a movable steel plate which applies the crushing force uniformly over a 100 mm length of the sample.

The edges of the movable plate are rounded with a adequate radius, so that the edges do not damage the cable during the crush test or they can be corrugated for more severe test condition.

The test procedure can fit into two categories:

(a) Short term crush - normally 10 minute test, and;

(b) Long term crush - normally a 2 hour test.

The crushing force is applied at different loads and measured for any attenuation change. For example, 4 kN/100 mm on the short term and 2 kN/100 mm on the long term. On completion of the test, the condition of the sheath, the core and fibres are examined for damage.

Figure 42(a) shows schematically an apparatus for a crush test and Figure 42(b) shows an example of a corrugated movable plate.

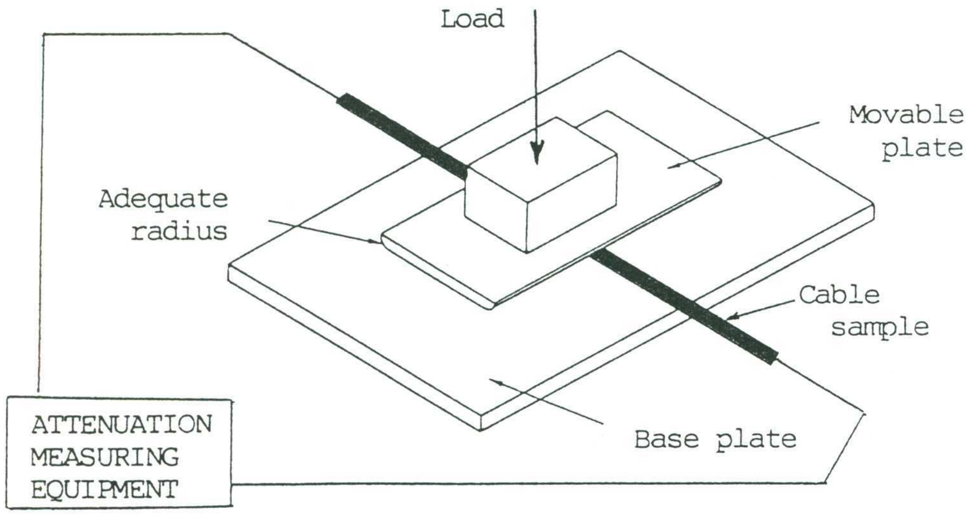


Figure 42(a). Example of a crush test apparatus.

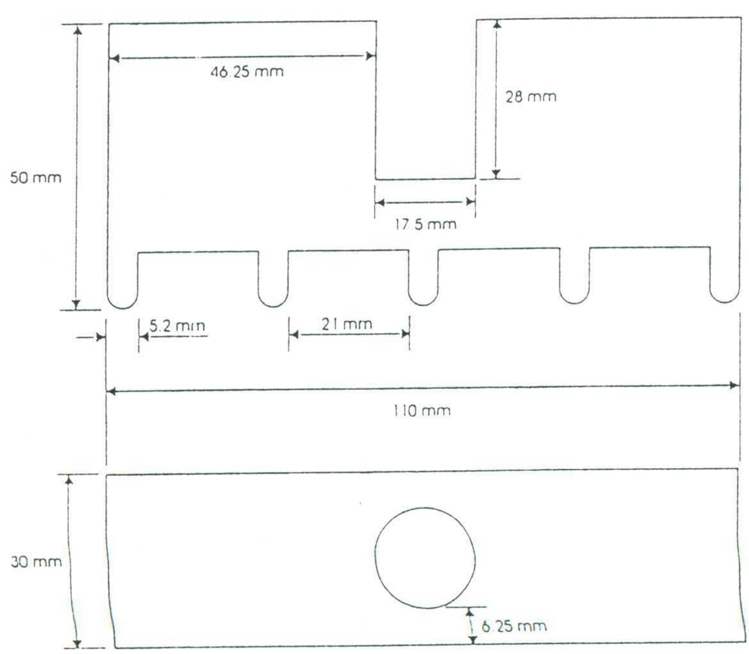


Figure 42(b). Example of a corrugated movable plate.

The attenuation measuring apparatus for the determination of attenuation change is a light source (1550 nm for SMOF or 1310 nm for MMOF) and power meter. The criteria of acceptance is less than 0.10 dB at 1550 nm for SMOF or less than 0.20 dB at 1310 nm for MMOF.

The test method and the test apparatus are described in IEC Publication 794-1-E3.

4.3.1.5 Impact Resistance

The purpose of this test is to determine the ability of the optical cable to withstand impact. The impact performance of a cable is determined onto a piece of steel. This weight transmits the impact to the cable sample which is fixed to a flat substantial steel base. The surface of the intermediate piece in contact with the sample is rounded. This is shown in Figure 43, as the radius R.

The acceptance criteria for the test depends on the cable specification, that is, the number of impacts, the mass of the weight falls and whether the attenuation change is allowed. For example, one impact with 1.5 kg mass dropped from a height of one metre.

After impact, the condition of the sheath is examined for damage. The sheath is then stripped, the core and fibres are examined and recorded for any damage (tube kinked, fibre broken, etc.). The fibre breakage however is not permitted in this test.

The attenuation measuring apparatus for the determination of attenuation change (if required) is a light source (1550 nm for SMOF or 1310 nm for MMOF) and power meter. The criteria of acceptance is less than 0.10 dB at 1550 nm for SMOF or less than 0.20 dB at 1310 nm for MMOF.

The test method and the test apparatus are described in IEC Publication 794-1-E4.

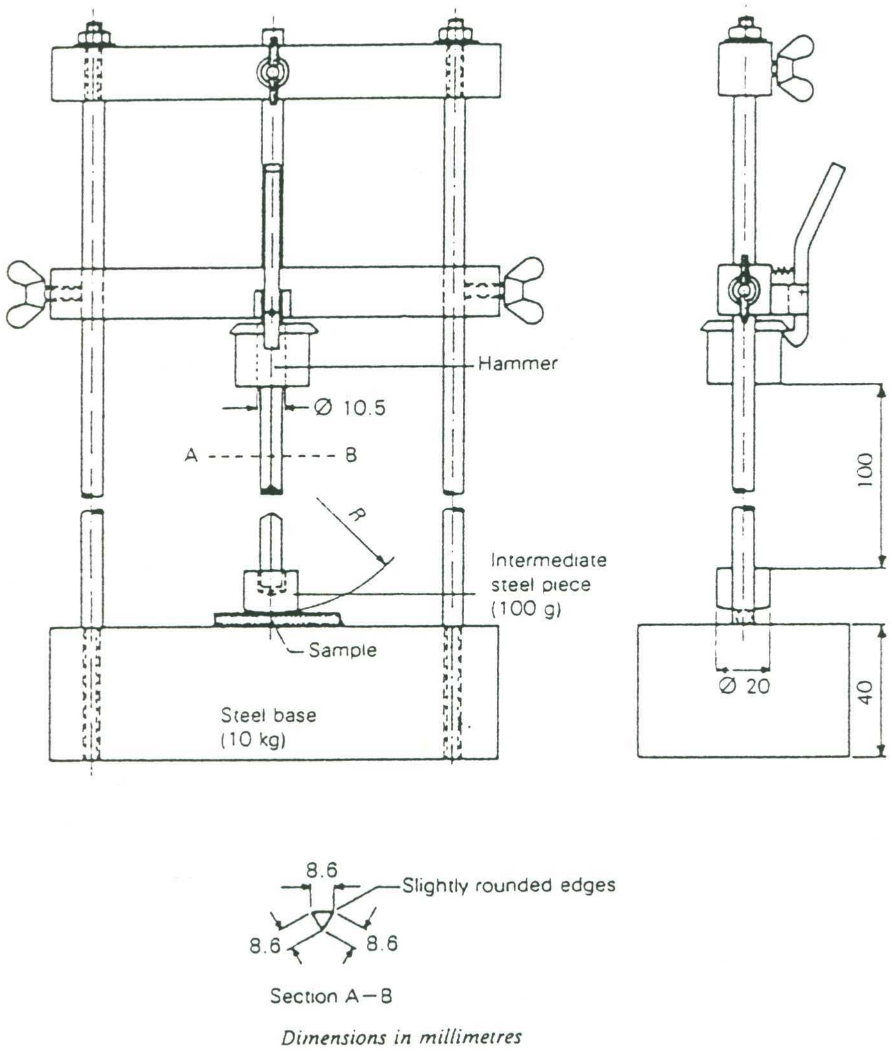


Figure 43. Example of an impact test apparatus. (After [14]).

