DEVELOPMENTS IN AUTOMATING THE DESIGN OF FIBRE-OPTIC CABLE

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DECLARATION

This dissertation has not been, nor is being currently submitted for the award of any other degree or similar qualification.

Llyr Roberts

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CONTENTS

ABSRACT

The design of optical fibre cables has for many years been a laborious manual task involving geometrical mathematics, a knowledge of materials, and past experience. The objectives of the work were to develop a series of design aids which would both automate the process of physical cable design and optimise the optical fibre performance within the cable.

The computer aided design system developed was restricted to the design of 'loose tube' fibre optic cables as this represents the main cable type manufactured by the company. Of several potential computing methods, an expert-system-shell was chosen as this presented the most effective way to harness all relevant information. The resulting knowledge base enables a user to design any variation of a 'loose-tube' cable, and obtain immediate data regarding its weight and dimensions. The expert-system was interfaced to software which subsequently generates a cross-sectional diagram of the eventual cable.

To optimise fibre performance within a cable, an investigation was made of the fibre overfeed or excess within the 'loose-tubes'. Too little excess may cause excessive fibre strain, whilst too much may result in fibre bends below a critical radius. As fibres become very lossy below this radius, experiments were performed to quantify this phenomenon. Comparisons were made between four commercially available fibre types, and the results found the Chemical-Vapour-Deposition, depressed cladding fibre type, to be the most bend-insensitive.

The expert system to design cables is fully functional within the technical department, and is estimated to save over 4000 man-hours per annum. Software has also been written to relate the maximum working tensions of a cable to the fibre excess, whilst the experimental results on fibre bend characteristics are presented in graphical form.

NOMENCLATURE

APD	Avalanche Photodiode
APL	Aluminium Plastic Laminate
BSI	British Standards Institution
CCITT	International Telegraph and Telephone Consultative Committee
CVD	Chemical Vapour Deposition
DC	Depressed Cladding
DOS	Disk Operating System
ESI	Equivalent Step Index
FEM	Finite Element Method
GRP	Glass Reinforced Plastic
GSWA	Galvanised Steel Wire Armour
HDPE	High Density Polyethylene
HPGL	Hewlett Packard - Graphics Language
IEC	International Electrotechnical Commission
IKBS	Intelligent Knowledge Based System
LDPE	Low Density Polyethylene
LP	Linearly Polarised
MC	Matched Cladding
MCVD	Modified Chemical Vapour Deposition
MDPE	Medium Density Polyethylene
NA	Numerical Aperture
NLQ	Near Letter Quality
OVD	Outside Vapour Deposition
PBTP	Polybutyl Teraphthelate
PC	Personal Computer

PIN	Positive - Intrinsic - Negative
PVC	Polyvinyl Chloride
SPL	Steel Plastic Laminate
STC	Standard Telephones and Cables
SWA	Steel Wire Armour
V	Normalised Frequency/Propogation Velocity Constant
VAD	Vapour Axial Deposition
Vco	Normalised Frequency at Cut-off Wavelength
ωo	Mode Field Radius
λ	Operating Wavelength
λco	Cut-off Wavelength
Δ	Normalisesd Refractive Index Diffference

PREFACE

The Teaching Company scheme operates through Teaching Company Programmes in which a University or Polytechnic participate in a company programme to achieve a substantial and comprehensive change in manufacturing.

It aims to develop active partnerships between academic institutions and manufacturing companies in order to:-

a. raise manufacturing performance by effective use of academic knowledge and capacity.

b. improve manufacturing methods and the effective implementation of advanced technology.

c. train able graduates for careers in manufacturing.

d. develop and re-train existing company and academic staff.

e. give academic staff broad and direct associations with industry for research and as a background for teaching.

The scheme was divised in 1974/1975 by a working party appointed jointly by the Science Research Council (SRC) and the Department of Industry (DOI). The Council published a consultative document and pilot programmes were initiated at three companies.

A second working party considered the results of consultations and the pilot programmes and recommended a Scheme with a target of 20 companies by 1981.

The Teaching Company Programme which enabled the work described in this Thesis to be undertaken, was the partnership between the Polytechnic of Wales (POW) and Standard Telephones and Cables PLC

(STC). The author was an associate of that programme.

CHAPTER 1

INTRODUCTION

In twenty years since optical waveguides became a reality for practical applications, there have been tremendous strides in the development of cabling. The goal of cable design and manufacture is to enable the multitude of advantages of optical waveguides to be fully realised.

The benefits of optical cables include such attributes as light weight, small diameter, and excellent transmission characteristics. The enormous information-carrying capacity over long distances offers a capability unmatched by any other guided-communication medium. However, the transmission characteristics of optical waveguides are sensitive to mechanical and environmental influences, and their conservation is a major challenge in cabling.

The brittle nature of the material used for most optical waveguides is in direct contrast to the ductile behaviour of the conductors in almost all electrical cables. The stress resistance of waveguides under tension and bending has improved over recent years due to advances in the waveguide and coating materials and in manufacturing techniques, but an optical conductor cannot be cabled without due consideration of its vulnerability. Nevertheless, an optical cable is expected to withstand as severe handling as equivalent copper cables.

Historically, the approach to cabling of optical waveguides tended to be one of designing the cable structure based on the ability of that structure to be applied to the fibre without impairing the inherent transmission capability. The degree and area of application for such a cable design was then evaluated. More recently the understanding of cabling technology, materials, and manufacturing methods has improved to the point where the application and environment can be considered first. This progression has led to the development of an increasing variety of cable designs, each with its own set of capability optimised for a given application.

In the early stages of optical-waveguide technology development, economic justifications were rare since new technology almost always cost more than a more conventional approach. Early applications used characteristics of optical waveguide cables that could not be matched by conventional technology at any price. Such characteristics include immunity from electromagnetic and radio-frequency interference (emi and rfi), small size and low weight. Process-control and very specialised scientific, analytical, and military applications were the forerunners for widespread utilization of the technology.

As the cost of cabled fibre came down, the applications where the cost effectiveness of the technology is significant have broadened noticeably. Trunk and toll-grade telephony applications have dominated the recent volume explosion and the cable costs have been driven down.

1.1. Basic Theory of Operation

Fibre optics can be defined as that branch of optics which deals with communication by transmission of light through ultrapure fibres of glass or plastic. It has become the mainstay or major interest in the world of electro-optics, the blending of the technology of optics and electronics.

In a fibre-optic system or link three major parts perform this task of communication:

(i) a light source

(ii) an optical fibre, and

(iii) a light detector or receiver

The light source can either be a light-emitting diode (LED) or a semiconductor laser diode. The optical fibre can be a strand as short as 1m or as long as 7 km. The detector can be either an avalanche photodiode (APD) or a positive-intrinsic-negative (PIN) diode.

Basically, a fibre-optic system simply converts an electrical signal to an infrared light signal, launches or transmits this light signal into an optical fibre, and then captures the signal at the other end, where it reconverts it to an electrical signal.

Two types of light-wave modulation are possible: analog and digital. In analog modulation the intensity of the light beam from the laser or LED is varied continuously. That is, the light source emits a continuous beam of varying intensity.

In digital modulation, on the other hand, the intensity is changed impulsively, in an on/off fashion. The light flashes on and off at an extremely fast rate. In the most typical system, pulse-code modulation (PCM), is used where the analog input signals are sampled for wave height. For voice signals this is usually at a rate of 8000 times a second. Each wave height is then assigned an 8-bit binary number which is transmitted in a series of individual time slots or slices to the light source. In transmitting this binary number, a 1 can be represented as a pulse of light and a 0 by the absence of light in a specific time slice.

Digital modulation is far more popular, as it allows greater transmission distances, for the same power intensity as analog modulation.

1.2. Advantages of Fibre Optics

In a number of situations fibre optics' advantages over conventional transmition media are so compelling that they cannot be ignored:

i. Extremely wide bandwidth
ii. Smaller - diameter, lighter - weight cables
iii. Absence of crosstalk between parallel fibres
iv. Immunity to inductive interference
v. Potential of delivering signals at a lower cost

But these are merely the primary advantages, there are also important secondary advantages:

i. Greater security
ii. Greater safety
iii. Longer life span
iv. High tolerance to temperature extremes as well as to liquids and corrosive gases.
v. Greater reliability and ease of maintenance
vi. No externally radiated signals
vii. Ease of expansion of system capability
viii. Use of common natural resources.

1.3. Fibre Optic Cables

A fibre-optic cable is one or more optical fibres formed into a cable for convenience and protection. Whether it is buried directly in the ground, hung on telephone poles, pulled through underground ducts, or dropped to the bottom of a lake or ocean, this cable is likely to receive much abuse and mistreatment during its lifetime.

While being installed, it may be stepped on and mistreated. Trucks and drums may roll over it. As it is being pulled through ducts, it may be stressed beyond expectation. Once in place it may be subjected to a very cold Canadian winter or a hot Mediterranean Summer. Ice may load it, causing it to sag or break. Gophers and other rodents may try to chew through it. In ice-clogged ducts, technicians may hit it with steam as they clear the ducts. It may be submerged in water in flooded manholes. The cable must be able to survive this abuse, yet it must be reasonably easy to repair if it breaks, be economically competitive with conventional cables, and be space efficient. Numerous designs or configurations have been developed to meet these requirements. These designs differ in materials and arrangements, but practically all of them include coatings to protect individual fibres, strength-bearing materials, filler or buffer materials, and an external protective jacket. In addition, for specific applications some cables include armour protection against rodents and copper wires for carrying electrical power.

The optical fibre is coated with soft silicone immediately upon fabrication to prevent damage from abrasion and moisture. This coating is considered part of the fibre, not the cable. An additional coating or jacket of a durable plastic may be added for still further protection. The jacket may be colour coded for easy identification during installation and repair.

The strength or tension member minimises or eliminates stretching force (tensile stress) applied to the optical fibres. It is also called the load-bearing member. It is made of either steel, glass reinforced plastic (GRP), or braided Kevlar aramid yarn. As both GRP and Kevlar are non-conducting, they are better than steel in places where the cable would be susceptible to lightning damage. Polyethylene cable fillers or buffers help to cushion the fibres.

The outer protective jacket may be made of polyethylene, polyurethane, polyvinyl chloride (PVC), or Tefzel. It protects the fibres from dirt, moisture, sunlight, abrasion, crushing, and temperature variations. Like the individual fibres, it may also be colour-coded. Length markers and cable type may be imprinted on this jacket. Flame-retardant types are available. In some cases this jacket may carry some of the load, just as the strength members do.

1.4 Optical Fibre Waveguides

Optional fibres are dielectric waveguiding structures used to confine and guide light. They consist of an inner dielectric material called a core which is surrounded by another dielectric (called a cladding) with a smaller refractive index. A plastic and lossy jacket is commonly applied to the outside of the fibre to prevent crosstalk with other guides and to keep the fibre strong by preventing chemical and abrasive attack on its surface.

Optical fibres are manufactured by three main processing techniques, which are:

i. Modified chemical vapour deposition (MCVD)

ii. Outside vapour deposition (OVD)

iii. Vapour Axial deposition (VAD)

The underlying mechanism for all vapour-phase fibre fabrication techniques can be summarised as:

i. Generation of a gas phase flow of source compound.

ii. Direction of that flow to a zone where oxidation occurs.

iii. Deposition of the resultant oxides onto a subtrate to produce a solid preform.

iv. Subsequent drawing of the preform into fibre.

Optical fibres manufactured by MCVD, OVD and VAD techniques are noticeably different in terms of their refractive index profiles as a consequency of the variations in processing techniques. This leads to significantly differing bending characteristics for fibres with nominally similar equivalent-step-indexes (1).

It is an inherent feature within the majority of optical fibres that when they are bent beyond a critical radius, light is radiated from the cladding causing a significant power reduction. The value of the critical radius depends upon the dimensions and shape of the fibre refractive index profile, which itself depends on the fibre manufacturing process.

1.5. Optimisation of Cabled-Fibre Performance

The main cable type manufactured by STC is of Loose Tube construction. These cables consist of either single or multiple fibres loosely contained within the tubes. The tubes are then helically laid around a central strength member, wrapped with tape and then sheathed to form a cable. Longitudinal freedom and cushioning within the tubes ensures the fibres are protected against stresses applied to the cables during handling and installation operations.

The degree of longitudinal freedom depends on the amount of excess fibre placed within the tubes during manufacture. Too little results in added losses due to tensile stress, whilst too much causes attenuation from fibre bends.

It is essential to be able to fully characterise the performance of optical fibres under cabled conditions. With this knowledge the cable design can be optimised so that the fibre excess level is kept within a safe operating window.

1.6. Objectives of the Investigation

Currently the design of optical fibre cables at STC is a manually intensive task, with no systematic method of relating new customer enquiries to previous cable specifications. The design philosophy is very much dependent on the expertise of key personnel, and is often based on experience acquired over a long period of time.

The company has recognised the need to introduce Computer Aided Engineering/Design techniques into the cable design section, and integrate these methods within the infrastructure of the company. From an initial investigation into the whole design procedure, covering all aspects from technical/production requirements to cable performance, the following objectives were identified.

i. To implement an expert system to design optical fibre cables from a specification of customer requirements.

ii. To implement a database so that existing cable designs may be retrieved quickly and efficiently.

iii. To develop advanced cable design rules so that the performance of cabled fibre under tension and bend is fully characterised.

iv. Investigate the various fibre designs available today, and compare their respective bend characteristics.

v. Combine objectives (i), (iii) and (iv) so that the physical cable construction is optimised to give the best possible optical waveguide performance.

The following chapters give an introduction to fibre optic transmission with a view to cabling, and subsequently the developments made in cable design aids.

CHAPTER 2

THEORY OF FIBRE OPTIC TRANSMISSION

Optical fibres are inherently brittle and fragile but have to be made into cables that will withstand installation and the often hostile environments in which they must operate reliably. Working environments that have been met range from the almost constant 2-4°C of the sea bed for deep-sea submarine cables to rapid changes from -55°C to + 115°C for some avionic applications; from normal pressures up to 70 MN/m ; from ambient air to hot corrosive liquids. The number of fibres in a cable may vary from one in rack wiring to several thousand in distribution cables now being proposed. The cable may be all-dielectric containing only fibres or may incorporate numerous copper conductors or other more complex elements.

Such diversity can only be met with a wide variety of cable designs and the state of the art is such that even some straight forward applications can be met by several designs. However, all optical fibre cables can be judged by their success in meeting two basic criteria. First, they must not significantly degrade the transmission properties of the fibre and second, they must maintain the integrity of the fibre during manufacture, installation and service.

The invention of the cladded waveguide in 1954 by Professor Van Heel (2) was the key that brought dielectric waveguides from the realm of scientific exploration to practical exploitation. A cladding, that is sufficiently thick and has a slightly lower refractive index than that of the core, ensures that any evanescent fields associated with the guided energy will decay to negligible values at the surface of the composite guide, so that the waveguide can be supported without incurring prohibitive losses. However, despite the enormous step forward that this invention represented, the problems of cabling such waveguides or optical fibres were still formidable.

The cabling engineer has two main targets

- to minimise optical attenuation increments associated with manufacture and use of cables.
- to maintain the physical integrity of the fibre during the cabling process and in service.

2.1. Attenuation Increments

To understand these problems it is necessary to examine the propagating characteristics of dielectric waveguides and how these may be modified by the cabling processes.

First, all dielectric waveguides radiate unless their axis is straight. For a particular guide, the amount of radiation is critically dependent on the radius of curvature and can rapidly increase from totally negligible to prohibitive values with a comparatively small reduction in radius (3). Although this rapid change will occur at some radius for every guide, for certain guides it will occur at much greater radius than for others, and this depends on the fibre used. Historically, emphasis has shifted from multimode step index to graded-index fibres and has now moved more towards single mode fibres; however, it is easier to consider the mechanisms that can cause increments in the reverse order.

2.2 Single Mode Fibre Waveguides

A single mode fibre waveguide is one where only the primary mode (LP01) propagates. This differs from multimode fibres where several hundred modes in addition to the LP01 propagate. A qualitative picture of how radiation occurs on bends can be obtained for a low-order mode waveguide by considering the field distribution associated with guidance by a curved fibre waveguide (Fig. 2.1.). Using a first approximation the field distribution follows a curve similar to the refractive index profile within the core and has an exponential decay within the cladding. Since the associated wavefront remains perpendicular to the fibre axis, there must be some radius ($R + X_R$ in Fig.2.1) at which the phase velocity of the guided radiation reaches the velocity of light in that medium. Beyond this point the wavefront cannot remain perpendicular to the fibre axis and guiding cannot occur. Therefore the evenescent energy represented by the field at greater distances from the centre of curvature will radiate. This simple picture is complicated in reality by:

(i) a shift of the field in relation to the fibre axis if the bend radius is steady and

(ii) by oscillation of the field in relation to the axis when transient conditions pertain.

It is also over-simplified in that it implies loss to a radiating continuum, where as fibre waveguides radiate into discrete modes. Nonetheless, the success of mode spot size as a measure of the susceptibility of single mode fibres to microbending loss does substantiate it to a certain extent (4). Similarly, any energy in the evanescent field may be lost to absorption if this field penetrates into the cladding as far as the transition from deposited material to the more absorbent original silica carrying tube. If, at this point, there is also an increase in the real part of the refractive index, further loss can occur from quantum tunnelling effects (5).

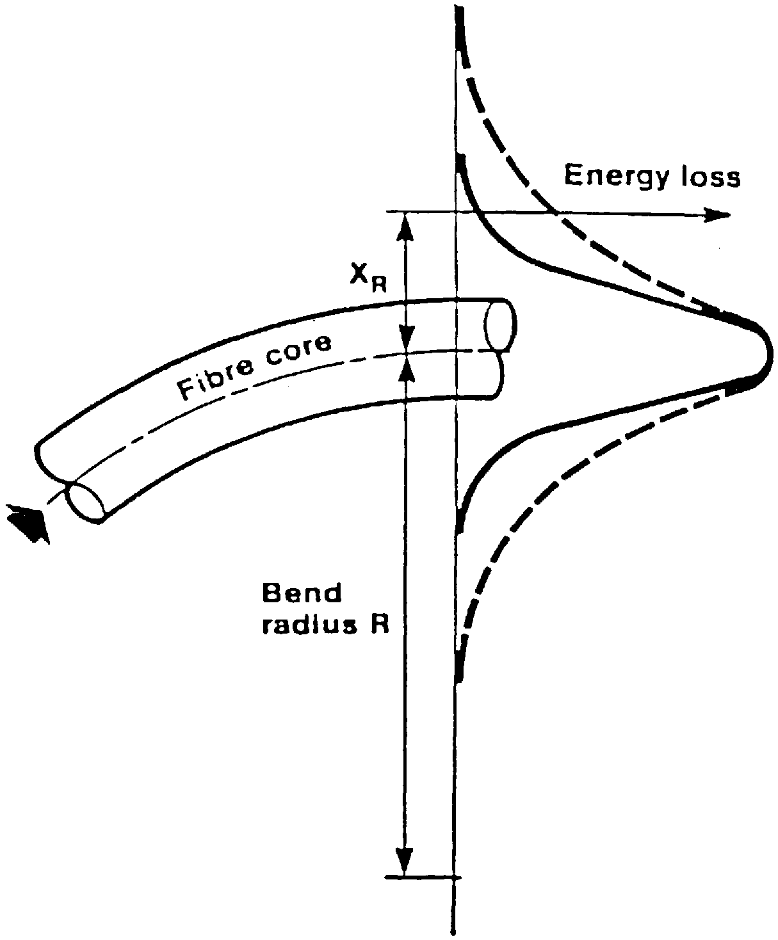


FIG 2.1 FIELD DISTRIBUTION IN A CURVED OPTICAL FIBRE WAVEGUIDE FOR A BOUND MODE (SOLID CURVE) AND A MODE NEAR CUT-OFF (DOTTED CURVE).

2.3. 'W' Guides

For some fibre waveguides a change in refractive index is introduced in the cladding comparatively close to the core. Such stratagems are used by the waveguide designer, for instance, to make significant reductions in waveguide dispersion, which are important to the cable engineer because they modify mode cut-off wavelengths. As mode cut-off is approached a greater proportion of evanescent energy is carried in the cladding, until the point is reached at which a mode is just not cut-off, when it becomes in effect a plane wave travelling in the cladding and hence very susceptible to minor perturbations of the fibre axis. It is quite possible, indeed likely, that a fibre with stepped cladding index (W Guide) will have a cut off point for all modes and no dominant mode, characteristic of normal single mode fibres (6). Unfortunately, steps in cladding refractive index can be introduced during fibre manufacture for quite other reasons and the effect on waveguide performance may not become apparent until an unfortunate cable engineer is faced with disastrous results that he cannot explain.

2.4. Multimode Fibre Waveguides

For multimode fibres there are always some modes close to cut-off and clearly more energy radiates from these modes than from the more tightly bound lower order modes. The close connection between cut-off and radiation has been demonstrated by Midwinter and Reeve in an experiment using a small core step-index fibre with a carefully set radius of curvature (7). The waveguide geometry chosen was such that tens rather than hundreds or thousands of modes were carried and a wavelength scan of the scattered power spectrum of this fibre showed clearly delineated peaks that could be assigned unambiguously to the expected cut-off wavelengths of the individual modes. As well as the bound and radiating modes, a third class of mode can be distinguished for multimode fibres, the so called leaky modes. These modes can be represented by highly skewed rays such that either the critical angle is exceeded in either the circumferential or medidional plane, but not both, or a quantum tunnelling loss of radiation is apparent. For small core fibres the radiation loss is rapid and is not relevant in cabling applications. However, for larger core fibres these modes may radiate over a kilometre or more and can be important because of their influence on measuring results in typical cabling experiments. Fortunately, for today's telecommunication applications, where multi-kilometre lengths are being considered, their effect is quite negligible.

2.5 Maintaining Mechanical Integrity

Despite silica possessing a high Young's Modulus value and quite exceptional elasticity, the small cross-section of a normal fibre means that it contributes very little to the cables strength except in the case of certain very specialised military cables. Usually the load and the Young's Modulus of the strength member determine the strain or elongation of the cable and hence that of the fibre. What matters most is the maximum strain that the fibre will withstand. Unfortunately, the answer to this simple question is very complex.

The following chapter describes a range of cable designs, which over several years of development have been optimised to give maximum fibre protection.

CHAPTER 3

FIBRE OPTIC CABLE DESIGNS

Within STC Cable Products Division at Newport, several variations of fibre optic cables are manufactured. The three major cable construction types are namely Loose Tube, Tight Construction, and Open Channel (Slotted Core). Other types not used as extensively or which are still under development are Fibrespan, Mini Open Channel, Figure of 8 and FOTS-LH (Fibre Optic Transmission System - Long Haul).

3.1. Loose Tube

These cables are suitable for trunk, inter-exchange junction and subscriber local loop applications. Various types of multimode and singlemode optical fibres and a wide selection of cable constructions are available for duct and direct buried applications.

Cable variants to suit customers' specifications include steel or dielectric central strain members, steel tape or wire armouring, polyethylene, PVC or low fire risk sheathing compounds. Copper pairs may also be incorporated.

The cable consists of either single or multiple fibres loosely contained within tubes which may be filled with a special compoud to prevent the ingress and transportation of gases and liquids. These tubes are laid around a central strength member, wrapped with tape and then sheathed to form a cable. The cable interstices may also be filled with special compound to provide a genuinely fully filled cable.

Longitudinal freedom and cushioning with the tubes ensures the fibres are protected against stresses applied to the cables during handling and installation operations. Fibres and tubes may be colour coded to enable easy identification.

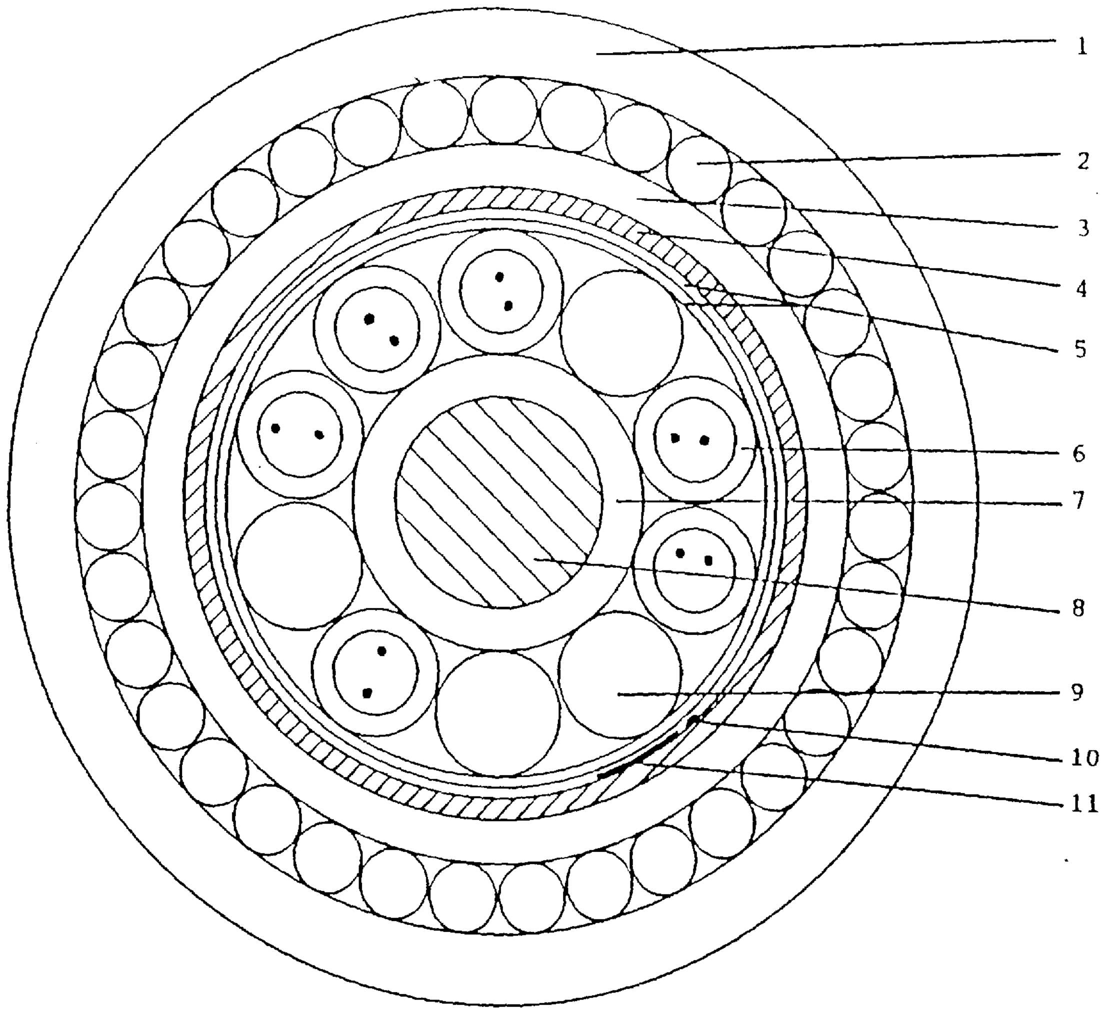
Figure 3.1. shows an unarmoured cable as used in the trunk network and installed in ducts. This particular design incorporates 12 optical fibres and two copper pairs. The cable consists of a strength member of compacted steel strand, coated with low density polyethylene. Three tubes, two fillers, and two copper pairs are stranded around the central member and wrapped with paper tape. The tubes are of extruded polybutylteraphthelate, and each tube contains four acrylate coated optical fibres. The fillers are of extruded polyethylene. An aluminium/plastic laminated moisture barrier is applied over the core and the cable is sheathed with low density polyethylene.

Figure 3.2. is also a 12 Fibre Loose Tube cable, but has six tubes (two fibres per tube), and four fillers. There are no copper pairs. Also present in this design is a galvanised steel wire armouring.

3.2 Tight Construction

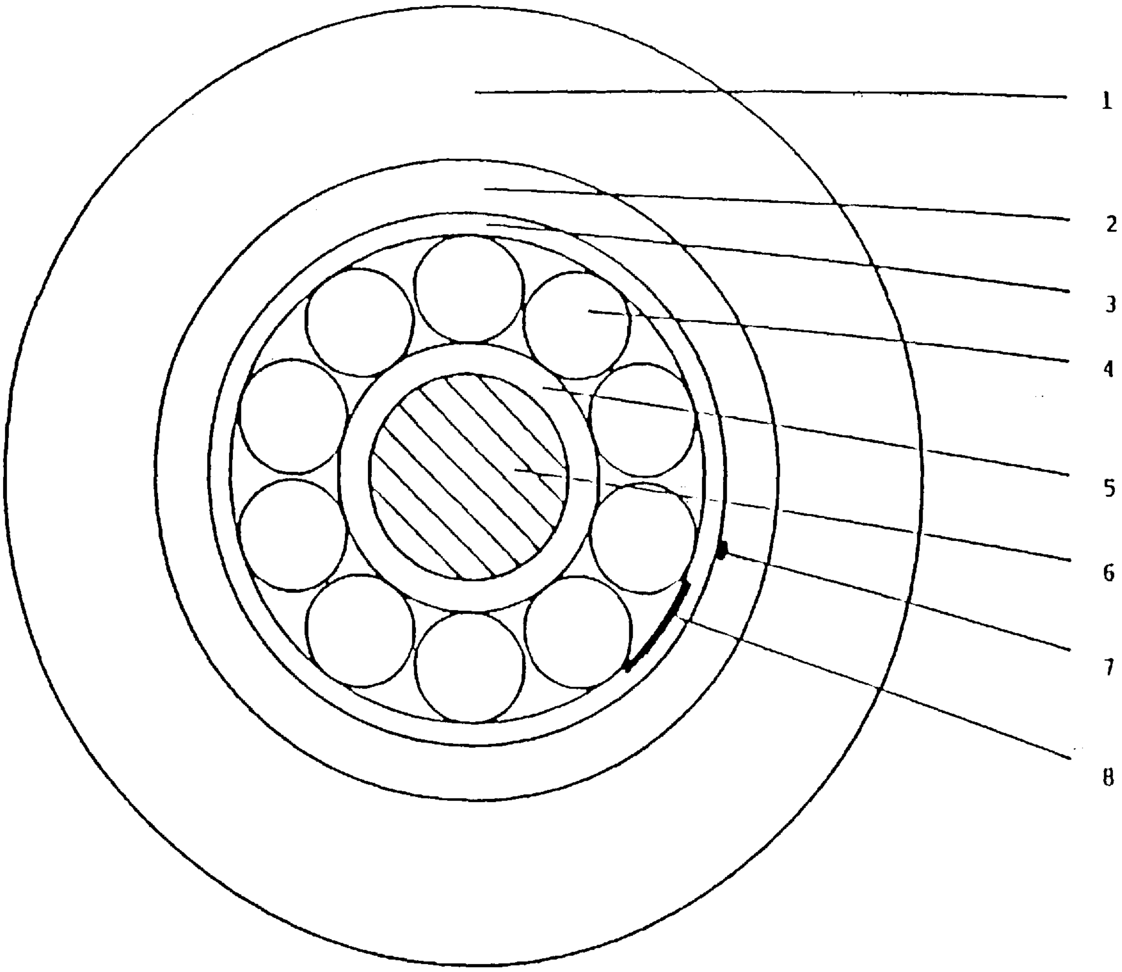
This type of tightly buffered cable is suitable for installation into ducts. Cables are designed with space for up to 10 elements, each of which may be either an optical fibre (secondary coated), filler or insulated copper wire. The cables are small, flexible, lightweight and optimise the use of existing duct space.

The cable construction as seen in Fig.3.3 which has 10 secondary coated fibres, has a polyethylene coated steel central strain member over which the fibres, copper conductors or filler elements are stranded. The interstices are filled with a water



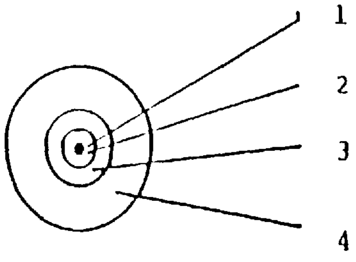
1. Outer Sheath
2. Galvanised Steel Wire
3. Inner Sheath
4. Aluminium/Plastic Tape
5. Paper Tape
6. Loose Tube
7. Strength Member Coating
8. Steel Strength Member
9. Filler
10. Rip Cord
11. Manufacturer's I.D. Tape

FIG. 3.2 ARMOURED LOOSE TUBE CABLE - 12 FIBRE VERSION



1. Outer Sheath
2. Aluminium Plastic Laminate
3. Paper Tape
4. Multimode Secondary Coated Optical Fibre
5. Strength Member Coating
6. Steel Strength Member
7. Ripcord
8. Manufacturer's ID Tape

SECONDARY COATED OPTICAL FIBRE



1. Core
2. Cladding
3. Silicon Resin
4. Nylon Coating

FIG. 3.3 10 FIBRE TIGHT CONSTRUCTION CABLE blocking compound, except when used in pressurised systems. The unit is wrapped with a paper tape and ripcord included, over which are applied an aluminium/plastic laminate and an outer sheath of polyethylene.

3.3. OPEN CHANNEL (Slotted Core)

These cables may be used as an alternative to loose tube designs in similar application areas.

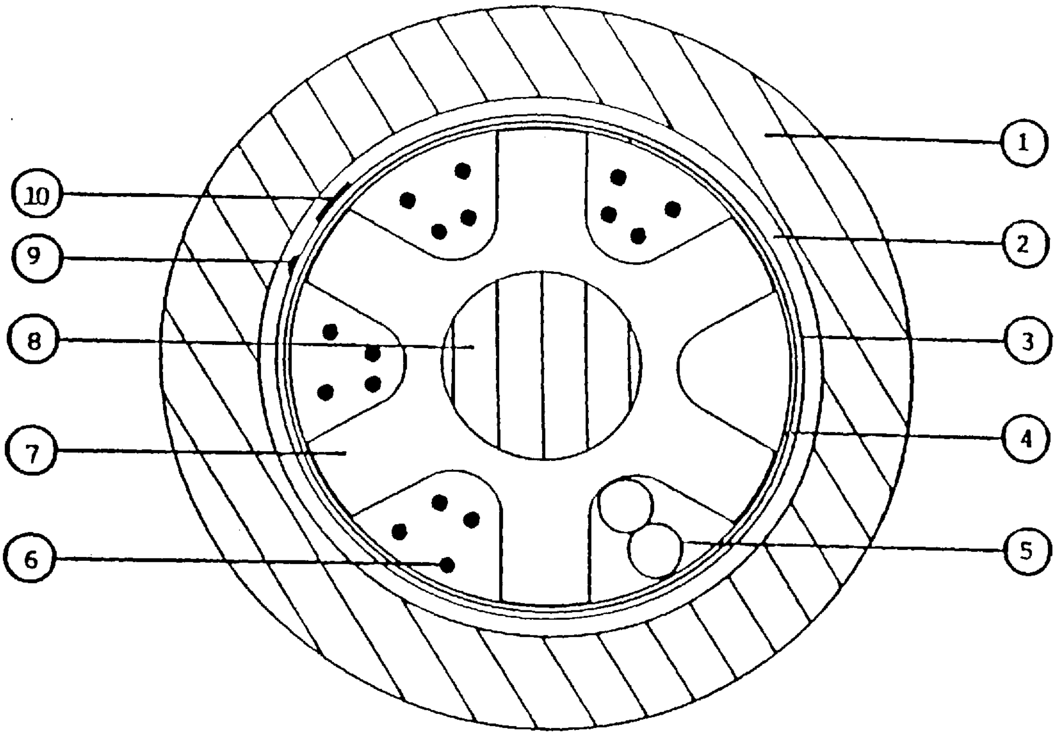
Cable variants to suit customers' specifications include steel or dielectric central strain members, steel tape or steel wire armouring, polyethylene, PVC or low fire risk sheathing compounds. Copper conductors may also be included.

The cable core is a six slot, reversing helix polyethylene former with an integral central strength member. Acrylate coated fibres are laid into the slotted former which protects them from the stresses applied during handling and installation. Fibres may be colour coded to enable easy identification.

The diagram in Fig. 3.4. shows a slotted core cable. For particular duct installations, it may consist of 16 optical fibres and one copper pair, assembled in the slots with a waterblocking compound. A binding yarn secures these elements in place and a paper tape helically applied followed by a longitudinal aluminium/plastic laminate. The cable is sheathed with low denstiy polyethylene.

3.4. Fibrespan Aerial Optical Cable

Fibrespan optical cable meets the requirements of electric power utilities as an efficient telecommunications medium for the transmission of data for supervisory, maintenance, control and telephony purposes. Fibrespan cable may be installed on existing



1. Outter LDPE Sheath
2. APL Tape
3. Polyester Tape
4. Binder Yarn
5. Insulated Copper Conductor Pair.
6. Singlemode Acrylate Coated Optical Fibres
7. Slotted Core
8. Central Steel Strength Member
9. Ripcord
10. Manufacturer's ID Tape

Fig. 3.4 OPEN CHANNEL CABLE

overhead power lines without the need for power cut-off and provies a simple and cost effective means of establishing a telecommunications data network.

Fibrespan is a low-loss, wide bandwidth, non-inductive, non-metallic, lightweight, self-supporting aerial cable, suitable for span widths up to 1 Km.

Fibrespan cable (8) has very high strength and withstands the combined effects of icing, wind loads and the high electric fields generated by adjacent power cables. The smooth circular profile of Fibrespan inhibits galloping, with spiral preformed dampers installed on each span to minimise aeolian vibration.

A prime feature of the design is the easy access to the fibres for terminating and splicing. Rapid installation is possible using lightweight equipment due to the low cable weight and tensions. The cable does not kink and preformed spiral clamps and dampers are easily fitted.

The design enables exceptionally high excess fibre lengths to be incorporated by snaking the fibres in the slot which is then filled with soft gel to cushion the fibres against vibration. It also prevents ingress of moisture whilst retaining freedom of movement. The cable design minimises the application of strain on the fibres, thus ensuring optimum and stable optical performance even at maximum working tension.

Fig. 3.5. shows a Fibrespan cable with 24 optical fibres. The fibres are bound together to form a ribbon.

3.5. Optical Fibre for Cables

Of the four cable designs described previously, three different

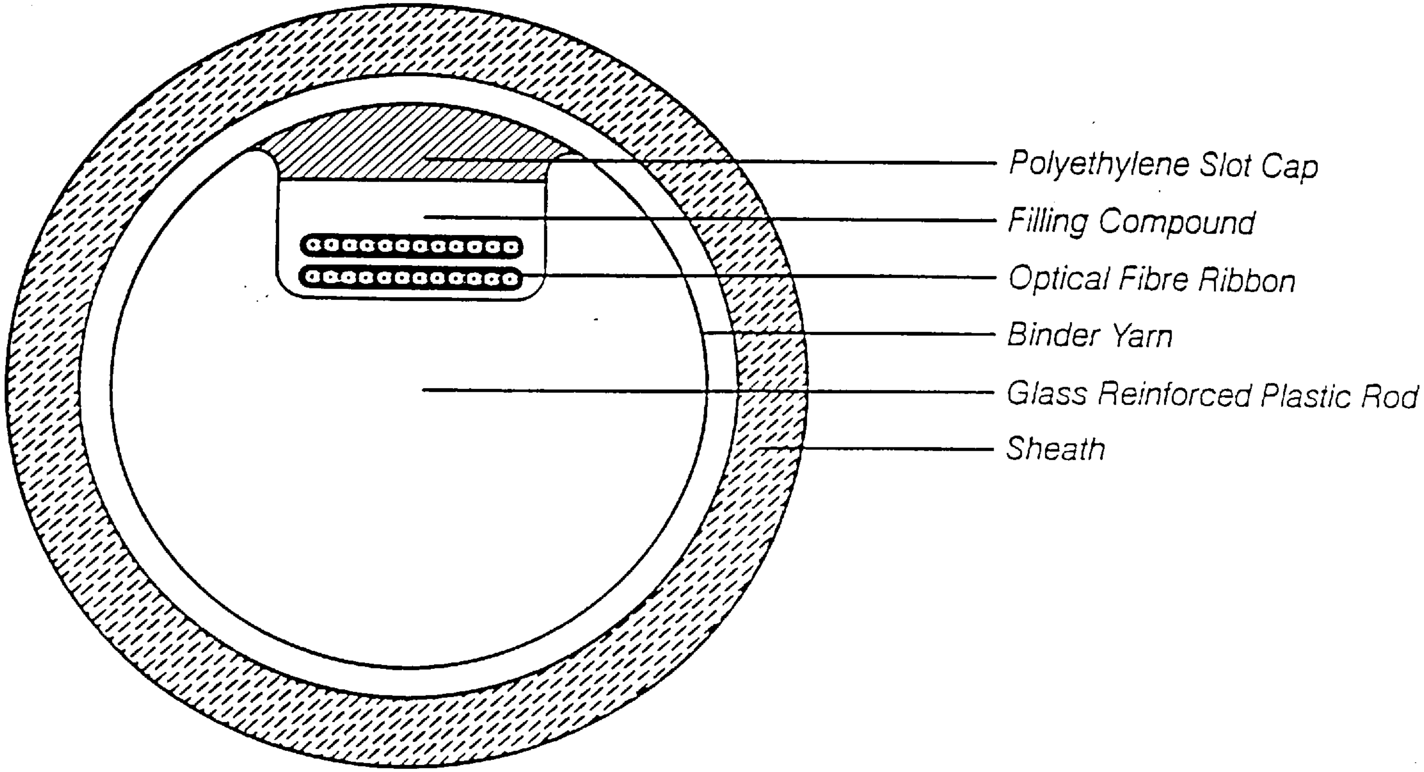


Fig. 3.5 FIBRESPAN CABLE

types of fibre constructions are used. These are namely acrylate coated fibre, secondary nylon coated fibre and resin coated ribbon fibre. In addition to these three, a triple coated fibre developed by STC is being manufactured to replace secondary nylon coated fibre.

3.5.1. Acrylate Coated Fibre

Loose Tube and Open Channel cable designs both use acrylate coated fibre. This type of fibre has a single coating of acrylate outside the fibre core and cladding (see Fig. 3.6.)

The dimensions of a singlemode acrylate fibre is as follows:-

Fibre Core - 8 µm

Fibre Cladding - 125 µm

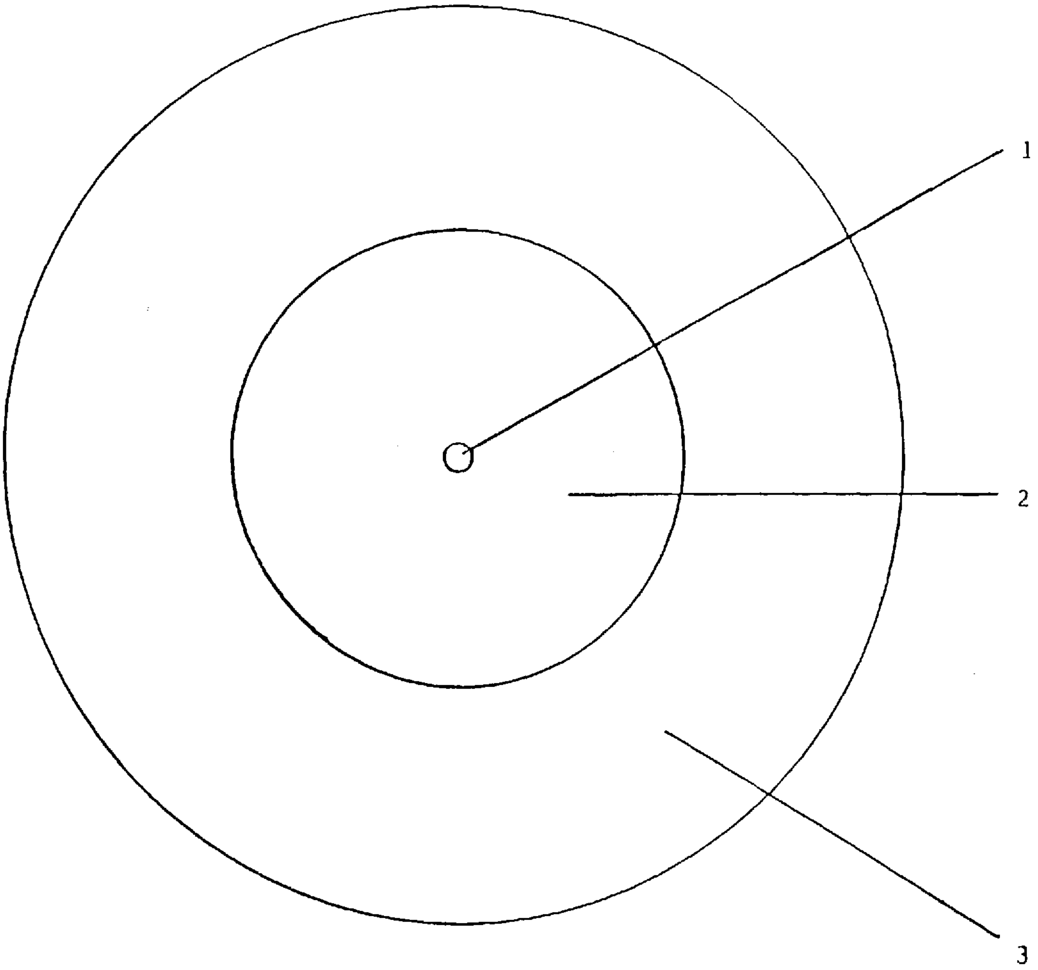
Acrylate Coating - 250 µm

The fibre core is made from doped silicone glass, whilst the fibre cladding is made from a similar material with either a different doping level, or different doping material. The reason for doping is to change, under controlled conditions, the refractive index of the glass.