4.3.1.6 Torsion

The purpose of this test is to determine the ability of the optical cable to withstand torsion under load which may occur during installation. The test is performed by subjecting the cable sample to many torsion cycles. The apparatus consists of a fixed clamp and a rotating clamp where the cable sample is terminated sufficiently tight to prevent movement of the cable sheath during the test. This is illustrated in Figure 44.

The torsion angle, the length of cable sample, the mass of the weight, the cycle number and the attenuation change (if allowed) for the test will depend on the cable specification. The test procedure involves the rotation of the cable sample in a clockwise direction for the number of turns given in the specification. The cable sample is then returned to the starting position and rotated in an anti-clockwise direction for the same number of turns and returned to the starting position. This complete movement constitutes one cycle.

Certain test conditions may apply to the test procedure such as the time period for which the cable takes to rotate over one direction and the time period for the cable to rest before returning to the other direction. Attenuation is normally monitored during these conditions.

An example of a test procedure is using one metre cable length, twisted without load, with the following requirements:

> The cable is rotated for one completed turn (360 degree) in clockwise direction over a period of approximately one minute, and allow to rest for one minute before recording any attenuation change of the fibre under test.
>
> The cable is then rotated for two complete turns (720 degree) anti-clockwise over a period of approximately two minutes and allowed to rest before recording any attenuation change.

On completion of the test, the condition of the cable sheath is examined for damage.

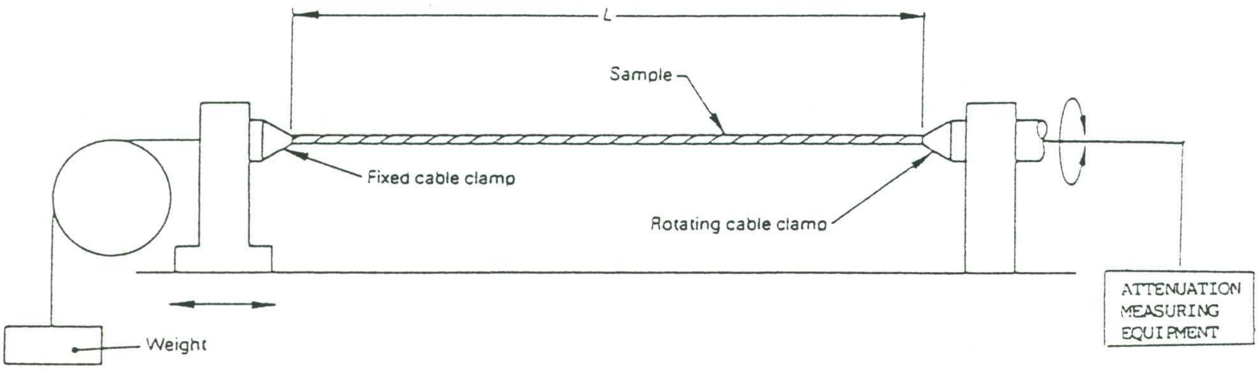


Figure 44. Example of a torsion test apparatus.

The attenuation measuring apparatus for the determination of attenuation change (if required) is a light source (1550 nm for SMOF or 1310 nm for MMOF) and power meter. The criteria of acceptance is less than 0.10 dB at 1550 nm for SMOF or less than 0.20 dB at 1310 nm for MMOF.

The test method and the test apparatus are described in IEC Publication 794-1-E7.

4.3.2 Environmental Tests

The purpose of environmental tests is to evaluate the behaviour of optical fibres in the presence of natural phenomena that may encounter during the life of an optical cable.

The ability of optical fibre cables to meet environmental requirements without deterioration of their mechanical or optical properties can be verified by a number of measuring methods. These will depend on the cable specification.

The following are some tests which measure environmental characteristics:

- climatic characteristics (Temperature Cycling Test);
- chemical resistance (Contamination Test);
- cable performance under fire conditions (Fire Conditions Test);
- sheath defects (Sheath Integrity Test);
- resistance to water penetration (Water Penetration Test);
- resistance to filling compound dripping at elevated temperature;

- flexibility at low temperature (Cold Bend Test);
- resistance to nuclear radiation (Nuclear Radiation Test), and;
- ageing tests (various test methods include subjecting the cable sample to a temperature and humidity for a period of time).

The environmental tests considered in this section are the temperature cycling test, sheath integrity test, water penetration test and ageing tests. These are the most common and important tests performed on optical cables.

4.3.2.1 Temperature Cycling

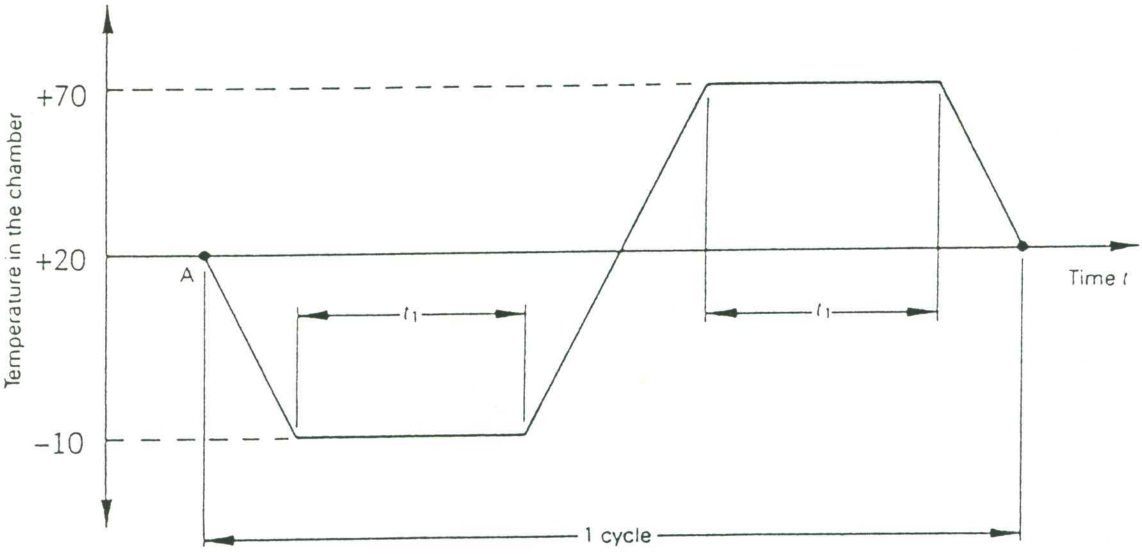
The purpose of this test is to determine the stability behaviour of the attenuation of the cable against temperature variations which may occur during storage, transportation and operation.

Temperature variation may cause microbending in the optical fibres and may limit the mechanical characteristics of the cable. The microbending is the result of the contraction of the tension of the fibres due to differences between their thermal expansion coefficient and the cable strength members and cable sheath.

The test procedure consists of a cable sample with adequate length to permit accurate measurement of fibre attenuation (normally greater than 1000 m). The cable sample is tested as a loose coil or loosely wound onto a drum in such a way that the cable's thermal expansion and contraction is not affected in the climatic chamber. The cable sample is stabilised at ambient temperature for 24 hours and subsequently a reference attenuation measurement is recorded.

The cable sample may have pre-conditioning conditions depending on the cable specification. The temperature in the chamber is cycled from ambient temperature to a low temperature at the appropriate rate of cooling. After temperature stability in the chamber has been reached (for a minimum of 24 hours) attenuation measurements are recorded.

The temperature in the chamber is then raised to the appropriate high temperature at the appropriate rate of heating. After temperature stability in the chamber has been reached (for a minimum of 24 hours), attenuation is again measured and recorded. The temperature in the chamber is lowered to the value of the ambient temperature at the appropriate rate of cooling, where the final attenuation measurement is performed. This procedure constitutes one cycle. See Figure 45.



A = start of first cycle

t_1 = 24 hours

Figure 45. Example of one temperature cycle procedure.

The temperature and the duration of each cycle will depend on the cable specification. An example of a temperature cycling for a cycle is illustrated below:

- Pre-conditioning (cycle 1)
  + 20°C, -10°C, +70°C and +20°C.

  All temperatures are maintained for a minimum of 24 hours. No attenuation measurements are required.

- Test Cycle (cycle 2)

  Attenuation measurements to be recorded at +20°C, -10°C, +70°C and + 20°C (in that order) after stabilising at those temperatures for a minimum of 24 hours.

The attenuation measuring apparatus for the determination of attenuation change is connected over the measurement time period.

Normally, an Optical Time Domain Reflectometer (OTDR) is used for continuity and attenuation detection. Alternatively, a light source (1550 nm wavelength for singlemode optical fibre - SMOF and 1310 nm wavelength for multimode optical fibre - MMOF) and power meter can be used, however, only attenuation change can be detected using this set-up.

The test criteria for attenuation increase is:

a) If using an OTDR, less than 0.05 dB/km at 1550 nm for SMOF or less than 0.05 dB/km at 1310 nm for MMOF.

b) If using a light source and power meter, less than 0.10 dB at 1550 nm for SMOF or less than 0.20 dB at 1310 nm for MMOF.

The test method and the test apparatus are described in IEC Publication 794-1-F1.

4.3.2.2 Sheath Integrity

This test method applies to unfilled external optical fibre cable to ensure the cable sheath is continuous and free from holes. This may be carried out as an internal pressure test or if the sheath is of the moisture barrier type (metal/plastic bonded sheath), alternatively a high voltage spark test may be applied during the extrusion process.

For the internal pressure test, the cable length has to withstand without leakage an internal applied gas pressure of typically 50 kPa to 100 kPa into the cable for 2 hours (after equalisation of pressure through the cable length is obtained).

For the spark test, the sheath is to withstand a spark test voltage of 7 kV r.m.s. or 10 kV d.c. (this will vary depend on the sheath material and thickness), throughout the cable length without breakdown.

The test method is described in IEC Publication 794-1-F3.

4.3.2.3 Water Penetration

This test method applies to completely filled external optical fibre cable to ensure all the interstices of a cable are continuously filled with jelly compound to prevent water penetration along its length.

A length of cable sample (2 metres) is prepared in accordance with Figure 46. A circumferential portion of sheath and wrapping is removed from one end of the cable sample and a watertight sleeve is applied over the exposed core so as to bridge the gap in the sheath.

The cable sample is supported horizontally and a 1 metre head of water, containing water soluble fluorescent dye, is applied to the core for 24 hours at ambient temperature.

The objective of this test is at end of this period, no dye is to be detected within the cable core when examined with ultraviolet nor water leakage occurs in the water vessel.

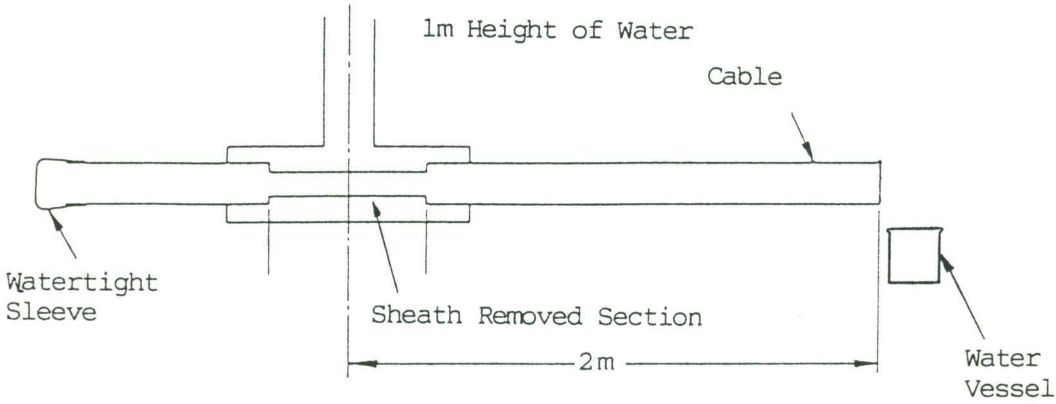


Figure 46. Water penetration test.

The test method is described in IEC Publication 794-1-F5.

4.3.2.4 Filling Compound Flow (Drip) Test

The purpose of this test is to verify the filling compounds will not flow from a filled optical fibre cable at stated temperature.

A cable sample length of 30 centimetres is used for this test, it is prepared so that the cable sheath(s) and the core wraps are removed from one end.

This sample is placed in a temperature oven, suspended in a vertical position, with the prepared end facing down. After 24 hours under 65°C, the collection container is weighted for the quantity of filling compound that may have dripped out of the cable.

A maximum flow quantity of 100 milligram is allowed in this test.

4.3.2.5 Ageing Tests

The purpose of this test is to determine the deterioration of optical fibre properties under a moisture environment or in water. This test has been recently developed (by Telecom Australia) to stimulate the long term effect of optical cable under high humidity with different temperature conditions.

Two types of tests will be discussed, one with cable sample immersed in water and aged for a period of time at an elevated temperature (at 70°C for 85 days). Another ageing test is to expose the cable sample at low temperature after being exposed to high humidity (at 50°C and 95% RH for 21 days then aged at -10°C).

- <u>Ageing test, in water</u>

A cable sample of not less than 500 metres, loosely wound onto a drum is accurately measured for attenuation at ambient temperature prior to ageing, and recorded as reference. The cable is then aged for 85 days at 70°C immersed in water and measurements are made at 1 day and subsequently at 40 and 85 days. A final measurement is conducted at ambient temperature at the end of the ageing period. The attenuation increase is not to be greater than 0.1 dB/Km at 1550 nm.

- <u>Ageing test, high relative humidity/low temperature performance</u>

A cable sample of 200 metres length loosely wound onto a drum is accurately measured for attenuation at ambient temperature prior to ageing and recorded as reference.

The cable is then wound onto a mandel with a diameter of 20 times that of the cable diameter. This is placed in an environmental chamber at 50°C and 95% RH, and aged for 21 days.

At the end of the period the cable is removed from the chamber and allowed to condition for one hour under ambient conditions, then transferred to a chamber at -10°C (uncontrolled humidity) for 24 hours. The attenuation is measured at this temperature.

The cable is then wound onto a cable drum maintaining the temperature at less than 0°C. The attenuation measurement is then repeated. After five hours under ambient temperature, the final measurement is taken. The attenuation increase at each individual measurement is not to be greater than 0.2 dB/Km at 1550 nm.

The test method and apparatus are described in Telecom Australia Specification OCN3 Issue 8, Section 3.4. [15].

4.3.3 Transmission and Optical Tests

The purpose of transmission and optical tests is to ensure the cables provided comply with the cable specification. The tests applied on the cable during manufacture comprise of the measurements shown in Table 6.

The test frequency is expressed in percentage of fibres measured. Where Sample is indicated, the fibre manufacturer performs a sample test on a batch of fibres.

The same test methods and test equipment described in Section 4.2 - Optical Fibre Test of this chapter will apply to the applicable type of measurement.