With advances in science and technology, the quality of the fibre used in cables will only increase. Its performance in terms of optical attenuation and bandwidth will improve with more purified silica, and greater knowledge in the area of doping.

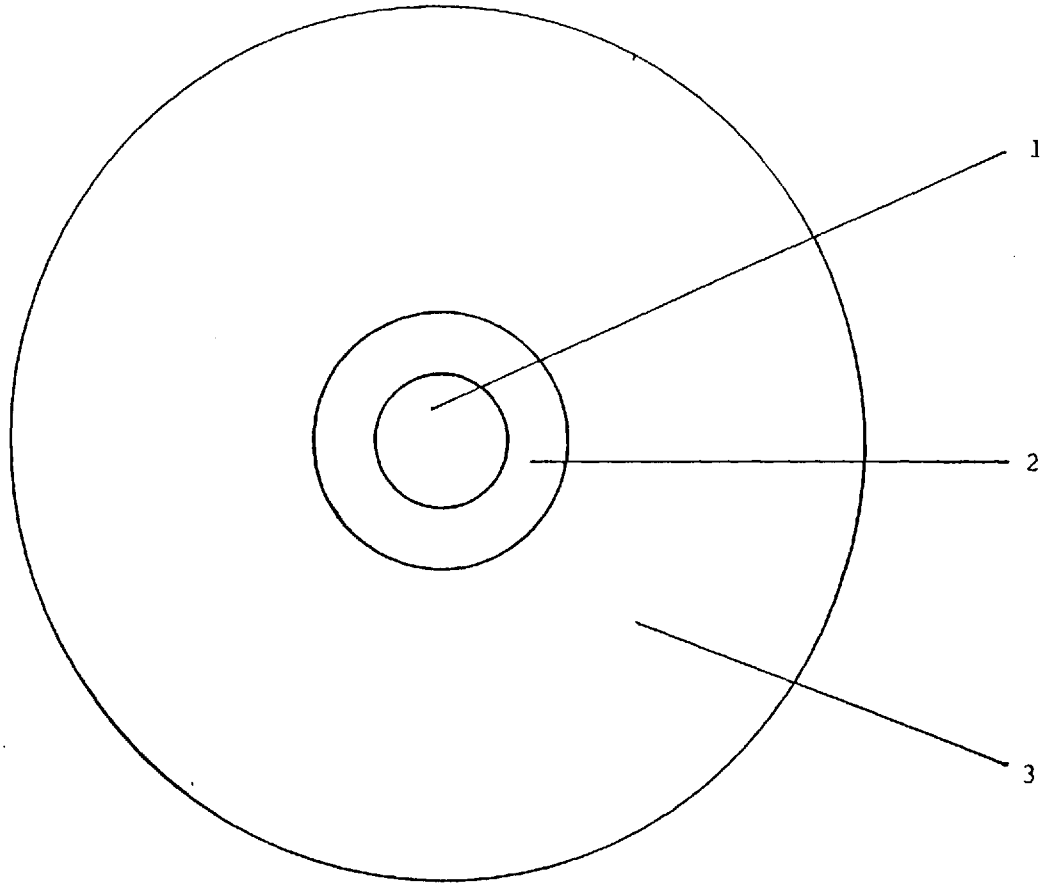
3.5.2.Secondary Coated Fibre

Tight construction cable designs use secondary coated fibre, since there are no tubes or slotted cores to protect the optical waveguides. The secondary coating involves an initial coat of Silicone Elastomer over the fibre cladding, and then a coat of Nylon 12 as the outer jacket (Fig. 3.7.)



1. Fibre Core
2. Fibre Cladding
3. Acrylate Coating

Fig. 3.6 ACRYLATE COATED FIBRE



1. Reference Surface Diameter
2. Silicone Elastomer (Sylgard)
3. Nylon 12

Fig. 3.7 SECONDARY COATED FIBRE

The dimensions of a singlemode secondary coated fibre is as follows:-

Fibre Core - 8 µm

Fibre Cladding - 125 µm

Silicone elastomer
(Sylgard) - 250 µm

Nylon 12 - 850 µm

Seconary coated fibres are also used in single fibre cables. These cables are binded in Kevlar yarn and then sheathed with PVC. Their main use are as terminating cables since they are physically flexible. They are always used internally to either link an external cable to terminal equipment, or to link equipment within a building (i.e. intra-office).

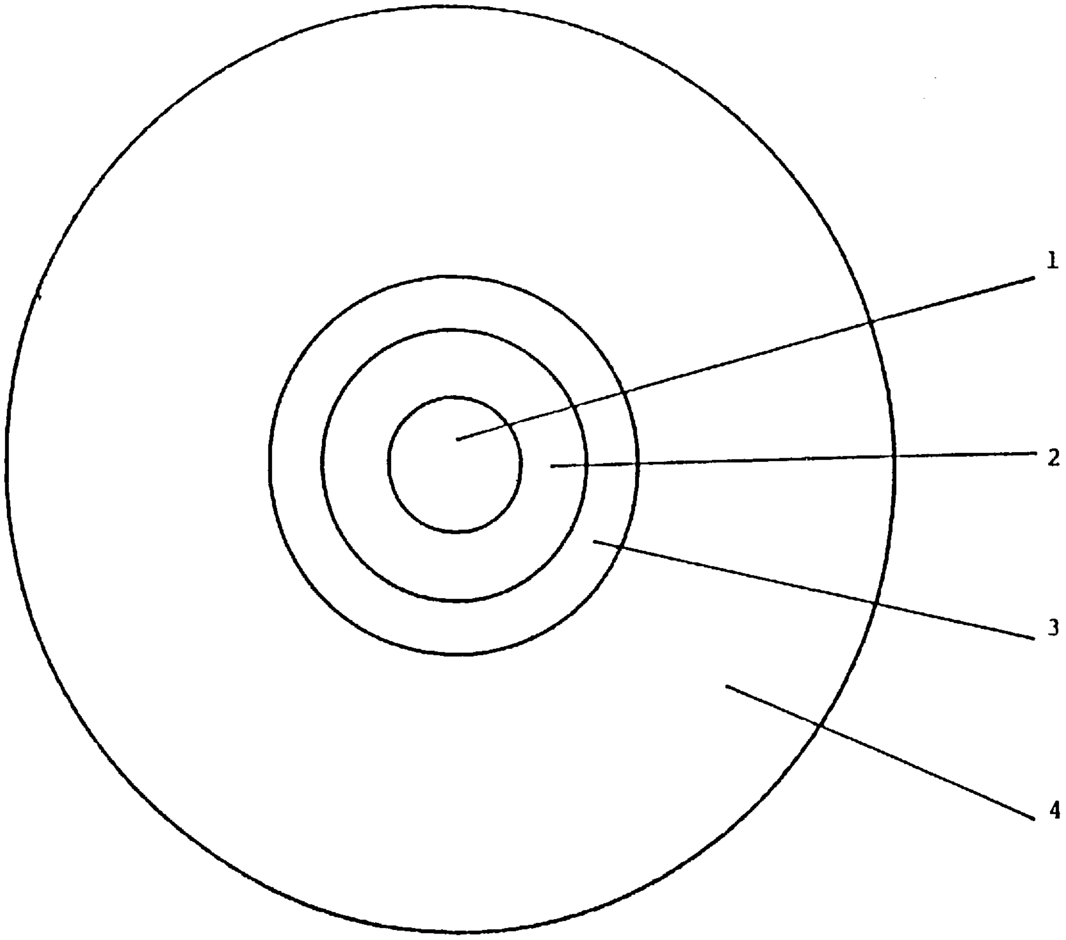
3.5.3. Triple Coated Fibre

Triple coated fibre developed by STC is a basic acrylate fibre coated with a thin layer of sylgard and an outer jacket of nylon 12. (Fig. 3.8).

The advantage of this type of fibre is that only one process is required to make the actual core and cladding. The two further coats (Sylgard & Nylon) can be applied at a later date by a different process.

The performance, strength, flexibility etc. of triple coated fibre is on par to secondary coated fibre. Therefore due to cost savings in manufacture, it is proving to be a viable alternative.

The dimensions of a singlemode triple coated fibre is as follows:-



1. Reference surface diameter.

2. Acrylate.

3. Silicone Elastomer (Sylgard)

4. Nylon 12

Fig. 3.8 TRIPLE COATED FIBRE

Fibre Core - 8 μm

Fibre Cladding - 125 μm

Acrylate Coating - 250 μm

Silicone Elastomer (Sylgard) - 350 μm

Nylon 12 - 850 μm

3.5.4. Ribbon Fibre

Ribbon fibre is a number of acrylate coated fibres joined together by a resin to form a ribbon. This ribbon would normally be used within a Fibrespan cable. Its main advantages are its neatness and compactness, and the easy manner by which it can be applied within the cable core without the fibres twisting and crossing.

Figure 3.5 shows two layers of ribbon, both with twelve fibres. The fibres are inked to allow easy identifaction when terminating. At present the greatest number of firbes that can be joined to form a ribbon is twelve. This may increase in the future, but since layers of ribbon can be stacked upon one another it is not an urgent requirement.

CHAPTER 4

LOOSE TUBE CABLE DESIGN THEORY

4.1. General Cable Construction

A loose tube cable consists of hollow cylinders extruded from Polybutylteraphthelate (PBTP) to carry one or more acrylate coated fibres. Tube sizes to date are 1.5, 2.2 and 3.0 mm, with fibrecounts ranging from 1 in a 1.5 mm tube to a maximum of 8 in a 3.0 mm tube.

These tubes are stranded helically around a central member, which may either be a sheathed steel dyform or sheathed/unsheated glass - reinforced-plastic (GRP) rod. The size of central member used is proportional to the strength requirements of the overall cable. Strengh of steel and GRP increases by a factor of 4 as the diameter doubles. As the size of the central member increases, the number of elements that can be stranded around it increases. Therefore if only a certain number of tubes and/or twisted copper pairs are required, then fillers must be included to allow a perfect lay up.

Paper tape is wrapped helically around the elements which binds them together and prevents any filling compound applied to the element interstices to escape.

The construction thus far is usually the same for most loose tube cables, with the only exceptions being double layered designs. Over the paper tape several options are available before an outer sheath is applied. The options taken will depend on customer requirements and the cable installation.

The options available are:-

(a) an Aluminium Plastic Laminate (APL),

(b) a Corrugated Steel Plastic Laminate (SPL) and bedding sheath,

(c) a Galvanised Steel Wire Armouring and bedding sheath.

4.2. Central Member

The material used as the cable strength member i.e. either steel or GRP, is selected as a direct result of the customer requirement.

If a customer specifies a non-metallic or dielectric strength member then GRP will be used, otherwise in all cases steel will be used.

The size of strength member depends upon the strengh requirement, whilst the size of the sheathed centre member depends on the number of outer elements required. The calculations used to find the diameter of centre member to support N elements are as follows (9):-

$$\text{Number of Elements } N = \frac{360}{2\theta} \qquad 4.1$$

where θ is the angle between the centre and radius of the element (Figure 4.1.)

$$\text{Therefore } 2\theta = \frac{360}{N}$$

$$\text{or } \theta = \frac{180}{N} \qquad 4.2$$

$$\text{Now, } \sin\theta = \frac{r}{R+r} \qquad 4.3$$

where r is the radius of the outer element and R is the radius of the central member.

The radius of the central member is therefore:-

$$R = \frac{r - r\sin\theta}{\sin\theta} \qquad 4.4.$$

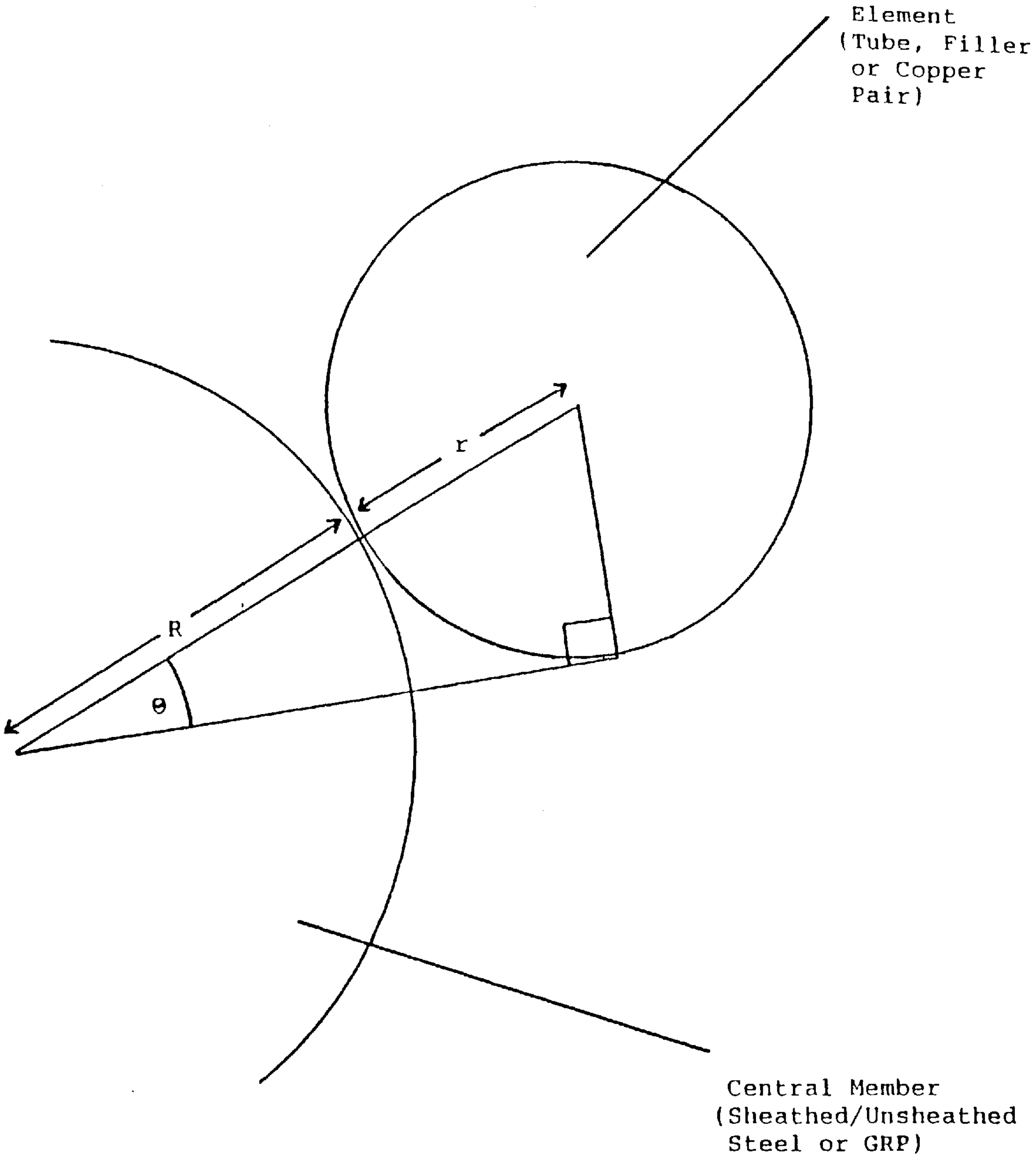


Fig. 4.1 GEOMETRY OF CABLE CENTRAL MEMBER AND OUTER ELEMENTS

Substituting the value of O from equation 4.2. into equation 4.4., R becomes:-

$$R = \frac{r - r \sin (180/N)}{\sin(180/N)} \qquad 4.5.$$

4.2.1 Example Calculation

Consider the case of 12 elements of 2.2 mm diameter, stranded around a sheathed steel central member containing a 3 mm steel dyform, then from equation 4.2.:-

$$\theta = \frac{180}{12} = 15^{o}$$

as from equation 4.4.

$$R = \frac{2.2 - (2.2 \times \sin 15^{o})}{\sin 15^{o}}$$

Therefore

$$R = 6.3 \text{ mm}$$

If the steel dyform is 3 mm then the radial thickness of sheath required to support 12 elements is:-

$$\frac{6.3 - 3}{2} = 1.65 \text{ mm}$$

4.3. Paper Tape

Around the elements are wrapped helically one or two layers of paper tape. The variable parameters involved with the application of paper are as follows (10):-

(a) Length of tape required per length of cable

(b) Width of tape

(c) Angle of application of tape on cable

(d) Tape lay length

The length of tape required per length of cable is:-

$$L = \frac{L'\pi\ C}{(1-P/100)} \qquad 4.6$$

where L is the length of tape (metres)

L' is the length of cable (metres)

π is 3.14159

C is the cable diameter over the tape (mm)

P is the percentage tape overlap (%)

The width of tape used is a user selectable parameter. Normally, the width chosen is between 10 and 30 mm, but for a very large cable this width may be increased. As we will see the width of tape has a direct influence on the angle of application, therefore the width can be varied to keep the angle within certain limits.

The angle of application (AngApp) of paper tape on a cable is:-

$$\text{AngApp}\ (\theta) = \cos^{-1} \frac{(\text{Effective tape width})}{\pi \times C} \qquad 4.7$$

where AngApp (θ) is the application angle (degrees)

and

$$\text{Effective tape width} = \text{Actual width} \times \frac{(100-P)}{100} \qquad 4.8$$

where Actual Width is the tape width selected (mm)

The tape lay length is the length of cable covered by one complete helical revolution of the tape. It can be calculated by the equation:-

$$\text{Tape Lay Length} = \frac{\text{Effective Tape Width}}{\sin(\text{AngApp}\ (\theta))}\ (\text{mm}) \qquad 4.9$$

4.4. Aluminium Plastic Laminate (APL)

An aluminium plastic laminate (APL) is often applied to cables as a moisture barrier. It is virtually always applied longitudinally over the paper tape layer.

The width of APL used is the circumference of the APL pitchdiameter (Fig.4.2.) plus the overlap required. The thickness of APL varies due to customer requirements but is usually 0.25 mm. Therefore, the width of APL required is:-

$$\text{APL width} = \pi \times \text{Pitchdiameter} + \chi \quad (\text{mm}) \qquad 4.10$$

where χ is the overlap in mm.

4.5. Steel Plastic Laminate (SPL)

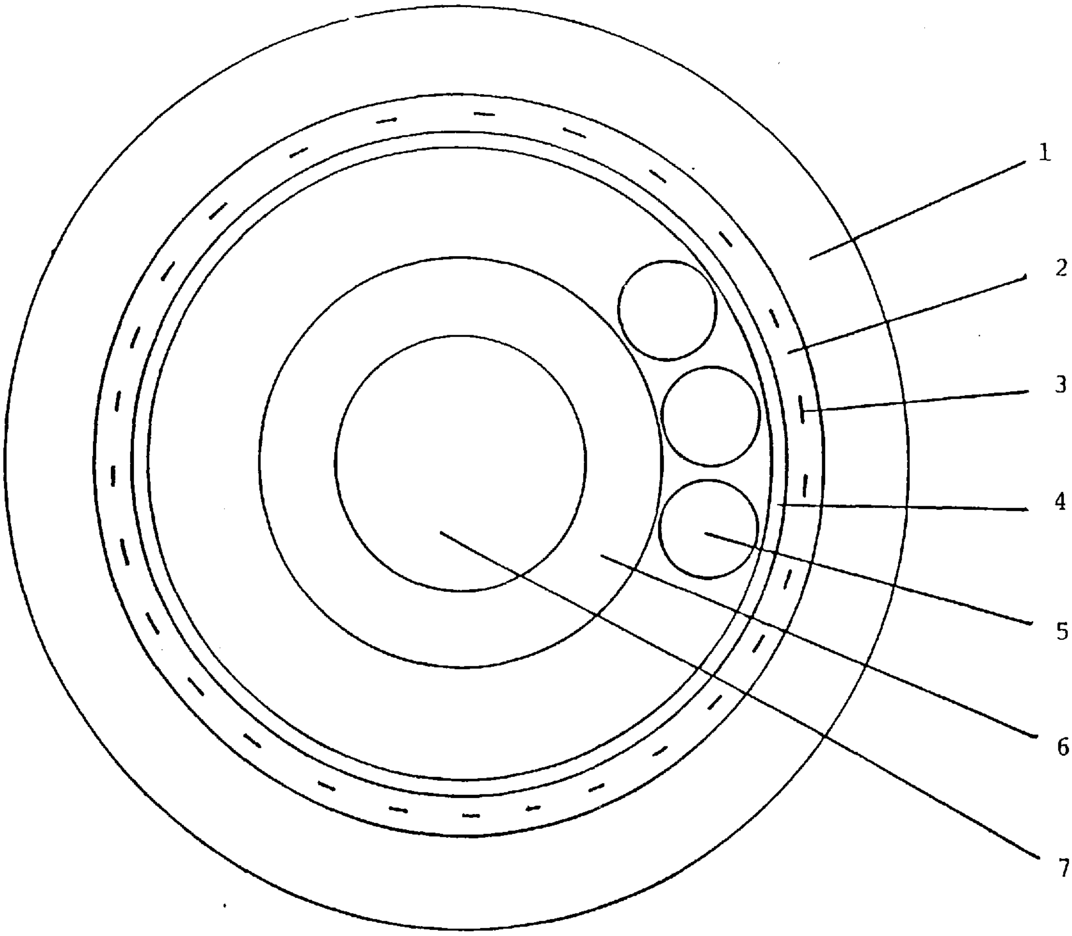
Steel Plastic Laminate is applied to cables as a rodent/moisture barrier. It can be either corrugated or uncorrugated. It is usually applied over a purposely extruded bedding sheath, which itself either lies over the paper tape or an APL.

Like APL, SPL is also applied longitudinally with the width required being calculated from the pitchdiameter and overlap. The thickness of SPL depends upon the plastic coating, whether it is corrugated or not, and the intial thickness of the steel.

An SPL adds considerably to the weight of a cable, but does not contribute directly to the strength. Therefore if any stringent strength/weight ratios are imposed, then SPL must be used with caution.

4.6. Galvanised Steel Wire Armour (GSWA)

Steel Wire Armouring is primarilly used to prevent a buried cable from being crushed. This type of armouring takes the form of a number of steel wires applied helically around a cable. Beneath the



1. Outer Sheath
2. Aluminium Plastic Laminate (APL)
3. APL Pitch Diameter
4. Paper Tape
5. Element (Tube, filler or twisted copper pair)
6. Strength member sheath
7. Central strength member

Fig. 4.2 CABLE CROSS-SECTION SHOWING APL PITCH DIAMETER armouring will always lie a bedding sheath to prevent the steel wires from crushing the optical fibres.

The number of steel wires required to fully armour a cable are given by the following equation (11):-

$$\text{Number of steel wires } N = \frac{180}{\sin^{-1}\dfrac{d}{P.D. \times \cos\phi}} \qquad 4.11$$

where d is the diameter of a single steel wire

P.D. is the pitch diameter of the wires

and ϕ is the angle of application of the steel wires away from the horizontal as indicated in Figure 4.3.

The 'laylength' of the steel wires which is the length of cable covered by one completed helical revolution of the steel wires, can be calculated by the equation:-

$$\text{Laylength} = \frac{P.D. \times Pi}{\tan\phi} \qquad 4.12$$

The length of steel wires required per unit length of cable is calculated by the equation:-

$$\text{Length of steel wires} = \text{Length of cable} \times \frac{1}{\cos\phi} \qquad 4.13$$

4.7. Cable Outer Sheath

The outer sheath applied to loose tube cables is usually a low, medium or high density polyethylene. The thickness of sheath depends upon either a customer requirement or the diameter of the cable beneath the sheath.

Its main function is to prevent the ingress of dirt and moisture and also exposure of the fibres to sunlight. It is also an excellent protection against abrasion and pollution.

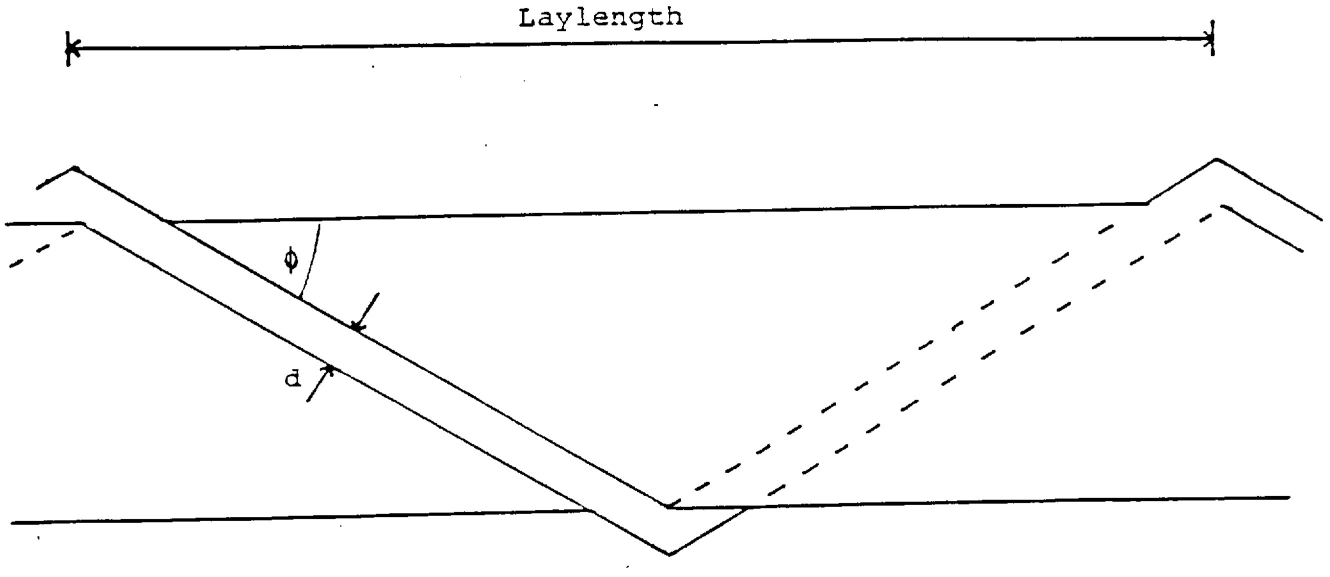


Fig. 4.3 LAYANGLE AND LAYLENGTH OF STEEL WIRE ARMOURING

4.8. Cable Strength/Weight Ratio

A loose tube cable will have a certain strength/weight ratio depending on its installation. This ratio is given by the factor n x W where W is the total weight of the cable in Newtons, and n is a multiplying factor to determine the ratio.

Once the strength requirement has been defined, a strength member must then be used which can keep the cable strain within allowed limits. The three main installations for loose tube cables are ducted, direct buried and aerial. Ducted cables usually require a ratio of 2 - 3 (x W) since they are physically pulled into ducts by winding machines, whilst direct buried cables only required a ratio of approximately 1 x W since they are laid and not pulled. The strength of an aerial cable depends upon the installation tension.

The main problem arising from specifying the size of strength member, is that the calculation of the cable weight must take into account a particular size of member initially. If this particular member is found not be strong enough, the next size up must be taken, whereby completely altering the weight of the cable. Therefore an iterative process must take place to equate the strength of the cable to its weight.

The following example shows how an iterative process is required to determine the correct size of strength member:-

The cable has a steel dyform strain member sheathed with low density polyethylene. Around the dyform 12 elements comprising ten 2.2 mm tubes and two twisted copper pairs (total diameter of one pair is 2.2 mm) are stranded.

The elements are wrapped with one layer of paper tape, followed by one layer of Aluminium Plastic Laminate, and finally a 1.6 mm outer sheath. The cable strength/weight requirement is 2 x W.

Size of central member required to support 12 elements is calculated as follows:

$$\text{The angle}\theta = \frac{180}{N} = \frac{180}{12} \quad 15^\circ$$

$$\sin\theta = \frac{r}{R + r}$$

therefore

$$R = \frac{r - r\sin\theta}{\sin\theta}$$

$$\text{where}\theta = 15^\circ \quad \text{and} \quad r = 2.2 \text{ mm.}$$

$$\text{then} \quad R = \frac{2.2 - (2.2 \times 0.2588)}{0.2588}$$

$$R = 6.30 \text{ mm}$$

Therefore the central member diameter is 6.3 mm, but the proportions of steel dyform and polyethylene sheath are now yet known.

Weight of 10 tubes is 27 Kgs/Km.

Weight of 2 insulated copper pairs is 12 Kgs/Km.

Weight of hyvis filling compound within the tube/copper pair interstices is 18 Kgs/Km.

Weight of 1 layer of paper tape is 3 Kgs/Km.

Weight of APL moisture barrier is 20 Kgs/Km.

Weight of outer sheath is 65 Kgs/Km.

We will initially assume a steel dyform of 3mm in diameter, therefore radial thickness of dyform sheath is 1.65mm. Weight of 3mm steel dyform is 49 Kgs/Km and the maximum pulling load assuming a modulus of 160 GPa is 4368 newtons. (Assume allowable strain = 0.4%).

Weight of 1.65 mm LDPE sheath is 22 Kgs/Km.

Therefore total weight of cable is 230 Kgs/Km.

Weight in newtons is 230 x 9.81 = 2256.3 N.

Since a 2 x W strength/weight ratio is required, this becomes 2 x 2256.3 = 4513 Newtons.

Strength available from 3 mm steel dyform is 4368, therefore the cable is not strong enough.

Possible solution:-

Use a 4 mm steel dyform.

Weight of 4 mm steel dyform is 86 Kgs/Km and the maximum pulling load is 7767 Newtons. (Again, assume allowable strain = 0.4%). Weight of 1.15 mm LDPE sheath is 18 Kgs/Km.

Therefore total weight of cable is 263 Kgs/Km.

Weight in newtons is 263 x 9.81 = 2580 N

2 x W strength/weight = 5160 N.

Since the strength available from a 4 mm steel dyform is 7767 N and the requirement is only 5160 N, the cable would pass any tests on its tensile strength.

The iterative process as shown can be a very time consuming task, especially if the size of strength member required is greater than the 6.3 mm (previous example). If this were to occur then the number of elements would have to be increased (using fillers) to physically enlarge the central member. This would involve the recalculation of all weights and dimensions, to equate the strength/weight ratio required to that available.

The previous example shows therefore that the art of cable design not only requires detailed knowledge of all the parameters involved, but also much time and effort to iterate and re-calculate weights and dimensions.

Whilst the previous example only showed the process of iteration, the example in Appendix A will give a detailed description of how the weights and dimensions of a loose tube cable are calculated.

Appendix A highlights the work confronted by a design engineer each time a new cable is required. The time taken by an experienced engineer to complete a design can be anything up to five hours. This depends upon the complexity of the customer requirement, and the number of iterations needed to satisfy the cable strength/weight ratio.

The design in Appendix A took three hours to do, and this was with only a single iteration, and the omission of such materials as "Steel Plastic Laminate" and "Galvanised Steel Wire Armouring".

The following chapter will show how the design of fibre optic cables is suited for implementation on a computer system.

CHAPTER 5

A COMPUTER AIDED SOLUTION

The task of designing Fibre Optic Cables is a process combining knowledge, experience and the ability to perform mathematical calculations. A computer system running specific software is therefore required to emulate the design stages involved.

5.1. Expert Systems

Expert Systems are being developed to solve a range of practical problems. As with fifth-generation computers they represnt a departure from traditional methods of problem solving. Expert systems have been defined as (12):

'programs that solve substantial problems generally conceded as being difficult and requiring expertise. They are called knowledge based because their performance depends critically on the use of facts and heuristics used by experts'.

The body of facts (knowledge) and the heuristics (which may be regarded as 'rules of thumb') are represented in the computer. The program uses the heuristics to operate on the stored knowledge in the light of an use enquiry, and ideally the system's reasoning can be explained to the user toindicate how a particular conclusion was reached.

Any expert system is characterised by three fundamental elements: the Knowledge Manager, the Knowledge Base and the Situation Model. The Knowledge Manager typically uses the information contained in the Knowledge Base to interpret the current contextual data in the Situation Model. Everything which is application-dependent can be kept in the Knowledge Base, allowing the knowledge Manager to function as a multi- application tool.

The more comprehensive the Knowledge Base, the less strain upon the inferential logic inside the Knowledge Manager when a question has to be answered. This means that the power of the system tends to be defined according to its depth of knowledge rather than its ability to reason. In the event, however, the user will only be interested in receiving a useful response to the initial query. It may be expected that an expert system will develop - as it accumulates more expertise either directly as new information is fed in, or indirectly as the system remembers the results of useful inferences. In addition to operating on the Knowledge Base, the Knowledge Manager will also be concerned with knowledge acquisition (i.e. developing the Knowledge Base), Knowledge updating (i.e. modifying the Knowledge Base), and providing explanations (i.e. explaining system features or details of operations such as inference - making). An expert system can operate at several levels - relatively superficially if a quick answer is sufficient, or more deeply if a more complex analysis is required.

It may be emphasised that expert systems are about software. Expert systems have been written in traditional languages such as FORTRAN and COBOL, but are more suited to a language such as PROLOG. The use of rules (e.g. an if -then relationship) does serve the development of a knowledge base. In this context, no distinction is drawn between a piece of factual information (e.g. an item of data) and a statement rule (e.g. a piece of program).

The various expert systems in existence depend upon accumulating knowledge in the form of rules. One advantage of this approach is that the knowledge concerning the particular specialist area can be expanded incrementally; furthermore, it is in a form easily expressed by an expert. The rules comprising the knowledge base are equivalent to an application program and they may have many different formats; the if-a-condition-then-an-action format is very common, with the 'then' section able to represent inferences, assertions, probabilities, precepts, etc. The first of several conditions associated with the rule determines whether the rule is potentially valid with respect to the current state of the situation model. A rule can require that a number of conditions be satisfied before an action is authorised.

5.2. Expert System Shells

Software packages are now available through which expert knowledge can be suitably entered into a computer and used by other people. The set of information on any one subject that is built up is called a knowledge base. This contains not only the essential rules appertaining to it but also the dialogue that enables the user to communicate with the computer. The knowledge base is refined over a period of time until it is both correct,and clear to the user.

Expert system shells contain the framework of an expert system, where the user only has to enter the rules (i.e. knowledge). The rules are worded in such a way that a future user of the system would be asked a series of questions, whereby the answers given would be used to either make decisions, or complete the unknowns in any equations/formulas.

Expert system shells are written in many languages including PASCAL, C etc. The main advantage of using a shell is that much time is saved in writing the software to control the rules and how they are generated.

There are many expert system shells commercially available on the market. These differ to a true Intelligent Knowledge Based System (IKBS) in that they are unable to develop new heuristic relationships from continous user-interaction. Three popular packages are Crystal by Intelligent environments, PAL by PAL Software and Xi Plus by Expertech. The two packages investigated were Crystal and Xi Plus, with a description of their features and architectures given in the following sections.

5.3. Crystal/Xi Plus Expert System Shells

5.3.1. Crystal

Crystal makes it easy to organise expertise, knowledge or the stages of a task so that other people can later have access to it. In Crystal knowledge is described in the form of rules which contain connected pieces of reasoning (13).

As a simple example the following rule will decide whether a customer required singlemode or multimode fibre. The three different criteria for selecting singlemode fibre are:

The link requires as few repeaters as possible
AND
The link is long in length
AND
The data capacity required is very high

The conclusion is "the customer requires singlemode fibre" and the conditions are the three that are stated above. A rule can therefore be thought of as the reasoning behind a decision.

Each condition will be either true or untrue in a particular case - an individual customer on this occasion. Crystal will use the conditions and prompt the user for replies. It will reach a conclusion depending on those replies, whether that conclusion is true or false.

The conditions mentioned above are not very precise. Asking if the link requires as few repeaters as possible would be a fair question if the term "few as possible" was fully explained. Crystal can deal with this by letting the user expand a condition to offer or gather further detail, thus turning a particular condition into a rule with conditions in its own right.

The next level of rule will now have the previous condition "the link requires as few repeaters as possible" as its conclusion and new conditions will be required within the new rule so that Crystal may test this next rule. A typical Crystal knowledge base will consist of a network of rules and conditions supporting them, some of which will be expanded into further rules (14). Indeed the same rule maybe used from different places in the same knowledge base: once Crystal has tested the answer it will not need to ask the user again since it already "knows" the answer. (There is an exception called a "Special Rule" which forces Crystal to look at the rule every time.) The rule which decides whether as few repeaters as possible are required has two alternative conditions, which are:

the link is for a submarine application

OR

electricity is unavailable in certain areas of the link

It must be noted that only one of these two methods is required, whereas the previous rule required correct answers about repeaters, link length and data capacity. This rule only requires one way of proving the link requires as few repeaters as possible, and both are alternative ways of reaching that conclusion. The word AND was used in the first rule, whilst OR was used in the sub-rule.

The difference between the word AND and the word OR assume a vital importance in building a knowledge base. Both words have important implications, particularly when used in combination with each other. These implications were not invented by the people who designed CRYSTAL, they were standard logical expressions.

The implications of this aspect of logic is best explained by elaborating on the previous example. Suppose it now reads like this:

the link is for a submarine application, AND the sea bed is very deep.

OR

Electricity is unavailable in certain areas of the link

The method shown above links the first two conditions with an AND before using the word OR. That means that if the number of repeaters depends on the fact that the link is undersea (because the cable itself carries power for the repeaters), then the sea bed must be very deep. The essential point is to use the word AND before the word OR. If the word AND were not there then the submarine application would have been just an alternative to the depth of the sea bed.

Crystal also has a series of commands which normally tell the computer to do something while going through rules and testing conditions. An example of a command would be displaying some information on a screen at a particular stage while the user is answering questions.

Commands are mixed into the sequence of conditions within a rule. Whether the commands are carried out or not, and in what order, will be determined by the result of testing the conditions and also on the pattern of AND's and OR's within the rules.

5.3.2. Xi Plus

Xi Plus is an expert system shell for the IBM PC designed around the production rule formalism. This means that knowledge is coded into the system in terms of rules of the form:

if identifier is value
and identifier is value
then identifier is value
and identifier is value

For example, in an expert system for selecting copper or fibre-optic cables we might find the rule:

if data capacity required is very high
and cable is installed in high interference area
then fibre-optic cable is most suitable.

The default inference mechanism in Xi Plus employs what is called backward chaining. This means that to run the system, the user normally selects a query from an initial menu. This query is then set up as the goal for the system to solve. It does this by searching through the knowledge base for a rule which has an identifier in its THEN part which matches the identifier in the goal. For instance, if the current query is 'cable most suitable', the rule above would "fire", meaning that two further sub-goals would be set up for capacity and interference. The value of capacity might then be requested of the user by a question set in the system.

The value of interference might be set by firing a further rule in the system:

if electric field intensity > E
then interference is high

This would mean that the inference engine would now try to find a value for electric field intensity.

Backward chaining is often referred to as goal-directed since reasoning moves back from the goal to initial data. In contrast, Xi Plus also supports forward chaining, so-called because the reasoning process is directed by the data available to the final goal. Here the user directs the inference process by writing explicit control into the knowledge base. One way of doing this is by means of 'deamons', that is, rules beginning with WHEN rather than IF. These are triggered as soon as the condition they test becomes tru. For example:

when capacity reaches maximum
then second cable is required

This is a product of Expertech. It is written in Microprolog and Assembler, and will run on a microcomputer with at least 512K of random access memory.

5.3.3. Xi Plus Vs Crystal

The primary motivations for implementing an expert system on a microcomputer are low cost, availability and transportability. It is possible to distribute cost-effectively multiple copies of the same system. The small size and robust design of micro-systems make them appropriate for applications where physical space is limited and/or in harsh environments.

These factors influence what is perhaps the primary advantage of implementing expert systems on microcomputers, namely that they are ideal tools for experimentation, exploration, learning and assessment. It is possible for a company to experiment with expert systems without making a sizeable investment in resources. As a result, it afford companies a low risk opportunity for determining the potential of this new area for their applications work.

For the application of designing loose tube cables, both expert system shells considered appeared adequate. There were more features in the Xi Plus shell, but many of them would never be used for the specific need. Crystal proved extremely flexible and easy to use, with menus allowing the user to develop a knowledge base without continually referencing the manual.

The deciding factor in choosing between the two shells was cost. Crystal proved considerably cheaper at the time of purchase, therefore it was selected in preference to Xi Plus.

5.4 Loose Tube Cable Expert System

The expert system like most computer programs has been written with an Input-Calculate-Output format. The basic principle of the program is to best fit the number of elements and other cabling materials, around a central strain member.

5.4.1. Program Inputs

The "user inputs" to the expert system are as follows:

(i) Number of outer elements?

Total number of tubes, fillers and copper pairs. This input is used in the equation to calculate the size of central member required. (Eqn.4.5)

(ii) Number of tubes?

This input is used to calculate the weight of tubes in the design.

(iii) Number of copper pairs?

Used to calculate weight of copper pairs in the design.

(iv) Diameter of outer elements?

Used in conjunction with the number of outer elements to calculate the size of central member required. Also in conjunction with the number of tubes, to calculate the weight of tube material.

(v) Diameter of insulated copper wires?

Used in conjunction with the number of copper pairs to calculate the weight of insulated copper in the design.

(vi) Laylength of stranded elements?

Used to instruct the process engineers on how the stranding machine should be set up.

(vii) Intersticial filling compound?

If the outer element interstices are filled with a water blocking compound, this input will ascertain which compound, from the choice available, is required.

(viii) Strength Member Material?

Cable strength members are normally made from a steel dyform or glass reinforced plastic. Both materials have different densities and moduli, therefore selecting one or another will greatly affect the cable strength and weight. Usually, a glass reinforced plastic (GRP) strength member will only be selected if its dielectric properties are required.

(ix) Aluminium Plastic Laminate?

If an Aluminium Plastic Laminate (APL) is required, the expert system will calculate the width required. (APL is applied longitudinally and always has a specified overlap). Since various widths are available from suppliers, the user must input the nearest width available to that required. (Eqn 4.10)

(x) Steel Plastic Laminate and Bedding Sheath?

Simularly to an APL, an SPL is applied longitudinally. Nearly always, a bedding sheath is applied under the SPL, the thickness of which is specified by the user. The expert system calculates the width of SPL required, and as with the APL, the user inputs the nearest width available.

(xi) Steel Wire Armour + Bedding Sheath?

Steel wire armouring entails helically wrapping individual steel wires of user definable diameters, around the cable. A bedding sheath must be present beneath the armouring to avoid any crushing of the existing cable. The user therefore selects the bedding sheath thickness, the diameter of steel wires, and the layangle of the wires. All three inputs are required to calculate the number of steel wires required to give a snug fit. (Eqn's 4.11,4.12,4.13).

(xii) Outer Sheath?

An outer sheath is present on all cables, therefore its thickness and material (LDP/MDP/HDP) are required to calculate its weight.

(xiii) Maximum allowable cable strain?

Normally a cable may be strained by a certain amount before the optical fibres are affected. The input required here is the percentage strain that a cable may be subjected to before the optical fibres see greater than a 0.25% strain. Obviously the greater the strain relief the greater the tension that can be applied to the cable.

(xiv) Strength/weight ratio (W-Factor) required?

This input is used to define a cable's strength/weight ratio. The W is the weight of the cable in newtons, whilst the input by the user is the number multiplied by the cable weight to give the cable strength required.

5.4.2. Crystal Master Rules

Crystal has a series of master rules from which all the other rules in the expert system stem (15). The master rules will be executed in sequence, therefore all the rules relating to one master rule must be satisfied before moving on to the next.

The master rules of the Loose Tube Cable Expert System are:-

1. Check Ascii Interface is Loaded and System Clear

   AND

2. Loose Tube Cables

   OR

3. Quit Crystal.

1. The first master rule does a self check to see whether the ASCII interface software has been loaded. Without this software, a feature at the end of the program whereby data is transferred to an external ASCII file cannot be executed.

Crystal also has a clearing function where all the answers and results from the previous run are erased. If this is not done, then the whole program can be corrupted by a previous result not required by the current run. To remind the user of this feature a message is displayed on the screen which must be acknowledged.

2. This is the main body of the expert system which is described in detail after covering the third master rule.

3. The third master rule is an OR condition. It is only ever executed if the ASCII interface has not been loaded. On execution it displays a message to the user stating that it cannot proceed and the reason why.

5.4.3. Second Master Rule-Loose Tube Cables

The Loose Tube Cables master rule is split up into 19 sub-rules, with each sub-rule having further sub-rules and so on. An explanation of each rule will now be given.

Loose Tube Cables - Sub Rules

(i) Sub Rule 1- Display Header

This rule simply displays the title of the expert system.

(ii) Sub Rule 2 - Fibrecount

This rule is used to ascertain how many fibres, or what is the range of numbers of fibres that can be incorporated within the cable.

(ii) Sub Rule 3 - Fibremode

Asks the question what type of fibre is required? Singlemore/Multimode.

(iv) Sub Rule 4 - Central Member

Calculates the diameter of central member from the number of outer elements and their diameters.

Also asks the questions:

(a) what is the strength member material? (Steel/GRP)

(b) what is the inner sheath material, (LDP/MDP/HDP).

Question (a) is used to assign a modulus and density to the strength member, for strength and weight calculations.

Question (b) is used to find the density of the inner sheath material so that its weight may be calculated.

(v) Sub Rule 5 - Tubes.

This rule calculates the cross-sectional area of any tube, and combined with knowledge of the the material density, the weight is found.

(vi) Sub Rule 6 - Copper Pairs

From details regarding the number of copper pairs, their individual diameters (copper and insulation), the total weight of both materials is found.

(vii) Sub Rule 7 - Outer Element Fillers.

The number of fillers required is calculated by substracting the total number of tubes and copper pairs from the number of outer elements. The diameter of the fillers will be the same as the tubes, therefore from knowledge of the filler material density the weight may be found,

(viii) Sub Rule 8 - Hyvis.

Hyvis, the filling compound used within the loose tubes is a form of liquid gel. The total amount required per tube (Kgs/Km) is the same as the volume of the internal section of the tube. The weight may therefore be calculated from multiplying the volume by the density of hyvis.

(ix) Sub Rule 9 - Filling Compound.

The filling compound referred to in this rule is the gel used as a water blocking compound in the element interstices. At present one of three compounds are used:

i. Syntec Rheogel 90

ii. Syntec Rheogel 210.

iii. Insojel 1921.

The volume of filling compound required is calculated from the following equation:

Volume of compound = $\pi/4((\text{DIAM1})^2 - (\text{DIAM0})^2) - (N.\pi.D^2/4)$

where DIAM1 is the diameter of the cable outside the outer elements.

DIAM0 is the diameter of the cable outside the central member.

N is the number of outer elements, and D is the diameter of the outer elements.

The above equation gives the volume of filling compound per metre of cable, assuming that all the dimensions are in metres. Therefore the weight of compound per kilometre:

Weight of filling compound/Km = Volume of compound x 1000 x density.

(x) Sub Rule 10 - Paper Tape

Paper tape is supplied in standard widths starting at 12.7 mm (1/2 inch) and increasing in 6.35 (1/4 inch) steps.

The equations for calculating the length of paper required per Km of cable and the paper tape application angle are given in section 4.3 It is generally recognised that the narrower the paper the better the lay around the elements. An important stipulation is that the application angle of the tape must lie within the range 40 to 65 degrees. The major control of the application angle is the width of tape, therefore the narrowest tape is required which results in an angle within the range.

Crystal performs this by generating a loop, whereby the width of paper tape is incremented from the smallest width in the available steps. Once an angle in the range has been reached, the loop is broken, and the width of tape is noted and used in the other calculations. i.e. length of paper, lay length etc.

Paper is costed by weight, therefore from the paper length, width, thickness and density its weight is calculated.

(xi) Sub Rule 11 - Aluminium Plastic Laminate (APL)

The width of APL required does not always match the supplies available. Therefore CRYSTAL calculates the theoretical width, and asks the user to input the nearest width available. The weight is found from standard figures relating APL area to weight. (These figures were found through practical experiments).

For a 0.15 mm thick APL with a 0.04 mm plastic coating on one side, the weight per square metre is 0.434 Kgs/m. For a 0.20 mm thick

APL with a 0.04 mm plastic coating on both sides the weight is 0.617 Kgs/m.

Crystal allows 1mm on the overall diameter of the cable if an APL is applied. The diameter outside the APL(if present) is assigned to the variable DIAMAPL.

(xii) Sub Rule 12 - Steel Plastic Laminate (SPL)

Simularly to APL, the width of SPL does not always match available supplies. In the same manner, the theoretical width is calculated, and the user inputs the closest match.

An option for SPL is the application of an underlying bedding sheath. If required, the radial thickness is entered by the user. The weight of the sheath is found by calculating its cross-sesctional area, and multiplying this by 1000 and the sheath material density. This will give an answer in kilograms per kilometre. The diameter outside the bedding sheath (if present) is assigned to the variable DIAMSPLBS.

The weight of SPL per square metre is 1.326 Kgs/m. (This was found through practical experiments). When SPL is applied to cables it is virtually always corrugated. Therefore since it is purchased in an uncorrugated form, this process must be carried out on site. After corrugation the length of SPL is reduced by 15%, therefore an extra length is required to compensate for this.

(xiii) Sub Rule 13 - Steel Wire Armour (SWA)

The theory involved with Steel Wire Armouring is given in section 4.6.

The steel wires used to armour cables come in three different sizes. These are 0.9,1.25 and 1.6 mm's. the user inputs the size required, depending on the level of armouring needed. A bedding sheath must always be present beneath the armour, to prevent any crushing of the underlying fibres on application. The thickness of bedding sheath should nearly always be as thick as the steel wires used. The user should bear this in mind when entering the sheath thickness.

An additional input required from the user is the armour 'layangle'. From the diameter of the wires, the armour pitch diameter (calculated from cable diameter beneath armour), and the 'layangle', the following parameters may be found:-

(a) Number of wires,

(b) 'Laylength'

(c) Length of wire per unit length of cable.

The total weight of the steel wire armour is calculated from the equation:-

$$W1 = N \times A(m^2) \quad \times 1000 \times D$$

where N is the number of wires.

A is the area of 1 wire in m^2

D is the density of galvanized steel wire in Kgs/m^3

The weight W1 wil be found in Kgs/Km.

The weight of the armour bedding sheath is found from the equation:-

$$W2 = A(m^2) \times 1000 \times D.$$

where A is the cross-sectional area of the sheath in m^2

D is the density of polyethylene (low, medium or high density) in Kgs/m^3

Again, the weight W2 will be found in Kgs/Km.

(xiv) Sub Rule 14 - Outer Sheath

The cable outer sheath is extruded on to the underlying material. The user inputs are the sheath thickness and material. Outer sheaths typically range from 1mm thick to 3mm, whilst the material may be Low,Medium or High density Polyethylene.

The weight of the sheath per Km is found by multiplying the cross-sectional area in m by 1000 and by the material density. The answer will be found in Kgs/Km.

(xv) Sub Rule 15 - ID tape and Ripcord.

An ID tape and ripcord are usually applied directly over the paper tape. Both are normally required by the customer but are not essential. The only calculations required are to find the weight of both items.

The ID tape has a standard weight of 0.2 Kgs/Km, whilst the ripcord has a standardweight of 0.32 Kgs/Km.

(xvi) Sub Rule 16 - Cable Strength/Weight.

To date, all the materials used in the design have been accounted for, and their weights recorded. Therefore by adding the weights of the relevant materials used, the total weight of the cable may be found.

The strength of a cable is normally related to its weight in Newtons (i.e. weight in Kgs x 9.81). A cable's strength when specified is given as N x W, where W is the weight of the cable in newtons, and N is the cable strength factor. If a cable has a particular centre size, then the strength will be directly proportional to the ratio of steel/sheath in the centre.

To save on costs, the smallest possible steel size is used which gives the required strength. Therefore since the weight of cable will vary with changes in steel size,a process of iteration is required which increases the steel size, calculates the new weight, and either stops or continues depending whether the strength is sufficient.

The two user inputs required are:

(a) Cable strength factor (as described above), and

(b) Maximum allowable cable strain i.e. the strain of the strength member to be tolerated.

The cable strain figure will have a direct influence on the strength of the strain member since:

$$F = E \times e \times A. \tag{5.2}$$

where

F is the strength in Newtons.

E is the Youngs Modulus in Pascals.

A is the area in m and

e is the strain (fractional).

Once the size of strain member is established, the size (or radial thickness) of the strain member sheath will be known. Its weight will have already been calculated on part of the total weight.

(xvii) Sub Rule 17 - Print Out of Results

This rule initially ascertains whether the user requires the output to be directed to the screen, the printer, or both. After this, a full breakdown of the cable materials is given, listing their weights, dimensions and strength.

The information produced should be sufficient so that the cable may be costed and consequently manufactured.

(xvii) Sub Rule 18 - Store Data.

An added feature to this expert system, is the facility to draw a cross-sectional representation of the cable designed, either on the screen or on a plotter. To facilitate this feature, the dimensions of the cable must be transferred from Crystal to an external text file. This is done through the " ASCII interface" package supplied by Intelligent Environments, which allows the cable Information to be accessed by other software.

This rule asks the question whether or not such a file should be created, and the data released.

(xix) Sub Rule 19 - Transfer Parameters to ASCII file.

This rule actually creates an ASCII file called CABLE.ASC and assigns the following variables to it:-

APL$ - APL (YES/NO)
SPL$ - SPL (YES/NO)
SPLBS$ - SPL Bedding Sheath (YES/NO)
SR$ - Filling compound (YES/NO)
SWA$ - Steel wire armour (YES/NO)
SWABS$ - Steel wire armour bedding sheath (YES/NO)
BSM$ - Bedding sheath material (LDP/MDP/HDP)
ISM$ - Inner sheath material (LDP/MDP/HDP)
OSM$ - Outer sheath material (LDP/MDP/HDP)
SMM$ - Strength member material (Steel/GRP)
SWABSM$ - SWA Bedding sheath material (LDP/MDP/HDP)
ID$ - Identification tape (YES/NO)
RIP$ - Ripcord (YES/NO)
D - Diameter of outer elements
DCW - Diameter of copper wire
DIAMO - Diameter of sheathed central member
DIAMI - Diameter outside elements
DIAM2 - Diameter outside paper tape
DIAM3 - Diameter outside APL
DIAM4 - Diameter of finished cable
DIAMETER - Diameter of steel/GRP strain member
DIAMAPLSPL - Diameter outside SPL
DIAMIOS - Diameter inside outer sheath
DIAMSPL - Diameter outside SPL if APL does not exist.
DIAMSPLBS - Diameter outside SPL Bedding Sheath
DIAMSWA - Diameter outside steel wire armour
DIAMSWABS - Diameter outside steel wire armour bedding sheath
DSW - Diameter of steel wires

IDT - Internal diameter of tubes
N - Number of outerelements
NCP - Number of copper pairs
NF - Number of Fillers
NT - Number of tubes
ANSW - Actual number of steel wires
OSRT - Outer sheath radial thickness
RTBS - Radial thickness of bedding sheath
RTCI - Radial thickness of copper insulation
RTIS - Radial thickness of inner sheath
SR - Filling Compound type (90/210/1921)
TOTALM - Total weight of cable
STRESS - Maximum pulling load on cable

5.4.4. Program Outputs

A complete listing of the Loose Tube Cable Knowledge Base is given in Appendix B, whilst an example of the output to the printer is given in Appendix C.

As we can see from Appendix C a summary of the cable is on the title sheet. The sections which follow are complete descriptions of the central member; tubes, fillers and copper pairs; tube filling compound - hyvis; stranding; filling compound - syntec/insojell; paper tape; ID tape and ripcord; APL; SPL bedding sheath; SPL; steel wire armour bedding sheath; steel wire armour; outer sheath; cable strength/weight; cable diameter.

Following the cable description is a separate sheet entitled "Processes and Speeds". This is for the process engineers to list the various stages of manufacture i.e. what machines are to be used and their line speeds.

5.5. Graphical Output of Cable Cross-Section

A further requirement to the printer output of weights and dimensions is a target diagram representing the cross section of the cable designed. The diagram should be fully labelled, have a brief technical specification, and an user defined title.

Cable data is available in a text file generated by Crystal. A graphics package, or programming language with graphics capability is required to utilise this information and create the visual representation.

The choices immediately available are:

(a) a Graphics Environment Manager (GEM) package.

(b) Microsoft BASIC or

(c) TURBO PASCAL & GRAPHIX TOOLKIT

Close inspection of the 3 alternatives identified (c) as the method with most potential.

5.5.1 Program Structure

Turbo Pascal programs are written as a series of procedures linked by a main program (16). The Graphix ToolKit is a series of subroutines sold by Borland International that perform various graphical functions. These procedures may be accessed from a Pascal program, thus allowing the integration of text and graphical outputs.

The graphix subroutines are included in a Pascal program by inserting the following three declarations at the start.

```
($i Typedef.sys)
($i Graphix.sys)
($i Kernel.sys)
```

A typical example of a graphix subroutine is Drawcircle (X,Y,R). If Drawcircle is executed then three parameters (X coordinate, Y coordinate and radius) of the circle in question must be stated.

The procedures used within PASCAL are sections of code. They are each given names so that they maybe called as required from the main line. The procedure names in the program "Drawcable" are:-

procedure READ

procedure DRAWSCREEN

procedure PENUP

procedure PLOTABSOLUTE

procedure PLOTCIRCLE

procedure DRAWPLOTTER

procedure LABELPLOTTER

They are now described in detail.

procedure READ

This procedure is used to read in the data from the external ASCII file into the program. The data is initially loaded into arrays, then is assigned to a working variable. The flow of data is shown in Figure 5.1.

The working variables used in the "Drawcable" program are the same as those used in the Crystal expert system.

procedure DRAWSCREEN

The variables read in by the previous procedure are called Global variables i.e. they are recognised throughout the whole program. Variables declared and used only within a particular procedure are called local variables. They are not recognised within any other procedure.

Therefore variables used as program counters, calculated parameters, condition characters etc. may be declared within one or more procedures and still remain separate of one another.

Procedure DRAWSCREEN uses the command Drawcircle to draw initially a series of concentric circles, and then a series of orbital circles. These circles would represent the cable material layers, and tubes, fillers and copper pairs respectively. Whether or not a

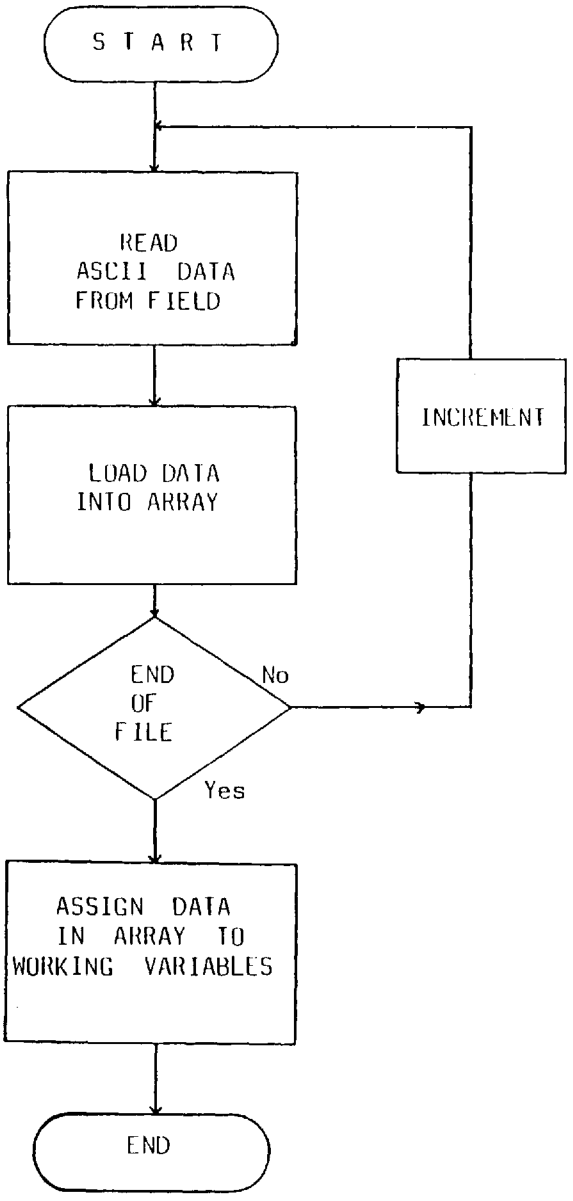


FIG. 5.1 PROCEDURE TO READ DATA FROM EXPERT SYSTEM

particular material is present in the cable is initially tested, and if so, its dimensions (read in from the ASCII file) are processed and the circle, whether concentric or orbital is drawn.

The screen drawing is scaled so that the cable outer diameter is always the same size. This ensures maximum utilisation of the screen.

The sequence of commands within the procedure are shown in Figure 5.2.

procedure PENUP

Procedure PENUP is called from within procedure DRAWPLOTTER. Sending commands to the plotter must be done via string variables. This means that any alpha-numeric characters must be converted into a string before they may be read by the plotter. This process of conversion is performed by this procedure.

procedure PLOTABSOLUTE

The plotabsolute command moves the pen from one point to another in absolute co-ordinates. This procedure converts the command and the numerical coordinates into a string.

procedure PLOTCIRCLE

The plotcircle command draws circles on the plotter to a specified radii and coordinates. This procedure again converts the command and following parameters into a string.

procedure DRAWPLOTTER

The Hewlett-Packard Colorpro plotter used accepts a series of HP graphics language instructions (HP-GL) passesd to its serial RS-232. port via a string variable (17).

An HP-GL instruction is a two-letter mnemonic, which may be upper or lowercase. A command is defined as an instruction followed

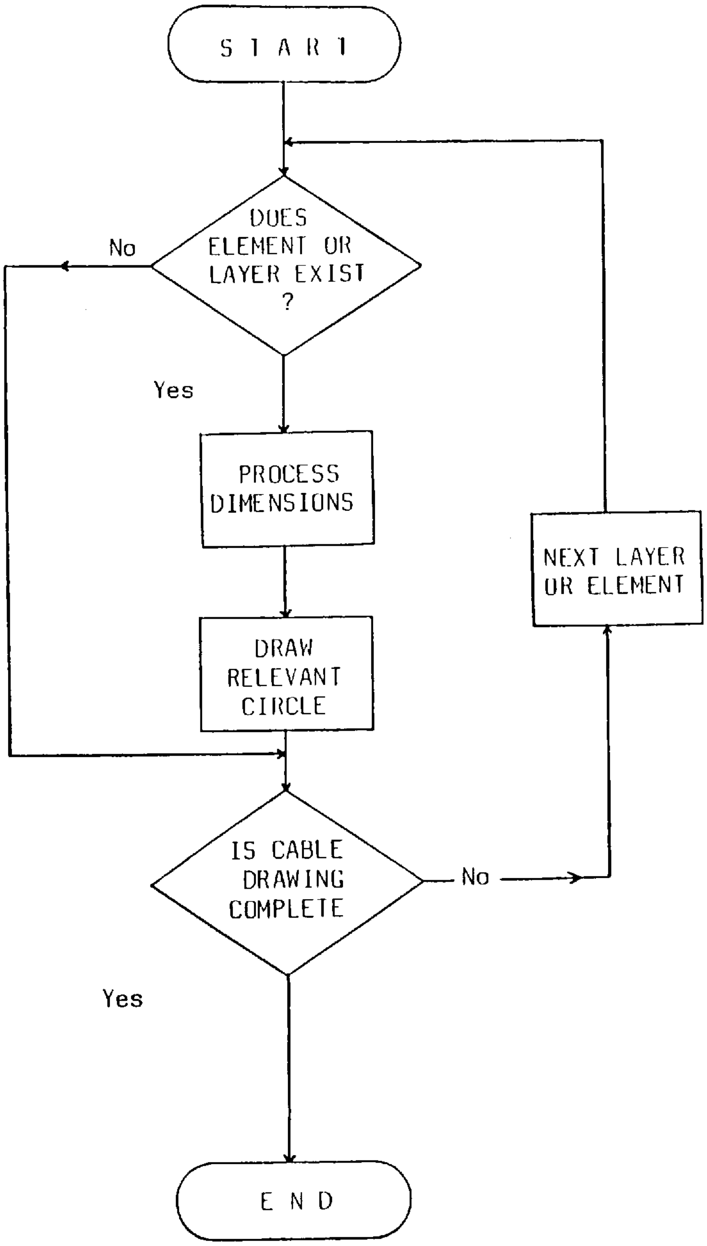


FIG. 5.2 PROCEDURE TO PLOT CABLE CROSS SECTION

by its parameter field, if any, and a terminator. If parameters follow the mnemonic, they must be separated from each other by at least one comma or space, or by a + or - sign which may be preceeded by commas or spaces. Optional commas and/or spaces may be used as separators before, after, and between the mnemonic and before the terminator. An instruction is terminated by a semicolon, nonalphabetic and nonnumeric characters such £ or $, or by the next mnemonic.

Some instructions have optional parameters which, when omitted, assume a default valve. In order to omit a parameter, all subsequent parameters in the same instruction must be omitted.

The label instruction, LB, is a special case; it must be terminated with the label terminator character. This character defaults to the ASCII end-of-text character, ETX, whose decimal equivalent is 3. The label terminator may be changed from its default value using the define terminator instruction, DT.

The parameter fields must be specified in the format defined by the syntax of each respective HP-GL instruction. The format can be of three types:

1. Integer Format - a parameter in integer format between -32768 and + 32767. Decimal fractions of parameters which must be integers are truncated. If no sign is specified, the parameter is assumed to be positive.

2. Decimal Format - a number between -128 and +127 with an optional decimal point and decimal fraction with up to four significant digits. If no sign is specified, the parameter is assumed to be positive.

3. Label Fields - any combination of text, numeric expressions, or

string variables.

The full plotter instruction set is listed in Appendix F.

To send a command to the plotter using PASCAL the following instruction is used:

```
WRITELN (AUX, 'STRING');
```

where AUX is the auxiliary device, i.e. plotter, and STRING is the plotter instruction recognised as a string function.

The sequence of commands within this procedure are virtually identical to those within the DRAWSCREEN procedure. The difference being that the DRAWPLOTTER procedure directs the output to the communications port, whilst the DRAWSCREEN procedure directs the output to the screen.

procedure LABELPLOTTER

A cross-sectional drawing of any cable requires three labelling features to complete it to presentation standards. These are:-

(a) An user-defined, underlined title.

(b) The name of each material used with pointing arrows.

(c) A brief technical summary giving the cable diameter, minimum bend diameter, weight and tensile strength.

Figure 5.3. shows a labelled drawing of a 16 fibre buried cable with steelwire armouring. This diagram together with a cable description would be sent to the customer as part of a contract bid.

The procedure reads whether or not a particular element or layer is present, and produces a label accordingly. The data outputed in the technical summary is transferred from the Crystal Expert System via the ASCII file.

The user defined heading is input into the program as a string variable,and is then sent to the plotter to plot at a pre-defined

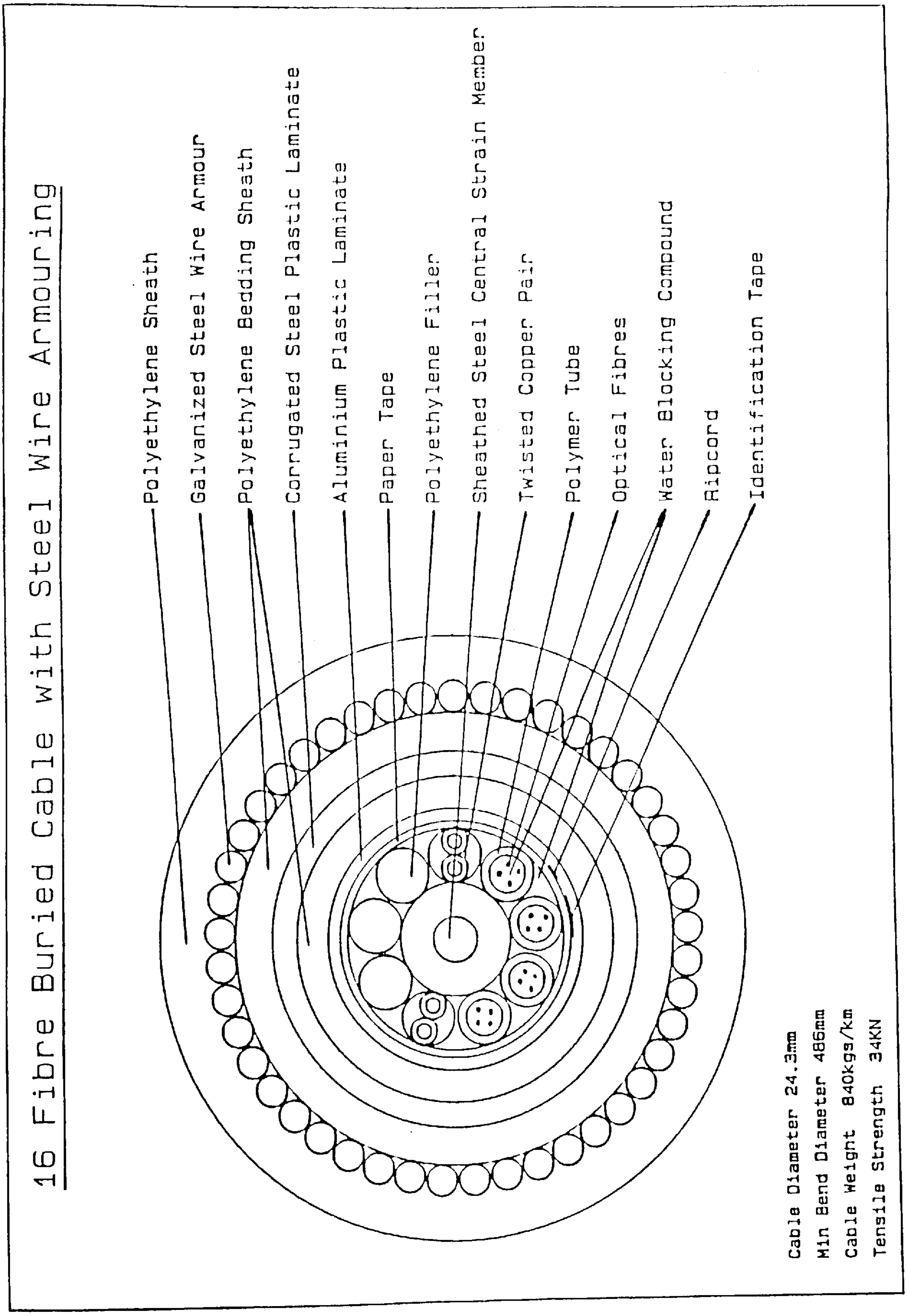


FIG. 5.3 ACTUAL OUTPUT FROM PLOTTING SYSTEM

starting point. The length ofthe string is then read using a PASCAL command, after which the length is converted into plotter coordinates to underline the title.

The flow of data within the procedure is shown in Figure 5.4.

Program Body

The body of the program is used to initialise certain conditions and then link together the procedures in the required sequence. Questions are asked to ascertain whether or not a particular procedure is required for example in some cases only the drawing is needed and the labelling can be omitted.

The mainline can be loooped so that a repeat plot feature is available.

A complete listing of the Pascal "Drawcable" programe is given in Appendix D.

5.6 Sequential Execution of Cable Design Package

Using the IBM PC's disk operating system (DOS), batch files can be written which execute a series of commands sequentially and automatically. Such a file is used to access and execute the Crystal expert system, copy the ASCII datafile generated from the Crystal directory to the Pascal directory, and finally execute the PASCAL "Drawcable" program.

Other commands are present in the batch file such as setting up the plotter to receive data at the required baud rate and configuring the printer to print in Near-Letter-Quality (NLQ) mode.

A list of the batch file written (Crystal.Bat) is given in Appendix E.

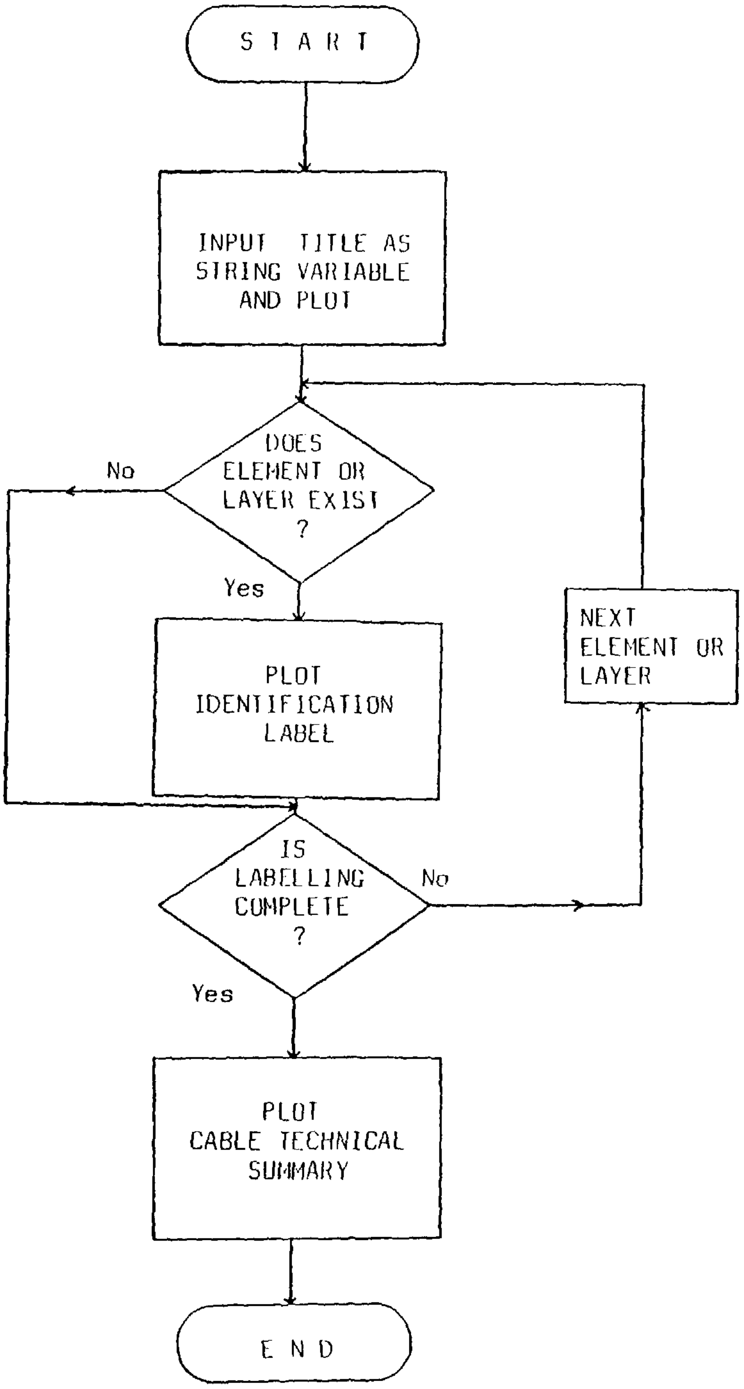


FIG 5.4 PROCEDURE TO LABEL CABLE CROSS-SECTION

CHAPTER 6

DATABASE TO RETRIEVE EXISTING CABLE-DESIGNS

With the number of existing cable designs increasing daily, the need arose for a database system to keep a record of the designs available. The idea was not to store the design itself, but to have a reference number that can be accessed by selecting a series of cable parameters.

6.1. Selecting a Database System

On the market today there are several packages which allow a database to be constructed. These include CARDBOX PLUS, OMNIS and DELTA. These three packages have the database framework already incorporated, with the user definable features being the number of fields and their contents.

Another possibility is a database programming language such as the DBASE series 1,2 and 3. Such a language provides for greater flexibility, but it is not as easy to use and considerable effort is required to learn the language.

It was finally decided that a package would be sufficient for the requirement. On inspection of the options available, CARDBOX PLUS by Business Simulations Limited, was found to possess all the necessary features at reasonable cost.

6.2. Defining the Search Fields

To be able to search for a particular cable design or series of compatible designs, a number of search fields are required. These fields must adequately describe a cable, but must not be too many in number, otherwise inputing a record becomes laborious.

After much deliberation the following 13 fields were decided upon:

1. Construction
2. Number of Fibres
3. Number of Elements
4. Number of Tubes
5. Number of Fillers
6. Number of Coppers
7. Installation
8. Cable Filled/Unfilled
9. Metalic/Non-Metallic
10. Armoured/non-armoured
11. Fibremode
12. Customer reference
13. STC reference.

The options available for each field, and the abbreviations used to described them are now discussed.

(1) Construction

The options available are:

Loose Tube - LT

Open Channel - OC

Tight Stranded - TS

Single Fibre Cable - SFC

Multiple Single Fibre Cable - MSFC

Fibrespan - FS

Figure of Eight - F8

Others - ANO

These are the cable types manufactured by STC.

(2) **Number of Fibres**

The total number of optical fibres contained within the cable.

(3) **Number of Elements**

The total number of outer orbital elements in the cable. This figure will not exist for Open Channel, Single Fibre Cable and Fibrespan designs, since there are no physical elements.

(4) **Number of Tubes**

The total number of tubes in a Loose Tube cable design.

(5) **Number of Fillers**

If a cable has orbital elements and a required centre size for strength purposes, then to have a good fit of elements, fillers may be used. For example, if there is room for 10 elements, but only 8 tubes or fibres are required, then the cheapest solution is to include solid polyethylene fillers. As with the number of elements, this figure will not exist for Open Channel, Single Fibre and Fibrespan designs.

(6) **Number of Coppers**

The total number of copper wires in the cable. This does not apply to Single Fibre, Multiple Single Fibre and Fibrespan designs.

Copper wires (or "coppers") are usually either a single conductor, or twisted pair. The abbreviation to denote a single conductor is:

Cn - where n is the total number of single conductors in the cable.

whilst the abbreviation to denote a copper pair is:

Pn - where n is the total number of copper pairs in the cable.

(7) **Installation**

The options available are:

Ducted - D

Direct Buried - B
Aerial - A

Internal - I

Other - O

The various installations have a direct bearing on how a cable is designed. One could usually predict the type of cable design required if the installation was known.

(8) Cable Filled/Unfilled

Whether or not a cable is filled. If a cable is filled then its interstices are flooded with a water blocking compound.

Cable Filled - F

Cable Unfilled - UF

(9) Metallic/Non-Metallic

If a cable has a steel strength member, an aluminium plastic laminate, a steel plastic laminate or steel wire armouring, then it is considered to be metallic. Non-metallic cables normally have a glass reinforced plastic strength member.

Metallic - M

Non-Metallic - NM

(10) Armoured/Non-Armoured

For a cable to be considered as armoured, it must have either a Steel plastic laminate or a steel wire armour. At present these are the only two forms of armouring used by STC.

Armoured - A

Non-Armoured - NA

(11) Fibremode

There are two types of fibremode, namely Singlemode and

Multimode. Variations in the dimensions of the fibre, and the resulting light propagating characteristics, determine whether an optical fibre is singlemode or multimode.

Singlemode	-	SM
Multimode	-	MM

(12) Customer Reference

Customers quite often have their own reference numbers for particular designs. For example, British Telecom has a code of four numbers preceded by the letters CW. (e.g. CW1531 is a 16 fibre Loose Tube Cable).

(13) Our Reference

Every design that has been manufactured by STC has a particular code assigned to it. The code is four numbers preceded by the letters RA (e.g. RA 3209).

In addition to the search fields, there is a possibility of adding text in a separate section. This extra text cannot be searched, but can be used to give a brief general description of the cable in question. The extra text can be accessed by pressing a single key.

Each field is given a two letter coding, so that a particular field from each record may be searched. Usually if a particular character or series of characters are required to be searched, then the database will search every field of every record.

If the field in which the data exists, is known, then only that field within each record will be searched. This is advantageous for two reasons:

i. Avoids confusion if two or more fields should have the same data. For example,two fields containing numerical data such as "Number of Fibres" and "Number of Tubes".

ii. If the number of records is large then the speed of search is dramatically increased.

The codings for each field are shown below:

Construction	-	AA
Number of Fibres	-	CC
Number of Elements	-	EE
Number of Tubes	-	GG
Number of Fillers	-	II
Coppers	-	KK
Installation	-	MM
Cable Filled/Unfilled	-	OO
Metallic/Non-Metallic	-	QQ
Armoured/Non-Armoured	-	SS
Fibremode	-	UU
Customer Reference	-	WW
Our reference	-	YY

6.3. Database Capacity

Each Cardbox-Plus database can contain up to 65,500 records, and as many independent databases as required can be had on any disk (18). The size of a database is limited only by the disk capacity of the machine used, or any limitations on the file size imposed by the machines's operating system.

At present, the number of fibre optic cable designs is approximately 300. It is envisaged that in the future, new designs will gradually decrease, with existing designs saturating the cable requirements. Therefore the maximum capacity of the database is never in danger of being exceeded.

CHAPTER 7

LOOSE TUBE CABLES - ADVANCED DESIGN THEORY

7.1. Introduction

The local area network market presents a number of problems to the cable designer. Firstly, the large fibre count in such cables means that the probability of a fibre failing per cable is increased, so the manufacturing process needs to be more reliable than that for a low fibre count cable to avoid increased scrap levels. Secondly, competition demands that lead times and costs are minimised, making development programs unviable if they use too much machine time or materials. Optimisation of designs cannot therefore proceed by trial and error, as in the early days of optical cables.

A theory is clearly required that can be used to identify which changes to existing designs and processes are most likely to yield significant improvements, to check the effect of tolerance variations, and to model new materials and procedures. To achieve this goal, the theory must use parameters that are known, or can be practically measured. Since it was felt that existing theories did not meet this criteria, a new approach was developed (20).

7.2. Theory

The excess length of fibre in a loose tube cable is linked to the tensile strength. In order to predict the tensile strength one must therefore consider the stages of the manufacturing process that put in and take out fibre excess.

(a) The length of tube in a given length of cable at stranding is calculated from the tube helix to obtain:

$$Z1 = \frac{((Pi(D1 + D2))^2 + L1^2)^{\frac{1}{2}}}{L1} \qquad 7.1$$

where Z1 = Length of tube at stranding/length of cable at stranding (unitless).

D1 = Diameter of built-up centre (mm)

D2 = Tube Outer Diameter (mm)

L1 = Laylength at stranding tension (mm)

(b) The diameter on which the fibres lie when the cable is at maximum working tension is then calculated. The fibres move toward the centre of the cable until they cannot move further. Those fibres at the centre touch the tube wall, and the subsequent fibres pack on top (21). As the cable strain increases, the fibre further from the cable centre is strained most. The maximum allowed strain for this fibre defines the maximum working strain for the cable. Thus the equation:

$$K3 = Pi[D1 + D2 - D3 + (2 \times K4[N] - 1)\ D4] \qquad 7.2$$

Where K3 = The circumference of the strained outer fibre helix (mm)

D3 = The tube inner diameter (mm)

D4 = The fibre diameter (mm)

K4(N) = The packing factor (unitless)

N = The number of fibres in the tube.

The packing factor is a reflection of the number of fibres sitting on top of each other in the tube. A single fibre (N=1) would therefore have a packing factor K4 (1) = 1. Two fibres sitting exactly on top of each other would have a packing factor K4 (2) = 2. In practice, the fibres are more likely to sit side by side, giving a packing factor for usual tube sizes of around K4 (2) = 1.2. By scale drawings, guesses for packing factor have been made as follows:

N	1	2	3	4	5	6	7	8	9	10
K4(N)	1	1.2	1.87	2.06	2.255	2.44	2.62	2.81	3.0	3.19

Table 7.1.

Fortunately, the packing factor has only a small effect on the fibre helix diameter, so such approximations seem reasonable. For example, a cable with a centre of 5 mm (D1 = 5) using 2.2/1.5 mm tubes and containing 4 fibres of 0.25 diameter where K4(N) = 2.06 gives a value of K3 as 20.4. If K4(N) is taken as 1.5 then K3 = 19.5, and if K4(N) is taken as 2.5, then K3 = 21.0. This means that a 25% error in K4(N) results in only a 4.4% error in K3. The errors introduced here are only likely to become significant for cables with very small centres, and small tubes.

(c) The amount of fibre in a tube after manufacture can be measured by cutting the tube between fixed points a set distance L apart at a known tension T5, removing the fibre and measuring the difference between the fibre length and the distance between the set points, with the fibre at a known tension U. The difference between the fibre and tube length is the excess, X. The ratio Z of strained fibre lengths against strained tube length is given by:

$$Z = \frac{L + X}{L} \qquad 7.3$$

(d) If the optical fibre's tensile modulus is measured on a tensometer or similar, then we can calculate how long the fibre would be if it were not strained.

Generally $T = \xi EA$ where
T is the Tension
ξ is the Strain
E is the Modulus
A is the Area

As for a given fibre type, the moduls and area are not expected to vary significantly, and the response of a fibre is near-linear (despite the modifying effect of the coatings), we can define a modulus-area product for the fibre as:-

$$K1 = E.A. \tag{7.4}$$

For a fibre tension of U,

$$\xi = \frac{U}{K1} \tag{7.5}$$

For a fibre of original length Lo, then

$$L = Lo(1 + \xi) \tag{7.6}$$

The tensioned fibre had a length of L + X, so using the above equation gives.

$$Lo = \frac{L + X}{1 + \xi} = \frac{L + X}{1 + (U/K1)}$$

Therefore, the ratio Z2 of unstrained fibre length Lo against strained tube length L is given by:

$$Z2 = \frac{L + X}{L(1 + U/K1)} \tag{7.7}$$

(e) If the loose tube material's tensile properties are measured, a problem is discovered. The polybutyl terephthalate (PBTP) material used by STC does not have a constant modulus, but the modulus varies with strain, i.e. in the rule $T = \xi EA$, $E = fn(\xi)$. The modulus becomes near linear at strains above 0.128% but falls off to almost zero at zero strain. With a tube of 2.2/1.5 mm dimensions, this means that all tensions below 200 g are operating in the non-linear region of the curve. Hence if this tube is stranded at a tension of 500 g, it will be strained by 0.19%, and not by the 0.10% that would be obtained using the modulus from the linear region of the graph.

The non-linearity can be coped with readily for single readings, simply by using the graph. For a different area of tube, one can generate an appropriate graph by remembering that the tension is proportional to the tube area for a given strain, so in the case of the graph for the 2.2/1.5 tube of area 2.03mm and requiring data for a tube of area A, with an original data set of (T,S) the new graph of tension against strain of the data set is (T.A/2.03,S). The set of data for a 1mm area tube is given in Table 7.2.

For a tube of area A3, using the data in Table 7.1, the tension is given by the equation:

$$T3 = T2 \times A3 \tag{7.8}$$

Clearly, for any new material, the table would need to be altered. Similarly the best results would be obtained by measuring a sample of the tube used, rather than referring to tubes of markedly different dimensions, which may have different properties due to different orientation, cooling rates etc.

Tension of 1mm Tube T2(N)	Strain of Tube S2(unitless)
0	0
0.1207	0.00057
0.2149	0.00077
0.3626	0.00090
0.4833	0.00100
0.6039	0.00100
0.7251	0.00117
0.8458	0.00123
0.9665	0.00128
1.4498	0.00150
4.8325	0.00285

Table 7.2.

To find the strain of tube at given tension, we can either use the area corrected graph, or interpolate/extrapolate between known points on the graph. This method, while less accurate, is reasonably suited to input on a computer.

Using the interpolation based on y = mx+c, between data pairs, then it can be shown from the tube stress/strain graph for pair I and I+1, that

$$M(I) = \frac{T3(I+1)-T3(I)}{S2(I+1)-S2(I)} \qquad 7.9$$

$$\text{Based on } T = MS + C \text{ or } S = \frac{T - C}{M}$$

and

$$C(I) = T3(I) - (M(I) \times S2\ (I)) \qquad 7.10$$

Repeating this for all the data pairs, then one can obtain a set of M(I) and C(I) that refer to the gradient and intercept of the straight line between I and I+1 pairs.