TABLE 6. OPTICAL TESTS PERFORMED BY CABLE MANUFACTURER

Type of Measurement		Stage of Testing and Test Frequency		
Multimode Fibre	Singlemode Fibre	Acceptance (Fibre Manufacturer)	In Process	Final
Length OTDR Loss Cutback Loss		100% 100% 100%	100% 100% -	100% 100% -
Bandwidth	Chromatic Dispersion	Sample	-	-
Numerical Aperture		Sample	-	-
Core Diameter	Mode Field Diameter	Sample	-	-
Core Non-Circularity	Mode Field Non-Circularity	Sample	-	-
	Cut-Off Wavelength	100%	-	-
Cladding Diameter		100%	-	-
Cladding Non-Circularity		Sample	-	-
Concentricity Error		Sample	-	-
Coating Diameter		100%	-	-
Proof Test		100%	-	-

CHAPTER FIVE

MINI REPORT : STANDARD OPTICAL FIBRE CABLE

5.1 Introduction

This chapter presents an example of practical cable design and testing. All matters discussed in previous chapters are considered during the design and development stages. Following the manufacture of the cable, tests are conducted in accordance with the cable specification.

The cable presented is the most commonly used in Telecom Australia's network, that is, the 2 to 30 fibre "standard" cable.

Firstly, the cable design criterion and Telecom Australia's cable specification requirements are described, followed by practical application to demonstrate the principles of cable design. The characteristics of the cable construction and components used in the cable are discussed.

An example of Mechanical and Environmental Test Report of this cable and the analysis of the results obtained are presented at end of the chapter.

5.2 Cable Specification

The standard optical fibre cables used by Telecom Australia are for digital transmission bearers, designed for singlemode operation of up to 2.4 Gbit/s with repeater spacing of 50 kilometres. The majority of standard cables are installed in ducts or directly buried.

The cable has loose tube design, dielectric construction and oscillating (S-Z) lay configuration. The standard optical fibre cable specification requirements and test acceptance criteria are summarised below:

(a) Optical Fibre - The fibre characteristics of a singlemode fibre is in accordance with IEC 793-1, with maximum attenuation in any drum length of 0.40 dB/km at 1310 nm and 0.30 dB/km at 1550 nm.

The entire length of the fibres used are to be proof tested by the fibre manufacturer to a minimum strain level of 0.7 percent for a duration of one second for singlemode fibres.

(b) Optical Cable - The standard optical fibre cable is filled, non-metallic cable components with black polyethylene sheath and blue nylon outer jacket.

The fibre counts per unit (tube) are 6 fibres per tube for cables up to 48 fibres and 12 fibres per tube for cables thereafter.

(c) Tensile Strength - Minimum 2000 Newtons.

(d) Bending - Cable minimum bending radius (mm) without change of attenuation is 10 times cable diameter under no load, and 200 mm under full load.

(e) Crush Resistance - 2 kN/100 mm short term and 1 kN/100 mm long term, without change of attenuation.

(f) Torsion - One cycle each direction without change of attenuation.

(g) Impact Resistance - 1.5 kg mass dropped once from a height of 1 metre without change of attenuation.

(h) Longitudinal Water Penetration - After 24 hours, no water leakage allowed through the tubes, a maximum leakage allowed of 200 grams between the sheath and core wrap, and a maximum leakage allowed of 10 grams between the loose tubes and the core wrap.

(i) Filling Compound Drip Test - Maximum of 100 mg dripped filling compounds from the tube and interstices of the cable is allowed, after 24 hours at 65°C.

(j) Temperature Cyclying - Maximum of 0.1 dB/km attenuation change is allowed at 1550 nm, within the temperature range of -10°C to +70°C.

(k) Cable Ageing Test:
- Immersion of cable in water at 70°C for 85 days, the attenuation increases not to be greater than 0.10 dB/km at 1550 nm.

- Relative humidity/low temperature performance, no individual measurement of attenuation increase of any fibres is to be greater than 0.20 dB/km at 1550 nm.

These requirements from the cable specification can be easily complied with proper selection of raw materials (jelly compounds, plastic materials and strength members) and cable dimensions (tube wall thickness and sheath thicknesses) during cable design stage. This must then be followed by controlled process conditions during manufacture of the cable.

5.3 Application of Cable Design Principles

This section demonstrates an example of practical cable design principles during the development stage. The cable presented is the 2 to 30 fibre counts standard optical fibre cable, using the cable specification described in Section 5.2. Certain matters in the example are omitted due to commercial confidentiality, in these instances quotes or assumptions will be taken.

The first step in cable design is to read the customer specification and determine if the current designs can comply with the specification. In the case of new development is required, the cable design engineer will take the following steps:

(a) Choose fibre type.

(b) Choose fibre protection and cable composition.

(c) Choose protective sheath/jacket.

(d) Choose unit length and type of packaging.

(e) Determine optical, mechanical and environmental tests.

After the design is completed, a prototype cable is manufactured and tested. The development of the cable is ended with the design engineer performing the analysis of the results obtained and consequently modify the design of the cable, if required.

DEVELOPMENT OF 2 - 30 FIBRE STANDARD OPTICAL FIBRE CABLE TO TELECOM AUSTRALIA SPECIFICATION

(A) FIBRE TYPE

The optical fibres are chosen from the fibre supplier's Technical Data Sheet. The characteristics of the fibres selected must satisfy the customer's transmission requirements and that will carry out the performance characteristics of the cable. These are:

> Singlemode fibre with maximum attenuation of 0.4 dB/km at 1310 nm and 0.30 dB/km at 1550 nm. The fibre is proof tested to a minimum strain level of 0.7 percent.

(B) FIBRE PROTECTION AND CABLE COMPOSITION

The design of this cable is based on loose tube construction, 6 fibre per tube, as specified in the specification. Therefore, the optimum design consists of five elements laid around a central strength member with a short oscillating lay (S-Z).

The loose tube is chosen from the cable manufacturer's standard 6 fibre tube design, the characteristics of tube design are on the dimensions.

The external diameter of the tube fulfils the geometrical requirements, that is, the five elements laid around a selected size of central strength member. The internal diameter of the tube must accommodate six optical fibres with some excess length and degree of freedom to move, such that any strain applied to the cable will not be transferred directly to the fibres.

Other aspects in tube design must be taken into consideration are the crush and impact requirements, which may impose on the type of material (harder) to be used and/or increase the wall thickness of the tube.

The number of tubes to be used in the cable will depend on the number of fibre count, solid filler(s) having the same external diameter of the loose tube will be used to fulfil the five elements requirement.

The cable is filled with filling compound inside the loose tube and interstices of the cable core. It is important to select the correct jelly compound not just to prevent the ingress of water and other impurities but to comply with the drip test requirements.

In order to meet the tensile strength requirements, both central strength member (GRP - Glass Reinforced Plastic) and peripheral strength member (aramid yarns) are used. The maximum allowable tensile force for an optical cable is determined by the following formula:

$$F = \frac{e}{100} * Y * A$$

where F is the tensile force in Newtons (N),

e is the cable elongation in percentage (%),

Y is the Young's modulus of elasticity of the material in N/mm^2, and;

A is the area of the strength member in millimetre square (mm^2).

The key parameter in this formula is the cable elongation. This allowance is based on the Fibre Proof Strain Level (FPSL) plus a Strain Free Window (SFW). The fibre strain at the maximum load is not to exceed 50 percent of FPSL and a SFW of 0.3 percent is applied for loose tube construction, due to excess fibre. Therefore, we can express the cable elongation allowance as:

$$e(\%) = (FPSL * 50\%) + SFW$$

The cable tensile strength is the total tensile forces calculated for the central strength member (GRP rod) and the peripheral strength member (number of rovings of aramid yarns).

The lay-up cable is finished with a S-Z laylength around 70 mm and helically applied polyethylene terephthalate tapes, normally with 20 percent overlap. The S-Z lay facilitates ease of mid-span access jointing and the tapes are for thermal barrier protection.

(C) PROTECTIVE SHEATH/JACKET

In this case, Telecom Australia's cable specification nominates the type of protective layers with respect to type of material and physical dimensions. These are:

> Black polyethylene sheath with 1.00 mm minimum spot thickness, and;
> Blue nylon outer jacket with 0.30 mm minimum spot thickness.

The hard outer jacket is for protection against insects, and to ensure a low coefficient of friction for cable hauling.

(D) UNIT LENGTH AND TYPE OF PACKAGING

This is not a issue during the development stage, normally a length of 1500 metres of cable is produced (long enough cable length to perform accurate the optical measurements) and wound onto a factory drum.

For commercial applications, these are mostly governed by the customer's requirements, that is, the nominal length and/or particular packaging requirements.

(E) OPTICAL, MECHANICAL AND ENVIRONMENTAL TESTS

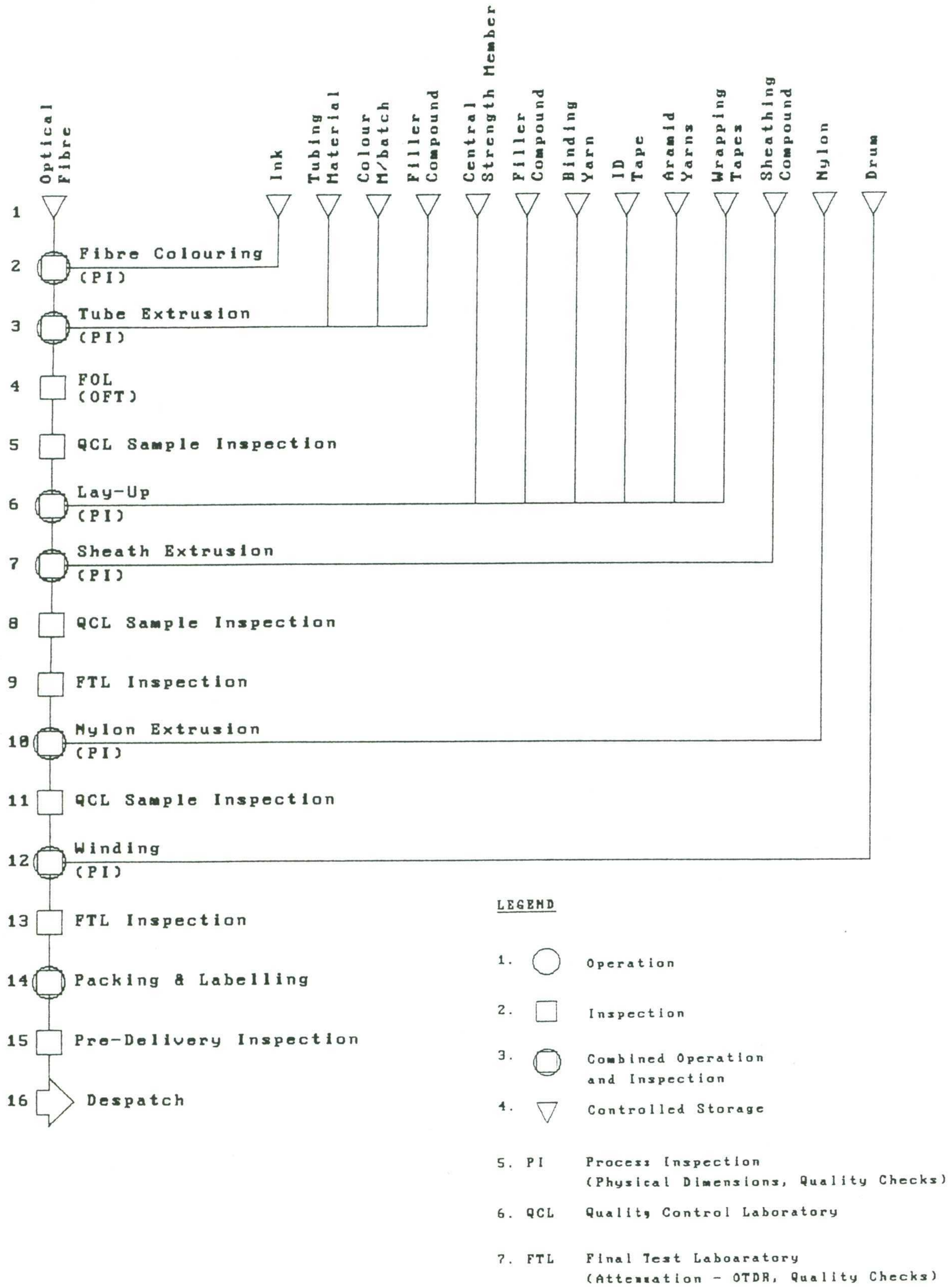
The transmission characteristics of the optical fibre and the physical parameters of the optical cable are important requirements during the cable manufacture. Tests are conducted to ensure the cable performance complies with the cable specification.

The routine tests performed on the optical cable during manufacture consist of measurements of attenuation and physical dimensions. These are highlighted in the Test Plan shown in Table 7.

Type testing is conducted during the development and annually thereafter on each design of optical cable. The optical transmission performance and stability of the optical characteristics under various mechanical and environmental conditions are tested according to the cable specification, these have already discussed in Chapter 4.

At end of testing, the cable design engineer assesses whether these parameters have been complied. The cable analysis will be presented at next Section 5.4.

TABLE 7. TEST PLAN FOR 2-30 FIBRE STANDARD OPTICAL CABLE



The Technical Data Sheet, Cross-Sectional Drawing and an example of the Type Test Report of this cable are provided at the end of this section.

In this design fibres are protected in the loose tubes with some excess length, hence providing a greater tensile strength allowance. The cable is very flexible and the tubes may be tee'd off during installation without exposing the optical fibres.

TECHNICAL DATA SHEET (for Optical Fibre Cables)			DATA SHEET NUMBER
DESCRIPTION: 2 TO 30 FIBRE RANGE (SINGLEMODE) FNPEHJ-STD, CATEGORY 1			DESIGN TYPE LOOSE TUBE
PREPARED BY:	APPROVED BY:	ISSUE: 1	DATE: 7/94

SPECIFICATION: Telecom Australia

BASE CONSTRUCTION DETAILS:

Number of elements = 5
CSM diameter (mm) = 2.00
Tube external diameter (mm) = 2.35

FIBRE DISTRIBUTION/ELEMENT CONFIGURATION:

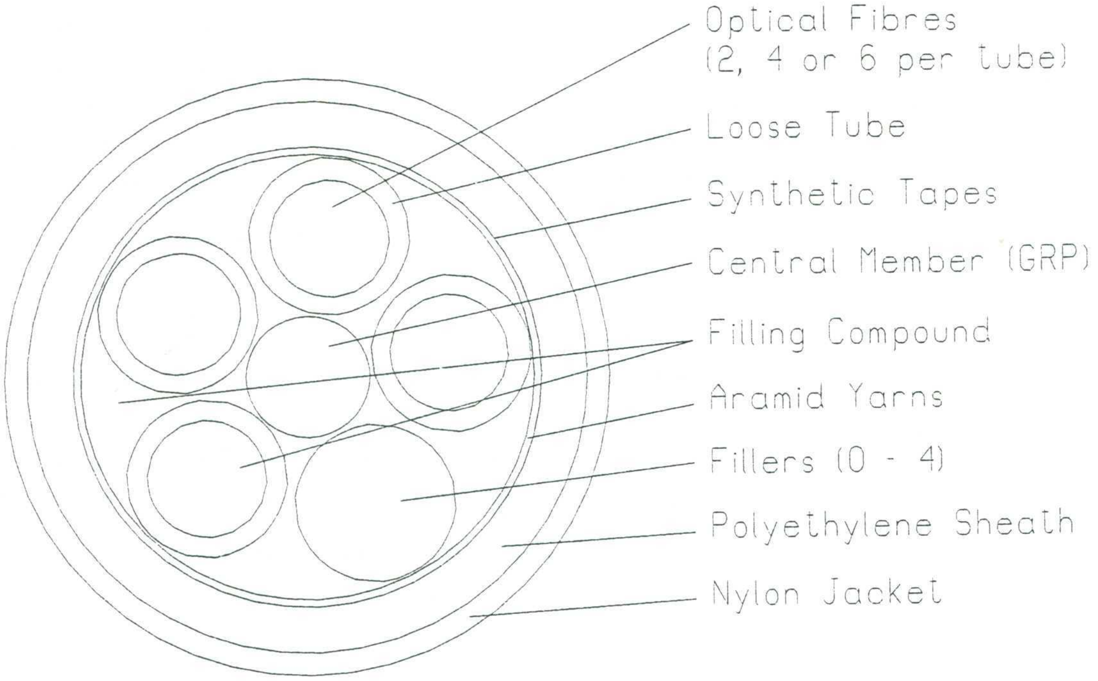
Schedule Item No.	Fibre Count	Tube X Fibres	Fillers
1, 46	2	1 x 2	4
2, 47	4	1 x 4	4
3, 48	6	1 x 6	4
4, 49	8	1 x 6 + 1 x 2	3
5, 50	10	1 x 6 + 1 x 4	3
6, 51	12	2 x 6	3
7, 52	14	2 x 6 + 1 x 2	2
8, 53	16	2 x 6 + 1 x 4	2
9, 54	18	3 x 6	2
10, 55	20	3 x 6 + 1 x 2	1
11, 56	22	3 x 6 + 1 x 4	1
12, 57	24	4 x 6	1
13, 58	26	4 x 6 + 1 x 2	0
14, 59	28	4 x 6 + 1 x 4	0
15, 60	30	5 x 6	0

FINISHED CABLE - MECHANICAL CHARACTERISTICS

Sheath Code	Cable Description	Net Weight (kg/km)	Tensile Strength (kN)	Aramid Yarn No. X Denier	Nominal Overall Diameter (mm)	Minimum Bending Radius (mm) No load / full load
25***	FNPEHJ-STD	82-86	2.1	6 x 2178	10.0	100 / 200

CROSS-SECTION DRAWING			DRAWING NUMBER
DESCRIPTION: 2 - 30 FIBRE CABLE FNPEHJ-STD			DESIGN TYPE LOOSE TUBE
PREPARED BY:	APPROVED BY:	ISSUE: 1	DATE: 7/94

SPECIFICATION: TELECOM AUSTRALIA



NOTE: DRAWING NOT TO SCALE

Example of Mechanical and Environmental Test Report

This Type Test Report contains the details of tests performed on the 2-30 fibre standard optical cable.

PIRELLI

PIRELLI CABLES AUSTRALIA Ltd,. Dee Why, NSW.

OPTICAL FIBRE CABLES MECHANICAL AND ENVIRONMENTAL TEST REPORT

Sheet 1 (6)

Cable ticket number - 6858

Cable length - 2000 Metres

Serial item No. - N/A

Fibre range of design - 2 - 30

Fibre type - Singlemode

Telecom Schedule - OS 3408

Contract No. - DI 5837 (R/D)

Product code - 399 10 1219 005

Date of manufacture - May 1994

Fibre manufacturer - 6 x Optix

Cable description - 6 SM FNPEHJ STD

Measurement wavelength - 1550 nm

GRP rod type / Manufacturer - Fibre Glass, E-Glass / Pacific Composites.

Interstitial Filling Compound Types - Isojell 2900B / Dussek Campbell.

Tape type / Manufacture - Polyethylene / Multiplex Pty. Ltd.

Aramid yarn type / Manufacture - Twaron / Akzo Chemical Ltd.

Nylon type / Manufacture - Nylon 12 / ELF Atochem.

Filler rod type / Manufacture - LD1333 / Compol.

Core construction - LOOSE TUBE

Materials used - TUBE : Celanex 1600A

FILLER : RHEOGEL 90S

Sheath construction - PEHJ

PE Materials used - ICI SHEA420

PE sheath thickness - 1.10 mm

Nylon Jacket thickness - 0.40 mm

Cable outer diameter - 10.3 mm

Maximum rated installation tension - 2100 N

Cable mass - 82 Kg/Km

Telecom Specification OCN - Isuue 8

PIRELLI CABLES AUSTRALIA Ltd,. Dee Why, NSW.

OPTICAL FIBRE CABLES MECHANICAL AND ENVIRONMENTAL TEST REPORT

Sheet 2 (6)

MECHANICAL CHARACTERISTICS

1. TENSILE STRENGTH

(Reference OCN3 - clause 2.1)

Length of cable sample - 2000 metres

Length actually under test - 77.6 metres

I. MAXIMUM ALLOWABLE TENSION VERSUS ATTENUATION CHANGE

Maximum load - 255 kg

Attenuation change - 0.0 dB/km.

II. CABLE STRAIN VERSUS FIBRE STRAIN CHARACTERISTICS

Fibre strain at maximum tensile load - 0.326 %

LOAD KG	0	50	100	125	175	185	195	204	215	225	235	245	255
CABLE STRAIN %	0	0.087	0.223	0.291	0.429	0.458	0.483	0.500	0.535	0.560	0.589	0.620	0.642
FIBRE STRAIN %	0	0.002	0.004	0.008	0.105	0.131	0.157	0.177	0.212	0.241	0.270	0.301	0.326

Refer to attached graphs:
a) Fibre Strain % versus Load kg
b) Fibre Strain % versus Cable Strain %
c) Cable Strain % versus Load kg

2. BENDING UNDER TENSION

(Reference OCN3 - clause 2.3)

Length of cable sample - 2000 metres

Length actually under test - 77.6 metres

Attenuation	Loaded	Unloaded	Mandrel size	Maximum load
Change (dB)	Nil	Nil	400 mm	255 kg

Fibre breaks - Nil

Sheath damage - Nil

Core damage - Nil

MECHANICAL CHARACTERISTICS Continued

3. BENDING

(Reference OCN3 - clause 2.2)

Length of cable sample - 10 metres

Length actually under test - 3.0 metres

Attenuation	Test 1	Test 2	Test 3	Mandrel size
Change (dB)	Nil	Nil	Nil	210 mm

Fibre breaks - Nil

Sheath damage - Nil

Core damage - Nil

4. CRUSH RESISTANCE

(Reference OCN3 - clause 2.4)

Length of cable sample - 10 metres

Length actually under test - 100 mm

	Crush term	Force	Test 1 Helical Lay	Test 2 Reversal Point	Test 3 Helical Lay	Test 4 Reversal Point
Attenuation change (dB)	Short term	2 kN/100mm	Nil	Nil	Nil	Nil
	Long term	1 kN/100mm	Nil	Nil	Nil	Nil

Fibre breaks - Nil

Nylon & PE sheath - Short term & Long term : No cracking, splitting, wrinking or creasing.

Tube - Short term & Long term : No kinking or creasing.
Long term : No flattening.
Short term : All tubes show flattening, the worst case = 32 % ovality.

MECHANICAL CHARACTERISTICS Continued

5. TWISTING (TORSION)

(Reference OCN3 - clause 2.5)

Length of cable sample - 10 metres

Length actually under test - 1.0 metres

Twist (turns)	Attenuation	Test
1 forward turns	Change (dB)	Nil
2 reverse turns	Change (dB)	Nil

Fibre breaks - Nil

Sheath damage - Nil

Core damage - Nil

6. IMPACT RESISTANCE

(Reference OCN3 - clause 2.6)

Length of cable sample - 10 metres

Length actually under test - 12.5 mm

Impact mass	Anvil radius	Attenuation	Test 1	Test 2	Test 3
1.5 kg	12.5 mm	Change (dB)	Nil	Nil	Nil

Fibre breaks - Nil

Nylon & PE Sheath - No cracking, splitting, creasing or wrinkling.