Now, the strain of the tube can be found at a given tension, such as the measurement tension T5, by scanning the data pairs until we find the pairs that T5 lies between, obtaining the corresponding gradient and intercept, and substituting these values into the equation:

$$S5 = \frac{T5 - C(J)}{M(J)} \qquad 7.11.$$

In the case of the tension being greater than that of the highest data point, one can use the M and C for the highest tension data pair available, since the modulus is near linear at high tension.

This equation is valid provided one assumes that the fibres did not bear any of the load at the measurement tension. This can only be assured by using a sufficiently low measurement tension, and cross-checking this against the excess. The tension used must be high enough to straighten the tube, and avoid the very low modulus area of tube strain (which would introduce large errors), and low enough not to strain the fibres. Typically a 100g tension would be used. For example a 2.2/1.5 tube would be strained by 0.057% at 100 g, and such a tube might have 0.15% excess fibre measured at a fibre tension of 50g. Using a fibre modulus-area of K1 = 886, the fibre strain at measurement = 0.056%. Hence the excess unstrained fibre at measurement = 1.0015/1.00056 = 1.000935 i.e. 0.094%. Since 0.094% > 0.057%, the fibre excess is greater than the tube strain, and so the equation is valid.

(f) Next, the tube strain at stranding tension needs to be calculated. This is more complex, since the fibres are likely to be strained. This can be checked by calculating ZS, the ratio of unstrained fibre length to unstrained tube length.

$$ZS = ((S5 + 1) \times Z2) - 1 \qquad 7.12$$

Z2 is the ratio of unstrained fibre length against strained tube length, and S5 is the tube strain at measurement.

i. The tube strain at stranding can be calculated from:

$$S6 = \frac{T6 - C(J)}{M(J)} \qquad 7.13$$

where T6 is the stranding tension of the tubes and C(J), M(J) are the corresponding tensile plot gradient and intercept, by using the method given in section (e), assuming the fibres bear no strain. If then, ZS is greater than S6, the fibres indeed bear no strain, so the value of S6 calculated here is the actual correct tube strain at stranding.

ii. If ZS is less than S6,then the fibres do bear strain, and so the value of S6 calculated above is incorrect, and must be given by the solution of the equation:

$$T6 = M(J).\ S6 + C(J) + \sum_{1}^{N} K1.\ (S6 - ZS(N)) \qquad 7.14$$

where M(J).S6 + C(J) is the tube contribution to the tension, and the contribution of the N fibres to the tension is:

$$\sum_{1}^{N} K1\ (S6 - ZS\ (N))$$

To evaluate the fibre contribution to the excess, we need to know the distribution of the fibre excess in multifibre tubes, i.e. the ZS(N) distribution. This ought to be determined by direct measurement. In the absence of such data, and for simplicity, it is assumed that fibres have the same excess. In this case

$$T6 = M(J).\ S6 + C(J) + N.K1.\ (S6 - ZS)$$

Rearranging this equation to obtain S6 gives

$$S6 = \frac{T6 - C(J) + N.K1.ZS}{M(J) + N.K1} \qquad 7.15$$

To evaluate this equation we need to know which data pairs to use. This is done by looking at the tube contribution to the tension:

$$QQ = M(J).\ S6 + C(J) \qquad 7.16$$

By trying each M(J), C(J) pair in turn, in equation 7.15 we obtain a value of S6 to substitue in 7.16. If the value QQ is between T(J) and T(J+1) then the correct value of J has been chosen, since the modulus used is appropriate for the tube strain. If the value of QQ is not between T(J) and T(J+1), another J is tried. If QQ is greater than the highest value of T(J), then the M(J) and C(J) for the highest data pair are used.

Note that equation 7.15 cannot be used to determine the tube strain when the fibres are not strained,since this would give a compressive tube strain contribution from the fibres, whereas in reality the fibres simply bend when present in excess, and have no contribution to tube strain. In summary for this section, section i. equation 7.13 is used if the fibres are not strained at stranding, and section ii. equation 7.15 is used if the fibres are strained at stranding.

(g) the following are now known:

Z2, ratio of unstrained fibre length against strained tube length at measurement.

S5, tube strain at measurement.

S6, tube strain at stranding.

So the ratio Z3 of unstrained fibre against strained tube length at stranding is:

$$Z3 = \frac{Z2.\ (S5 + 1)}{(S6 + 1)} \qquad 7.17$$

(h) The following are also known:

Z1, ratio of tube length at stranding against cable length at stranding.

Z3, ratio of unstrained fibre at stranding against tube length at stranding.

So the ratio Z4 of unstrained fibre at stranding against cable length at stranding is

$$Z4 = Z1 \times Z3 \qquad 7.18$$

(i) Consider one lay length of cable, at the stranding tension. The cable length is L1 and the fibre length is Z4.L1. When the cable is taken to its maximum working tension, the fibre length is then (Z5.Z4.L1) where Z5 is the maximum allowed fibre strain. Since the fibre helix circumference K3 is known, the new lay length L2 at maximum working tension can be calculated to obtain.

$$L2 = ((Z5.Z4.L1)^2 - K3^2)^{\frac{1}{2}} \qquad 7.19.$$

(j) The maximum working tension is then calculated from the increase in lay length. Using the formula T = E.A. on the central strength member (or members) at the stranding tension of the centre T7 is:

$$T7 = \zeta.E\ \ A4 = S7.\ E.\ A4 \qquad 7.20.$$

where E is the modulus of the centre member (N/mm^2)

and A4 is the area of the centre member (mm^2)

Simularly at the maximum working tension T8:

$$T8 = S8.E.A4 \qquad 7.21$$

If a lay at zero centre tension had length Lo, then

$$L1 = Lo\,(1 + S7)$$

$$\text{and } L2 = Lo\,(1 + S8)$$

Substituting to eliminate Lo gives:

$$L2 = \frac{(1 + S8)}{(1 + S7)}$$

Substituting for S7 and S8 gives:

$$L2 = L1\frac{(1 + T8/E.A4)}{(1 + T7/E.A4)}$$

$$\text{If } RR = 1 + \frac{T7}{E.A4} \qquad 7.22$$

$$\text{then } \frac{L2.RR}{L1} = 1 + \frac{T8}{E.A4}$$

$$\text{If } SS = \frac{L2.RR}{L1} \qquad 7.23$$

$$\text{then } SS = 1 + \frac{T8}{E.A4}$$

So,

$$T8. \ = (SS - 1).E.A4 \qquad 7.24$$

where T8 is the maximum working tension of the cable.

7.3. Computer Program to Calculate Maximum Working Tension of Cable

As mentioned in the previous section, this theory is suited for implementing into a computer program. The format of the theory i.e. input, calculation via several repetetive loops, output, would make working through the required procedure manually a low and laborious task.

The program written to solve the theory is in PASCAL and is made up of five procedures linked by a main line program. The inputs to the program are as follows:

Packing Factor Array:- K4[1] = 1
K4[2] = 1.2
K4[3] = 1.87
K4[4] = 2.06
K4[5] = 2.25
K4[6] = 2.44
K4[7] = 2.62
K4[8] = 2.81
K4[9] = 3.0
K4[10] = 3.19

Stress - Strain data array of 1mm^{2}tube :-

T2[1] = 0 S2[1] = 0
T2[2] = 0.1207 S2[2] = 0.00057
T2[3] = 0.2149 S2[3] = 0.00077
T2[4] = 0.3626 S2[4] = 0.00090
T2[5] = 0.4833 S2[5] = 0.00010
T2[6] = 0.6039 S2[6] = 0.0011
T2[7] = 0.7251 S2[7] = 0.00117
T2[8] = 0.8458 S2[8] = 0.00123
T2[9] = 0.9665 S2[9] = 0.00128
T2[10] = 1.4498 S2[10] = 0.0015
T2[11] = 4.8325 S2[11] = 0.00285

Tube Measurement Tension (Newtons) - T5

Fibre Measurement Tension (Newtons) - U

Tube Length Measured (mm) - L

Fibre Diameter (mm) - D4

Maximum Allowed Fibre Strain (fractional)Z5

Diameter of strength member (mm) - D10

Strength Member Modulus (N/mm^2 - E

Diameter of sheathed centre (mm) - D1

Tube Inner Diameter(mm) - D3

Number of Fibres per Tube (integer) - N

Laylength at Stranding (mm) - L1

Tube stranding tensions (N) - T6

Cable Stranding Tension (N) - T7

Fibre Excess (mm) - X

The five procedures are:-

1. LOADARRAYS
2. INPUT
3. CALCS
4. CALCULATE
5. PRINT

The main body of calculation within the program is in procedure CALCULATE, with theoretical equations linking the array data and user inputs. The output from the program is the maximum allowed cable tension before the optical fibres see a strain of greater than 0.25%. This is the limit where attenuation increments become significant.

The flow of information within the program is shown in Fig. 7.1. whilst a complete program listing is given in Appendix E.

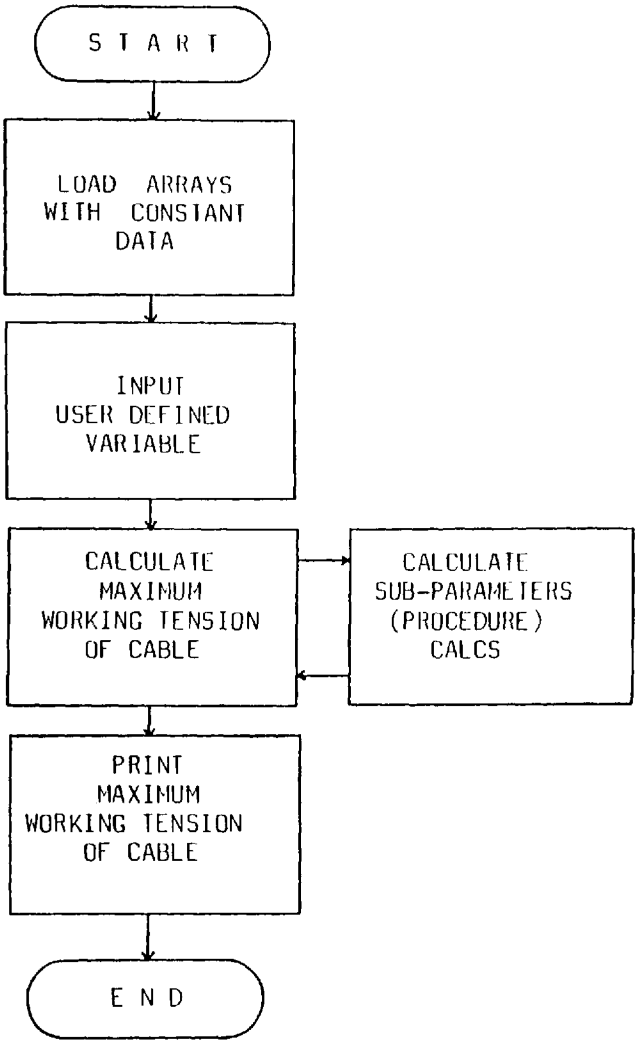


FIG 7.1 PROGRAM TO CALCULATE MAXIMUM WORKING TENSION OF CABLE

CHAPTER 8

FIBRE BEND CHARACTERISTICS - THEORETICAL CONSIDERATIONS

8.1 Introduction

In estimating the maximum tensile strength of a Loose Tube Cable, the parameter of most interest is the excess fibre placed within the tubes. This can be accurately controlled by the fibre pay-off tension and the cooling rate of the extruded tube. At present the fibre excess level is kept to approximately 0.15%. With the maximum allowable working fibre strain being 0.25% (22) the total available cable strain is 0.25 + 0.15 = 0.4%. If the modulus of the cable strength member is known, then from the equation:

$$\text{Modulus} = \text{Stress}/(\text{Strain} \times \text{Area}) \qquad 8.1$$

the maximum working tension of the cable can be calculated. Therefore using the fibre excess level and maximum allowable fibre strain a simplistic relationship can be formed.

To obtain an accurate representation of what actually happens to a fibre in a cable, one must take into account such parameters as tube laylength, fibre packing density etc, in addition to fibre excess. Chapter 7 describes a theory which calculates the maximum working tension of a cable from knowledge of these and other easily measured parameters.

Fibres in tubes follow a helical path, with a greater excess resulting in smaller bend diameters,i.e. more helical revolutions per unit distance. The actual bend diameter experienced by a fibre following a helical path in a tube, with the tube being helically wrapped around a central member (double helix) depends upon several parameters, e.g. central member diameter, tube inner and outer diameters, fibre diameter etc. Houghton et al have related these parameters to the actual fibre bend diameter experiencd (23).

$$I = \int_0^{2\pi} \sqrt{r^2 \sin^2 Q + F \sin QA + Grd}\; d\theta \qquad 8.2$$

where $F = 2\, rs - 2\, rsfQ$

$G = s^2 + r^2Q^2 + f^2$

$I = YL\,(1 + \sigma t)$

and $f = N/2\pi$

where Q is the number of helixes per lay

θ is the point on the helix at which the curvature is measured,

N is the laylength on the drum at the test temperature

r is the radius of the helix of the fibres within the tube

s is the supporting helix radius

σ is the coefficient of thermal expansion

t is the difference between the stranding temperature and test temperature

and Y is the fibre excess

It is known that bending an optical fibre beyond a critical radius results in attenuation increments. The value of the critical radius depends upon the dimensions and shape of the fibre refractive index profile, which itself depends on the fibre manufacturing process. The following two chapters describe theoretical aspects involved with fibre bend performance, and also a series of practical tests which attempt to empirically characterise the bend performance of fibre with reference to its index profile and resulting secondary parameters.

Once the fibre bend performance has been characterised, optical fibre cables can then be designed to keep the bend radii experienced by cabled fibres within a safe operating window.

8.2. Waveguide Attentuation

The losses due to waveguide structure arise from bending, microbending of the fibre axis, and defects at joints between axes.

The simplest qualitative description of bending losses in a fibre can be obtained by assuming that in the bent fibre the field is not significantly changed compared with the field in the straight fibre. The plane wavefronts associated with the guided mode are pivoted at the centre of the curvature of the bent fibre, and their longitudinal velocity along the local fibre axis increases with the distance from the centre of curvature. As the phase velocity in the core is slightly smaller than that of a plane wave in the cladding, there must be a critical distance from the centre of curvature above which the phase velocity would exceed that of a plane wave in the cladding.

The electromagnetic field resists this phenomenon by radiating power away from the guide, causing radiation losses. The bending losses increase when the radius of curvature decreases. Also, a mode close to cutoff is affected more than a mode far from cutoff. A high-index difference will decrease bending losses. Fig. 8.1 shows how a fibre under bending conditions has a new refractive index profile characterised by the equation (24):-

$$N(eff) = n(r)\ (1 + \frac{r}{R} \cos\phi) \qquad 8.3$$

where N(eff) is the effective refractive index difference between core and cladding, and N(r) is the actual refractive index difference.

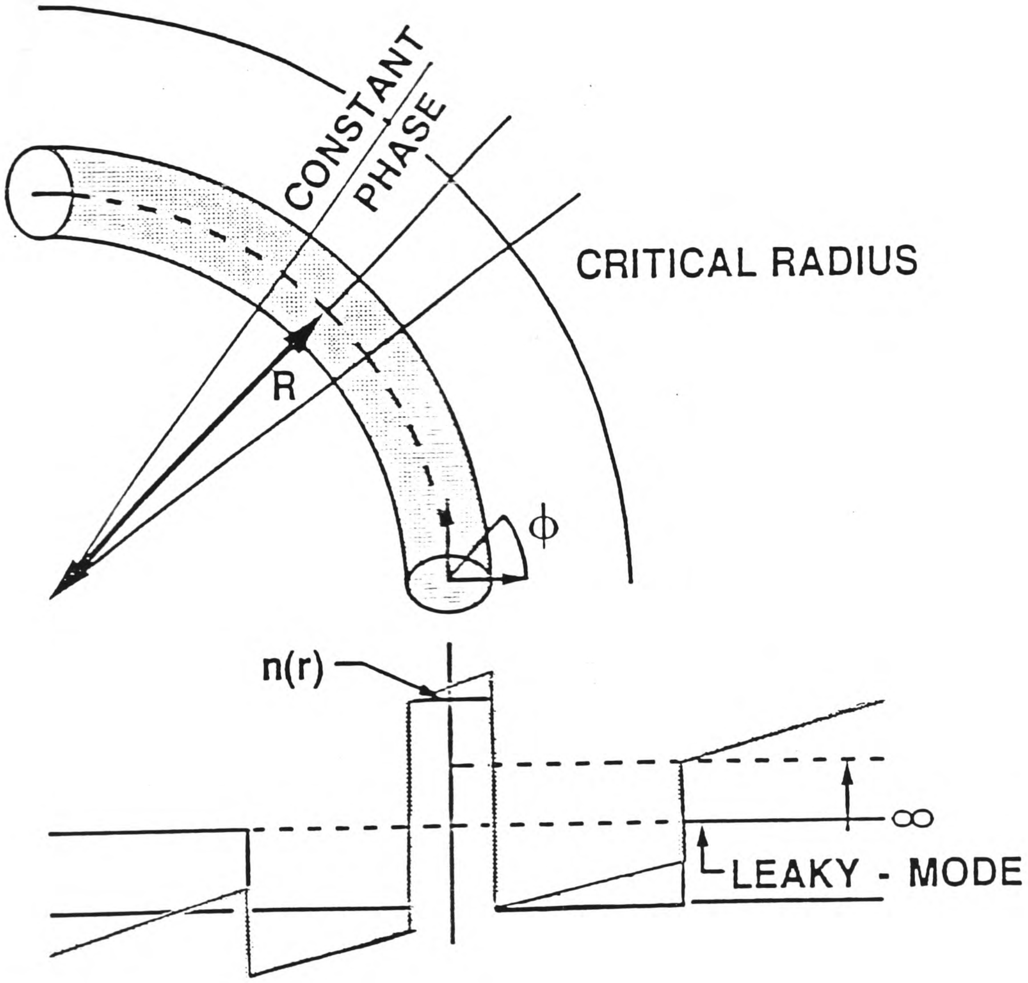


FIG. 8.1 CHANGE OF REFRACTIVE INDEX UNDER BEND

Microbending losses correspond to a fibre randomly oscillating around its nominal position with small deviations. Despite the small deviation the typical periods of the oscillations may be small and therefore the fibre may have sharp local bending. There are thus two loss sources, one arising from the permanent coupling between the LP(01) mode (section 2.2) and leaky and radiation modes, and another arising from the pure bending - loss effect of the LP (01) mode, which becomes leaky at some radial distance in a curved fibre.

8.3. Cutoff Wavelength

The cutoff wavelength of a single-mode fibre generally refers to the wavelength at which the LP(11) mode cuts off, i.e. can no longer propagate. It is important to know this wavelength because, below it the presence of the LP(11) mode can cause bimodal noise as well as a bandwidth decrease due to timodal dispersion. The strict definition of cut-off wavelength corresponds to the theoretical cutoff wavelength, which is only appropriate for very short (millimeteres) straight fibres. A more practical definition allows for the fact that in the region approaching cutoff, the growth of the spot size of the LP(11) with increasing wavelength contributes to an increasing attentuation excess over the fundamental mode's attenuation. Thus the actual propagation of the LP(11) mode through a particular length of fibre depends on the distribution (length, radius) of bends in the fibre, the presence of fluctuations in diameter and index, and the fibre length. This leads to an effective cutoff wavelength, co, that is always less than the theoretical value since it takes into account the fact that the fibre in its "environment" tends to suppress the LP(11) mode at wavelengths for which it would be present in a short, straight fibre. It is the cutoff wavelength that is observed experimentally (e.g. in Fig. 8.2) and is the wavelength at which the bimodal problems referred to above disappear. Since co is a function of the fibre length and environment (bends etc.) any measurement of it must be made under standardised conditions. Perhaps the most precise method of defining effective cutoff wavelength is the wavelength at which a certain suppression (LP(11) power a given amount of decibels below the LP(01) power at the fibre end) occurs. Fig. 8.3 shows the relationship between cutoff wavelength and cable length for depressed and matched clad fibres.

8.4 Mode-Field Diameter

For single-mode fibres the geometric distribution of light in the propagating mode, rather than the core diameter and umerical aperture (NA), is what is important in predicting such operational properties as splice loss, micro and macro bending losses and dispersion (25). In particular, a single parameter, the mode-field diameter (MFD) or spot size, which is a measure of the width of the distribution of electric field intensity, can be used in the prediction of many of these properties.

The first generation single-mode fibres operated near cutoff so as to give minimum micro bending losses, e.g. with co in the 1.2 um range and the operating wavelength near the minimum dispersion wavelength, i.e. near 1.3 um, the electric field distribution can be approximated by a Gaussian distribution (26,27). The width of the distribution has been related to the sensitivity of splice loss, to micro-macro bending loss, and, through its variation with wavelength, to the waveguide dispersion of the fibre. The ability to characterise

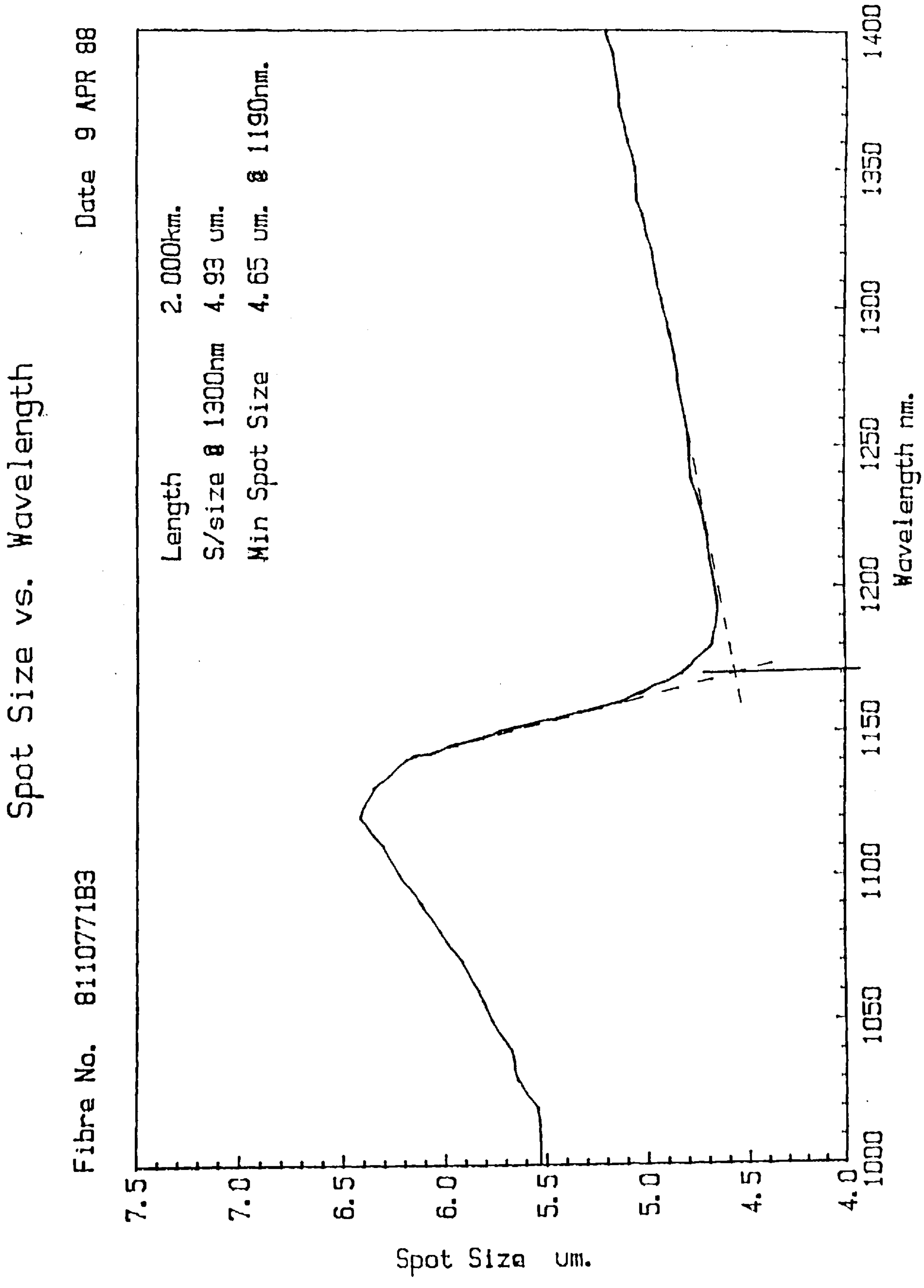


FIG. 8.2 SPOT SIZE VS. WAVELENGTH SHOWING CUT-OFF

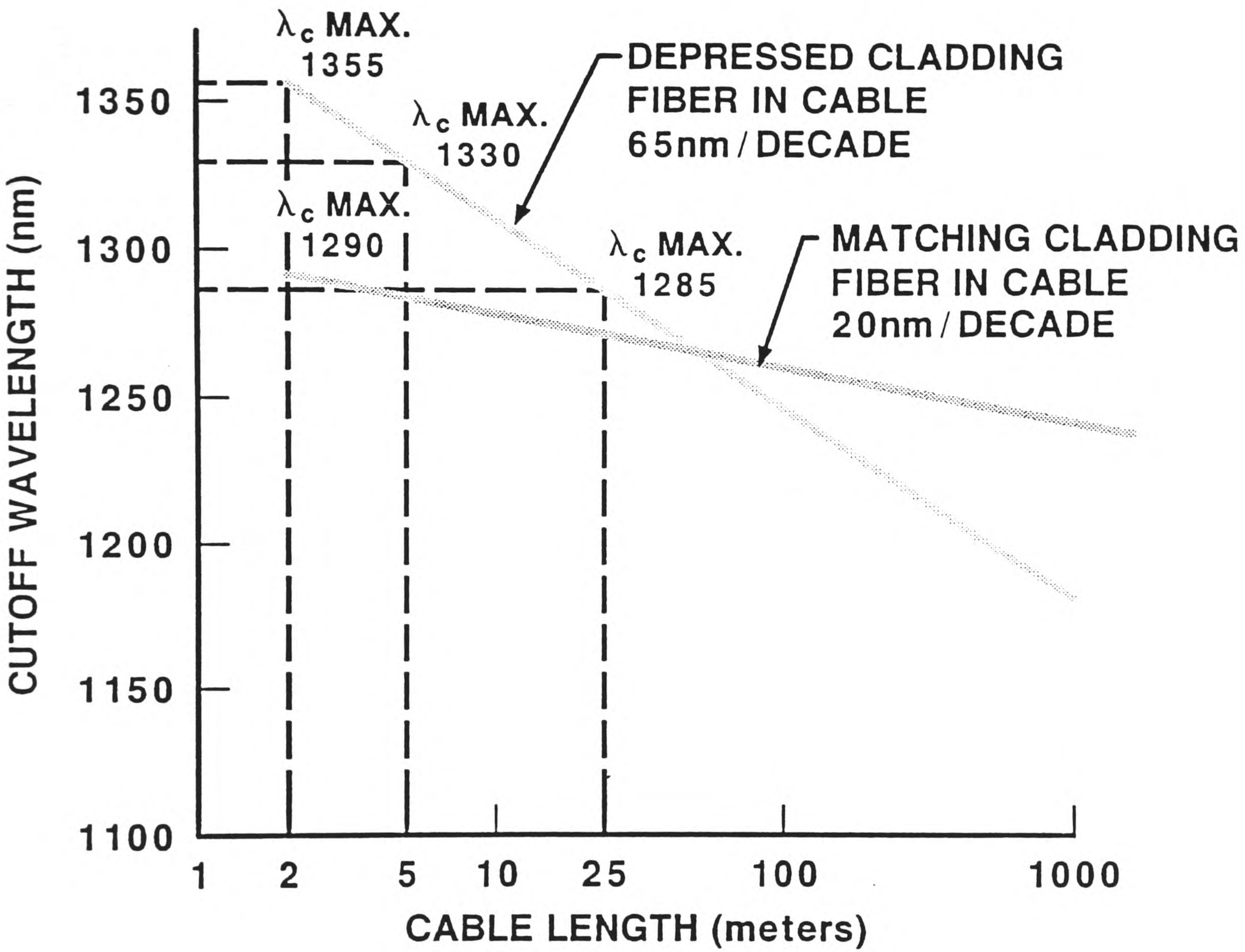


FIG. 8.3 LENGTH DEPENDENCE OF CUT-OFF WAVELENGTH

these properties depends on the exact way the width is defined, since the distribution is not exactly Guassian. One technique (28) is to take the width (i.e. the mode field diameter), to be twice the 1/e radius of the optical electric field (1/e.e) radius of optical power) of the Gaussian radial dependence:

$$Eg(r) = Eo \exp (- r^2 / W6^2) \qquad 8.4$$

where r is the radius, Eo the field at zero radius and W6 the mode field radius. Fig. 8.4 shows a typical mode field power distribution for a step index fibre. The mode field diameter, taking the previous definition, is the diameter of the field at 1/e of its maximum intensity.

8.5 Fabrication Techniques for Optical Fibres

Low-loss optical fibre fabrication techniques, developed in the early to mid 1970's have matured into fully industrialised automated manufacturing processes. All of the processes are based on a common vapour deposition technology. The pre-eminence of this technology is because it produces the highest purity material and has the necessary capability, in refractive index profile and dimensional control, to produce precision waveguide structures. The three most dominant processes used today in manufacturing optical fibres are the modified chemical vapour deposition (MCVD) process, the ouside vapour deposition (OVD) process, and the vapour axial deposition (VAD) process.

All of the vapour deposition processes produce high quality silica fibres, in which different dopants, such as germanium, phosphorus, and flourine, are added to silica to modify refractive

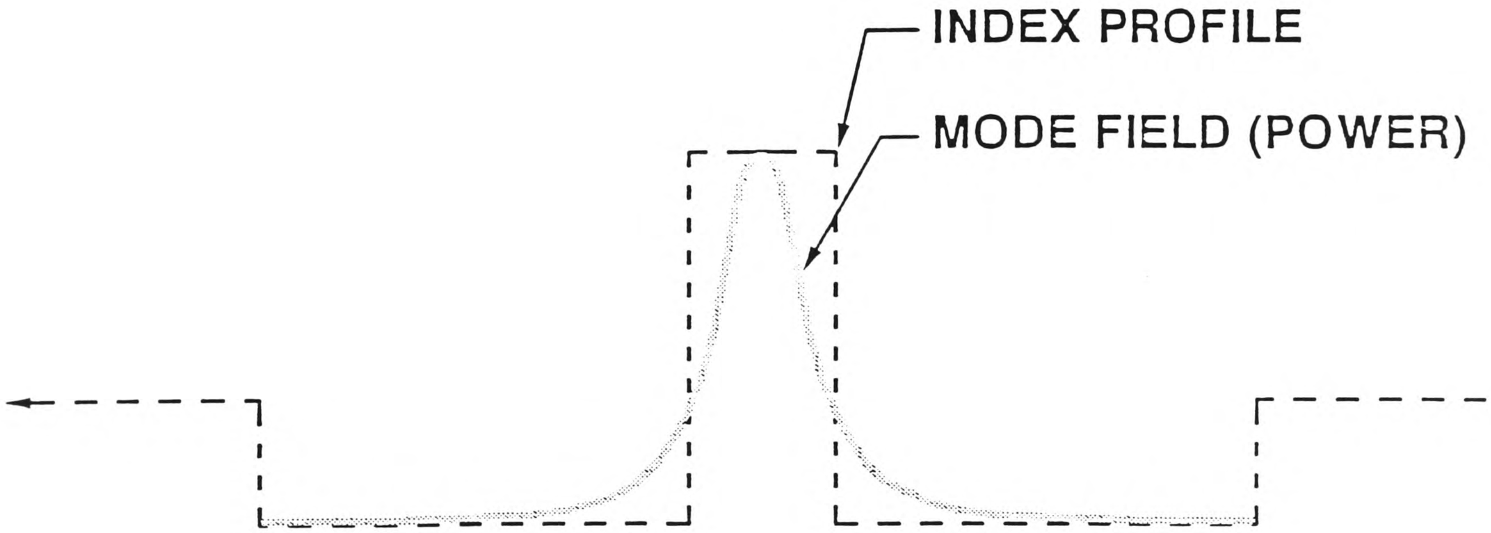


FIG. 8.4 DISTRIBUTION OF MODE FIELD

indices to form the waveguide structure. The raw materials used are vapours or high-vapour pressure liquids of these glass-forming materials. Most raw materials used today are halides, such as silicon tetrachloride, germanium tetrachloride, and phosphorus oxychloride, which are liquids, and boron trichloride, sulphur hexaflouride, and ethylene hexaflouride, which are vapours. The raw materials need to be converted into vapour phase and mixed with oxygen to form the reactant vapour stream.

Reactant generation, control of composition, and transport is normally done with a vapour-delivery system. The vapour-delivery system concept most commonly used is a bubbler system in which liquid raw materials are converted into vapour phase by bubbling a carrier gas through the reactant. This resultant vapour stream is then mixed with vapour reactants and transported to the reaction zone. Care has to be taken to prevent any condensation within the delivery lines. Some manufacturers use nonmetallic vapour delivery systems, in which the engineering materials in contact with the reactants are strictly glass and teflon. This is one to eliminate the possibility of contamination of the reactants of transitional metal ions. The only adverse effect of minor leaks in non metallic systems is pressure buildup. Others use metallic systems primarily made of strainless steel. Such systems have to be leak-tight to prevent corrosion within the system and consequent contamination of the raw materials.

The preform fabrication processes can be divided into two generic groups. The processes where soot is collected to form a porous preform, which is sintered in a separate process step are referred to as the soot processes. The OVD and VAD belong to this category. The simplest and the most used inside process is the MCVD process. In this process, the reactants are fed into a rotating, fused silica substrate tube. A traversing oxy-hydrogen burner heats the substrate tube to generate soot. The soot deposits downstream of the burner, and, as the burner traverses by, the collected soot layer is sintered into a clear glass layer. Deposition is continued until the desired amount of cladding and the core glass are deposited, after which the tube is heated to a higher temperature. Burner gas pressure and surface tension forces, cause the tube to collapse into a rod.

8.5.1.Design Flexibility

The key features of processes that dictate design flexibility are essentially threefold.

(1) The dopants that can be used.

(2) The level of doping possible, and the accuracy of composition control.

(3) The dimensional control and the degrees of freedom in the process dictate the different waveguide structures that can be formed.

All of the established processes have demonstrated the capability of producing the dominant fibre designs being used today.

8.6. Single-Mode Fibre Design Considerations

Single mode fibres are primarily designed to operate at a wavelength of 1.3 um. Such fibres have low loss and low dispersion at this wavelength, but also have a low loss at the 1.55 um window. Two alternate designs used for this application are called matched-cladding and depressed cladding. Fig 8.5. shows the refractive index profiles of both fibre desings, whilst Table 8.1 states the fibre secondary parameters, and the design characteristics which influence

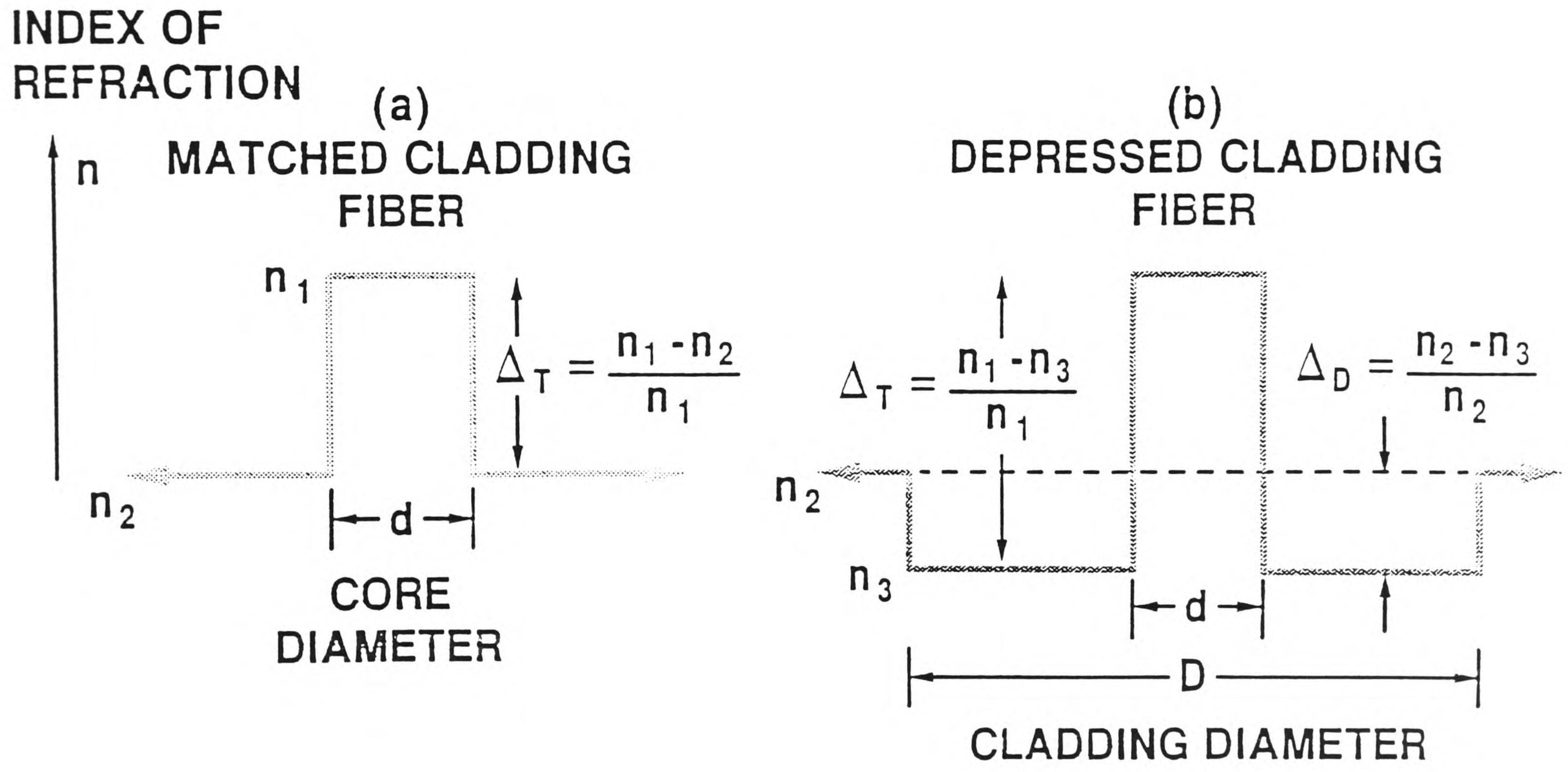


FIG. 8.5 MATCHED AND DEPRESSED FIBRE REFRACTIVE INDEX PROFILES

	MATCHED CLADDING DESIGN	DEPRESSED CLADDING DESIGN
INTRINSIC LOSS	Δ_T	Δ_T , Δ_D
MODE FIELD DIAMETER	Δ_T , d	Δ_T , d
ZERO DISPERSION WAVELENGTH	Δ_T , d	Δ_T , d, Δ_D
CUTOFF WAVELENGTH	Δ_T , d	Δ_T , d, Δ_D , D

TABLE 8.1 MATCHED VS. DEPRESSED FIBRE DESIGN PARAMETERS

them.

The matched-cladding design is produced by all three processes, MCVD, OVD and VAD, whilst the depressed-cladding design is only produced by the MCVD process. Both designs are used for similar applications, but with different cable and system configurations.

In single-mode fibre design one has to ensure that the signal propagated is indeed single-mode. The condition of single-mode propagation is that the cut-off wavelength (section 8.3.) is less than the operating wavelength. The cut-off wavelength of an optical fibre can be calculated theoretically by the equation:

$$\lambda co = 2\pi na\ (2\Delta)^{\frac{1}{2}}\ /Vco \qquad 8.5$$

where

n = refractive index of core

a = core radius

Δ = normalised refractive-index difference

and Vco = normalised frequency V at the cutoff wavelength.

The value of Vco depends on the refractive-index profile of the core and is 2.404 for a step-index profile.

From this it is apparent that the control parameters for single-mode fibres are the normalised refractive index difference. , the core diameter, the fibre diameter, and the refractive-index profile. The secondary parameters are fibre loss, dispersion, and mode-field radius.

Although all fibres are designed to have a step-index core, process constraints (section 8.5.) cause the actual profiles to have significant deviations from a step profile, and so they can at best be called nominally step-index fibres.

Because secondary properties such as dispersion and mode-field radius are affected by fibre index profiles, it is important to find a convenient way to represent the arbitrary refractive-index profiles of fibres and express them in terms of step-index profile parameters. This is most elegantly done by converting the fibre parameters into equivalent-step-index (ESI) parameters (29). Thus the equation for cut-off wavelength can be changed to:-

$$\lambda co = 2\pi na(ESI)(2\Delta(ESI))^{\frac{1}{2}}/Vco \qquad 8.6$$

Accuracy of prediction of functional parameters from the ESI parameters depends on the computation technique used. Refinement of the computation technique for ESI parameters to improve modelling of functional parameters of fibres has continued. A recent work that includes the fourth moment of the refractive-index profiles in the computation of the equivalent step-index parameters (30) has improved the predictability of functional parameters a great deal.

8.7 Refractive Index Profile Shapes

As mentioned previously, process constraints cause actual profile shapes to deviate from the normal step-index. The index profile shape of fibres manufactured by the CVD process is markedly different from those manufactured by the OVD and VAD processes, which are themselves nominally similar. A major difference between the CVD and OVD/VAD processes is the ability of CVD to produce, under controlled conditions, either a matched or depressed cladding fibre.