Tube - No kinking

- All tubes showed creasing and flattening, the worst case = 58 %

ENVIRONMENTAL CHARACTERISTICS

Sheet 5 (6)

7. LONGITUDINAL WATER PENETRATION (Reference OCN3 - clause 3.2)

Length of cable sample - 2.00 metres

Length actually under test - 2.00 metres

Leakage between the sheath and core wrap - 0.00 gram

Leakage between the cores within the core wrap - 0.00 gram

Leakage from the tubes - 0.00 gram

8. FILLING COMPOUND DRIP TEST (Reference OCN3 - clause 3.3)

Length of cable sample - 30 cm

Filling compound drip - 0.00 gram

9. TEMPERATURE CYCLE (Reference OCN3 - clause 3.1)

Temperature (Centigrade) / Attenuation (dB/km)

Fibre colour	Fibre colour	Reference attenuation at 20 deg.	Attenuation change at +20 deg.	Attenuation change at -10 deg.	Attenuation change at +70 deg.	Attenuation change at +20 deg.
BU	BU	0.20	+0.01	0.00	+0.01	0.00
	OR	0.20	+0.01	0.00	+0.01	0.00
	GN	0.20	-0.01	-0.01	0.00	-0.01
	BN	0.21	-0.01	-0.02	-0.01	-0.01
	GY	0.21	0.00	-0.01	0.00	-0.01
	WH	0.21	0.00	-0.01	0.00	-0.01

ENVIRONMENTAL CHARACTERISTICS Continued

10. AGEING TESTS

(Reference OCN3 - clause 3.4)

A) IN WATER

Length of cable sample - 500 metres in a loose coil not less than one metre in diameter.

Test Condition	Total loss in dB at 1550 nm
Cable preconditioned @ 21 deg C	3.74
1 day after immersion @ 70 deg C	3.51
40 days after immersion @ 70 deg C	3.51
85 days after immersion @ 70 deg C	3.55
1 day after removal @ 21 deg C	3.52

Maximum loss increase = 0.04 dB.

B) HIGH RELATIVE HUMIDITY/LOW TEMPERATURE PERFORMANCE

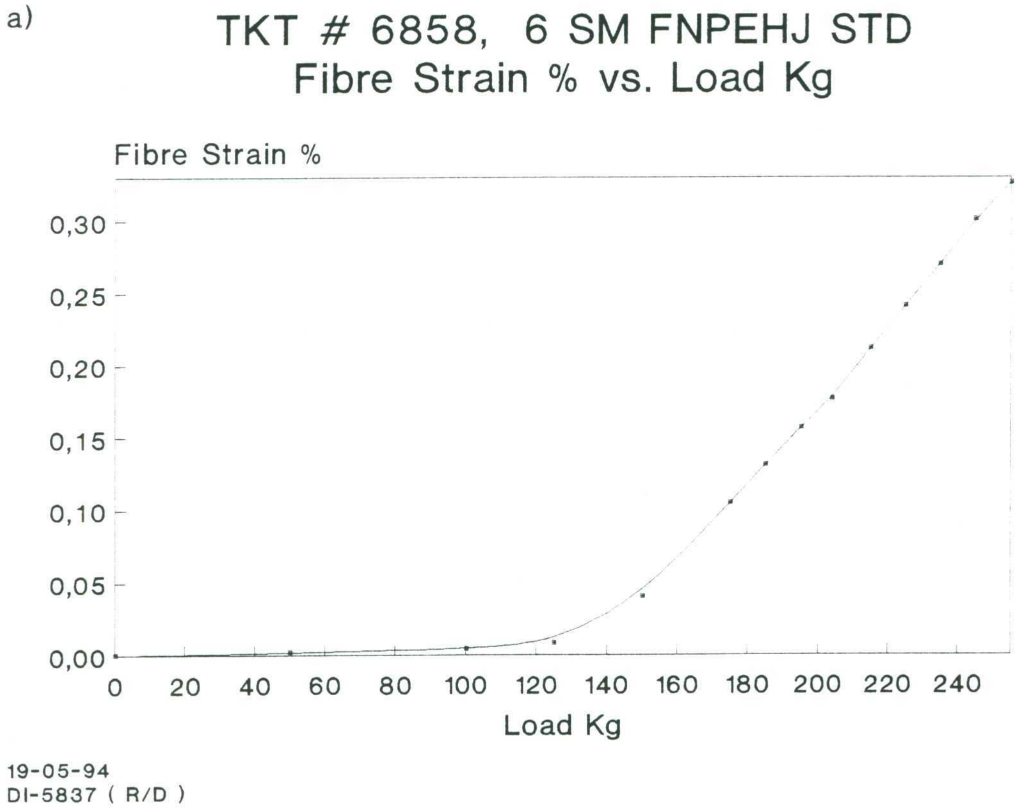
Length of cable sample - 200 metres.

Precondition - The cable was wound onto a steel drum with 0.80 metre barrel diameter.
High humidity test - The cable was wound onto a mandrel of 200 mm in diameter (20 x cable diameter).
Low temperature performance - After 24 hours at -10 deg C, the cable was wound onto a steel drum with 0.80 metre barrel diameter inside the environmental chamber (< 0 deg C).

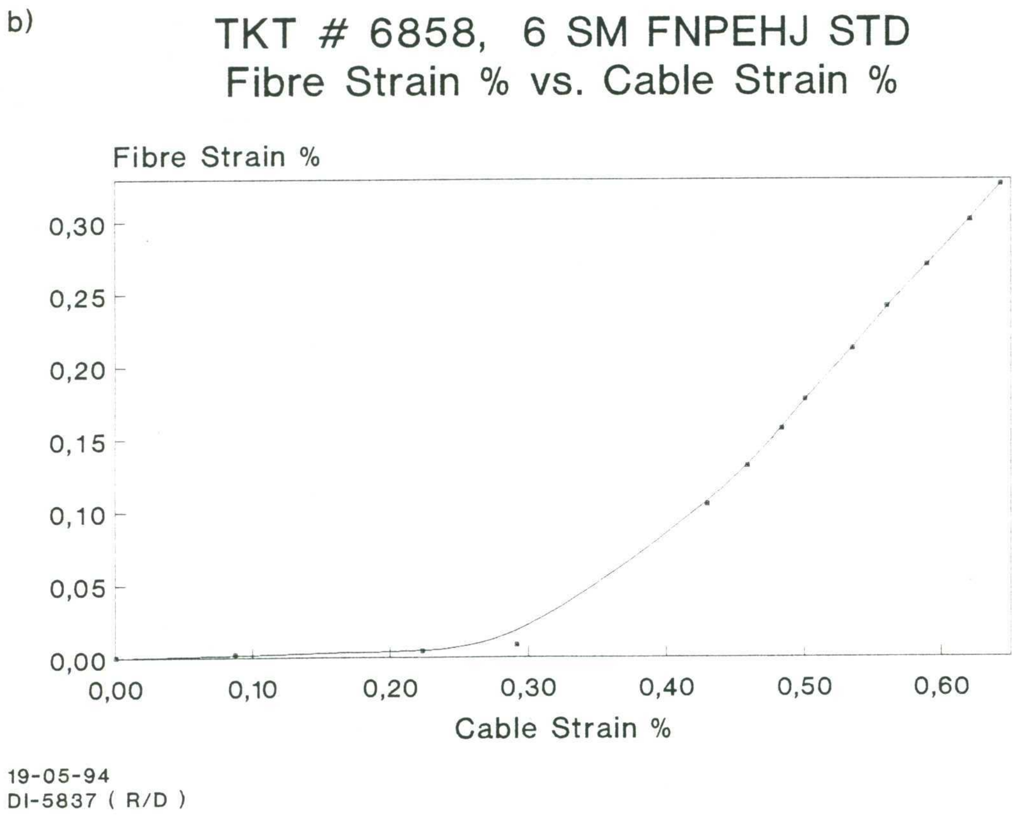
Test Condition	Total loss in dB at 1550 nm
Cable preconditioned @ 18 deg C	0.81
After winding onto 0.20 m mandrel	0.81
After 24 hr in water @ 50 deg C	0.79
After 21 days in water @ 50 deg C	0.81
After 24 hr at -10 deg C in air	0.81
After winding onto 0.80 m barrel	0.81
After 14 hr at 20 deg C in air	0.79

Maximum loss increase = 0.02 dB.