Differences in profile shape include the central dip seen in CVD fibres (Figs. 8.6.,8.7) due to the depletion of dopant during preform collapse. Also with OVD and VAD fibres, the ill defined boundary seen

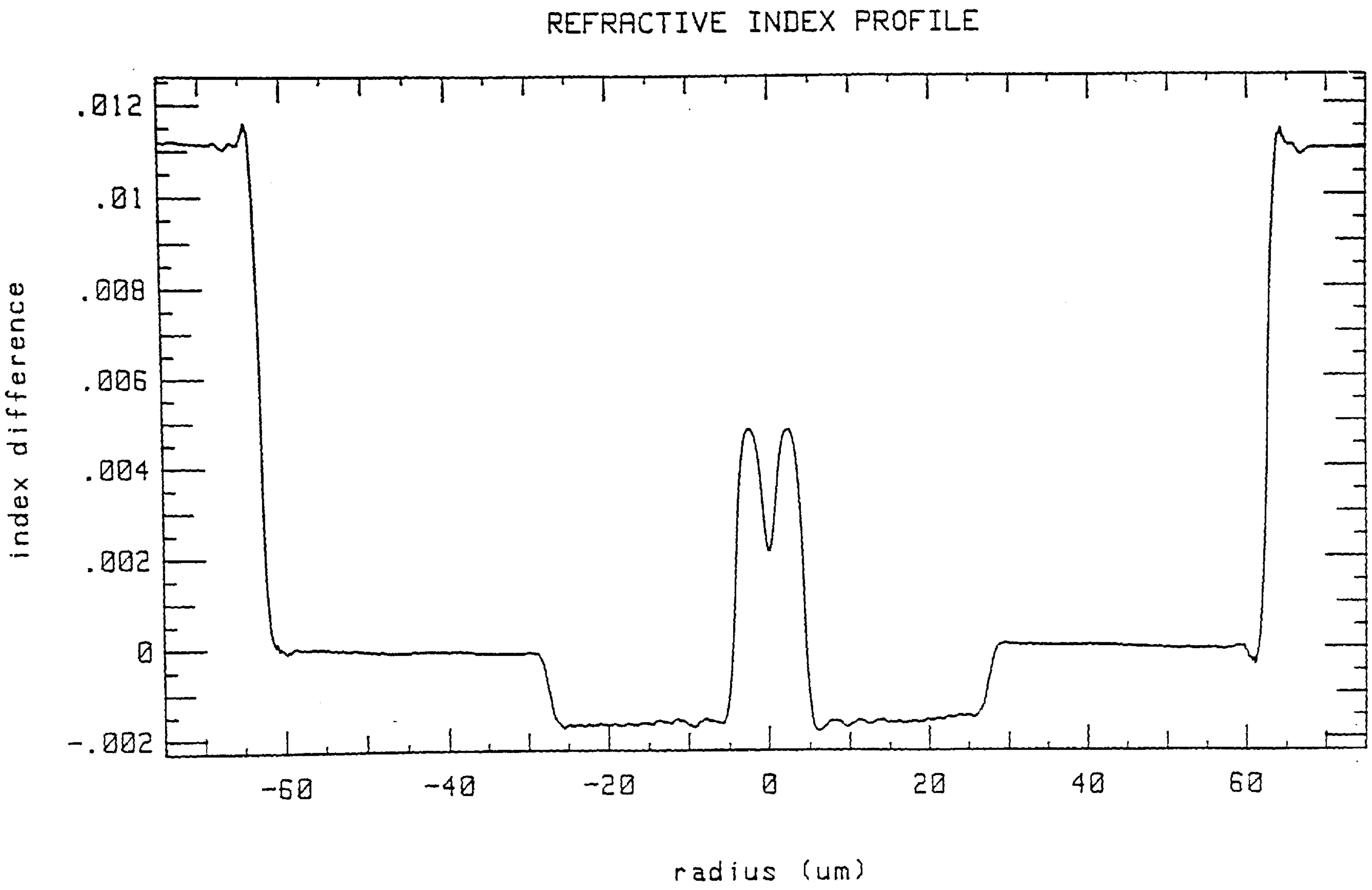


FIG. 8.6 CVD DEPRESSED CLADDING FIBRE

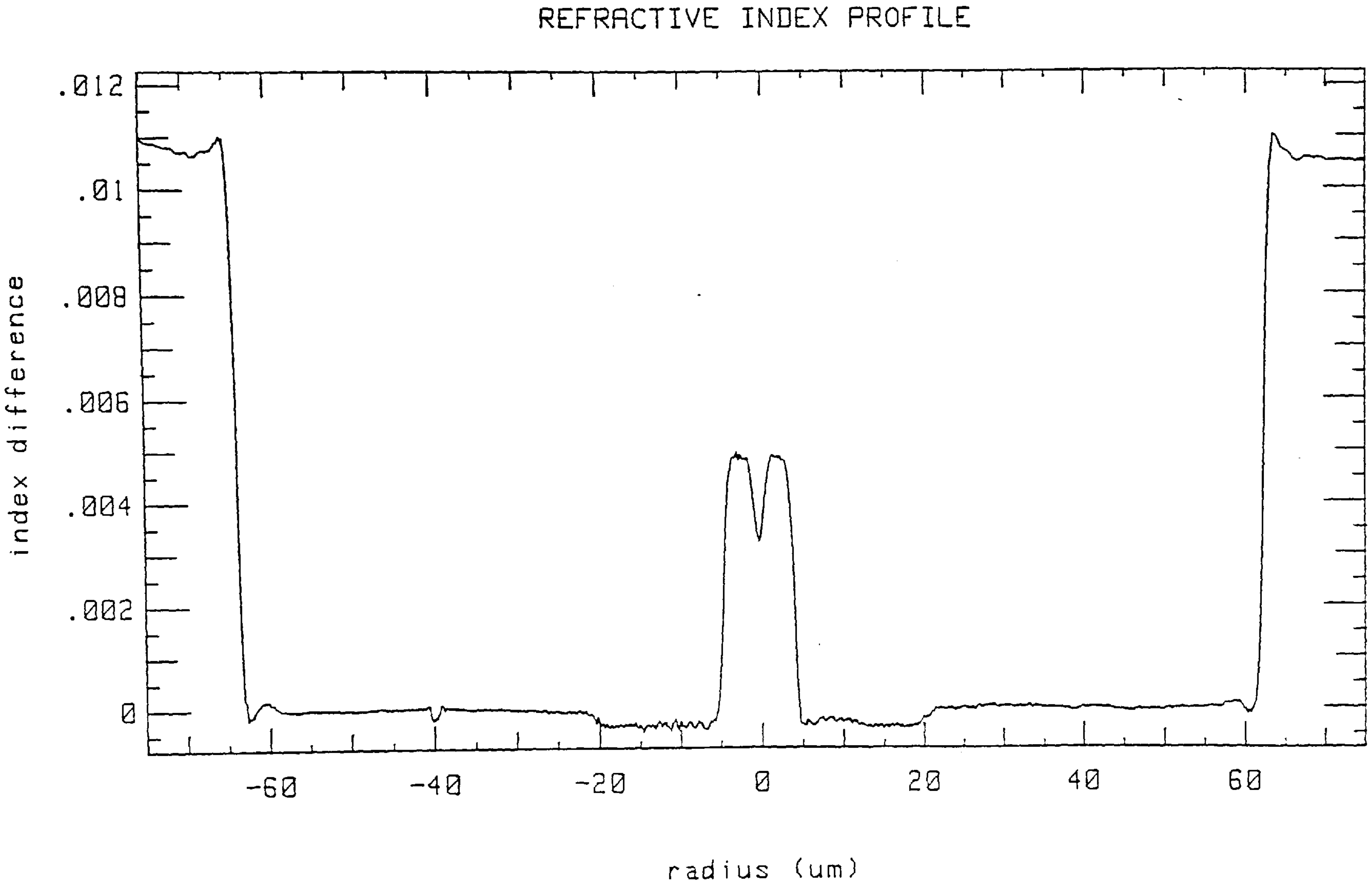


FIG. 8.7 CVD NOMINALLY MATCHED CLADDING FIBRE

at the core-clad interface,characterised by a slight grading of the index in that region, (Figs. 8.8.,8.9). This is due to the diffusion of dopant from the core under high temperatures, during the sintering process. This diffusion does not occur with the CVD process since the glass deposition occurs layer by layer, whereby each layer is fused before the next is applied. The OVD and VAD processes deposit all of the glass as a soot, where diffusion can occur before the glass is finally fused.

8.8 Practical Investigation

Fibre bend performance can be predicted theoretically using a range of techniques developed by scientists/engineers throughout the world. One such technique relies on the determination of the fibre mode field distribution. This can be done by analysing a fibre refractive index profile using a finite element method. (FEM). Once the field distribution is known, the amount of light radiated (when the field is shifted due to bending) can be calculated.

Predictions of this nature are often inaccurate due to anomolies/imperfections which cannot be accounted for. It was therefore decided to pursue a practical approach which would be a true representation of a fibre's bend characteristics. In an attempt to relate theory to practice, the equivalent-step-index of fibres were calculated, and the propagation velocity constant (V-number) correlated to bend loss. In addition, correlations between mode field radius, mode cut-off wavelength and bend loss were made.

Chapter 9 describes the tests performed, the results obtained, and consequent analysis of the data.

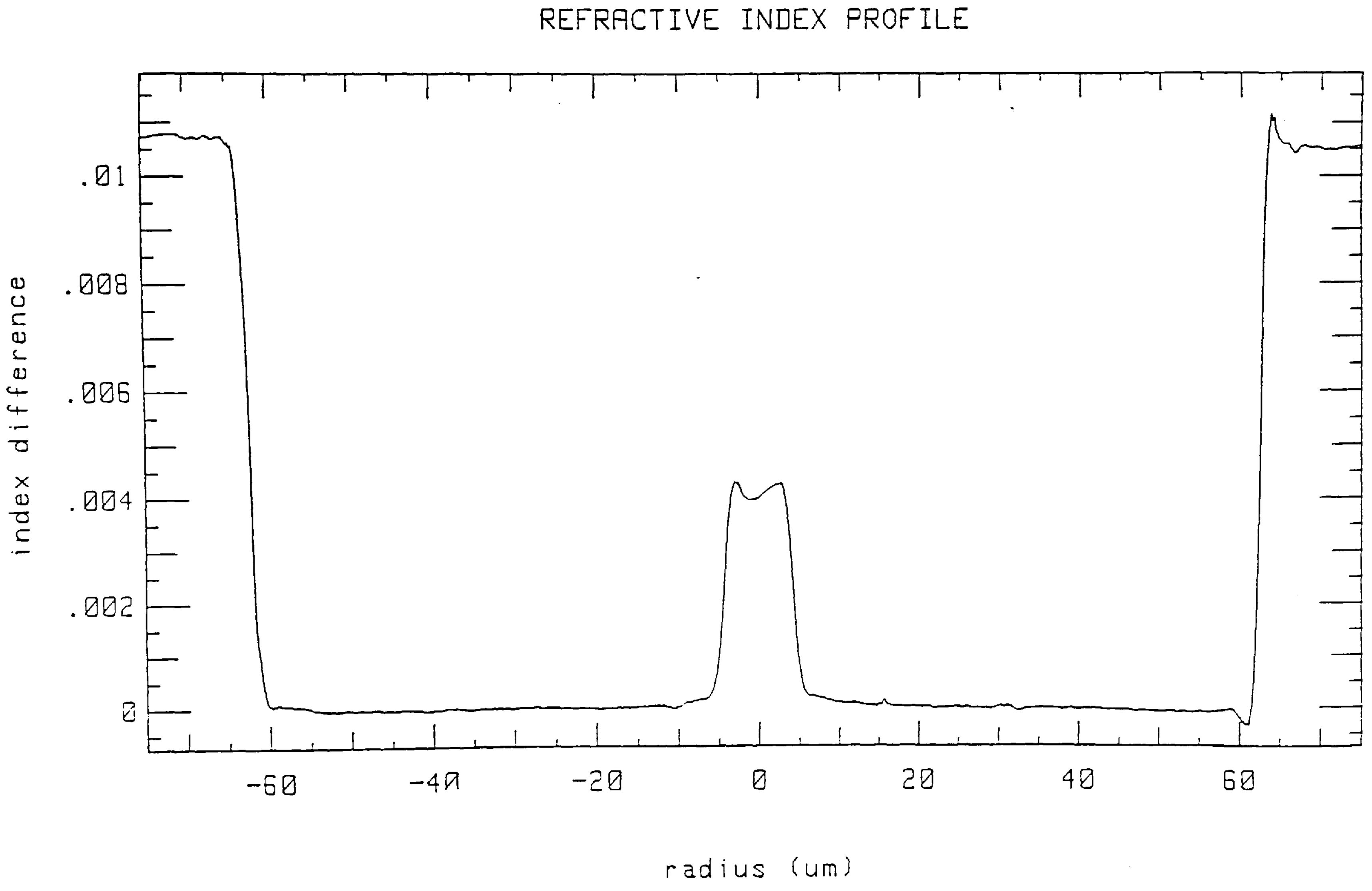


FIG. 8.8 OVD FIBRE

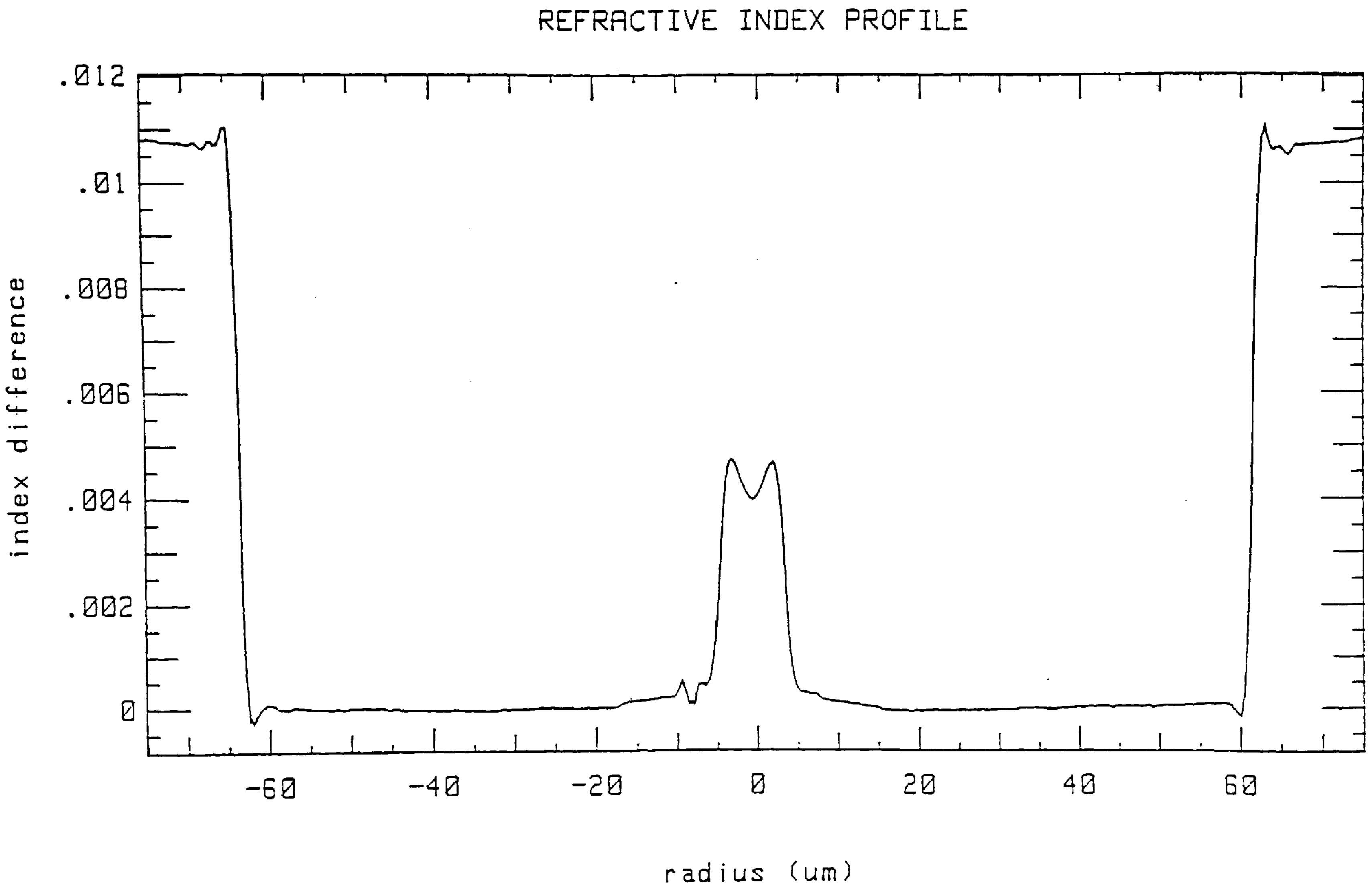


FIG. 8.9   VAD FIBRE

CHAPTER 9

EMPIRICAL ANALYSIS OF FIBRE BEND LOSS

9.1 Measurement Equipment/Techniques

Where possible measurement techniques compatible with CCITT Recommendations G652 (Red Book, Oct.84) were used. The equipmnent repeatability has been fully characterised and so a tolerance has been stated for each parameter. This is of particular significance in the case of the Refractive-Index profile, where "state of the art" measurement equipment does not have as high a resolution as would be ideal.

Table 9.1. shows the test techniques used to measure relevant parameters, together with their tolerances. The test techniques employed are now discussed in detail.

9.1.1. Fibre Refractive Index

One end of approximately one metre of fibre is cleaved such that the end is perfectly flat and has no flaws. The fibre is then inserted in a cell which is filled with liquid of slightly higher index than the cladding. A lens with a numerical aperture much greater than that of the fibre brings a beam of light to focus on the cleaved end of the fibre (31).

Some of the impinging light propagates along the fibre, whilst the remainder appears as a hollow cone of light outside. The inner region of this hollow cone contains leaky modes (whose contribution is difficult to assess), whereas the outer part contains purely refracted light.

The leaky modes are removed by placing a disc in such a manner as to stop them reaching the detector. The remaining light in the

Technique	Parameters	Tolerance
Fibre Refractive Index by the Refractive near Field Technique	Core Diameter	0.053 um
	Core delta N.	0.118 x 10
	Deposited Cladding Level	0.034 x 10
Mode Cut-off Wavelength	LP11 Cut-off Wavelength	7.25 nm
Mode Field Radius by Far Field Technique	Diameter of normalised Field @ 1/e	0.058 um
Attenuation	Increment due to Macrobending @ 1300 nm & 1550 nm	0.009 dB 0.997 dB

TABLE 9.1 FIBRE PARAMETER TEST TECHNIQUES AND RELEVANT TOLERANCES

cone is a measure of the refractive index at the point of focus. This point of focus can now be scanned across the whole face of the core and cladding; at each point the measured light level is an indication of the index of refraction and a complete picture can be built up of both the core and the cladding.

Calibration of the Refractive Index level is achieved by calibrating the liquid at a specified temperature and extrapolation using tables to other temperatures. The spot of light is focused on the liquid and, with the stop at a pre-determined position (i.e. subtending a pre-determined angle), a power measurement is made. The stop is moved so as to change the angle and the power measurement is taken again.

By knowing the movement of the disc and the change in refracted power, the index of refraction can be calculated. This is an absolute measurement of refractive index - whereas some devices use the silica substrate as a standard value and calibrate from that.

9.1.2. Mode Cut-off Wavelength

This is defined as the condition for single mode operation, whereby the usefulness of the high bandwidth of singlemode operation can be exploited.

With both mode-field-radius and mode cut-off wavelength, standard organisations are in somewhat of a quandary as to a definitive measurement technique. Each technique is rather subjective and the results must always be related to the measurement.

A theoretical mode cut-off can be obtained from a preform profile, although this is invariably higher than the effective cut-off of the resultant fibre.

9.1.2.1. Principles

The second mode in a fibre can no longer propagate as a guided wave when, with increasing wavelength, the phase index experienced by that mode falls to that of the cladding.

A detailed examination of Maxwell's equations, and their solution (with the boundary conditions defined within an optical fibre), defines the criteria for singlemode operation.

$$\text{Curl } E = \frac{dB}{dt} \qquad \text{Curl } H = \frac{dD}{dt}$$

$$\text{div } B = 0 \qquad \text{div } D = 0$$

(Maxwells Equations)

The results of the aforementioned analysis yields the following: For singlemode operation the normalised frequency (V) is 2.405.

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

and a = core diameter

λ = operating wavelength

n_1 = core refractive index

n_2 = cladding refractive index

Any deformation of the fibre will cause a shift in effective mode cut-off wavelength. Because of this, it is essential that the operating wavelength is a considerable distance from the effective cut-off wavelength.

Over a long length of fibre, operation near the effective cut-off is feasible - since the natural attenuation of the fibre will cause the second mode to decay.

It is in short links and pigtails (link between external cable and terminal equipment) that second mode propagation causes problems, since the second mode still present at the end of the link causes modal noise.

9.1.2.2. Difficulties

Because of the effects mentioned above, cut-off is dependant upon the condition of the fibre during the measurement:

(i) micro-bending will cause the cut-off to be shifted to a shorter wavelength, and

(ii) a very short length will allow the LP (11) mode to continue to propagate

Both of which will contribute to producing an unacceptably inaccurate result.

9.1.2.3.Equipment

The equipment used to measure the cut-off wavelength is shown in Fig. 9.1. (a), whilst Figs. 9.1. (b) and (c) respectively show the input power and fibre attentuation Vs wavelength.

9.1.3. Mode Field Radius

The spot size, or mode field radius, of a single mode fibre is an important parameter to measure, since it can be used to calculate the splice loss between two fibres. In addition it has been theoretically related to bend sensitivity.

One technique for measuring spot size if the transverse offset method. This method is recognised as a standard test and can be directly related to splice loss. However, it is a very tedious

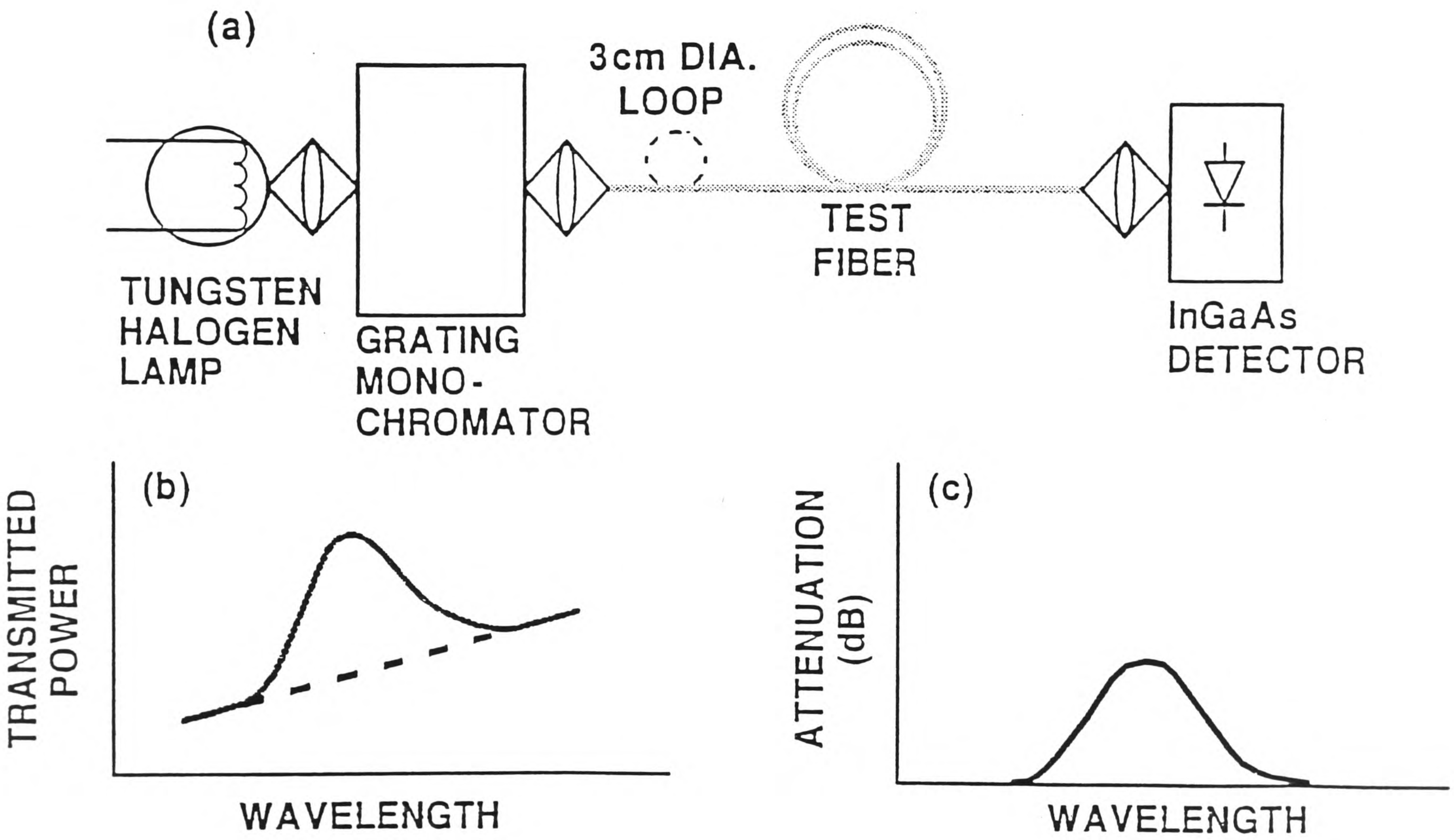


FIG. 9.1 CUT-OFF WAVELENGTH MEASUREMENT

measurement to perform and a great amount of care needs to be taken in preparation of the fibre ends.

The far field technique on the other hand requires a lot less fibre preparation and also does not require accurate measurement of position to fractions of a micron, as in the transverse offset method. The far field method does not directly measure splice loss, but for this particular applcation, it is not required.

In the far field measurement a detector is placed several centimetres away from the output of a fibre. The detector is then scanned in an arc about the fibre, the apparatus for such a measurement is shown in Figure 9.2.

Having obtained the far field, there are several methods that can be used to calculate the mode field diameter. Three such methods are:

i. the far field inversion integral technique (32)

ii. the far field gaussian beam technique (33)

iii.derivation of spot size from Peterman method (34)

9.1.4. Attenuation

A 6 metre length of fibre is set up on a standard spectral attenuation rig (Fig. 9.3) - care being taken to ensure that the minimum bend radius seen by the fibre is not less than 150 mm. Under these conditions a reference power level is taken at the wavelength of interest, or a scan across a wavelength window. Controlled bends are then introduced into the sample; a range of stainless steel polished mandrels are used for this, with radii ranging from 5 mm to 30 mm. Tension is kept to a minimum to ensure that microbending effects do not effect the results. It is estimated that the tension during

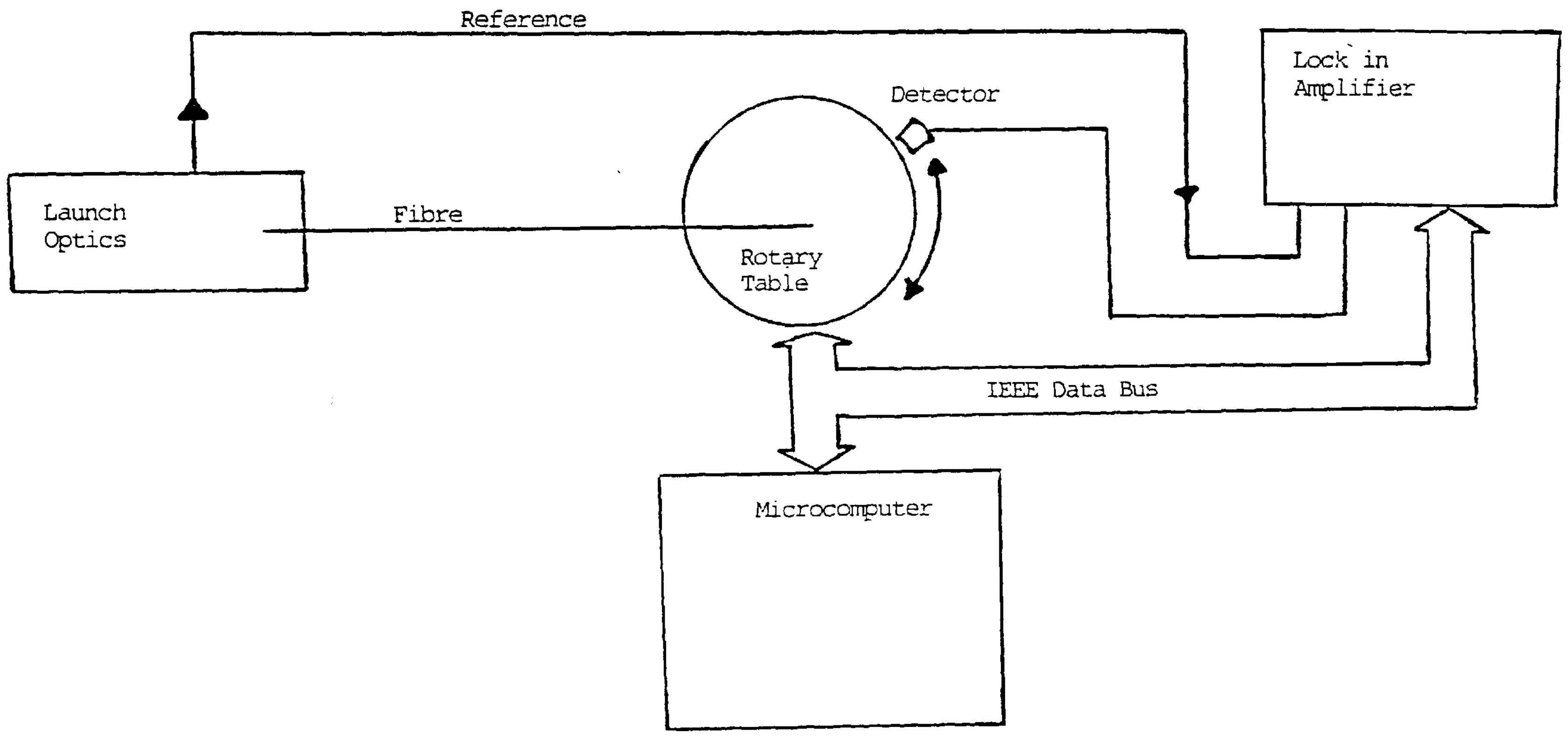


FIG. 9.2 TEST ARRANGEMENT FOR FAR FIELD MEASUREMENT

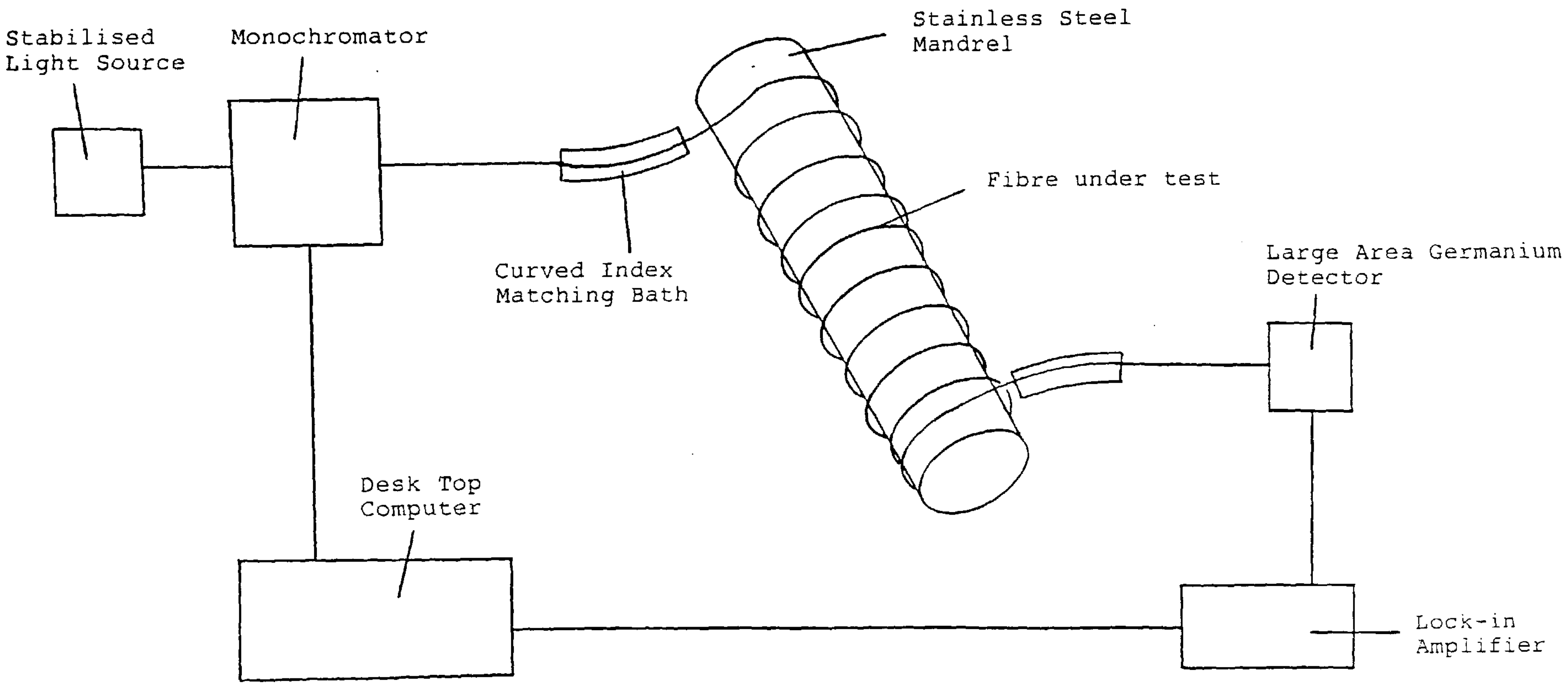


FIG. 9.3 TEST ARRANGEMENT FOR MACROBEND MEASUREMENTS

winding is below 30 grammes. Under these conditions a second power reading is taken (or spectral scan), the macrobending loss being defined as:

$$\text{Macrobending loss dB}(\lambda) = 10 \text{ Log } \frac{P1(\lambda)}{P2(\lambda)} \qquad 9.1$$

9.2. Macrobend Results

The macrobend characeristics of CVD, OVD and VAD fibres were investigated at the two operating wavelengths, 1300 @ 1550 nm. (Figs. 9.4, 9.5). Both graphs were plotted on a log-linear scale so that the loss region below 1 dB was expanded to show the break points between two obvious regions, hence showing that the loss mechanisms are bi-functional. The relationship between loss and bend diameter for each of the fibre types tested, was found to be linear in each respective region, but the gradients of the lines in all cases was greater in the low bend diameter region.

For CVD fibres (both matched and depressed cladding), the second region, i.e. higher diameters, show 1300 nm losses approaching that of experimental error. This suggests that the accuracy of the gradients are in doubt. However, the existence of this second region is confirmed by the 1550 nm graph which shows significantly greater losses.

From both graphs it is clear that CVD (depressed cladding) fibre is most bend insensitive, followed by CVD (matched cladding), OVD and VAD respectively.

It should be noted that 20 samples of each fibre were tested, with each type being nominally 8/125 μm fibre, step index germanium doped cores, coated up to 250 μm with a UV cureable urethane acrylate (double and single layer).

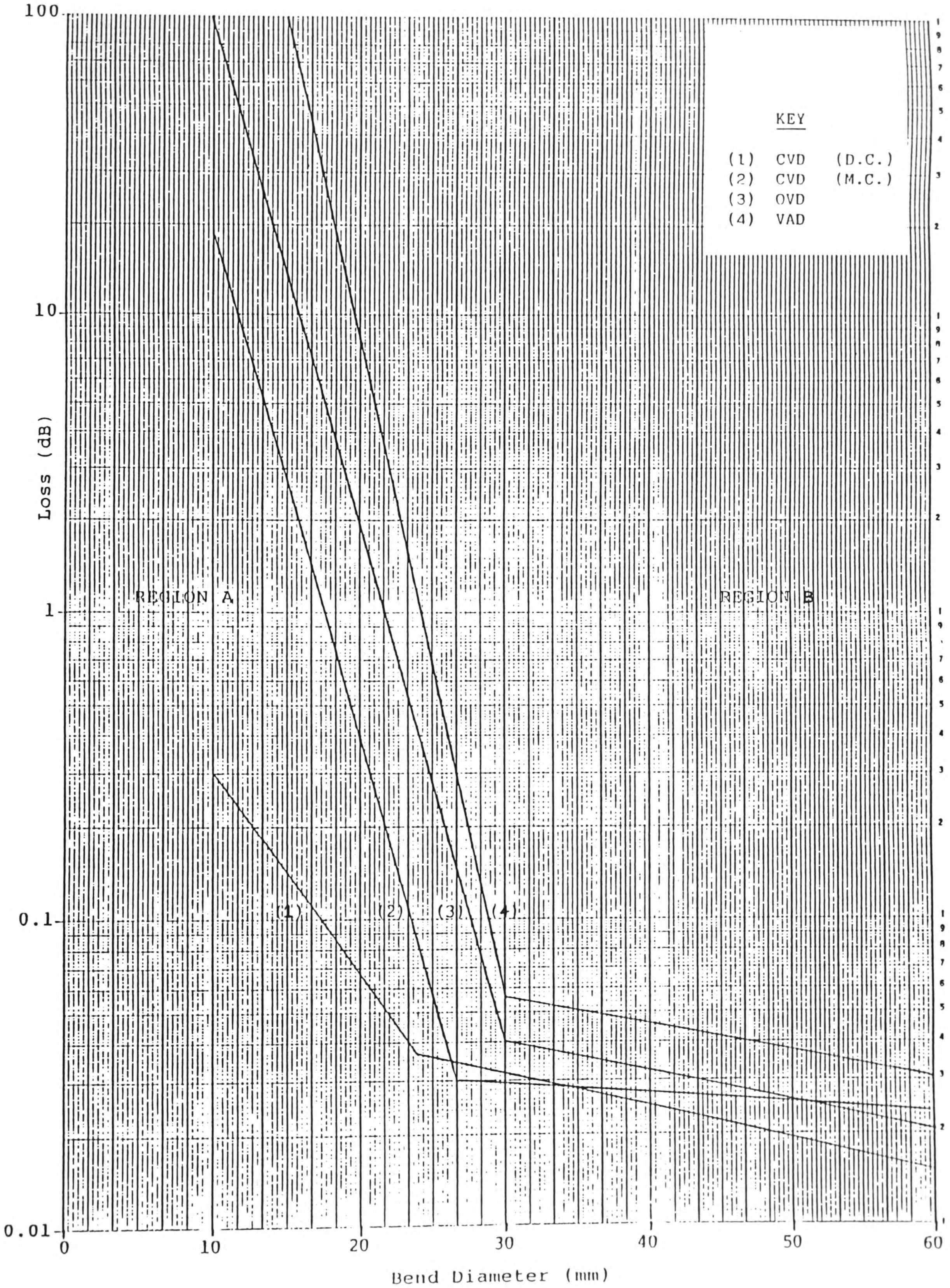


FIG. 9.4 MACROBEND CHARACTERISTICS OF FIBRES AT 1300 nm (10 TURNS)

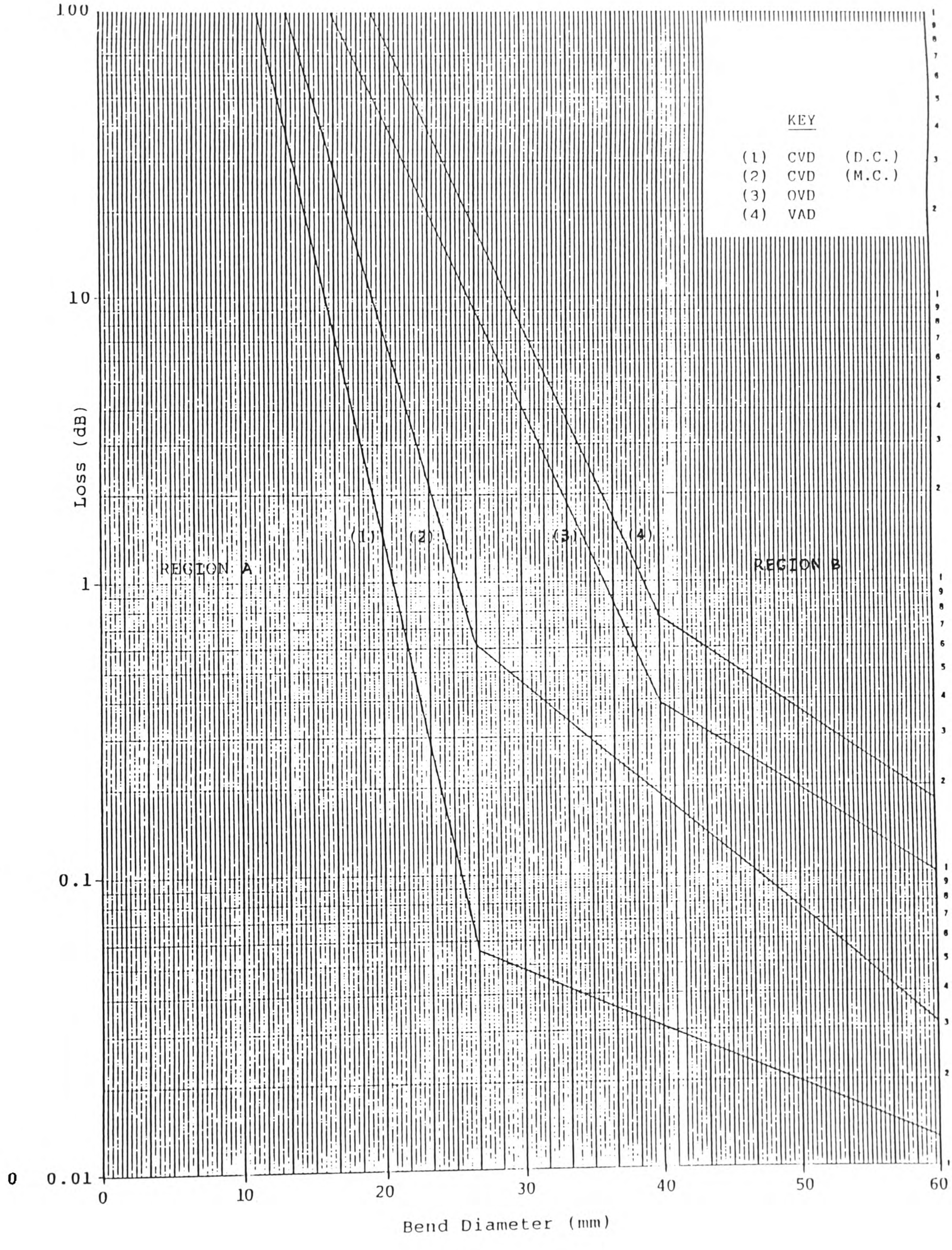


FIG. 9.5 MACROBEND CHARACTERISTICS OF FIBRES AT 1550 nm (10 TURNS)

In addition to the macrobend tests, each fibre was refractive index profiled and measured for spot size and cut-off. Since mode field radius and cut-off wavelength tend to be indicators of bend performance, an attempt has been made to use fibres with similar values although CVD depressed fibre had significantly higher cut off values. The distributions are shown in table 9.2.

9.3. Macrobend Analysis

The analysis attempts to provide simplified solutions to the fundamental fibre propagation characteristics by firstly, characterising the profile using an equivalent step index (ESI) algorithm, and then using the ESI parameters (core diameter 'a' and delta N) to define a value for the propagation velocity constant (V).

The ESI profile is defined as (35):

$$Mn = \int_0^{\infty} (n^2(r) - n^2(a))\, r^n \, dr \qquad 9.2$$

and the propagation velocity constant V:

$$V = \frac{2\pi a}{\lambda} (ESI) \quad (n_1^2 \, (ESI) \; - \; n_2^2 \;)^{\frac{1}{2}} \qquad 9.3$$

The propagation velocity constant is a single parameter which is dependant upon the two basic fibre design criteria, core radius and core/cladding refractive index difference. V can now be used to characterise parameters such as Wo, λco and λo, since their dependancy upon two variables has been simplified (36).

The theoretical model for cut off wavelength (λco) and mode field radius (Wo) was firstly tested upon the range of fibre samples of each manufactured type.

Fibre Type	Mode Field Radius		Mode Cut-off Wavelength	
	mean	Std.Dev	mean	Std.Dev
CVD(DC)	4.48	0.06	1253	23
CVD (MC)	4.86	0.13	1171	26
OVD	5.14	0.08	1173	29
VAD	5.05	0.05	1204	19

TABLE 9.2 PARAMETER DISTRIBUTION FOR FIBRE SAMPLES

9.3.1. Cut-off Wavelength

Cut-off wavelength is traditionally a difficult parameter to measure, being extremely dependant upon sample length and fibre conditioning. Consequently, comparison of a measurement of a 3 metre fibre sample with a calculation from a cross section (effectively an infinitesimally short length) is fraught with difficulty.

Fig. 9.6. shows the measured cut-off wavelength of the four fibre designs against ($V * \lambda$), so making the constant independent of wavelength. Regression analysis showed that good agreement existed between the data points and straight lines for each design. The theoretical line confirms the trend,and so with the exception of the offset, this method of predicting λco is reliable.

The prediction based on the profile does not take into account the fact that λco is dependent upon fibre conditioning and length (37). Appendix H shows that λco drops by up to 20 nm/decade, purely as a result of the length dependence. This would suggest that the theoretical model based upon the equivalent step index (ESI) and V, defines the cut-off seen on long lengths of fibre (>10Km). This is as a result of cable induced bends and/or bends seen at splice housings.

9.3.2. Mode Field Radius

The comparison of mode field radius to theory at 1300 nm wavelength provided very little correlation. In fact the trend of increasing V corresponding to a decreasing Wo (for V<2.405) was shown to be reversed in certain cases.

Comparison of ESI based predictions with predictions based upon a finite element method (FEM) show significant descrepancies (38). Consequently it is hardly surprising that comparisons of ESI based

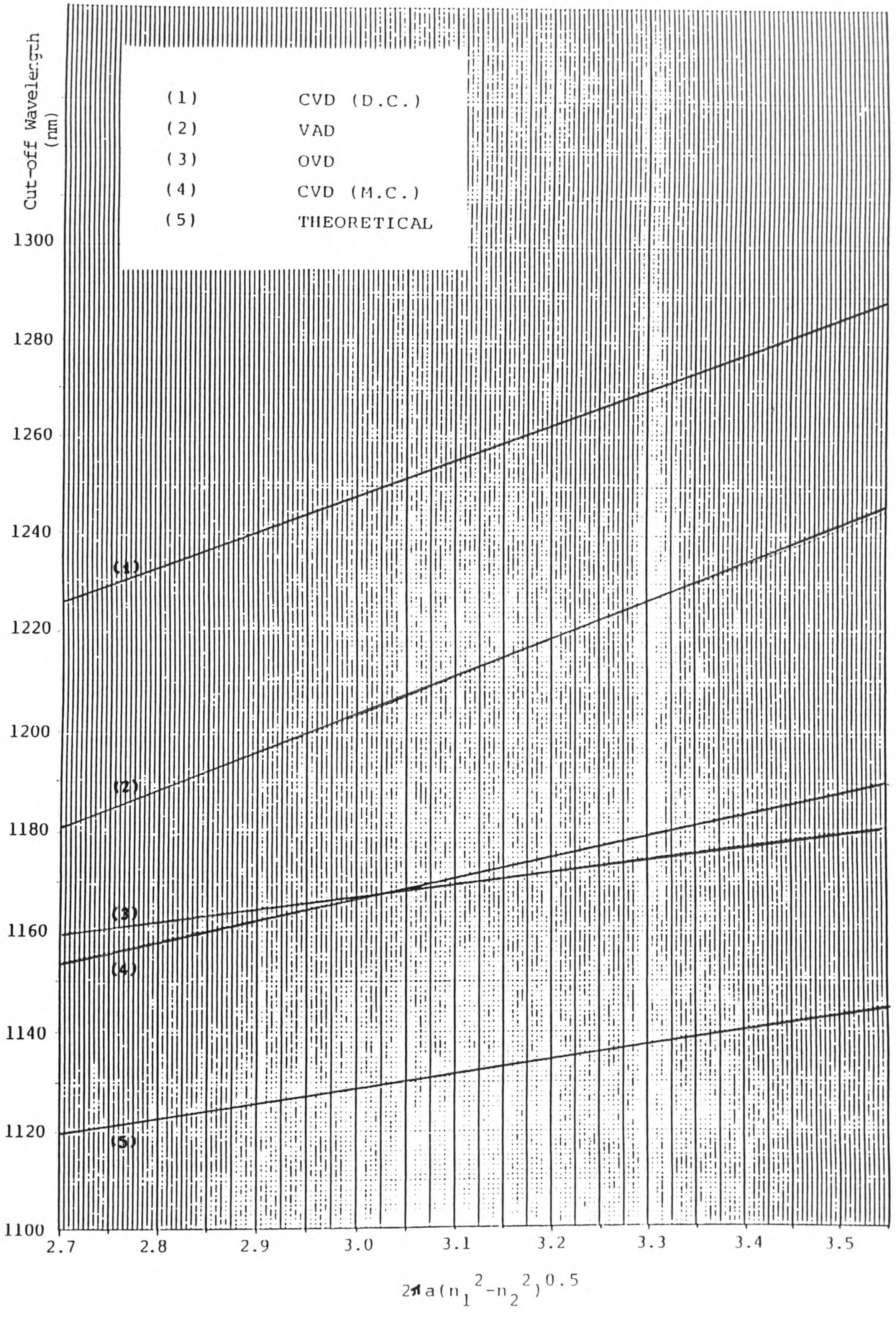


FIG. 9.6 CUT-OFF WAVELENGTH VS. $2\pi a(n_1{}^2-n_2{}^2)^{\frac{1}{2}}$

predictions with actual measurements are very unreliable. This result shows that the profile structure cannot be ignored, as the ESI does, in the prediction of Wo.

9.3.3. Macrobending Performance

As can be seen from Figs.9.4,9.5 in all cases there are two distinct regions of loss. For the CVD fibre design the diameter at which the two regions converge is almost independent of wavelength, the OVD and VAD on the other hand is dependent upon wavelength.

The two regions are due to two distinct effects,

- region A due to bend loss
- region B due to transition loss

Figures 9.7 and 9.8 demonstrate the difference in performance in these two regions by showing the relationship between loss and V-number. Generally however, although the absolute values are different, the trend of decreasing 'V' producing poorer bend performance is common to all the fibres tested, in both regions. The variation in absolute values is highlighted by a comparison between figures 9.7 and 9.8 - 9.7. being bend loss against 'V' and 9.8 being transition loss against 'V'.

The performance in the transition loss region is very similar from fibre to fibre i.e. similar gradients and offsets. Since measurements in this region are of small losses it would be fair to assume that measurement errors play a significant role in these differences. The true bend loss region however, shows some more significant differences in that bend varies with 'V' to different degrees for each fibre. This is more significant since its effect is greater, and so contributes most to the loss attributable to cabling.

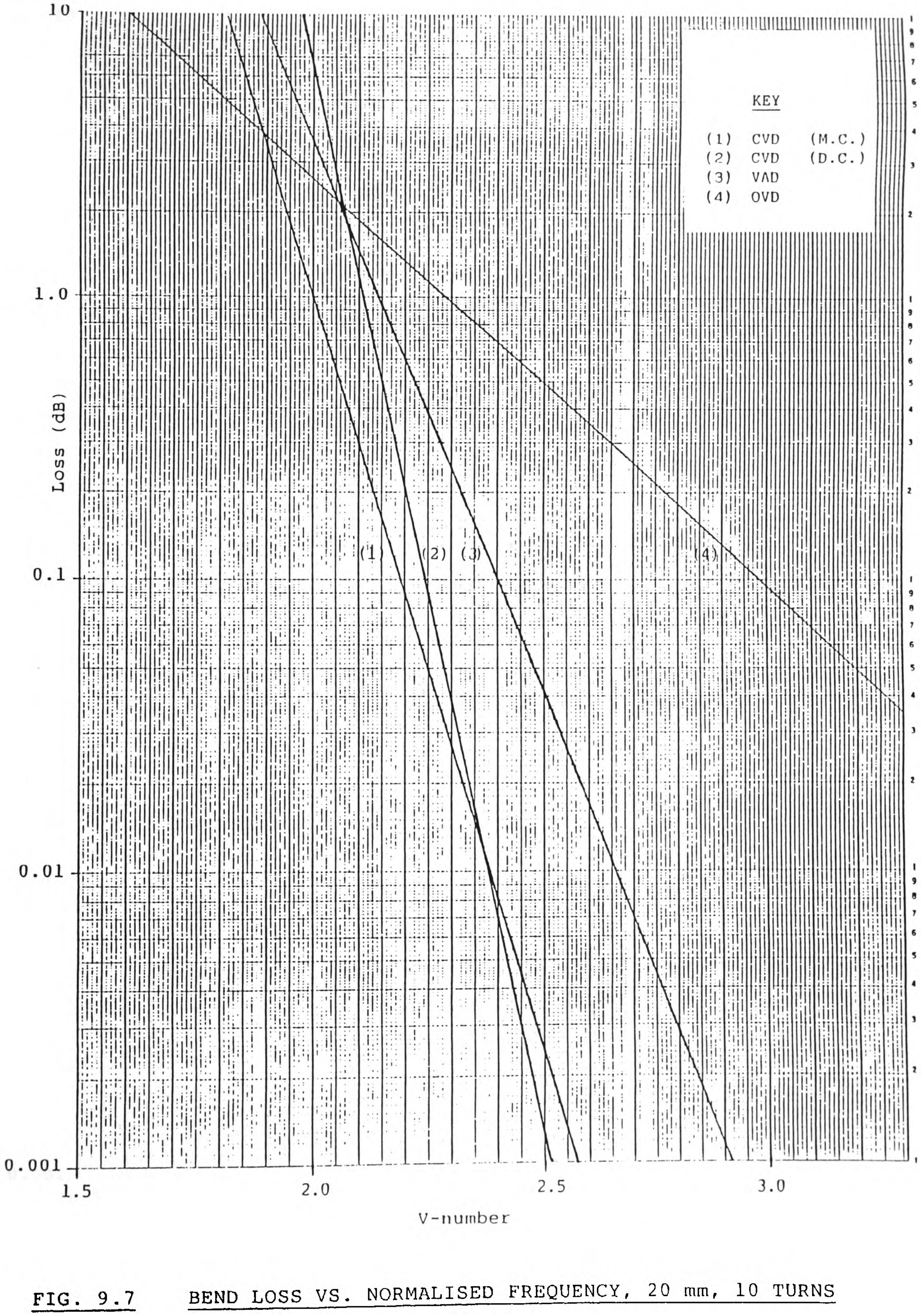


FIG. 9.7 BEND LOSS VS. NORMALISED FREQUENCY, 20 mm, 10 TURNS

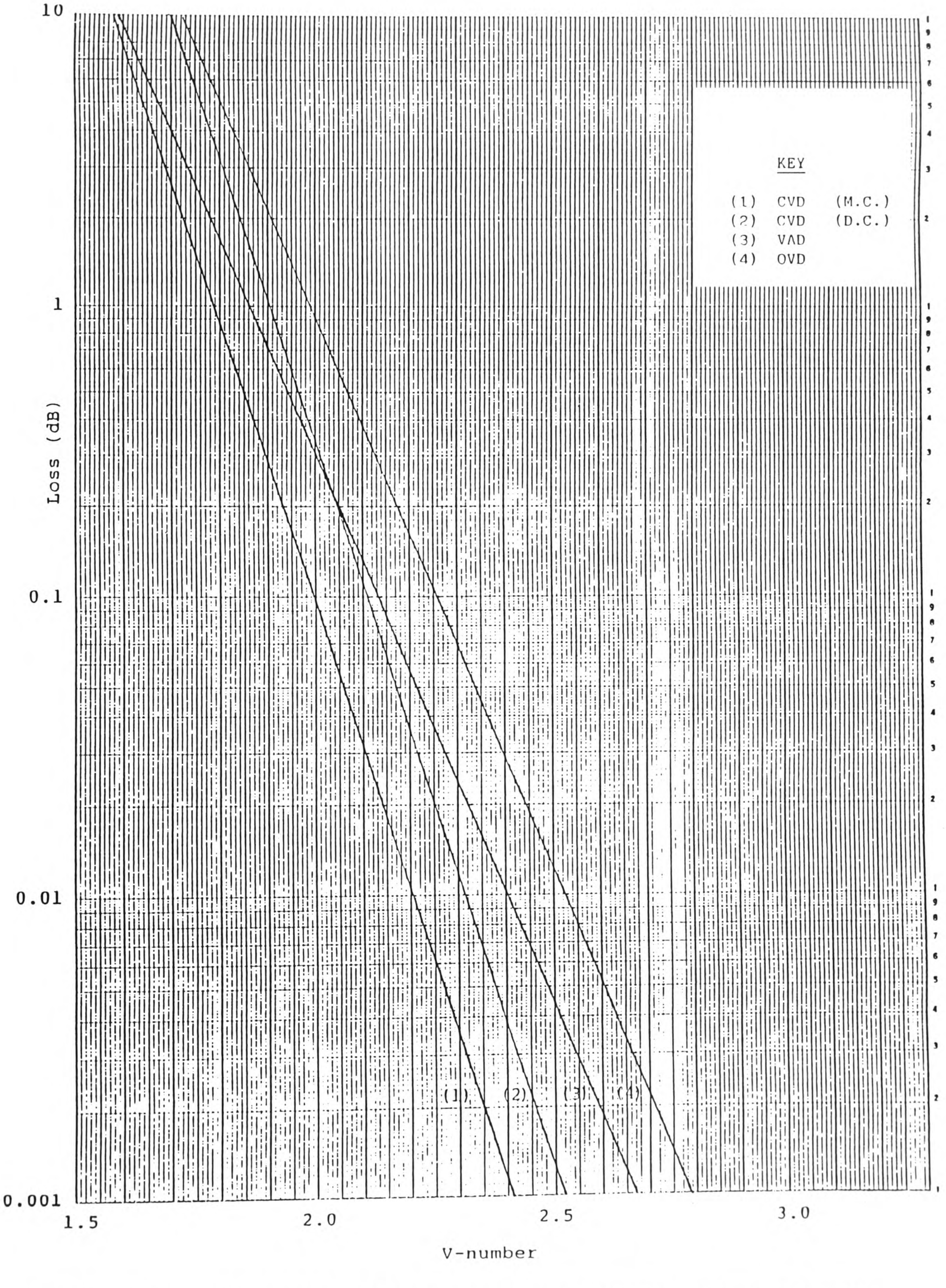


FIG. 9.8 BEND LOSS VS. NORMALISED FREQUENCY, 40 mm, 10 TURNS

The bend loss is characterised by the different propagation characteristics for a bent as compared to a straight fibre. In a straight fibre the primary mode (LP01) propagation can be defined as a TEM wave with the plane of constant phase being orthogonal to the direction of propagation - or Z axis.

If the fibre is bent in an arc of radius C (Fig 9.9.), the phase velocity of the wave front will be required to vary depending upon its distance from the centre of the arc. The group velocity will be that of the speed of light relative to the medium. For this to be consistent throughout the core and cladding of the fibre, light travelling at a radius greater than that at a particular distance from the core, will have to travel faster than the relative light speed within core/inner cladding region. Since the cladding level is uniform, this is impossible. Light in this region is therefore converted into radiation modes. Attenuation due to this uniform bending is defined as the pure bending loss and is proportional to the length of the fibre bent.

The second mode of loss is experienced as a result of the effects at the interface between the straight and bent fibre. In the straight fibre the field is uniform and positioned in the centre of the fibre, whilst just beyond the interface, the field is distorted as shown in Fig 9.10. To achieve this, the field in the straight section must excite the field that actually propagates in the curved section, and also the radiation modes that exist on the outer edge of the bent fibre. The mismatch in power between the field propagating in the straight and bent section is defined as the transition loss, and is independent of length.

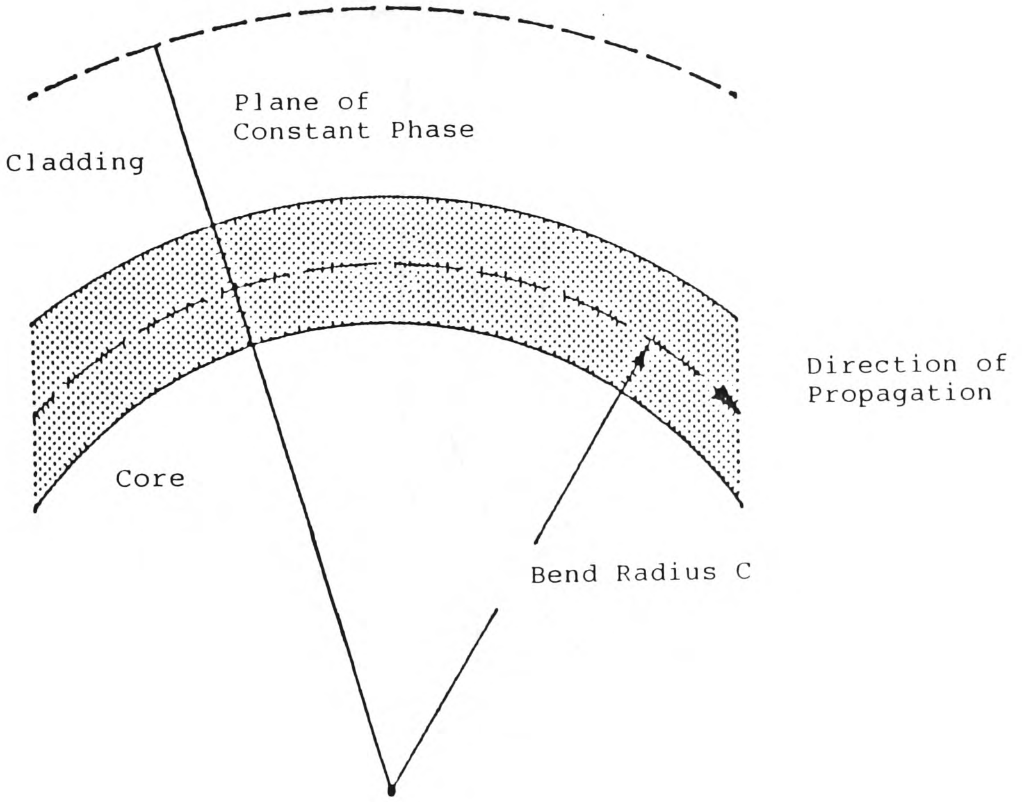


FIG. 9.9 WAVE PROPAGATION IN A UNIFORMLY BENT FIBRE

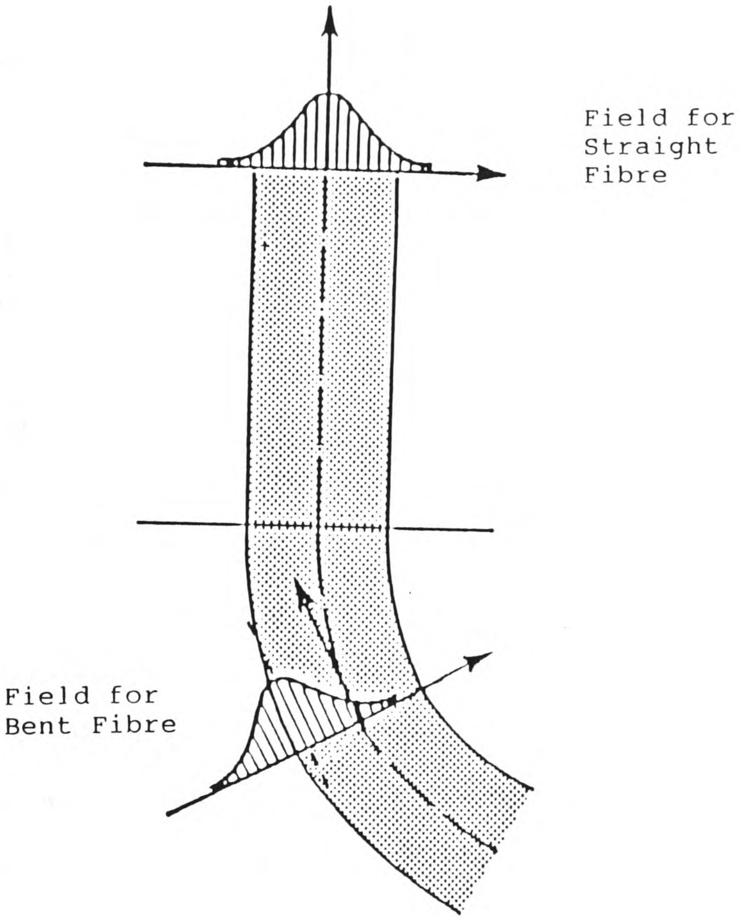


FIG. 9.10 BEND LOSS AS A RESULT OF TRANSITION FROM STRAIGHT TO BENT FIBRE

9.4. Discussion of Results

The relationship between the ESI profile and cut-off wavelength has been shown to be consistent, although theoretical analysis based on the ESI produces a cut-off considerably lower than the actual. This phenomena has been explained by consideration of length and bend dependacy of effective cut-off wavelength (39).

The relationship between mode field radius and ESI based predictions has been found to be unreliable, which concurs with previous work (40). Future work will incorporate a technique of finite element analysis (FEM) to take account of profile structure and processing characteristics associated with each design.

The attenuation dependence upon bend has been shown to be consistent with theoretical analysis, highlighting the bi-functional dependence upon diameter exhibited by each design under a particular bending regime. Where possible, fibres with similar performance characteristics were used, although the depressed cladding fibre samples had significantly higher cut-off wavelengths, and the OVD fibre samples had slightly higher mode field radii. By relating the bend performance to the propogation velocity constant (V), these effects are normalised.

Performance in the transition loss region is similar for all fibre designs, any differences being potentially due to measurement error. This effect, however, is considered to be of particular importance to the cabling industry and so it is proposed to investigate the phenomena further. The importance of the bend loss region is the bend diameter at which it takes effect, since as soon as this loss mechanism occurs, severe bend induced losses ensue. This is highlighted in the long wavelength region where changes in wavelength have a significant effect upon loss.

A third mode of loss has been hypothesised, occuring at relatively large bend diameters. This effect was observed on a relatively small number of fibres. It's existence however, would have significant effect on cabling and so it is proposed to investigate this further.

Since V is related to wavelength, the effect of increasing wavelength can be predicted using Figs.9.7 and 9.8. Using these figures it can be seen that the CVD based designs require lower V values to produce similar bend performances. By comparing this with the cut-off and mode field radii relationship, it would appear that for similar values CVD designs provide a significantly better bend performance.

CHAPTER 10

SUMMARY AND CONCLUSIONS

The expertise required in the design of optical cables is a mixture of geometrical mathematics, knowledge of materials, and practical experience. To incorporate these three areas in a computer program using conventional software would be very laborious, in terms of embodying the various design rules used in cable design. Therefore clearly, another solution was needed, one which would allow the basic construction of such a program and then allow quick and efficient entry of additional information.

An expert system approach seemed to offer most promise in that engineers experience and heuristic design principles could be embodied within a computer program in a straight forward manner. Rather than write an inference engine from scratch, a proprietary expert system builder,or "shell" was employed, namely Crystal by Intelligent Environments, a package written in the 'C' language. It proved very flexible since each rule can be reduced to a hierarchy of sub rules, an essential requirement in the design of optical fibre cables.

The main type of optical cable manufactured by STC Cable Products Division is of the Loose Tube variety, with over 90% of the total output being of this kind. For this reason it was decided to concentrate on developing an expert system to aid the design of cables of this type.

The expert system implemented to perform the equivalent manual design procedure requires a total of 680 rules. The complete implementation from identifying requirements, learning Crystal and training system users took approximately 10 months. Much of the time was spent collating cable design aspects from records and design staff. As expected, several conflicting viewpoints on certain 'grey areas' were apparent. Thus a number of 'best approach' decisions were taken before incorporating these results within the knowledge base.

The expert system was written so that interaction with the user led to the progressive solution of rules. The questions asked are designed to allow a non-technical user run the package. Obviously some expertise in cable requirements and materials is necessary, but all the mathematical calculations are performed by the system. The output of results is a three page description of the cable requirements in terms of weights and dimensions, preceeded by a title and summary sheet.

A cross-sectional view of the finished cable design must accompany all specifications issued by the fibre optic cable section, traditionally drawn by hand with stencils and compasses. Crystal itself is not capable of producing a graphical plot of the cable. A data transfer utility was thus used to input cable dimensions to a program written in Turbo Pascal which generates, on a plotter, a fully labelled cross-sectional diagram of the cable designed.

Running Crystal takes approximately five minutes. This compares with anything up to three hours for a manual design. In addition a fully labelled diagram on the plotter may take another five minutes, whilst to physically draw and label a diagram can take two hours - therefore resulting in a total time difference of ten minutes against five hours (i.e. 4 hours 40 mins).

With a total of three design engineers in the department, each performing approximately one design per day, there is a total time saving of 14 hours/day where those engineers can be working on new designs and developments. If an engineer's time is measured at £20/hour (salary & overheads) the cost saving per day is £290, i.e. £72,500 per year.

Once a cable has been designed by the system, its description and drawing are filed chronologically under a unique reference number. In the future, the same cable may be required for another contract, or as an extension of the same contract. Even though a duplicate design could be generated very quickly by the expert system, it would be useful to access the previous tender documents to check on any queries, contract details etc.

The solution to this was by means of a database package namely Cardbox Plus. It was configured so that various cable parameters can be input to identify the cable in question. Once adequate identification has occurred, the required cable details will be displayed. Included in the details will be the original reference number, which with its chronological ordering system, will allow quick access to the required documents.

The work done to define the maximum working tension of a loose tube cable was a study of the excess fibre in a tube, and its changes during the various stages of cable manufacture. The excess fibre is initially set in the tube making process, but during the subsequent stranding process and cable installation the fibre excess characeristics change.

The major factors which cause these changes are the tensions of both the tubes and central member during stranding. It has been found however that an accurate control over these changes is the stranding laylength. This can be altered as required to keep the fibre excess level in a safe operating window.

A computer program was written in Pascal to calculate the maximum working tension of a cable. It uses information gathered from each stage of manufacture regarding the cable design, process conditions, line speeds etc., together with theoretical data about the stress-strain characteristics of fibre and tube material. The output is a figure in newtons which represents the maximum tension a cable can withstand before the fibres see a strain of greater than 0.25%.

The bend performance of optical fibres is an important factor when considering that excess fibre in a tube induces bends. These bends decrease in radii as the excess increases, and according to theory will cause a greater loss. The degree of this loss cannot accurately be predicted by theory, due to the various design quirks and imperfections associated with each fibre. Therefore an emipirical study of fibre bend performance was necessary to gain an overall picture of the fibre characteristics in a Loose Tube Cable.

The attenuation dependence upon bend diameter of four fibre types i.e. CVD (M.C.), CVD (D.C.),OVD and VAD were found to be bi-funtional. The two modes of loss are explained by a transition region where the loss is experienced as a result of the effects at the interface between the straight and bent fibre, and a pure bend region, where the loss is due to the failure of the wavefront phase-velocity at a distance X from the fibre central axis to travel beyond the speed of light in the respective medium, and keep up with the overall group velocity of the light in the fibre.

From detailed analysis of the effects of mode-field-radius, mode cut-off wavelength and normalised propagation velocity constant (V-number) on fibre bend performance, and the inter-relationships between these performance criteria, it would appear that for similar fibre parameter values, CVD designs provide a significantly better bend performance.

The four work areas described, namely an expert system for Loose Tube optical fibre cable design, a database to store existing designs, prediction of the maximum working tension of Loose Tube cables, and the bend characteristics of optical fibres, have all been investigated thoroughly and have all been implemented as software for the IBM PC with the exception of bend loss. The optical fibre bend characteristics have thus far been developed as a series of graphs, but it is envisaged that in the future they may be translated to a computer. This would allow quick prediction of fibre bend performance in a cable.

The four working tools can be used progressively to fully design a Loose Tube cable from scratch, or can be used individually to aid particular development programmes.

Further work necessary to enhance the impirical model of fibre bend characteristics, is an analysis of factors affecting microbending sensitivity. Microbends are the small pertubations seen on the surface of an optical fibre, as opposed to the large diameter bends (macrobends).

The objectives of the further work would be to:

- evaluate "state of the art" microbending procedures,
- define effect seen in cablng due to microbending,
- specify a test procedure to characerise the loss,
- promote procedure for inclusion in IEC and CCITT specification
- propose changes to fibre/tube manufacture to improve cable yields and performance.

Since microbending is based upon probabilities and not on a uniquely definable physical characteristic, as is macrobending, it is expected that method dependant parameters must be included in the result. As a consequence of an anlysis of current test procedures and processing effects, a method should be developed that mimics the processing effects. Once proposed, the effectiveness of the test method must be proven across all fibre types - including the dependence upon fibre parameters.

As a direct result of the work undertaken to date, two technical papers have been accepted in the following conferences: "Development of an Expert System for Optical Fibre Cable Design", accepted at Expert Systems and their Applications' 88, Avignon, France. "Bend Characteristics of Fibres Manufactured by CVD, OVD and VAD Techniques", accepted at EFOC/LAN '88, Amsterdam, The Netherlands.

They are both listed in Appendix I.

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APPENDIX A

Example of Loose Tube Cable Design

Example of a Loose Tube Cable Design

A.1.Requirement

Sheathed steel dyform (sheath-Low density polyethylene) 9 outer elements (5 x tubes, 2 x copper pairs, 2 x fillers)

Tubes of 3 mm outer diameter and 2 mm internal diameter. Copper pair is 2x 0.9mm copper wires with 0.2 mm insultation twisted together.

Tubes should be filled with a gel, whilst the element interstices should also be filled with a similar water blocking compound.

The elements should be wrapped with 1 layer of paper tape.

An aluminium plastic laminate moisture barrier is required over the paper tape.

An outer sheath of nominal radial thickness 1.6 mm should be applied over the APL (Material - LDPE).

The cable should have a tensile strength of at least 3 x W where W is the weight of the cable in newtons.

The cable will comprise 20 singlemode fibres, with 4 fibres placed in each tube.

A.2. Design

Using 9 x 3 mm elements, from equation 4.2.4. the radius of central member required is:

$$R = 2.885 \text{ mm.}$$

Therefore

$$\text{Diameter} = 5.8 \text{ mm}$$

Let us initially assume that a steel dyform of 5 mm is required.

Therefore the dyform sheath will have a radial thickness of

$(5.8-5)/2 = 0.4$ mm.

Steel Dyform

Since a steel dyform is made up from several steel strands, the weight cannot be calculated by the usual Volume x Density equation.

A formula developed to calculate the weight per kilometre of a steel dyform is:-

$$\text{Weight} = 5.4 \times (\text{diameter})^2$$

where diameter is the diameter of the dyform in mm.

Therefore,

$$\text{weight} = 5.4. \times 5^2 = 135 \text{ Kgs/Km.}$$

Dyform Sheath

$$\text{Area of LDPE sheath} = \text{Pi} \times (2.9)^2 - \text{Pi} \times (2.5)^2$$

$$= 6.79 \text{ mm}^2 = 65.79 \times 10^{-3}\text{m}^3$$

Therefore

$$\text{Volume/Km} = 6.79 \times 10^{-3}\text{m}^3$$

$$\text{Density of LDPE} = 925 \text{ Kgs/ m}^3$$

Therefore

$$\text{Weight of sheath} = 6.79 \times 10^{-3} \times 925$$

$$= 6.28 \text{ Kgs/Km}$$

2 Fillers

Fillers are made from solid LDPE rods.

$$\text{Area of 3 mm filler} = \text{Pi} \times (1.5 \times 10^{-3})^2$$

$$= 7.069 \times 10^{-6} \text{mm}^2$$

$$\text{Therefore volume/Km} = 7.069 \times 10^{-3} \text{m}^3$$

$$\text{Weight of 2 fillers} = 2 \times 7.069 \times 10^{-3} \times 925$$

= 13.1 Kgs/Km

Twisted Copper Pairs

Area of 1 copper wire = Pi x $(0.45)^2$

= 0.636 mm^2

= 0.636 x 10^{-6} m^2

Density of copper = 8930 Kgs/m^3

Volume/Km of 1 copper wire = 0.636 x $10^{-3} m^3$

Weight of 4 wires (2 pairs) = 4 x 0.636 x 10^{-3}x 8390

= 22.7 Kgs/Km.

Radial thickness of copper insulation = 0.2 mm

Therefore area of insulation per wire:

$$= Pi \times (0.65 \times 10^{-3})^2 - Pi \times (0.45 \times 10^{-3})^2$$

$$= 6.91 \times 10^{-7} m^2$$

Volume/Km = 6.91 x $10^{-4} m^3$

Density of polyethylene insulation = 940 Kgs/Km.

Weight of insulation for 4 copper wires:

= 4.691 x 10^{-4}x 940

= 2.60 Kgs/Km

Therefore total weight of 2 insulated, twisted copper pairs is:

= 22.7 + 2.6

= 25.3 Kgs/Km.

Tubes

Area of 1 tube of outer diameter 3 mm and inner diameter 2 mm is:-

$$= Pi \times (1.5 \times 10^{-3})^2 - Pi \times (1 \times 10^{-3})^2$$

$= 3.93 \times 10^{-6} m^2$

$\text{Volume/Km} = 3.93 \times 10^{-3} m^3$

Tube material is vestadour HI15 and has the density 1290 Kgs/Km.

Therefore the weight of 5 tubes $= 55 \times 3.93 \times 10^{-3} \times 1290$

$= 25.3$ Kgs/Km

Tube Filling Compound

Within the tubes in addition to the fibres, a water blocking compound is applied. The compound usually used is PBTP.

Area inside tube $= \text{Pi} \times (1 \times 10^{-3})^2$

$= 3.142 \times 10^{-6} m^2$

Volume/Km $= 3.142 \times 10^{-3} m^3$

Density of Hyvis $= 850$ Kgs/m^3

Therefore weight of Hyvis for 5 tubes is:

$= 5 \times 3.142 \times 10^{-3} \times 850$

$= 13.35$ Kgs/Km.

Element Interstices Filling Compound

A filling compound e.g. Syntec Rheogel, is applied to the interstices of the cable elements to prevent the ingress of water.

Diameter outside elements = 5.8 + 3.0 + 3.0 = 11.8 mm.

Total area $= \text{Pi} \times (5.9 \times 10^{-3})^2$

$= 1.094 \times 10^{-4} m^2$

Area of sheathed steel dyform $= 2.64 \times 10^{-5} m^2$

Area of 5 tubes + 2 fillers $= 4.95 \times 10^{-5} m^2$

Area of 2 insulated, twisted copper pairs $= 5.31 \times 10^{-6} m^2$

Therefore Area of element interstices is:

$= 1.094 \times 10^{-4} - 2.64 \times 10^{-5} - 4.95 \times 10^{-5} - 5.31 \times 10^{-6}$

$$= 2.815 \times 10^{-2} m^3$$

$$\text{Volume/Km} = 2.815 \times 10^{-2} m^3$$

Density of Syntec Rheogel = 900 Kgs/

Therefore weight of Interstice filling compound is:

$$= 2.815 \times 10^{-2} \times 900$$

$$= 25.34 \text{ Kgs/Km.}$$

Paper Tape

Diameter of cable outside elements = 11.8 mm

Any width of paper between 10 mm and 30 mm could be used, but for this application we will use a 20 mm tape.

Assume tape overlap = 10%.

$$\text{Therefore effective paper tape width} = 20 \times \frac{(100 - 10)}{100}$$

$$= 18 \text{ mm}$$

$$\text{Angle of Application} = \cos^{-1} \frac{18}{\text{Pi} \times 11.8}$$

$$= 61 \text{ degrees}$$

Length of tape required to cover 1 Km of cable:

$$= \frac{1000 \times \text{Pi} \times 12.48}{20 \times 0.9} = 2178 \text{ m}$$

where 12.48 is the diameter of the cable outside the paper tape.

Thickness of tape = 0.17 mm, therefore at the overlapping part, increase in diameter due to tape is 0.17 x 4 = 0.68 mm.

$$\text{Therefore diameter of cable outside tape} = 11.8 + 0.68$$

$$= 12.48 \text{ mm.}$$

$$\text{Volume of paper used per Km} = 2178 \times 20 \times 10^{-3} \times 0.17 \times 10^{-3}$$

$$= 7.4 \times 10^{-3} m^3$$

Density of paper = 600 Kgs/m^3

Therefore weight of paper = $7.4 \times 10 \quad \times 600$

= 4.5 Kgs.

Aluminium Plastic Laminate (APL)

APL Radial Thickness (including overlap) = 0.5 mm.

Therefore APL Pitch diameter = 12.48 + 0.5

= 12.98 mm.

Width of APL required = (Pi x Pitchdiameter) + overlap.

Nominally, overlap = 8 mm.

Therefore Width = (Pi x 12.98) + 8

= 49 mm.

Area of APL (cross-sectional) = $9.31 \times 10^{-6} m^2$

Volume/Km = 9.31×10^{-6}

Density of APL = 2284 Kgs/m^3

Therefore weight of APL = $9.31 \times 10 \quad \times 2284$

= 21.3 Kgs/Km

Outer Sheath

Diameter of cable inside outer sheath = 13.5 mm

Radial thickness of LDPE sheath required = 1.6 mm

Diameter of cable outside outer sheath = 16.7 mm

Area of sheath = $Pi \times (8.35 \times 10^{-3})^2 - Pi \times (6.75 \times 10^{-3})^2$

= $7.59 \times 10^{-5} m^2$

Volume/Km = $7.59 \times 10^{-2} m^3$

Density of Low Density Polyethylene (LDPE) = 925 Kgs/m^3

Therefore weight of outer sheath = $7.59 \times 10^{-2} \times 925$

= 70.2 Kgs/Km.

Total Weight of Cable

Material	Weight (Kgs/Km)
Steel Dyform	135
Dyform Sheath	6.3
2 Fillers	13.1
2 Copper Pairs	25.3
5 Tubes	25.3
Tube Filling Compound	13.4
Element Interstices Filling Compound	25.4
Paper Tape	4.5
APL	21.3
Outer Sheath	70.2
	339.8

Cable Dimensions

Material	Cummulative Diameter(mm)
Steel Dyform	5
Dyform Sheath	5.8
Elements	11.8
2 x 3 mm fillers	
2 x Copper Pairs - copper wire 0.9 mm - insulation 0.2 mm	
5 x 3 mm Tubes	
Paper Tape	12.48
APL	13.48
Outer Sheath	16.7

Cable Strength/Weight

Weight of Cable in newtons = 339.8 x 9.81
= 3334 N

Strength factor required is 3 x W, where W is the weight of the cable in newtons.

Therefore strength required = 3 x 3334
= 10,002 N

Assuming a maximum cable strain of 0.4%, and a modulus of steel of 155 GPa, the maximum pulling force on a 5 mm steel is:

$$F = Pi \times \frac{25}{4} \times \frac{0.4}{100} \times 155 \times 1000$$

$$= 12{,}174 \text{ Newtons.}$$

$$\text{Therefore strength factor available} = \frac{12174}{3334}$$

$$= 3.65 \times W$$

This proves that the cable has adequate tensile strength.

Optical Fibres

The weight of the fibres have been neglected, since the filling compound in the tubes has approximately the same density as silicone glass. Therefore the weight of the filling compound takes into account the weight of the fibres.

The fibres used are singlemode operating at a wavelength of 1300 nm. The maximum allowable attenuation is 0.5dB/Km.

Four fibres will be placed in each tube with the following four colours used as identification for each of the fibres respectively.