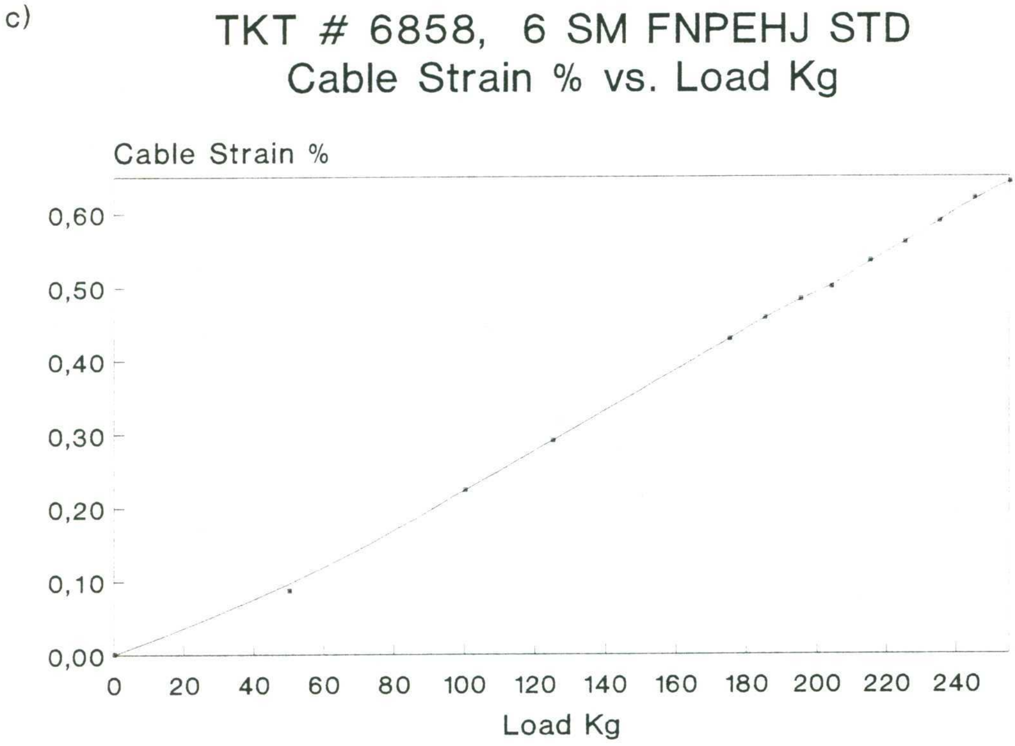
a)


TKT # 6858, 6 SM FNPEHJ STD
Fibre Strain % vs. Load Kg
Fibre Strain %
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0
20
40
60
80
100
120
140
160
180
200
220
240
Load Kg
19-05-94
DI-5837 (R/D)

b)


TKT # 6858, 6 SM FNPEHJ STD
Fibre Strain % vs. Cable Strain %
Fibre Strain %
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0,00
0,10
0,20
0,30
0,40
0,50
0,60
Cable Strain %
19-05-94
DI-5837 (R/D)

c)



19-05-94
DI-5837 (R/D)

5.4 Cable Analysis

The purpose of cable analysis is to determine how close are the results obtained to the cable specification and how might they be further improved.

The first step is to check at the results obtained from the routine tests performed, if these results comply with the cable specification then it is progressed to the type test report. The type testing represents the major requirements for qualification of the development cable, these are presented in this section.

The comparison between actual and expected results are summarised as following:

1. <u>Tensile Strength</u>

Four key parameters are determined from the graphs plotted:

(a) Attenuation change at maximum load
- no change allowed at 215 kg.

Result: 0.0 dB/km.

(b) The fibre strain at maximum load
- not to exceed 50 percent of the fibre proof strain (0.35%) at 215 kg.

Result: 0.212%.

(c) The cable strain at no fibre strain
- to determine Strain Free Window (0.3%)

Result: 0.33%.

(d) The cable strain at maximum load
- not to exceed 0.65 percent at 215 kg.

Result: 0.535%.

2. <u>Bending Under Tension</u>

Bend cable sample under full load, on 200 mm minimum bending radius, without change of attenuation, fibre breaks, or sheath and core damages.

Result: Complied.

3. <u>Bending</u>

Bend cable sample without load, on 105 mm minimum bending radius, without change of attenuation, fibre breaks, or sheath and core damages.

Result: Complied.

4. Crush Resistance

Crush cable sample at 2 kN/100 mm for short term and at 1 kN/100 mm for long term, without change of attenuation, fibre breaks, or sheath and core damages.

Result: Complied.

5. Twisting (Tortion)

Twist cable sample 1 turn forward (360°) and 2 turns in reverse (720°), without change of attenuation, fibre breaks, or sheath and core damages.

Result: Complied.

6. Impact Resistance

Drop once, 1.5 kg mass from 1 metre height on cable sample without change of attenuation, fibre breaks, or sheath and core damages.

Result: Complied.

7. Longitudinal Water Penetration

After 24 hours, no water leakage allowed through the tubes, a maximum leakage allowed of 200 grams between the sheath and core wrap, and a maximum leakage allowed of 10 grams between the loose tubes and the core wrap.
Result: No leakage recorded, complied.

8. Filling Compound Drip Test

After 24 hours at 65°C, a maximum of 100 mg dripped filling compounds from the tube and interstices of the cable is allowed.
Result: No dripping, complied.

9. Temperature Cyclying

Maximum of 0.1 dB/km attenuation change is allowed at 1550 nm, within the temperature range of -10°C to +70°C.
Result: Complied.

10. <u>Ageing Test</u>

- Immersion of cable in water at 70°C for 85 days, the attenuation increases not to be greater than 0.10 dB/km at 1550 nm.

- Relative humidity/low temperature performance, no individual measurement of attenuation increase of any fibres is to be greater than 0.20 dB/km at 1550 nm.

Results: Complied

All type test results have shown compliance and they are well within the cable specification, therefore, no design changes are required. However, certain issues may be further improved as a cost effective exercise. These are listed as follows:

* Revise parameters used in the tensile strength calculations, this may result one less roving of aramid yarn for the cable.

* Better control of manufacturing process, resulting less overusage of materials and smaller overall cable diameter and weight.

* Use cheaper materials with equal or better properties.

All changes given above require further prototype cable to be manufactured, tested and analysed.

CHAPTER SIX

C O N C L U S I O N

Practical aspects of design and testing of optical fibres and cables were presented in this thesis. Some historical background and an outline of manufacturing processes, cable construction and test methods were presented. The effect of mechanical and environmental conditions on optical fibres and cables were discussed. The significant effects concerning the final cable performance were also discussed. Finally, an example of a cable developed for Telecom Australia was presented, the design principles were demonstrated together with its test report and analysis.

Although research into optical fibres and cables is still in progress, significant advances in both fibre and cable fabrication have occurred, based on an understanding of optics fundamentals and manufacturing technologies.

Examples of such developments in optical fibres in recent years include fluoride fibres, optical amplifiers, and nuclear resistant fibres. Developments in optical cables include the use of new materials which are cheaper but have better properties, and specialised cable constructions for particular applications. The latter include composite power/optical underground cable, long span aerial optical cable (greater than 1000 m span), and lead-in cable (Fibre-To-The-Home).

These developments will contribute towards more reliable and less expensive optical communication systems of the future.

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