1. Blue
2. Orange
3. Green
4. Brown

APPENDIX B

Loose Tube Cable Expert System - Rule List

```
*
* RULE LIST                                   Mon Sep 07 02:28:29 1987  Page:    1
* ---------
[  1]  ACCURACY OF DIMENSIONS
           IF              DO: Assign Variable
                             DIAM0:=DIAM0+0.049
             AND           DO: Assign Variable
                             DIAM1:=DIAM1+0.049
             AND           DO: Assign Variable
                             DIAM2:=DIAM2+0.049
             AND           DO: Assign Variable
                             DIAM3:=DIAM3+0.049
             AND           DO: Assign Variable
                             DIAM4:=DIAM4+0.049
             AND           DO: Assign Variable
                             TAPELAY:=TAPELAY+0.49
             AND           DO: Assign Variable
                             APPANGLE:=APPANGLE+0.49



[  2]  ALUMINIUM PLASTIC LAMINATE
           IF              DO: Yes/No Question
                                IS AN "ALUMINIUM PLASTIC LAMINATE" MOISTURE
                                BARRIER REQUIRED  ?
             AND           DO: Assign Variable
                             APL$:="Y"
             AND           DO: Assign Variable
                             CIRCUM:=(DIAM2+1)*PI
             AND           DO: Assign Variable
                             APLW:=CIRCUM+8
             AND           DO: Display Form
                                     APL WIDTH REQUIRED IS [APLW.]mm


                                ENTER NEAREST APL WIDTH AVAILABLE (mm) <NAPLW
             AND           DO: Menu Question   APLTHICKNESS

                                     ENTER THICKNESS OF APL REQUIRED  ?


                                          (0.15)          (0.20)
        +    AND [    4] APLTHICKNESS
             AND           DO: Assign Variable
                             MASS4:=NAPLW*APLTHICK
             AND           DO: Assign Variable
                             DIAM3:=DIAM2+1
             AND           DO: Assign Variable
                             DIAMAPLSPL:=DIAM3

           OR              DO: Assign Variable
                             APL$:="N"



[  3]  APL
           IF              DO: Test Expression
                             APL$="N"

           OR              DO: Print Form
             AND           DO: Print Form
                             APL
                             ---
                             WIDTH OF APL REQUIRED IS[APLW.] mm
*
```

```
                               NEAREST APL WIDTH AVAILABLE IS[NAPLW] mm

                               APL THICKNESS IS[APL.T] mm

                               WEIGHT OF[NAPLW] mm APL IS[MASS4] kgs/km
              AND            DO: Print Form

                               DIAMETER OF CABLE OUTSIDE APL IS[DIAM3.] mm
              AND            DO: Print Form



[   4]  APLTHICKNESS
          IF                 DO: Test Expression
                               APLTHICKNESS=1
              AND            DO: Assign Variable
                               APLTHICK:=0.434
              AND            DO: Assign Variable
                               APLT:=0.15

          OR                 DO: Assign Variable
                               APLTHICK:=0.620
              AND            DO: Assign Variable
                               APLT:=0.20



[   5]  ARMOUR
          IF                 DO: Test Expression
                               SWA$="N"

          OR                 DO: Print Form
              AND            DO: Print Form
                               STEEL WIRE ARMOUR BEDDING SHEATH
                               --------------------------------
                               RADIAL THICKNESS OF STEEL WIRE ARMOUR BEDDING
                               SHEATH IS[RTSWABS.] mm

                               WEIGHT OF STEEL WIRE ARMOUR BEDDING SHEATH
                               IS[MASS16] kgs/km

                               DIAMETER OF CABLE OUTSIDE STEEL WIRE ARMOUR
                               BEDDING SHEATH IS[DIAMSWABS.] mm
              AND            DO: Print Form
              AND            DO: Print Form
              AND            DO: Print Form
                               STEEL WIRE ARMOUR
                               -----------------
                               NUMBER OF STEEL WIRES REQUIRED IS[ANSW]

                               DIAMETER OF STEEL WIRES ARE[DSW. ] mm

                               LAYANGLE OF STEEL WIRE ARMOUR IS[SWALA] degrees

                               LAYLENGTH OF STEEL WIRE ARMOUR IS[SWALL] mm
              AND            DO: Print Form
              AND            DO: Print Form
                               WEIGHT OF STEEL WIRE ARMOUR IS[MASS17] kgs/km

                               DIAMETER OF CABLE OUTSIDE STEEL WIRE ARMOUR
```

*

```
                                 IS[DIAMSWA.] mm
                  AND          DO: Print Form
                  AND          DO: Display Form

                                              END OF PRINT OUT SHEET

                                      WIND ON TO NEXT SHEET AND PRESS ANY KEY


 [   6]  ARMOURED
                IF             DO: Test Expression
                                 SPL$="N"
                  AND          DO: Test Expression
                                 SWA$="N"
                  AND          DO: Assign Variable
                                 ARMOURED$:="NO"

                OR             DO: Assign Variable
                                 ARMOURED$:="YES"


 [   7]  BEDDING SHEATH
                IF             DO: Test Expression
                                 SPLBS$="Y"
                  AND          DO: Print Form
                  AND          DO: Print Form
                                 SPL BEDDING SHEATH
                                 ------------------
                                 RADIAL THICKNESS OF BEDDING SHEATH IS[RTBS.] mm

                                 WEIGHT OF [BSM$]BEDDING SHEATH IS[MASS12] kgs/k

                                 DIAMETER OF CABLE OUTSIDE BEDDING SHEATH
                                 IS[DIAMSPLBS.] mm
                  AND          DO: Print Form

                OR             DO: Succeed


 [   8]  BEDDING SHEATH MATERIAL - DENSITY
                IF             DO: Test Expression
                                 BSM$="LDPE"
                  AND          DO: Assign Variable
                                 DENSITY2:=925

                OR             DO: Test Expression
                                 BSM$="MDPE"
                  AND          DO: Assign Variable
                                 DENSITY2:=940

                OR             DO: Test Expression
                                 BSM$="HDPE"
                  AND          DO: Assign Variable
                                 DENSITY2:=950


 [   9]  CABLE CENTRAL MEMBER
*
```

```
*
* RULE LIST
* ---------
          IF            DO: Print Form
                          CENTRAL MEMBER
                          --------------
                          DIAMETER OF CORE REQUIRED TO SUPPORT[N] ELEMENTS
                          IS[DIAMO.] mm

                          DIAMETER OF [SMM$]STRENGTH MEMBER REQUIRED
                          IS[DIAMETE.R] mm

                          RADIAL THICKNESS OF [ISM$]INNER SHEATH MATERIAL
                          IS[RTI.S] mm
            AND         DO: Print Form
            AND         DO: Print Form
                          WEIGHT OF [SMM$] STRENGTH MEMBER IS[MASS1] kgs/k

                          WEIGHT OF [ISM$]INNER SHEATH IS[MASS2] kgs/km
            AND         DO: Print Form



[  10]  CABLE STRENGTH/WEIGHT
          IF            DO: Display Form
                                      WHAT IS THE MAXIMUM ALLOWABLE
                                      CABLE STRAIN  (% age)  ?

                                              <STRAIN>
     +      AND [   68] STRENGTH MEMBER MATERIAL - MODULUS
            AND         DO: Display Form
                            ENTER CABLE STRENGTH FACTOR REQUIRED (xW)  ?

                                              <CSF>
     +      AND [   35] INSTALLATION
     +      AND [   33] INNER SHEATH MATERIAL - DENSITY
     +      AND [   20] DIAMETER OF STRENGTH MEMBER
            AND         DO: Assign Variable
                          W:=CSF*STRESS/CSR



[  11]  CENTRAL MEMBER
          IF            DO: Display Form
                              ENTER NUMBER OF OUTER ELEMENTS REQUIRED ?

                                                <N>
            AND         DO: Menu Question  DO
                                ENTER DIAMETER OF OUTER ELEMENTS (mm) ?

                                         {1.5}  {2.2}  {3.0}
     +      AND [   76] TUBE DIAMETER
            AND         DO: Assign Variable
                          PI:=3.141592654
            AND         DO: Assign Variable
                          R:=(D/2)*(1-SIN(PI/N))/SIN(PI/N)
            AND         DO: Assign Variable
                          DIAMO:=2*R+0.3
            AND         DO: Menu Question  SMM$
                                  ENTER STRENGTH MEMBER MATERIAL ?

                                          {STEEL}    {GRP}
            AND         DO: Menu Question  ISM$
                                   ENTER INNER SHEATH MATERIAL ?
*
```

```
                                       <LDPE>    <MDPE>    <HDPE>
           AND          DO: Assign Variable
                          DIAM1:=DIAM0+(2*D)
           AND          DO: Assign Variable
                          PW:=6.35
       +   AND [   37] LAYLENGTH


[  12]  CHECK ASCII INTERFACE IS LOADED AND SYSTEM CLEAR
         IF             DO: Display Form
                                                   CAUTION
                                                   -------

                                  HAVE ALL ANSWERS AND RESULTS BEEN CLEARED  ?

                                IF NOT PRESS "ESCAPE" AND USE THE CLEAR FUNCTIO
           AND          DO: User Program
                          VERIFY("CRASC");


[  13]  COPPER PAIRS
         IF             DO: Test Expression
                          N-NT>0
           AND          DO: Display Form
                                ENTER NUMBER OF COPPER PAIRS REQUIRED ?

                                                   <NCP>
           AND          DO: Test Expression
                          NCP>0
           AND          DO: Display Form
                                 ENTER DIAMETER OF SINGLE COPPER WIRE ?

                                                   <DCW>


                              ENTER RADIAL THICKNESS OF COPPER INSULATION ?

                                                   <RTCI>
           AND          DO: Assign Variable
                          A7:=((DCW/2000)^2)*PI
           AND          DO: Assign Variable
                          A8:=((((2*RTCI)+DCW)/2000)^2)*PI
           AND          DO: Assign Variable
                          A9:=A8-A7
           AND          DO: Assign Variable
                          DENCOPP:=8930
           AND          DO: Assign Variable
                          MASS7:=A7*1000*DENCOPP*2*NCP
           AND          DO: Assign Variable
                          DENCOPINS:=940
           AND          DO: Assign Variable
                          MASS8:=A9*1000*DENCOPINS*2*NCP

         OR             DO: Succeed


[  14]  COPPERS
*
```

```
      IF              DO: Test Expression
                        NCP=0

      OR              DO: Print Form
        AND           DO: Print Form
                        DIAMETER OF SINGLE COPPER WIRE IS[DCW.] mm

                        RADIAL THICKNESS OF COPPER INSULATION IS[RTC.I] mm

                        WEIGHT OF[NCP] COPPER PAIR(S) IS[MASS7] kgs/km

                        WEIGHT OF COPPER INSULATION FOR[NCP] PAIRS IS
                        [MASS8] kgs/km



[5]  DENSITY OF SYNTEC
      IF              DO: Test Expression
                        SR=90
        AND           DO: Assign Variable
                        DENSYN:=900

      OR              DO: Test Expression
                        SR=210
        AND           DO: Assign Variable
                        DENSYN:=890

      OR              DO: Test Expression
                        SR=1921
        AND           DO: Assign Variable
                        DENSYN:=800



[6]  DIAMETER INSIDE OUTER SHEATH
      IF              DO: Test Expression
                        SWA$="N"
        AND           DO: Test Expression
                        APL$="N"
        AND           DO: Test Expression
                        SPL$="N"
        AND           DO: Assign Variable
                        DIAMIOS:=DIAM2

      OR              DO: Test Expression
                        SWA$="N"
        AND           DO: Test Expression
                        APL$="Y"
        AND           DO: Test Expression
                        SPL$="Y"
        AND           DO: Assign Variable
                        DIAMIOS:=DIAMAPLSPL

      OR              DO: Test Expression
                        SWA$="N"
        AND           DO: Test Expression
                        APL$="Y"
        AND           DO: Test Expression
                        SPL$="N"
        AND           DO: Assign Variable
                        DIAMIOS:=DIAM3
```

```
        OR              DO: Test Expression
                          SWA$="N"
          AND           DO: Test Expression
                          APL$="N"
          AND           DO: Test Expression
                          SPL$="Y"
          AND           DO: Assign Variable
                          DIAMIOS:=DIAM3

        OR              DO: Assign Variable
                          DIAMIOS:=DIAMSWA


17]  DIAMETER OF SPL BEDDING SHEATH
        IF              DO: Test Expression
                          APL$="N"
          AND           DO: Assign Variable
                          DIAMSPLBS:=DIAM2+(2*RTBS)

        OR              DO: Assign Variable
                          DIAMSPLBS:=DIAM3+(2*RTBS)


18]  DIAMETER OF STEEL                                      Sp
        IF              DO: Test Expression
                          LOOP=1
          AND           DO: Assign Variable
                          DIAMETER:=1.83

        OR              DO: Test Expression
                          LOOP=2
          AND           DO: Assign Variable
                          DIAMETER:=2.5

        OR              DO: Test Expression
                          LOOP=3
          AND           DO: Assign Variable
                          DIAMETER:=3.0

        OR              DO: Test Expression
                          LOOP=4
          AND           DO: Assign Variable
                          DIAMETER:=4.0

        OR              DO: Test Expression
                          LOOP=5
          AND           DO: Assign Variable
                          DIAMETER:=5.0

        OR              DO: Test Expression
                          LOOP=6
          AND           DO: Assign Variable
                          DIAMETER:=6.0

        OR              DO: Test Expression
                          LOOP=7
          AND           DO: Assign Variable
                          DIAMETER:=7.0
```

```
        OR              DO: Test Expression
                          LOOP=8
          AND           DO: Assign Variable
                          DIAMETER:=8.0

        OR              DO: Test Expression
                          LOOP=9
          AND           DO: Assign Variable
                          DIAMETER:=9.0

        OR              DO: Test Expression
                          LOOP=10
          AND           DO: Assign Variable
                          DIAMETER:=10.0

        OR              DO: Succeed


19]  DIAMETER OF STEEL WIRES
        IF              DO: Test Expression
                          DIAMSTEELWIRES=1
          AND           DO: Assign Variable
                          DSW:=0.9

        OR              DO: Test Expression
                          DIAMSTEELWIRES=2
          AND           DO: Assign Variable
                          DSW:=1.25

        OR              DO: Test Expression
                          DIAMSTEELWIRES=3
          AND           DO: Assign Variable
                          DSW:=1.6


20]  DIAMETER OF STRENGTH MEMBER
        IF              DO: Test Expression
                          SMM$="STEEL"
          AND           DO: Assign Variable
                          LOOP:=0
   +      AND [  63] STEEL STRENGTH MEMBER

        OR              DO: Test Expression
                          SMM$="GRP"
          AND           DO: Assign Variable
                          DIAMETER:=0.75
   +      AND [  26] GRP STRENGTH MEMBER


21]  DIAMETER UNDER STEEL WIRE ARMOUR BEDDING SHEATH
        IF              DO: Test Expression
                          APL$="N"
          AND           DO: Assign Variable
                          DIAMAPLSPL:=DIAM2

        OR              DO: Succeed
```

```
22]  DISPLAY HEADER
        IF             DO: Display Form
                               LOOSE TUBE CABLE  -  EXPERT SYSTEM



                                                  WRITTEN BY


                                                 LLYR ROBERTS



23]  FIBRECOUNT
        IF             DO: Yes/No Question
                           IS THIS A DESIGN FOR A FIXED FIBRECOUNT  ?
         AND           DO: Display Form
                         ENTER NUMBER OF FIBRES REQUIRED IN THE DESIGN  ?


                                                   <F>

        OR             DO: Display Form
                        ENTER LOWEST FIBRECOUNT REQUIRED IN THE DESIGN  ?


                                                    <L>
         AND           DO: Display Form
                        ENTER HIGHEST FIBRECOUNT REQUIRED IN THE DESIGN  ?


                                                    <H>



24]  FIBREMODE
        IF             DO: Menu Question  FIBREMODE$
                                    ENTER FIBREMODE  ?


                              {SINGLEMODE}        {MULTIMODE}



25]  FILLING COMPOUND - SYNTEC/INSOJELL
        IF             DO: Yes/No Question
                          ARE THE OUTER ELEMENT INTERSTICES FILLED  ?
         AND           DO: Assign Variable
                         SR$:="Y"
         AND           DO: Assign Variable
                         SR1$:="YES"
         AND           DO: Menu Question  SR0
                               ENTER FILLING COMPOUND REQUIRED  ?


                                  {1}  SYNTEC RHEOGEL 90

                                  {2}  SYNTEC RHEOGEL 210
```

```
                                         {3}   INSOJELL 1921
     +    AND [   73] SYNTEC TYPE
     +    AND [   15] DENSITY OF SYNTEC
          AND         DO: Assign Variable
                        AREASYN1:=((DIAM1/2000)^2)*PI
          AND         DO: Assign Variable
                        AREASYN2:=((DIAMO/2000)^2)*PI
          AND         DO: Assign Variable
                        AREASYN3:=(NT+NF)*A5+(2*A8*NCP)
          AND         DO: Assign Variable
                        AREASYN:=AREASYN1-AREASYN2-AREASYN3
          AND         DO: Assign Variable
                        MASS11:=AREASYN*1000*DENSYN

        OR            DO: Assign Variable
                        SR$:="N"
          AND         DO: Assign Variable
                        SR1$:="NO"



26]  GRP STRENGTH MEMBER                                                Sp
        IF            DO: Assign Variable
                        DIAMETER:=DIAMETER+0.25
          AND         DO: Assign Variable
                        RTIS:=(DIAMO-DIAMETER)/2
          AND         DO: Assign Variable
                        MASS1:=PI*((DIAMETER/2000)^2)*1000*2100
          AND         DO: Assign Variable
                        A1:=PI*((DIAMO/2000)^2)
          AND         DO: Assign Variable
                        A2:=PI*((DIAMETER/2000)^2)
          AND         DO: Assign Variable
                        MASS2:=(A1-A2)*DENSITY*1000
     +    AND [   70] STRESS
          AND         DO: Assign Variable
                        TOTALM1:=MASS1+MASS2+MASS3+MASS4+MASS5+MASS6+MASS7
          AND         DO: Assign Variable
                        TOTALM2:=MASS8+MASS9+MASS10+MASS11+MASS12+MASS13
          AND         DO: Assign Variable
                        TOTALM3:=MASS14+MASS15+MASS16+MASS17
          AND         DO: Assign Variable
                        TOTALM:=TOTALM1+TOTALM2+TOTALM3
          AND         DO: Assign Variable
                        WEIGHT:=TOTALM*9.81
          AND         DO: Assign Variable
                        CSR:=CSF*WEIGHT
          AND         DO: Test Expression
                        STRESS>=CSR

        OR            DO: Test Expression
                        DIAMETER<=DIAMO
          AND         DO: Restart Rule

        OR            DO: Display Form
                                   ------  CONCLUSION  ------

                                CABLE CANNOT CONFORM TO STRENGTH REQUIREMENT
          AND         DO: Assign Variable
                        PRINT:=1
```

```
27] HYVIS
      IF                DO: Assign Variable
                          MASS10:=NT*A6*1000*850


28] HYVIS JELLY
      IF                DO: Print Form
        AND             DO: Print Form
                          TUBE FILLING COMPOUND - HYVIS
                          ------------------------------
                          WEIGHT OF HYVIS REQUIRED FOR[NT] TUBES
                          IS[MASS10] kgs/km
        AND             DO: Print Form


29] ID
      IF                DO: Test Expression
                          MASS14>0
        AND             DO: Print Form
                          WEIGHT OF IDENTIFICATION TAPE IS[MASS1.4] kgs/km

      OR                DO: Print Form
                          NO IDENTIFICATION TAPE


30] ID AND RIP
      IF                DO: Print Form
        AND             DO: Print Form
                          ID TAPE AND RIPCORD
                          --------------------
 +      AND [   29] ID
        AND             DO: Print Form
 +      AND [   58] RIP
        AND             DO: Print Form


31] ID TAPE
      IF                DO: Yes/No Question
                                   IS AN "ID" TAPE REQUIRED   ?
        AND             DO: Assign Variable
                          MASS14:=0.2
        AND             DO: Assign Variable
                          ID$:="Y"

      OR                DO: Succeed
        AND             DO: Assign Variable
                          ID$:="N"


32] ID TAPE AND RIPCORD
 +    IF    [   31] ID TAPE
 +      AND [   59] RIPCORD
```

```
33]  INNER SHEATH MATERIAL - DENSITY
        IF               DO: Test Expression
                           ISM$="LDPE"
          AND            DO: Assign Variable
                           DENSITY:=925

        OR               DO: Test Expression
                           ISM$="MDPE"
          AND            DO: Assign Variable
                           DENSITY:=940

        OR               DO: Test Expression
                           ISM$="HDPE"
          AND            DO: Assign Variable
                           DENSITY:=950



34]  INST
        IF               DO: Test Expression
                           INST=1
          AND            DO: Assign Variable
                           INSTALLATION$:="DUCT"

        OR               DO: Test Expression
                           INST=2
          AND            DO: Assign Variable
                           INSTALLATION$:="BURIED"

        OR               DO: Test Expression
                           INST=3
          AND            DO: Assign Variable
                           INSTALLATION$:="AERIAL"

        OR               DO: Test Expression
                           INST=4
          AND            DO: Assign Variable
                           INSTALLATION$:="INTERNAL"

        OR               DO: Test Expression
                           INST=5
          AND            DO: Assign Variable
                           INSTALLATION$:="OTHER"



35]  INSTALLATION
        IF               DO: Menu Question  INST
                                     ENTER CABLE INSTALLATION  ?


                                                {1}  DUCT
                                                {2}  BURIED
                                                {3}  AERIAL
                                                {4}  INTERNAL
                                                {5}  OTHER

     +   AND [  34] INST
```

```
36]  INTERNAL DIAMETER OF TUBE
        IF             DO: Test Expression
                         D=1.5
          AND          DO: Assign Variable
                         IDT:=1.0

        OR             DO: Test Expression
                         D=2.2
          AND          DO: Assign Variable
                         IDT:=1.5

        OR             DO: Test Expression
                         D=3.0
          AND          DO: Assign Variable
                         IDT:=2.3



37]  LAYLENGTH
        IF             DO: Display Form
                            ENTER LAYLENGTH OF STRANDED ELEMENTS  (mm)  ?

                                              <LAYLENGTH>
          AND          DO: Assign Variable
                         PITCHDIAM:=DIAMO+D
          AND          DO: Assign Variable
                         LAYANGLE1:=ARCTAN(PITCHDIAM*PI/LAYLENGTH)
          AND          DO: Assign Variable
                         LAYANGLE:=LAYANGLE1*180/PI



38]  LOOSE TUBE CABLES
      + IF     [  22] DISPLAY HEADER
      +   AND  [  23] FIBRECOUNT
      +   AND  [  24] FIBREMODE
      +   AND  [  11] CENTRAL MEMBER
      +   AND  [  77] TUBES
      +   AND  [  13] COPPER PAIRS
      +   AND  [  42] OUTER ELEMENT FILLERS
      +   AND  [  27] HYVIS
      +   AND  [  25] FILLING COMPOUND - SYNTEC/INSOJELL
      +   AND  [  47] PAPER TAPE
      +   AND  [   2] ALUMINIUM PLASTIC LAMINATE
      +   AND  [  62] STEEL PLASTIC LAMINATE
      +   AND  [  64] STEEL WIRE ARMOUR
      +   AND  [  44] OUTER SHEATH
      +   AND  [  32] ID TAPE AND RIPCORD
      +   AND  [  10] CABLE STRENGTH/WEIGHT
      +   AND  [  75] TRANSFER PARAMETERS TO ASCII FILE
      +   AND  [  53] PRINT OUT OF RESULTS



39]  MATALLIC
        IF             DO: Test Expression
                         SMM$="GRP"
          AND          DO: Test Expression
                         APL$="N"
          AND          DO: Test Expression
```

```
                          SPL$="N"
        AND             DO: Test Expression
                          SWA$="N"
        AND             DO: Assign Variable
                          METALLIC$:="NO"

      OR                DO: Assign Variable
                          METALLIC$:="YES"


40]  METALLIC/ARMOURED
       + IF      [  39] MATALLIC
       +   AND [     6] ARMOURED


41]  NUMERICAL VARIABLES
         IF             DO: User Program
                          OPENW("CABLE");
                          WRITENUM("[D. ]");NEWLINE();
                          WRITENUM("[DCW. ]");NEWLINE();
                          WRITENUM("[DIAM0. ]");NEWLINE();
                          WRITENUM("[DIAM1. ]");NEWLINE();
                          WRITENUM("[DIAM2. ]");NEWLINE();
                          WRITENUM("[DIAM3. ]");NEWLINE();
                          WRITENUM("[DIAM4.]");NEWLINE();
                          WRITENUM("[DIAMETER. ]");NEWLINE();
                          WRITENUM("[DIAMAPLSPL. ]");NEWLINE();CLOSE();
           AND          DO: User Program
                          OPENW("CABLE");
                          WRITENUM("[DIAMIOS. ]");NEWLINE():
                          WRITENUM("[DIAMSPL. ]");NEWLINE();
                          WRITENUM("[DIAMSPLBS. ]"):NEWLINE();
                          WRITENUM("[DIAMSWA. ]"):NEWLINE();
                          WRITENUM("[DIAMSWABS. ]");NEWLINE();
                          WRITENUM("[DSW. ]");NEWLINE();
                          WRITENUM("[IDT. ]");NEWLINE();
                          WRITENUM("[N]");NEWLINE();
                          WRITENUM("[NCP]");NEWLINE();CLOSE();
           AND          DO: User Program
                          OPENW("CABLE");
                          WRITENUM("[NF]");NEWLINE();
                          WRITENUM("[NT]");NEWLINE();
                          WRITENUM("[ANSW]");NEWLINE();
                          WRITENUM("[OSRT. ]");NEWLINE();
                          WRITENUM("[RTBS. ]");NEWLINE();
                          WRITENUM("[RTCI. ]");NEWLINE();
                          WRITENUM("[RTIS. ]");NEWLINE();
                          WRITENUM("[SR  ]");NEWLINE();
                          CLOSE();
           AND          DO: User Program
                          OPENW("CABLE");
                          WRITENUM("[TOTALM]");NEWLINE();
                          WRITENUM("[STRESS]");NEWLINE();
                          CLOSE();


42]  OUTER ELEMENT FILLERS
         IF             DO: Assign Variable
```

```
                        NF:=N-NT-NCP
        AND           DO: Test Expression
                        NF>0
        AND           DO: Assign Variable
                        MASS9:=A5*1000*925*NF

      OR              DO: Succeed



43] OUTER ELEMENTS
      IF              DO: Print Form
        AND           DO: Print Form
                        TUBES, FILLERS AND COPPER PAIRS
                        -------------------------------
                        DIAMETER OF TUBES & FILLERS ARE[D.] mm

                        WEIGHT OF[NT] TUBES IS[MASS6] kgs/km
   +    AND [   14] COPPERS
   +    AND [   50] POLYETHYLENE FILLERS
        AND           DO: Print Form



44] OUTER SHEATH
   + IF     [   16] DIAMETER INSIDE OUTER SHEATH
        AND           DO: Display Form
                               ENTER RADIAL THICKNESS OF OUTER
                               SHEATH REQUIRED (mm)   ?

                                             <OSRT>
        AND           DO: Menu Question  OSM$
                               ENTER OUTER SHEATH MATERIAL   ?

                                 {LDPE}     {MDPE}     {HDPE}
   +    AND [   46] OUTER SHEATH MATERIAL - DENSITY
        AND           DO: Assign Variable
                        A3:=(((2*OSRT+DIAMIOS)/2000)^2)*PI
        AND           DO: Assign Variable
                        A4:=PI*((DIAMIOS/2000)^2)
        AND           DO: Assign Variable
                        OSVOL:=(A3-A4)*1000
        AND           DO: Assign Variable
                        MASS5:=OSVOL*DENSITY1
        AND           DO: Assign Variable
                        DIAM4:=(2*OSRT)+DIAMIOS



45] OUTER SHEATH COATING
      IF              DO: Print Form
        AND           DO: Print Form
                        OUTER SHEATH
                        ------------
                        RADIAL THICKNESS OF [OSM$]OUTER SHEATH
                        IS[OSRT.] mm

                        WEIGHT OF OUTER SHEATH IS[MASS5] kgs/km

                        DIAMETER OF CABLE OUTSIDE OUTER SHEATH
                        IS[DIAM4.] mm
```

```
           AND          DO: Print Form



 46]  OUTER SHEATH MATERIAL - DENSITY
        IF              DO: Test Expression
                          OSM$="LDPE"
          AND           DO: Assign Variable
                          DENSITY1:=925

        OR              DO: Test Expression
                          OSM$="MDPE"
          AND           DO: Assign Variable
                          DENSITY1:=940

        OR              DO: Test Expression
                          OSM$="HDPE"
          AND           DO: Assign Variable
                          DENSITY1:=950



 47]  PAPER TAPE                                                   Sp
      + IF    [  49] PAPER TAPE LAYERS
          AND           DO: Assign Variable
                          PW:=PW+6.35
          AND           DO: Assign Variable
                          ANGLE:=((PW*0.9)/(PI*(DIAM1+0.68)))
          AND           DO: Test Expression
                          ANGLE<1
          AND           DO: Assign Variable
                          ANGAPP:=ARCCOS(ANGLE)
          AND           DO: Test Expression
                          ANGAPP>40*PI/180
          AND           DO: Test Expression
                          ANGAPP<66*PI/180
          AND           DO: Assign Variable
                          PL:=(1000*PI*(DIAM1+PTTH))/(PW*0.9)
          AND           DO: Assign Variable
                          TAPELAY:=PW*0.9/SIN(ANGAPP)
          AND           DO: Assign Variable
                          MASS3:=(PL*PW*0.125*600*0.000001)*NPTL
          AND           DO: Assign Variable
                          DIAM2:=DIAM1+PTTH
          AND           DO: Assign Variable
                          APPANGLE:=ANGAPP*180/PI

        OR              DO: Restart Rule



 48]  PAPER TAPE BINDER
        IF              DO: Print Form
          AND           DO: Print Form
                          PAPER TAPE
                          ----------
                          NUMBER OF PAPER TAPE LAYERS IS[NPTL]
          AND           DO: Print Form
          AND           DO: Print Form
                          LENGTH OF [PW]mm WIDE PAPER TAPE REQUIRED PER km
                          OF CABLE IS [PL] m PER LAYER
```

```
                         ANGLE OF APPLICATION OF PAPER TAPE IS
                         [APPANGLE] degrees

                         PAPER TAPE LAY LENGTH IS[TAPELAY] mm

                         TOTAL WEIGHT OF PAPER TAPE IS[MASS3] kgs/km
         AND           DO: Print Form
         AND           DO: Print Form
                         THICKNESS OF PAPER TAPE IS 0.125 mm

                         DIAMETER OF CABLE OUTSIDE TAPE IS [DIAM2.] mm
         AND           DO: Print Form



49]  PAPER TAPE LAYERS
       IF              DO: Menu Question  NPTL
                           ENTER NUMBER OF PAPER TAPE LAYERS REQUIRED    ?



                                             {1}       {2}
         AND           DO: Test Expression
                         NPTL=1
         AND           DO: Assign Variable
                         PTTH:=0.4

       OR              DO: Assign Variable
                         PTTH:=0.6



50]  POLYETHYLENE FILLERS
       IF              DO: Test Expression
                         N-NT-NCP=0

       OR              DO: Print Form
         AND           DO: Print Form
                         WEIGHT OF[NF] FILLERS IS[MASS9] kgs/km



51]  PRINT
       IF              DO: Print Form
         AND           DO: Print Form
         AND           DO: Print Form
         AND           DO: Print Form



52]  PRINT CABLE SUMMARY
     + IF     [  54] PRINT TITLE
         AND           DO: Print Form



                         SUMMARY
                         -------

         AND           DO: Print Form
```

```
                   ---------------------------------------------------------------
                   :CONSTRUCTION :                 :NUMBER OF ELEMENTS :        :
                   :                               :                            :
                   :                               :                            :
                   :        LOOSE TUBE             :           [N]              :
                   :_______________________________:____________________________:
      AND          DO: Print Form
                   :NUMBER OF TUBES :              :NUMBER OF FILLERS :         :
                   :                               :                            :
                   :                               :                            :
                   :            [NT]               :           [NF]             :
                   :_______________________________:____________________________:
                   :NUMBER OF COPPER PAIRS :       :INSTALLATION :              :
                   :                               :                            :
                   :                               :                            :
                   :            [NCP]              :         [INSTALLATION$]    :
                   :_______________________________:____________________________:
  +   AND [   40] METALLIC/ARMOURED
      AND          DO: Print Form
                   :FILLED :                       :METALLIC :                  :
                   :                               :                            :
                   :                               :                            :
                   :            [SR1$]             :           [METALLIC$]      :
                   :_______________________________:____________________________:
                   :ARMOURED :                     :FIBREMODE :                 :
                   :                               :                            :
                   :                               :                            :
                   :          [ARMOURED$]          :         [FIBREMODE$]       :
                   :_______________________________:____________________________:
      AND          DO: Print Form
                   :CUSTOMER :                     :REFERENCE NUMBER :          :
                   :                               :                            :
                   :                               :                            :
                   :                               :                            :
                   :_______________________________:____________________________:
      AND          DO: Display Form
                    END OF PRINT OUT SHEET   -   WIND ON TO NEXT SHEET


                             PRESS ANY KEY TO CONTINUE


53]  PRINT OUT OF RESULTS
    + IF     [   55] PRINTER OPTIONS
      AND          DO: Test Expression
                     PRINTOUT=0
  +   AND [   52] PRINT CABLE SUMMARY
  +   AND [    1] ACCURACY OF DIMENSIONS
  +   AND [   51] PRINT
  +   AND [    9] CABLE CENTRAL MEMBER
  +   AND [   43] OUTER ELEMENTS
  +   AND [   28] HYVIS JELLY
  +   AND [   66] STRANDING PROCESS
  +   AND [   72] SYNTEC
  +   AND [   48] PAPER TAPE BINDER
```

```
  +    AND [  30] ID AND RIP
  +    AND [   3] APL
  +    AND [   7] BEDDING SHEATH
  +    AND [  60] SPL
  +    AND [   5] ARMOUR
  +    AND [  45] OUTER SHEATH COATING
  +    AND [  69] STRENGTH/WEIGHT
  +    AND [  56] PROCESSES AND SPEEDS

     OR              DO: Succeed



54] PRINT TITLE
      IF             DO: Print Form
                                                         DATE :    /    / 19
  +    AND [  51] PRINT
       AND           DO: Print Form

                         ----------------------------------------
                         :                                      :
                         :  LOOSE TUBE CABLE  -  EXPERT SYSTEM  :
                         :                                      :
                         :______________________________________:
       AND           DO: Test Expression
                       F>0
       AND           DO: Print Form


                       CABLE DESCRIPTION FOR A[F] FIBRE CABLE

     OR              DO: Test Expression
                       L>0
       AND           DO: Test Expression
                       H>0
       AND           DO: Print Form


                       CABLE DESCRIPTION FOR A[L] TO[H] FIBRE CABLE

     OR              DO: Print Form

                       INCORRECT FIBRECOUNT INPUT



55] PRINTER OPTIONS
      IF             DO: Test Expression
                       PRINT=1
       AND           DO: Menu Question  PRINTOUT$


                           DO YOU REQUIRE A PRINTOUT OF THE DESIGN  ?


                           WARNING - DATA MAY BE INCORRECT DUE TO
                                     INSUFFICIENT STRENGTH OF CABLE.

                                         {YES}        {NO}
       AND           DO: Test Expression
                       PRINTOUT$="NO"
       AND           DO: Assign Variable
```

```
                              PRINTOUT:=1

        OR             DO: Succeed


561  PROCESSES AND SPEEDS
        IF             DO: Print Form

                              PROCESSES AND SPEEDS
                              --------------------
          AND          DO: Print Form


                              PROCESS 1    -


                              PROCESS 2    -
          AND          DO: Print Form


                              PROCESS 3    -


                              PROCESS 4    -
          AND          DO: Print Form


                              PROCESS 5    -


                              PROCESS 6    -
          AND          DO: Print Form


                              PROCESS 7    -


                              PROCESS 8    -
          AND          DO: Print Form


                              PROCESS 9    -


                              PROCESS 10   -
          AND          DO: Print Form
```

```
                              PROCESS 11  -


                              PROCESS 12  -


57]  QUIT CRYSTAL
        IF             DO: Display Form
                                            PLEASE NOTE
                                            -----------

                          CRYSTAL ASCII INTERFACE HAS NOT BEEN LOADED


                          QUIT CRYSTAL AND RE-START BY TYPING "CRASC"



58]  RIP
        IF             DO: Test Expression
                         MASS15>0
          AND          DO: Print Form
                         WEIGHT OF RIPCORD IS[MASS1.5] kgs/km

        OR             DO: Print Form
                         NO RIPCORD



59]  RIPCORD
        IF             DO: Yes/No Question
                                  IS A "RIPCORD" REQUIRED   ?
          AND          DO: Assign Variable
                         MASS15:=0.32
          AND          DO: Assign Variable
                         RIP$:="Y"

        OR             DO: Succeed
          AND          DO: Assign Variable
                         RIP$:="N"



60]  SPL
        IF             DO: Test Expression
                         SPL$="N"

        OR             DO: Print Form
          AND          DO: Print Form
                         SPL
                         ---
                         WIDTH OF SPL REQUIRED IS[SPLW.] mm

                         NEAREST SPL WIDTH AVAILABLE IS[NSPLW] mm

                         WEIGHT OF[NSPLW] mm SPL IS[MASS13] kgs/km

                         DIAMETER OF CABLE OUTSIDE SPL IS[DIAMAPLSPL.] mm
          AND          DO: Print Form
```

```
          AND          DO: Display Form
                          END OF PRINT OUT SHEET   -   WIND ON TO NEXT SHEET


                                         PRESS ANY KEY TO CONTINUE



61]  SPL BEDDING SHEATH
        IF             DO: Yes/No Question
                                IS AN SPL BEDDING SHEATH REQUIRED  ?
          AND          DO: Assign Variable
                         SPLBS$:="Y"
          AND          DO: Display Form
                           ENTER RADIAL THICKNESS OF BEDDING SHEATH (mm) ?

                                                   <RTBS>
          AND          DO: Assign Variable
                         A10A:=(((DIAM2+2*RTBS)/2000)^2)*PI
          AND          DO: Assign Variable
                         A10B:=((DIAM2/2000)^2)*PI
          AND          DO: Assign Variable
                         A10:=A10A-A10B
          AND          DO: Menu Question  BSM$
                                  ENTER BEDDING SHEATH MATERIAL   ?

                                        {LDPE}     {MDPE}     {HDPE}
     +    AND [    8] BEDDING SHEATH MATERIAL - DENSITY
          AND          DO: Assign Variable
                         MASS12:=A10*1000*DENSITY2
     +    AND [   17] DIAMETER OF SPL BEDDING SHEATH

        OR             DO: Succeed



62]  STEEL PLASTIC LAMINATE
        IF             DO: Assign Variable
                         SPL$:="N"
          AND          DO: Yes/No Question
                           IS A "STEEL PLASTIC LAMINATE" RODENT/MOISTURE
                           BARRIER REQUIRED  ?
          AND          DO: Assign Variable
                         SPL$:="Y"
          AND          DO: Test Expression
                         APL$="N"
     +    AND [   61] SPL BEDDING SHEATH
          AND          DO: Assign Variable
                         DIAM3:=DIAM2+(2*RTBS)+2
          AND          DO: Assign Variable
                         CIRCUM1:=(DIAM2+(2*RTBS)+2)*PI
          AND          DO: Assign Variable
                         SPLW:=CIRCUM1+4
          AND          DO: Display Form
                                  SPL WIDTH REQUIRED IS [SPLW.] mm


                               ENTER NEAREST SPL WIDTH AVAILABLE ? <NSPLW>
          AND          DO: Assign Variable
                         MASS13:=(NSPLW*1.326*15/100)+NSPLW*1.326
```

```
        AND          DO: Assign Variable
                       DIAMAPLSPL:=DIAM3
        AND          DO: Assign Variable
                       DIAMSPL:=DIAM3

      OR             DO: Test Expression
                       SPL$="Y"
  +     AND [   61] SPL BEDDING SHEATH
        AND          DO: Assign Variable
                       DIAMAPLSPL:=DIAM3+(2*RTBS)+2
        AND          DO: Assign Variable
                       CIRCUM1:=(DIAM3+(2*RTBS)+2)*PI
        AND          DO: Assign Variable
                       SPLW:=CIRCUM1+4
        AND          DO: Display Form
                               SPL WIDTH REQUIRED IS[SPLW.] mm

                          ENTER NEAREST SPL WIDTH AVAILABLE ? <NSPLW>
        AND          DO: Assign Variable
                       MASS13:=(NSPLW*1.326*15/100)+NSPLW*1.326

      OR             DO: Assign Variable
                       SPLBS$:="N"
        AND          DO: Assign Variable
                       BSM$:="DEFAULT"
  +     AND [   21] DIAMETER UNDER STEEL WIRE ARMOUR BEDDING SHEATH
        AND          DO: Succeed



63] STEEL STRENGTH MEMBER                                 Sp
      IF             DO: Assign Variable
                       LOOP:=LOOP+1
  +     AND [   18] DIAMETER OF STEEL
        AND          DO: Test Expression
                       DIAMETER<=DIAMO-0.5
        AND          DO: Assign Variable
                       RTIS:=(DIAMO-DIAMETER)/2
        AND          DO: Assign Variable
                       MASS1:=5.4*(DIAMETER^2)
        AND          DO: Assign Variable
                       A1:=PI*((DIAMO/2000)^2)
        AND          DO: Assign Variable
                       A2:=PI*(((DIAMETER/2000))^2)
        AND          DO: Assign Variable
                       MASS2:=(A1-A2)*DENSITY*1000
  +     AND [   70] STRESS
        AND          DO: Assign Variable
                       TOTALM1:=MASS1+MASS2+MASS3+MASS4+MASS5+MASS6+MASS7
        AND          DO: Assign Variable
                       TOTALM2:=MASS8+MASS9+MASS10+MASS11+MASS12+MASS13
        AND          DO: Assign Variable
                       TOTALM3:=MASS14+MASS15+MASS16+MASS17
        AND          DO: Assign Variable
                       TOTALM:=TOTALM1+TOTALM2+TOTALM3
        AND          DO: Assign Variable
                       WEIGHT:=TOTALM*9.81
        AND          DO: Assign Variable
                       CSR:=CSF*WEIGHT
        AND          DO: Test Expression
                       STRESS>=CSR
```

```
    OR              DO: Test Expression
                      DIAMETER<=DIAMO-0.5
      AND           DO: Restart Rule

    OR              DO: Display Form
                                --------  CONCLUSION  --------

                         CABLE CANNOT CONFORM TO STRENGTH REQUIREMENT
      AND           DO: Assign Variable
                      PRINT:=1



64]  STEEL WIRE ARMOUR
       IF           DO: Yes/No Question
                              IS A STEEL WIRE ARMOUR REQUIRED  ?
  +    AND [   65] STEEL WIRE ARMOUR BEDDING SHEATH
       AND          DO: Menu Question   DIAMSTEELWIRES
                        ENTER DIAMETER OF STEEL WIRES REQUIRED (mm)   ?


                                  {0.9}     {1.25}     {1.6}
  +    AND [   19] DIAMETER OF STEEL WIRES
       AND          DO: Assign Variable
                      DIAMSWA:=DIAMSWABS+(2*DSW)
       AND          DO: Assign Variable
                      SWAPITCHDIAM:=DIAMSWABS+DSW
       AND          DO: Display Form
                        ENTER STEEL WIRE ARMOUR LAY ANGLE (degrees)   ?


                                         <SWALA>
       AND          DO: Assign Variable
                      NSW1:=DSW/(SWAPITCHDIAM*COS(SWALA*PI/180))
       AND          DO: Assign Variable
                      SWALL:=PI*SWAPITCHDIAM/TAN(SWALA*PI/180)
       AND          DO: Assign Variable
                      NSW:=PI/ARCSIN(NSW1)
       AND          DO: Assign Variable
                      ANSW1:=(NSW*0.97)-0.3
       AND          DO: Assign Variable
                      ANSW:=INT(ANSW1)
       AND          DO: Assign Variable
                      A12:=ANSW*(PI*(DSW/2000)^2)
       AND          DO: Assign Variable
                      MASS17:=A12*1000*7700
       AND          DO: Assign Variable
                      SWA$:="Y"
       AND          DO: Assign Variable
                      SWABS$:="Y"

     OR             DO: Assign Variable
                      SWA$:="N"
       AND          DO: Assign Variable
                      SWABS$:="N"
       AND          DO: Assign Variable
                      SWABSM$:="DEFAULT"
```

```
---------
65]  STEEL WIRE ARMOUR BEDDING SHEATH
       IF                DO: Yes/No Question
                           IS A STEEL WIRE ARMOUR BEDDING SHEATH REQUIRED  ?
         AND             DO: Display Form
                              ENTER RADIAL THICKNESS OF STEEL WIRE ARMOUR
                              BEDDING SHEATH  ?

                                              <RTSWABS>
         AND             DO: Assign Variable
                           DIAMSWABS:=DIAMAPLSPL+2*RTSWABS
         AND             DO: Assign Variable
                           A11A:=PI*((DIAMSWABS/2000)^2)
         AND             DO: Assign Variable
                           A11B:=PI*((DIAMAPLSPL/2000)^2)
         AND             DO: Assign Variable
                           A11:=A11A-A11B
         AND             DO: Menu Question  SWABSM$
                                   ENTER BEDDING SHEATH MATERIAL  ?


                                     {LDPE}    {MDPE}    {HDPE}
      +   AND [   71] SWABSM - DENSITY
          AND            DO: Assign Variable
                           MASS16:=A11*1000*DENSITY3

       OR                DO: Assign Variable
                           SWABSM$:="DEFAULT"



66]  STRANDING PROCESS
       IF                DO: Print Form
         AND             DO: Print Form
                           STRANDING
                           ---------
                           LAY LENGTH OF STRANDED ELEMENTS IS[LAYLENGTH] mm

                           LAYANGLE IS[LAYANGLE.] degrees
         AND             DO: Print Form



67]  STRENGTH
       IF                DO: Test Expression
                           SWA$="N"
         AND             DO: Print Form
                           CABLE STRENGTH/WEIGHT
                           ---------------------
                           MAXIMUM PULLING LOAD ON A[DIAMETER. ] mm [SMM$]
                           STRENGTH MEMBER AT[STRAI.N]% STRAIN
                           IS[STRESS] Newtons
         AND             DO: Print Form

       OR                DO: Print Form
                           CABLE STRENGTH/WEIGHT
                           ---------------------
                           MAXIMUM PULLING LOAD ON A[DIAMETER. ] mm [SMM$]
                           STRENGTH MEMBER, AND STEEL WIRE ARMOURING
                           AT[STRAI.N]% STRAIN IS[STRESS] Newtons
         AND             DO: Print Form
```

```
68]  STRENGTH MEMBER MATERIAL  -  MODULUS
        IF                DO: Test Expression
                            SMM$="STEEL"
          AND             DO: Assign Variable
                            MODULUS:=1.55*100000000000
          AND             DO: Assign Variable
                            MODULUS1:=1.55*100000000000

        OR                DO: Test Expression
                            SMM$="GRP"
          AND             DO: Assign Variable
                            MODULUS:=5*10000000000
          AND             DO: Assign Variable
                            MODULUS1:=1.55*100000000000



 69]  STRENGTH/WEIGHT
        IF                DO: Print Form
    +     AND [   67]    STRENGTH
          AND             DO: Print Form
                            OVERALL WEIGHT OF CABLE IS[TOTALM] kgs/km

                            CABLE STRENGTH REQUIRED FOR[CSF.] x W STRESS
                            IS [CSR] Newtons
          AND             DO: Print Form
          AND             DO: Print Form
                            CABLE STRENGTH RATIO AVAILABLE IS [W.  ] x W
          AND             DO: Print Form
          AND             DO: Print Form
          AND             DO: Print Form
                            CABLE DIAMETER
                            --------------
                            OVERALL CABLE DIAMETER IS[DIAM4.] mm



                            ----------  DESIGN COMPLETE  ----------
          AND             DO: Display Form
                              END OF PRINT OUT SHEET  -  WIND ON TO NEXT SHEET



                                         PRESS ANY KEY TO CONTINUE



                                                                   Sp
 70]  STRESS
        IF                DO: Test Expression
                            SWA$="N"
          AND             DO: Assign Variable
                            STRESS:=MODULUS*PI*((DIAMETER/2000)^2)*STRAIN*0.01

        OR                DO: Assign Variable
                            STRESS:=MODULUS1*A12*STRAIN*0.01


[ 71]  SWABSM  -  DENSITY
```

```
        IF           DO: Test Expression
                       SWABSM$="LDPE"
          AND        DO: Assign Variable
                       DENSITY3:=925

        OR           DO: Test Expression
                       SWABSM$="MDPE"
          AND        DO: Assign Variable
                       DENSITY3:=940

        OR           DO: Test Expression
                       SWABSM$="HDPE"
          AND        DO: Assign Variable
                       DENSITY3:=950



72]  SYNTEC
        IF           DO: Test Expression
                       SR$="N"

        OR           DO: Print Form
          AND        DO: Test Expression
                       SR<500
          AND        DO: Print Form
                       FILLING COMPOUND - SYNTEC RHEOGEL
                       ---------------------------------
                       WEIGHT OF SYNTEC RHEOGEL[SR] IS[MASS11] kgs/km
          AND        DO: Print Form
          AND        DO: Display Form
                        END OF PRINT OUT SHEET  -  WIND ON TO NEXT SHEET


                                  PRESS ANY KEY TO CONTINUE

        OR           DO: Print Form
                       FILLING COMPOUND - INSOJELL 1921
                       --------------------------------
                       WEIGHT OF INSOJELL 1921 IS[MASS11] kgs/km
          AND        DO: Print Form
          AND        DO: Display Form
                        END OF PRINT OUT SHEET  -  WIND ON TO NEXT SHEET



73]  SYNTEC TYPE
        IF           DO: Test Expression
                       SRO=1
          AND        DO: Assign Variable
                       SR:=90

        OR           DO: Test Expression
                       SRO=2
          AND        DO: Assign Variable
                       SR:=210

        OR           DO: Test Expression
                       SRO=3
          AND        DO: Assign Variable
                       SR:=1921
```

```
 74]  TEXT VARIABLES
        IF               DO: User Program
                           OPENW("CABLE");
                           WRITETXT("[APL$]");NEWLINE();
                           WRITETXT("[SPL$]");NEWLINE();
                           WRITETXT("[SPLBS$]");NEWLINE();
                           WRITETXT("[SR$]");NEWLINE();
                           WRITETXT("[SWA$]");NEWLINE();
                           WRITETXT("[SWABS$]");NEWLINE();
                           WRITETXT("[BSM$   ]");NEWLINE();
                           WRITETXT("[ISM$   ]");NEWLINE();
                           CLOSE();
           AND           DO: User Program
                           OPENW("CABLE");
                           WRITETXT("[OSM$   ]");NEWLINE();
                           WRITETXT("[SMM$]");NEWLINE();
                           WRITETXT("[SWABSM$]");NEWLINE();
                           WRITETXT("[ID$]");NEWLINE();
                           WRITETXT("[RIP$]");NEWLINE();
                           CLOSE();


 75]  TRANSFER PARAMETERS TO ASCII FILE
       + IF     [  74] TEXT VARIABLES
       +    AND [  41] NUMERICAL VARIABLES


 76]  TUBE DIAMETER
        IF               DO: Test Expression
                           DO=1
          AND            DO: Assign Variable
                           D:=1.5

        OR               DO: Test Expression
                           DO=2
          AND            DO: Assign Variable
                           D:=2.2

        OR               DO: Test Expression
                           DO=3
          AND            DO: Assign Variable
                           D:=3.0


 77]  TUBES
       + IF     [  36] INTERNAL DIAMETER OF TUBE
          AND            DO: Display Form
                                 ENTER NUMBER OF TUBES REQUIRED ?  <NT>
          AND            DO: Assign Variable
                           DENVEST:=1287.97
          AND            DO: Assign Variable
                           A5:=((D/2000)^2)*PI
          AND            DO: Assign Variable
                           A6:=((IDT/2000)^2)*PI
          AND            DO: Assign Variable
```

```
                          CSAT:=A5-A6
          AND            DO: Assign Variable
                          MASS6:=CSAT*1000*DENVEST*NT


78]                      CRYSTAL  MASTER  RULE
     + IF     [   12] CHECK ASCII INTERFACE IS LOADED AND SYSTEM CLEAR
     +   AND [   38] LOOSE TUBE CABLES

     + OR     [   57] QUIT CRYSTAL
```

APPENDIX C

Printer Output of Expert System Run

DATE : 13 / 7 / 1988

LOOSE TUBE CABLE - EXPERT SYSTEM

CABLE DESCRIPTION FOR A 16 FIBRE CABLE

SUMMARY

CONSTRUCTION : LOOSE TUBE	NUMBER OF ELEMENTS : 9
NUMBER OF TUBES : 4	NUMBER OF FILLERS : 3
NUMBER OF COPPER PAIRS : 2	INSTALLATION : BURIED
FILLED : YES	METALLIC : YES
ARMOURED : YES	FIBREMODE : SINGLEMODE
CUSTOMER : British Telecom	REFERENCE NUMBER : RA 3079

```
CENTRAL MEMBER
--------------
DIAMETER OF CORE REQUIRED TO SUPPORT  9 ELEMENTS
IS      4.6 mm

DIAMETER OF STEEL STRENGTH MEMBER REQUIRED
IS        1.83 mm

RADIAL THICKNESS OF LDPE  INNER SHEATH MATERIAL
IS   1.35 mm

WEIGHT OF STEEL  STRENGTH MEMBER IS      18 kgs/km

WEIGHT OF LDPE  INNER SHEATH IS      12 kgs/km


TUBES, FILLERS AND COPPER PAIRS
-------------------------------
DIAMETER OF TUBES & FILLERS ARE 2.2 mm

WEIGHT OF   4 TUBES IS      10 kgs/km

DIAMETER OF SINGLE COPPER WIRE IS   0.6 mm

RADIAL THICKNESS OF COPPER INSULATION IS   0.25 mm

WEIGHT OF    2 COPPER PAIR(S) IS      10 kgs/km

WEIGHT OF COPPER INSULATION FOR    2 PAIRS
IS        3 kgs/km

WEIGHT OF   3 FILLERS IS      11 kgs/km


TUBE FILLING COMPOUND - HYVIS
-----------------------------
WEIGHT OF HYVIS REQUIRED FOR   4 TUBES
IS        6 kgs/km


STRANDING
---------
LAY LENGTH OF STRANDED ELEMENTS IS        200 mm

LAYANGLE IS         6.0 degrees


FILLING COMPOUND - INSOJELL 1921
--------------------------------
WEIGHT OF INSOJELL 1921 IS      13 kgs/km
```

```
PAPER TAPE
----------
NUMBER OF PAPER TAPE LAYERS IS      2

LENGTH OF   19mm WIDE PAPER TAPE REQUIRED PER km
OF CABLE IS 1747 m PER LAYER

ANGLE OF APPLICATION OF PAPER TAPE IS
        56 degrees

PAPER TAPE LAY LENGTH IS        21 mm

TOTAL WEIGHT OF PAPER TAPE IS       5 kgs/km

THICKNESS OF PAPER TAPE IS 0.125 mm

DIAMETER OF CABLE OUTSIDE TAPE IS       9.6 mm


ID TAPE AND RIPCORD
-------------------
WEIGHT OF IDENTIFICATION TAPE IS      0.20 kgs/km

WEIGHT OF RIPCORD IS      0.32 kgs/km


APL
---
WIDTH OF APL REQUIRED IS    41.1 mm

NEAREST APL WIDTH AVAILABLE IS       41 mm

APL THICKNESS IS    0.15 mm

WEIGHT OF       41 mm APL IS       18 kgs/km

DIAMETER OF CABLE OUTSIDE APL IS     10.6 mm


SPL BEDDING SHEATH
------------------
RADIAL THICKNESS OF BEDDING SHEATH IS     1.3 mm

WEIGHT OF LDPE  BEDDING SHEATH IS       41 kgs/km

DIAMETER OF CABLE OUTSIDE BEDDING SHEATH
IS         13.1 mm


SPL
---
WIDTH OF SPL REQUIRED IS    51.5 mm

NEAREST SPL WIDTH AVAILABLE IS       51 mm

WEIGHT OF       51 mm SPL IS       78 kgs/km

DIAMETER OF CABLE OUTSIDE SPL IS          15.1 mm
```

```
STEEL WIRE ARMOUR BEDDING SHEATH
--------------------------------

RADIAL THICKNESS OF STEEL WIRE ARMOUR BEDDING
SHEATH IS        1.5 mm

WEIGHT OF STEEL WIRE ARMOUR BEDDING SHEATH
IS       72 kgs/km

DIAMETER OF CABLE OUTSIDE STEEL WIRE ARMOUR
BEDDING SHEATH IS         18.1 mm


STEEL WIRE ARMOUR
-----------------

NUMBER OF STEEL WIRES REQUIRED IS    45

DIAMETER OF STEEL WIRES ARE   1.25 mm

LAYANGLE OF STEEL WIRE ARMOUR IS     13 degrees

LAYLENGTH OF STEEL WIRE ARMOUR IS    264 mm

WEIGHT OF STEEL WIRE ARMOUR IS     425 kgs/km

DIAMETER OF CABLE OUTSIDE STEEL WIRE ARMOUR
IS       20.6 mm
```

```
OUTER SHEATH
------------
RADIAL THICKNESS OF LDPE  OUTER SHEATH
IS    1.8 mm

WEIGHT OF OUTER SHEATH IS    117 kgs/km

DIAMETER OF CABLE OUTSIDE OUTER SHEATH
IS    24.3 mm


CABLE STRENGTH/WEIGHT
---------------------
MAXIMUM PULLING LOAD ON A        1.83 mm STEEL
STRENGTH MEMBER, AND STEEL WIRE ARMOURING
AT      0.40% STRAIN IS   34238 Newtons

OVERALL WEIGHT OF CABLE IS     840 kgs/km

CABLE STRENGTH REQUIRED FOR   3.00 x W STRESS
IS 24731 Newtons

CABLE STRENGTH RATIO AVAILABLE IS  4.15 x W


CABLE DIAMETER
--------------
OVERALL CABLE DIAMETER IS    24.3 mm



----------  DESIGN COMPLETE  ----------
```

PROCESSES AND SPEEDS

PROCESS 1 -

PROCESS 2 -

PROCESS 3 -

PROCESS 4 -

PROCESS 5 -

PROCESS 6 -

PROCESS 7 -

PROCESS 8 -

PROCESS 9 -

PROCESS 10 -

PROCESS 11 -

PROCESS 12 -

APPENDIX D

Program Drawcable - Screen and Plotter Graphics Program

```
program DRAWCABLE;

{$i Typedef.sys}
{$i Graphix.sys}
{$i Kernel sys}

const pi=3.141592654;

type strng5=string[5];
     strng10=string[10];
     strng15=string[15];
     strng50=string[50];

var textin:array[1..5] of strng10;
    textin1:array[1..8] of char;
    numbersin:array[1..28] of real;

    DIAMSPL,DSPLBS,DIAMAPLSPL,DIAMIOS:real;
    D,DCW,DIAMO,DIAM1,DIAM2,DIAM3,DIAM4,DIAMETER:real;
    DIAMSWA,DIAMSWABS,DSW,IDT,N,NCP,NF,NT,ANSW:real;
    RTIS,OSRT,RTBS,RTCI,SRN,TOTALM,STRESS:real;

    BSM,ISM,OSM,SMM,SWABSM:strng5;
    command1,command2,command3:strng15;

    APL,SPL,SPLBS,SRT,SWA,SWABS,ID,RIP,PLOT,LABELPLOT,RPT,RPT1:CHAR;


procedure READ;

var i:integer;filvar:text;

begin
     assign(filvar,'cable.asc');
     reset(filvar);
     i:=1;
     while (not eof(filvar)) and (i<7) do

     begin
          readln(filvar,textin1[i]);
          i:=i+1;
     end;

     i:=1;
     while (not eof(filvar)) and (i<6) do

     begin
          readln(filvar,textin[i]);
          i:=i+1;
     end;

     i:=7;
     while (not eof(filvar)) and (i<9) do

     begin
          readln(filvar,textin1[i]);
          i:=i+1;
     end;

     i:=1;
     while (not eof(filvar)) and (i<29) do
```

```
     begin
           readln(filvar,numbersin[i]);
           i:=i+1;
     end;

     close(filvar);

     D:=(numbersin[1]);
     DCW:=(numbersin[2]);
     DIAM0:=(numbersin[3]);
     DIAM1:=(numbersin[4]);
     DIAM2:=(numbersin[5]);
     DIAM3:=(numbersin[6]);
     DIAM4:=(numbersin[7]);
     DIAMETER:=(numbersin[8]);
     DIAMAPLSPL:=(numbersin[9]);
     DIAMIOS:=(numbersin[10]);
     DIAMSPL:=(numbersin[11]);
     DSPLBS:=(numbersin[12]);
     DIAMSWA:=(numbersin[13]);
     DIAMSWABS:=(numbersin[14]);
     DSW:=(numbersin[15]);
     IDT:=(numbersin[16]);
     N:=(numbersin[17]);
     NCP:=(numbersin[18]);
     NF:=(numbersin[19]);
     NT:=(numbersin[20]);
     ANSW:=(numbersin[21]);
     OSRT:=(numbersin[22]);
     RTBS:=(numbersin[23]);
     RTCI:=(numbersin[24]);
     RTIS:=(numbersin[25]);
     SRN:=(numbersin[26]);
     TOTALM:=(numbersin[27]);
     STRESS:=(numbersin[28]);
     APL:=(textin1[1]);
     BSM:=(textin[1]);
     ID:=(textin1[7]);
     ISM:=(textin[2]);
     OSM:=(textin[3]);
     RIP:=(textin1[8]);
     SMM:=(textin[4]);
     SPL:=(textin1[2]);
     SPLBS:=(textin1[3]);
     SRT:=(textin1[4]);
     SWA:=(textin1[5]);
     SWABS:=(textin1[6]);
     SWABSM:=(textin[5]);
end; (* procedure READ *)


procedure DRAWSCREEN;

var X,Y,R1,R2,R3,R4,R5,scale,angle,angle1,ang,ang1:real;
    DIAMSPLBS,f,X1,Y1,fint,R51,factor,ZZZ,AA,AAA,BBB,CCC,DDD:real;
    num,num1,num4,num5,EEE,FFF:real;
    number,num2,num3,XXX,YYY:real;

begin
     scale:=2/DIAM4;
     angle1:=0;
     angle:=0;
```

iL

```
ang:=2*pi/N;
number:=0;

if NCP>0 then
begin
      f:=N/NCP;
      fint:=int(f);
end;

drawcircle(320,100,(DIAM4*scale));
if SWA=’N’ then
drawcircle(320,100,(DIAMIOS*scale));
drawcircle(320,100,(DIAM2*scale));
drawcircle(320,100,(DIAM1*scale));
drawcircle(320,100,(DIAM0*scale));
drawcircle(320,100,(DIAMETER*scale));


if (APL=’N’) and (SPL=’Y’) and (SWA=’N’) then
drawcircle(320,100,(DSPLBS*scale));

if (APL=’Y’) and (SPL=’Y’) and (SWA=’N’) then
begin
      drawcircle(320,100,(DIAM3*scale));
      drawcircle(320,100,(DSPLBS*scale));
end;

if (APL=’N’) and (SPL=’N’) and (SWA=’Y’) then
drawcircle(320,100,(DIAMSWABS*scale));

if (APL=’Y’) and (SPL=’N’) and (SWA=’Y’) then
drawcircle(320,100,(DIAM3*scale));

if (APL=’N’) and (SPL=’Y’) and (SWA=’Y’) then
begin
      drawcircle(320,100,(DSPLBS*scale));
      drawcircle(320,100,(DIAM3*scale));
end;

if (APL=’Y’) and (SPL=’Y’) and (SWA=’Y’) then
begin
      drawcircle(320,100,(DIAM3*scale));
      drawcircle(320,100,(DSPLBS*scale));
      drawcircle(320,100,(DIAMAPLSPL*scale));
end;

if SWA=’Y’ then
begin
      drawcircle(320,100,(DIAMSWABS*scale));
      repeat
              ang1:=2*pi/ANSW;
              X:=320+((DIAMSWABS/2+DSW/2)*cos(angle1))*200*scale;
              Y:=100+((DIAMSWABS/2+DSW/2)*sin(angle1))*86*scale;
              R3:=DSW*scale;
              drawcircle(X,Y,R3);
              angle1:=angle1+ang1;
      until angle1>=2*pi-ang1;
end;

if NCP>0 then
```

```
begin
      repeat
             R4:=(DCW)*scale;
             R51:=((2*RTCI)+DCW)/2;
             R5:=((2*RTCI)+DCW)*scale;
             X:=320+((DIAMO/2+R51)*cos(angle))*200*scale;
             Y:=100+((DIAMO/2+R51)*sin(angle))*86*scale;
             X1:=320+((DIAMO/2+(3*R51))*cos(angle))*200*scale;
             Y1:=100+((DIAMO/2+(3*R51))*sin(angle))*86*scale;
             drawcircle(X,Y,R5);
             drawcircle(X,Y,R4);
             drawcircle(X1,Y1,R5);
             drawcircle(X1,Y1,R4);
             number:=number+1;
             angle:=angle+(fint*ang);
      until number=NCP;
end;

angle:=0;

repeat
       X:=320+((D/2+DIAMO/2)*cos(angle))*200*scale;
       Y:=100+((D/2+DIAMO/2)*sin(angle))*86*scale;
       R1:=D*scale;
       drawcircle(X,Y,R1);
       angle:=angle+ang;
until angle>=2*pi-ang;

if NCP>0 then
begin
      angle:=0;
      num:=0;
      num1:=0;
      num2:=0;
      num3:=0;
      num4:=0;
      factor:=(N-(fint*NCP));
      XXX:=0;
      YYY:=0;
      AA:=0;
      AAA:=0;
      EEE:=0;

      if NF>0 then
      begin

            if NF>(fint-1) then
            begin
                  AA:=NF/(fint-1);
                  AAA:=int(AA+0.995);
            end;

            repeat
                   angle:=angle+ang;
                   num:=num+1;
                   num3:=num3+1;
                   if NF>(fint-1) then
                   ZZZ:=(fint-1) else
                   ZZZ:=NF;
            until num3=ZZZ;
            XXX:=1;
      end;
```

```
if AAA>1 then
begin
     BBB:=((AAA*(fint-1))-NF);
     FFF:=(fint-1)-BBB;

     if BBB=0 then
     FFF:=(fint-1);

     num4:=1;
     num5:=0;
     repeat
           angle:=angle+ang;
           num4:=num4+1;
           repeat
                 num5:=num5+1;
                 angle:=angle+ang;
                 if num4=AAA then
                 CCC:=FFF else
                 CCC:=(fint-1);
           until num5=CCC;
           num5:=0;
     until num4=AAA;
end;


if (NF=0) or (XXX=0) then
num:=0;

if AAA>1 then
num1:=AAA-1;

if AAA>1 then
num:=FFF;

repeat
      num1:=num1+1;
      repeat

            if (num1=NCP) and (factor>0) then
            EEE:=1;

            if (num=(fint-1)) and (EEE=0) then
            begin
                 angle:=angle+ang:
                 num:=0;
                 num1:=num1+1;
            end;

            angle:=angle+ang;
            R2:=IDT*scale;
            X:=320+((D/2+DIAMO/2)*cos(angle))*200*scale;
            Y:=100+((D/2+DIAMO/2)*sin(angle))*86*scale;
            drawcircle(X,Y,R2);
            num:=num+1;

            if EEE=1 then
            DDD:=fint+(factor-1) else
            DDD:=fint-1;

      until num=DDD;
      angle:=angle+ang;
```

```
               num:=0;
         until num1=NCP;

    end;

    if (NCP=0) and (NF=0) then
    begin
         angle:=0;
         repeat
               X:=320+((D/2+DIAMO/2)*cos(angle))*200*scale;
               Y:=100+((D/2+DIAMO/2)*sin(angle))*86*scale;
               R2:=IDT*scale;
               drawcircle(X,Y,R2);
               angle:=angle+ang;
         until angle>=2*pi-ang;
    end;

    if (NCP=0) and (NF>0) then
    begin
         angle:=0;
         repeat
               X:=320+((D/2+DIAMO/2)*cos(angle))*200*scale;
               Y:=100+((D/2+DIAMO/2)*sin(angle))*86*scale;
               R2:=IDT*scale;
               drawcircle(X,Y,R2);
               angle:=angle+ang;
         until angle>=2*pi-(NF*ang)-ang;
    end;

end; (* procedure DRAWSCREEN *)



procedure PENUP(a,b:real);

var x,y:string[5]:
   a1,b1:integer;

begin
    a1:=round(a);
    b1:=round(b);
    str(a1:5,x);
    str(b1:5,y);
    command3:='pu'+x+','+y+';';
end;



procedure PLOTABSOLUTE(a,b:real);

var x,y:string[5];
   a1,b1:integer;

begin
    a1:=round(a);
    b1:=round(b);
    str(a1:5,x);
    str(b1:5,y);
```

```
     command1:='pa'+x+','+y+';';
end;



procedure PLOTCIRCLE(radius:real);

var r:string[5];
    radius1:integer;

begin
     radiusi:=round(radius);
     str(radius1:3,r);
     command2:='ci'+r+',3;';
end;



procedure DRAWPLOTTER;

var X,Y,R1,R2,R3,R4,R5,scale,angle,angle1,ang,ang1:real;
    DIAMSPLBS,f,X1,Y1,fint,R51,factor,ZZZ,AA,AAA,BBB,CCC,DDD:real;
    num,num1,num4,num5,EEE,FFF:real;
    number,num2,num3,XXX,YYY:real;
    DIAM40,DIAMIOS1.DIAM20,DIAM10,DIAM00,DIAMETER1:real;
    DSPLBS1,DIAM30,DIAMSWABS1,DIAMAPLSPL1,DIAMSPLBS1:real;
    TITLE,TITLE1:strng50;
    TITLE2:integer;
    TITLE3:real;

begin
     TITLE:='';
     writeln('Please input title for plotter drawing - Max 50 characters'
     writeln;
     readln(TITLE1);
     TITLE:='LB'+TITLE1;
     TITLE2:=length(TITLE1);
     TITLE3:=TITLE2*178;

     command1:='';
     command2:='';
     command3:='';
     scale:=2500/DIAM4;
     angle1:=0;
     angle:=0;
     ang:=2*pi/N;
     number:=0;

     if NCP>0 then
     begin
          f:=N/NCP;
          fint:=int(f);
     end;

     write(aux,'sp1;','pu0,0;','pd;');
     write(aux,'pa0,7650;','pa10900,7650;','pa10900,0;','pa0,0;','pu;');
     write(aux,'si 0.3,0.43;');
     write(aux,'sp3;','pu1000,7250;',TITLE,chr(3),'pu;');
     write(aux,'si 0.19,0.27;');

     if TITLE3>0 then
     begin
          write(aux,'sp2;','pu1000,7150;','pd;');
          X:=1000+TITLE3;
```

```
    Y:=7150;
    PLOTABSOLUTE(x,y);
    write(aux,command1);
    write(aux,'pu;','sp1;','pu3000,3825;');
end
else
write(aux,'sp1;','pu3000,3825;');

DIAM40:=DIAM4*scale;
PLOTCIRCLE(DIAM40);
write(aux,command2);

if SWA='N' then
begin
    DIAMIOS1:=DIAMIOS*scale;
    PLOTCIRCLE(DIAMIOS1);
    write(aux,command2);
end;

DIAM20:=DIAM2*scale;
PLOTCIRCLE(DIAM20);
write(aux,command2);
DIAM10:=DIAM1*scale;
PLOTCIRCLE(DIAM10);
write(aux,command2);
DIAM00:=DIAM0*scale;
PLOTCIRCLE(DIAM00);
write(aux,command2);
DIAMETER1:=DIAMETER*scale;
PLOTCIRCLE(DIAMETER1);
write(aux,command2);

DSPLBS1:=DSPLBS*scale;
DIAM30:=DIAM3*scale;
DIAMSWABS1:=DIAMSWABS*scale;
DIAMAPLSPL1:=DIAMAPLSPL*scale;
DIAMSPLBS1:=DIAMSPLBS*scale;

if (APL='N') and (SPL='Y') and (SWA='N') then
begin
    PLOTCIRCLE(DSPLBS1);
    write(aux,command2);
end;

if (APL='Y') and (SPL='Y') and (SWA='N') then
begin
    PLOTCIRCLE(DIAM30);
    write(aux,command2);
    PLOTCIRCLE(DSPLBS1);
    write(aux,command2);
end;

if (APL='N') and (SPL='N') and (SWA='Y') then
begin
    PLOTCIRCLE(DIAMSWABS1);
    write(aux,command2);
end;

if (APL='Y') and (SPL='N') and (SWA='Y') then
begin
    PLOTCIRCLE(DIAM30);
    write(aux,command2);
end;

if (APL='N') and (SPL='Y') and (SWA='Y') then
```

```
begin
      PLOTCIRCLE(DIAMSPLBS1);
      write(aux,command1);
      PLOTCIRCLE(DIAM30);
      write(aux,command2);
end;

if (APL='Y') and (SPL='Y') and (SWA='Y') then
begin
      PLOTCIRCLE(DIAM30);
      write(aux,command2);
      PLOTCIRCLE(DSPLBS1);
      write(aux,command2);
      PLOTCIRCLE(DIAMAPLSPL1);
      write(aux,command2);
end;

if SWA='Y' then
begin
      PLOTCIRCLE(DIAMSWABS1);
      write(aux,command2);
end;

repeat
       X:=3000+((D/2+DIAMO/2)*cos(angle))*scale*2;
       Y:=3825+((D/2+DIAMO/2)*sin(angle))*scale*2;
       R1:=D*scale;
       PENUP(X,Y);
       write(aux,command3);
       PLOTCIRCLE(R1);
       write(aux,command2);
       angle:=angle+ang;
       delay(5000);
until  angle>=2*pi-ang;

angle:=0;

if (NCP=0) and (NF=0) then
begin
      angle:=0;
      repeat
              X:=3000+((D/2+DIAMO/2)*cos(angle))*scale*2;
              Y:=3825+((D/2+DIAMO/2)*sin(angle))*scale*2;
              R2:=IDT*scale;
              PENUP(X,Y);
              write(aux,command3);
              PLOTCIRCLE(R2);
              write(aux,command2);
              angle:=angle+ang;
      until   angle>=2*pi-ang;
end;

if (NCP=0) and (NF>0) then
begin
      angle:=2*pi;
      repeat
              X:=3000+((D/2+DIAMO/2)*cos(angle))*scale*2;
              Y:=3825+((D/2+DIAMO/2)*sin(angle))*scale*2;
              R2:=IDT*scale;
              PENUP(X,Y);
```

```
         write(aux,command3);
         PLOTCIRCLE(R2);
         write(aux,command2);
         angle:=angle-ang;
    until angle<=(NF*ang)+ang;
end;

if SWA='Y' then
begin
    repeat
         ang1:=2*pi/ANSW;
         X:=3000+((DIAMSWABS/2+DSW/2)*cos(angle1))*scale*2;
         Y:=3825+((DIAMSWABS/2+DSW/2)*sin(angle1))*scale*2;
         R3:=DSW*scale;
         PENUP(X,Y);
         write(aux,command3);
         PLOTCIRCLE(R3);
         write(aux,command2);
         angle1:=angle1+ang1;
         delay(10000);
    until angle1>=2*pi-ang1;
end;

if NCP>0 then
begin
    repeat
         R4:=DCW*scale;
         R51:=((2*RTCI)+DCW)/2;
         R5:=((2*RTCI)+DCW)*scale;
         X:=3000+((DIAMO/2+R51)*cos(angle))*scale*2;
         Y:=3825+((DIAMO/2+R51)*sin(angle))*scale*2;
         X1:=3000+((DIAMO/2+(3*R51))*cos(angle))*scale*2;
         Y1:=3825+((DIAMO/2+(3*R51))*sin(angle))*scale*2;
         PENUP(X,Y);
         write(aux,command3);
         PLOTCIRCLE(R5);
         write(aux,command2);
         PLOTCIRCLE(R4);
         write(aux,command2);
         PENUP(X1,Y1);
         write(aux,command3);
         PLOTCIRCLE(R5);
         write(aux,command2);
         PLOTCIRCLE(R4);
         write(aux,command2);
         number:=number+1;
         angle:=angle+(fint*ang);
         delay(10000);
    until number=NCP;
end;

if NCP>0 then
begin
    angle:=0;
    num:=0;
    num1:=0;
    num2:=0;
    num3:=0;
```

```
num4:=0;
factor:=(N-(fint*NCP));
XXX:=0;
YYY:=0;
AA:=0;
AAA:=0;
EEE:=0;

if NF>0 then
begin
    if NF>(fint-1) then
    begin
        AA:=NF/(fint-1);
        AAA:=int(AA+0.95);
    end;

     repeat
          angle:=angle+ang;
          num:=num+1;
          num3:=num3+1;
          if NF>(fint-1) then
          ZZZ:=(fint-1) else
          ZZZ:=NF;
     until num3=ZZZ;
     XXX:=1;
end;

if AAA>1 then
begin
    BBB:=((AAA*(fint-1))-NF);
    FFF:=(fint-1)-BBB;

    if BBB=0 then
    FFF:=(fint-1);

    num4:=1;
    num5:=0;
    repeat
         angle:=angle+ang;
         num4:=num4+1;
         repeat
              num5:=num5+1;
              angle:=angle+ang;
              if num4=AAA then
              CCC:=FFF else
              CCC:=(fint-1);
         until num5=CCC;
         num5:=0;
    until num4=AAA;
end;

if (NF=0) or (XXX=0) then
num:=0;

if AAA>1 then
num1:=AAA-1;

if AAA>1 then
num:=FFF;

repeat
     num1:=num1+1;
     repeat
```

```
                      if (num1=NCP) and (factor>0) then
                      EEE:=1;

                      if (num=(fint-1)) and (EEE=0) then
                      begin
                           angle:=angle+ang;
                           num:=0;
                           num1:=num1+1;
                      end;

                      angle:=angle+ang;
                      R2:=IDT*scale;
                      X:=3000+((D/2+DIAMO/2)*cos(angle))*scale*2;
                      Y:=3825+((D/2+DIAMO/2)*sin(angle))*scale*2;
                      PENUP(X,Y);
                      write(aux,command3);
                      PLOTCIRCLE(R2);
                      write(aux,command2);
                      num:=num+1;
                      if EEE=1 then
                      DDD:=fint+(factor-1) else
                      DDD:=fint-1;

                until num=DDD;
                angle:=angle+ang;
                num:=0;
          until num1=NCP;

     end;

     if ID='Y' then
     begin
          X:=3000;
          Y:=(3805-DIAM20);
          PENUP(x,y);
          write(aux,command3);
          write(aux,'pd;','aa3000,3825,20,3;','pu;');
     end;

     if RIP='Y' then
     begin
          X:=3000+(DIAM20*0.5);
          Y:=3805-(DIAM20*0.8660254);
          PENUP(x,y);
          write(aux,command3);
          write(aux,'pd;','aa3000,3825,7,3;','pu;');
     end;

end;



procedure LABELPLOTTER;

var  diam42,diam43,MBD,x,y:real;
     diam41,diam44,MBD1,TOTALM1,STRESS1:integer;
     diam400,MBD100,TOTALM100,STRESS100,SMM1,SPL100:string[50];
     STRESS10:string[5];
     MBD10,TOTALM10:string[3];
     d4:string[2];
     d41:string[1];
```

```
begin
        diam41:=trunc(diam4);
        diam42:=diam4-diam41;
        diam43:=diam42*10;
        diam44:=round(diam43);
        str(diam44:1,d41);
        str(diam41:2,d4);
        diam400:='lbCable Diameter '+d4+'.'+d41+'mm'+chr(3);
        write(aux,'sp3;','si0.15,0.23;','pu300,900;');
        write(aux,diam400,'pu300,650;');

        if (SWA='N') and (SPL='N') then
        MBD:=12*DIAM4;

        if (SPL='Y') and (SWA='N') then
        MBD:=15*DIAM4;

        if (SWA='Y') then
        MBD:=20*DIAM4;

        MBD1:=round(MBD);
        str(MBD1:3,MBD10);
        MBD100:='lbMin Bend Diameter '+MBD10+'mm'+chr(3);
        write(aux,MBD100,'pu300,400;');

        TOTALM1:=round(TOTALM);
        str(TOTALM1:3,TOTALM10);
        TOTALM100:='lbCable Weight '+TOTALM10+'kgs/km'+chr(3);
        write(aux,TOTALM100,'pu300,150;');

        STRESS1:=round(STRESS);
        str(STRESS1:5,STRESS10);
        STRESS100:='lbTensile Strength '+STRESS10+'N'+chr(3);
        write(aux,STRESS100,'pu6665,6325;');

        write(aux,'si0.19,0.27;');

        delay(20000);

        x:=6665;
        y:=6725;

        y:=y-400;
        PENUP(x,y);
        write(aux,command3);
        write(aux,'lbPolyethylene Sheath',chr(3));

        if SWA='Y' then
        begin
            y:=y-400;
            PENUP(x,y);
            write(aux,command3);
            write(aux,'lbGalvanized Steel Wire Armour',chr(3));
        end;

        if SPLBS='Y' then
        begin
            y:=y-400;
            PENUP(x,y);
            write(aux,command3);
            write(aux,'lbPolyethylene Bedding Sheath',chr(3));
```

```
end;

if SPL='Y' then
begin
      y:=y-400;
      PENUP(x,y);
      write(aux,command3);
      SPL100:='lbCorrugated Steel Plastic Laminate'+chr(3);
      write(aux,SPL100);
end;

if (SWABS='Y') and (SPLBS='N') then
begin
      y:=y-400;
      PENUP(x,y);
      write(aux,command3);
      write(aux,'lbPolyethylene Bedding Sheath',chr(3));
end;

if APL='Y' then
begin
      y:=y-400;
      PENUP(x,y);
      write(aux,command3);
      write(aux,'lbAluminium Plastic Laminate',chr(3));
end;

y:=y-400;
PENUP(x,y);
write(aux,command3);
write(aux,'lbPaper Tape',chr(3));

if NF>0 then
begin
      y:=y-400;
      PENUP(x,y);
      write(aux,command3);
      write(aux,'lbPolyethylene Filler',chr(3));
end;

delay(10000);

y:=y-400;
PENUP(x,y);
write(aux,command3);
if (SMM='STEEL') or (SMM='steel') then
SMM1:='lbSheathed Steel Central Strain Member'+chr(3) else
SMM1:='lbSheathed GRP Central Strain Member'+chr(3);
write(aux,SMM1);

if NCP>0 then
begin
      y:=y-400;
      PENUP(x,y);
      write(aux,command3);
      write(aux,'lbTwisted Copper Pair',chr(3));
end;

y:=y-400;
PENUP(x,y);
write(aux,command3);
write(aux,'lbPolymer Tube',chr(3));

y:=y-400;
```

```
    PENUP(x,y);
    write(aux,command3);
    write(aux,'lbOptical Fibres',chr(3));

    y:=y-400;
    PENUP(x,y);
    write(aux,command3);
    write(aux,'lbWater Blocking Compound',chr(3));

    if RIP='Y' then
    begin
         y:=y-400;
         PENUP(x,y);
         write(aux,command3);
         write(aux,'lbRipcord',chr(3));
    end;

    if ID='Y' then
    begin
         y:=y-400;
         PENUP(x,y);
         write(aux,command3);
         write(aux,'lbIdentification Tape',chr(3));
    end;

end;



begin  (* main line *)
       initgraphic;
       READ:
       clearscreen;
       setaspect(1.0);
       drawborder;
       DRAWSCREEN:
       repeat until keypressed;
       leavegraphic;
       clearscreen;
       write('Do you require a hard copy on the plotter (Y/N)  ?    ');
       readln(PLOT);
       clearscreen;
       if (PLOT='Y') or (PLOT='y') then
       begin
            repeat
                  write('Do you require a labelled diagram (Y/N)  ?    ')
                  readln(LABELPLOT);
                  clearscreen;
                  DRAWPLOTTER;
                  if (LABELPLOT='Y') or (LABELPLOT='y') then
                  LABELPLOTTER;
                  clearscreen;
                  write('Do you require another plot (Y/N)  ?    ');
                  readln(RPT);
                  if (RPT='Y') or (RPT='y') then
                  begin
                       RPT1:='Y';
                       writeln('Please insert another sheet of paper');
                       writeln;
```

```
                              writeln;
                          end
                          else RPT1:='N';
                     until RPT1='N';
               end;
end. (* main line *)


C>
```

APPENDIX E

Loose Tube Cable - Advanced Design Rules Program

```
program TUBE;

const pi=3.141592654;

var  K4,M,C,T2,S2,T3:array [1..20] of real;

     T5,U,L,K1,D4,Z5,E,D1,D2,L1,D3,A3,T6,A4,X,T7,FM,D10:real;
     Z1,K3,Z2,S5,S6,ZS,QQ,Z3,Z4,L2,RR,SS,T8:real;

     j,i,N,zzz,xxx:integer;


procedure LOADARRAYS;

begin
     K4[1]:=1;
     K4[2]:=1.2;
     K4[3]:=1.87;
     K4[4]:=2.06;
     K4[5]:=2.25;
     K4[6]:=2.44;
     K4[7]:=2.62;
     K4[8]:=2.81;
     K4[9]:=3.0;
     K4[10]:=3.19;

     T2[1]:=0;S2[1]:=0;
     T2[2]:=0.1207;S2[2]:=0.00057;
     T2[3]:=0.2149;S2[3]:=0.00077;
     T2[4]:=0.3626;S2[4]:=0.00090;
     T2[5]:=0.4833;S2[5]:=0.001;
     T2[6]:=0.6039;S2[6]:=0.0011;
     T2[7]:=0.7251;S2[7]:=0.00117;
     T2[8]:=0.8458;S2[8]:=0.00123;
     T2[9]:=0.9665;S2[9]:=0.00128;
     T2[10]:=1.4498;S2[10]:=0.0015;
     T2[11]:=4.8325;S2[11]:=0.00285;

end;


procedure INPUT;

begin
     clrscr;
     write('Enter Tube Measurement Tension (N) ?  ');readln(T5);
     writeln;
     write('Enter Fibre Measurement Tension (N) ?  ');readln(U);
     writeln;
     write('Enter Tube Length Measured (mm) ?  ');readln(L);
     writeln;
     write('Enter Fibre Diameter (mm) ?  ');readln(D4);
     writeln;
     write('Enter Maximum Allowed Fibre Strain (fract) ?  ');readln(Z5);
     writeln;
     write('Enter Diameter of Strength Member (mm) ?  ');readln(D10);
     writeln;
     write('Enter Strength Member Modulus (N/mm²) ?  ');readln(E);
     writeln;
     write('Enter Diameter of Sheathed Centre (mm) ?  ');readln(D1);
     writeln;
     write('Enter Tube Outer Diameter (mm) ?  ');readln(D2);
```

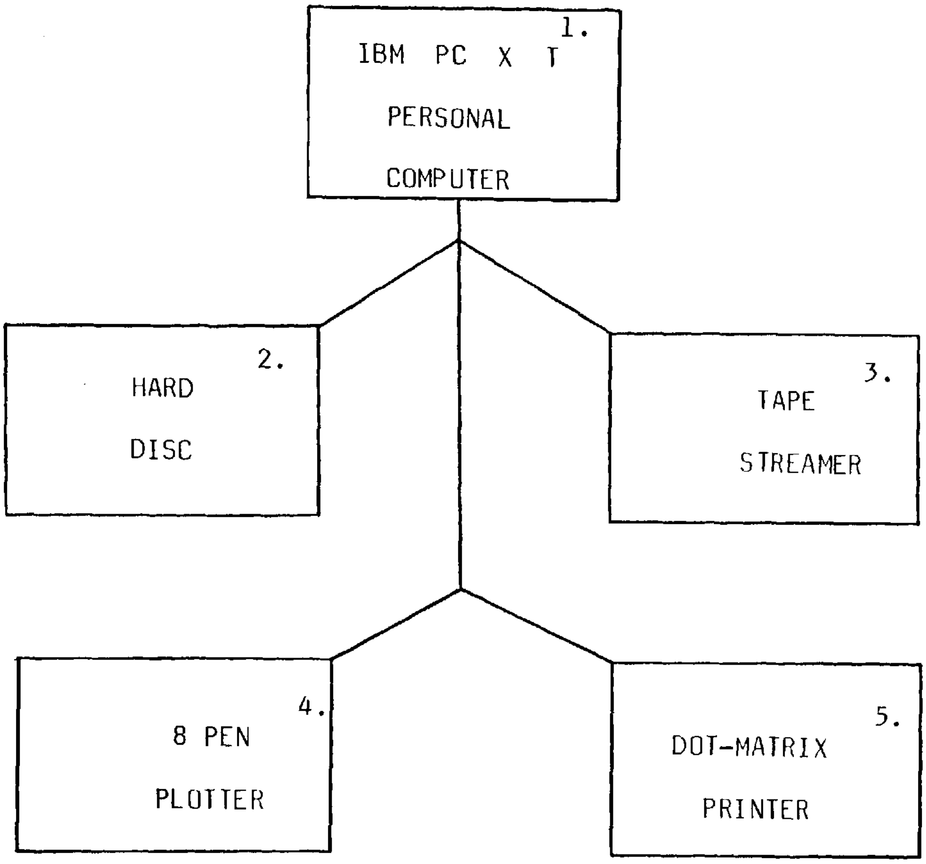
```
          writeln;
          write('Enter Tube Inner Diameter (mm) ?  ');readln(D3);
          writeln;
          write('Enter Number of Fibres per Tube ?  ');readln(N);
          writeln;
          write('Enter Laylength at Stranding (mm) ?  ');readln(L1);
          writeln;
          write('Enter Tube Stranding Tension (N) ?  ');readln(T6);
          writeln;
          write('Enter Cable Stranding Tension (N) ?  ');readln(T7);
          writeln;
          write('Enter Fibre Excess (mm) ?  ');readln(X);
          writeln;

     end;



     procedure CALCS;

     begin
          Z3:=Z2*(S5+1)/(S6+1);
          Z4:=Z1*Z3;
          L2:=sqrt((sqr(Z4*Z5*L1))-(sqr(K3)));
          RR:=1+(T7/(E*A4));
          SS:=L2*RR/L1;
          T8:=(SS-1)*E*A4;
          T8:=int(T8);
     end;



     procedure CALCULATE;

     begin
          K1:=886.4;
          A3:=2.030;
          A4:=(sqr(D10/2)*pi);
          Z1:=(sqrt((sqr(pi*(D1+D2)))+sqr(L1)))/L1;
          K3:=pi*(D1+D2-D3+((2*K4[N]-1)*D4));
          Z2:=(L+X)/(L*(1+U/K1));

          for i:=1 to 11 do
          begin
               T3[i]:=T2[i]*A3;
          end;

          for i:=1 to 10 do
          begin
               M[i]:=(T3[i+1]-T3[i])/(S2[i+1]-S2[i]);
               C[i]:=T3[i]-(M[i]*S2[i]);
          end;

          zzz:=0;
          xxx:=0;
          j:=10;

          repeat
               if T5>T3[j] then
               zzz:=1;
               j:=j-1;
               if j=0 then
               xxx:=1;
```

```
     until (zzz=1) or (xxx=1);

     S5:=(T5-C[j])/M[j];

     zzz:=0;
     xxx:=0;
     j:=10;

     repeat
           if T6>T3[j] then
           zzz:=1;
           j:=j-1;
           if j=0 then
           xxx:=1;
     until (zzz=1) or (xxx=1);

     S6:=(T6-C[j])/M[j];
     ZS:=((S5+1)*Z2)-1;

     if ZS>=S6 then
     CALCS else
     begin
          zzz:=0;
          xxx:=0;
          j:=10;
          repeat
                S6:=(T6-C[j]+(N*K1*ZS))/(N*K1+M[j]);
                QQ:=M[j]*S6+C[j];
                if QQ>T3[j] then
                zzz:=1;
                j:=j-1;
                if j=0 then
                xxx:=1;
          until (zzz=1) or (xxx=1);
          CALCS;
     end;
end;


procedure PRINT;

begin
     writeln;
     writeln('--------------------------------------------------');
     writeln('! Maximum Allowed Cable Tension = ',T8:6:0,' Newtons !');
     writeln('--------------------------------------------------');
     writeln;
end;


begin
     LOADARRAYS;
     INPUT;
     CALCULATE;
     PRINT;
end.
```

C>

APPENDIX F

Computer Hardware Configuration


1.
IBM PC X T
PERSONAL
COMPUTER
2.
HARD
DISC
3.
TAPE
STREAMER
4.
8 PEN
PLOTTER
5.
DOT-MATRIX
PRINTER

1. IBM PC XT Personal Computer

The Personal Computer available has the following modifications/additions:

- 640K internal memory
- Dual 360K Floppy disk drives
- IBM Colour/Graphics card
- Colour Terminal
- Hard Disk controller board
- Tape streamer controller board

2. Hard Disk

The hard disk system used is an external 10 Mb disk by Sigma Designs. The disk is linked to the controller board located within the computer.

3. Tape Streamer

The tape streamer is an external tape backup unit by Sysgen. The Sysgen Image subsystem was designed to create magnetic tape backup for the IBM Personal Computer using PC-DOS. Backing up files with this system will allow quick and easy re-storage of large files on disk should a catastrophic failure occur when working with active files. In addition, the Sysgen Image subsystem allows the transfer of large data files between two IBM Personal Computers equipped with the Sysgen Image sybsystem.

The Sysgen Image subsystem contains an 11 - megabyte (formatted) magnetic tape cassette that allows tape-to-disk or disk-to-tape transfers at speeds of over 2.5 million bytes per minute. The user can choose to transfer data by selecting certain files or can backup an entire disk volume on a single cassette.

The Sysgen unit is connected to the Tape Streamer controller board located within the computer.

4. 8 Pen Plotter

The plotter used is a Hewlett-Packard ColorPro 8 pen plotter. It is connected to the serial RS-232 port of the IBM computer. Details regarding Baud rate options, Parity options and the Plotter interface connector are given overleaf.

An addition to the plotter is a Graphics Enhancement Cartridge. It is a simple add-on unit which plugs into a purpose built slot on the base of the plotter. It is required to upgrade the plotter so that it accepts certain graphics commands, and also to increase the input buffer up to 1024 bytes.

RS-232-C/CCITT V.24 Information

Baud Rate Options

Baud rate is selected using the **B1**, **B2**, **B3**, and **B4** baud rate switches on the plotter's rear panel. The following table lists the possible baud rates, along with their related switch settings. The plotter is configured to automatically verify and generate one or two stop bits, depending on the setting of the baud rate switches.

Baud Rate Switch Settings

	Switch Settings							
	1 Stop Bit				2 Stop Bits			
Baud Rate	B1	B2	B3	B4	B1	B2	B3	B4
75	—	—	—	—	1	0	0	0
110	—	—	—	—	0	1	0	0
150	1	1	0	0	—	—	—	—
200	0	0	1	0	—	—	—	—
300	1	0	1	0	1	1	0	1
600	0	1	1	0	0	0	1	1
1200	1	1	1	0	1	0	1	1
2400	0	0	0	1	0	1	1	1
4800	1	0	0	1	1	1	1	1
9600	0	1	0	1	0	0	0	0

Parity Options

Parity is selected using the **S1** and **S2** parity switches on the rear panel. The following table provides a list of parity switch settings.

Parity Switch Settings

	Switch Settings	
Parity	S1	S2
none	0	0 or 1*
even	1	0
odd	1	1

*Setting S2 to 0 sets parity bits sent by the plotter to 0 (space parity); setting S2 to 1 sets the parity bits to 1 (mark parity).

Plotter Interface Connector

The plotter's RS-232-C connector is a standard DB-25 female connector. The following table provides a listing of the interface pin allocations.

RS-232-C/CCITT V.24 Pin Allocations

Wire/Signal Name	Pin #	RS-232-C	CCITT V.24
Protective Ground	1	AA	101
Transmitted Data	2	BA	103
Received Data	3	BB	104
Request to Send	4	CA	105
Clear to Send	5	CB	106
Data Set Ready	6	CC	107
Signal Ground	7	AB	102
Data Carrier Detect	8	CF	109
Data Terminal Ready	20	CD	108.2

5. Dot-Matrix Printer

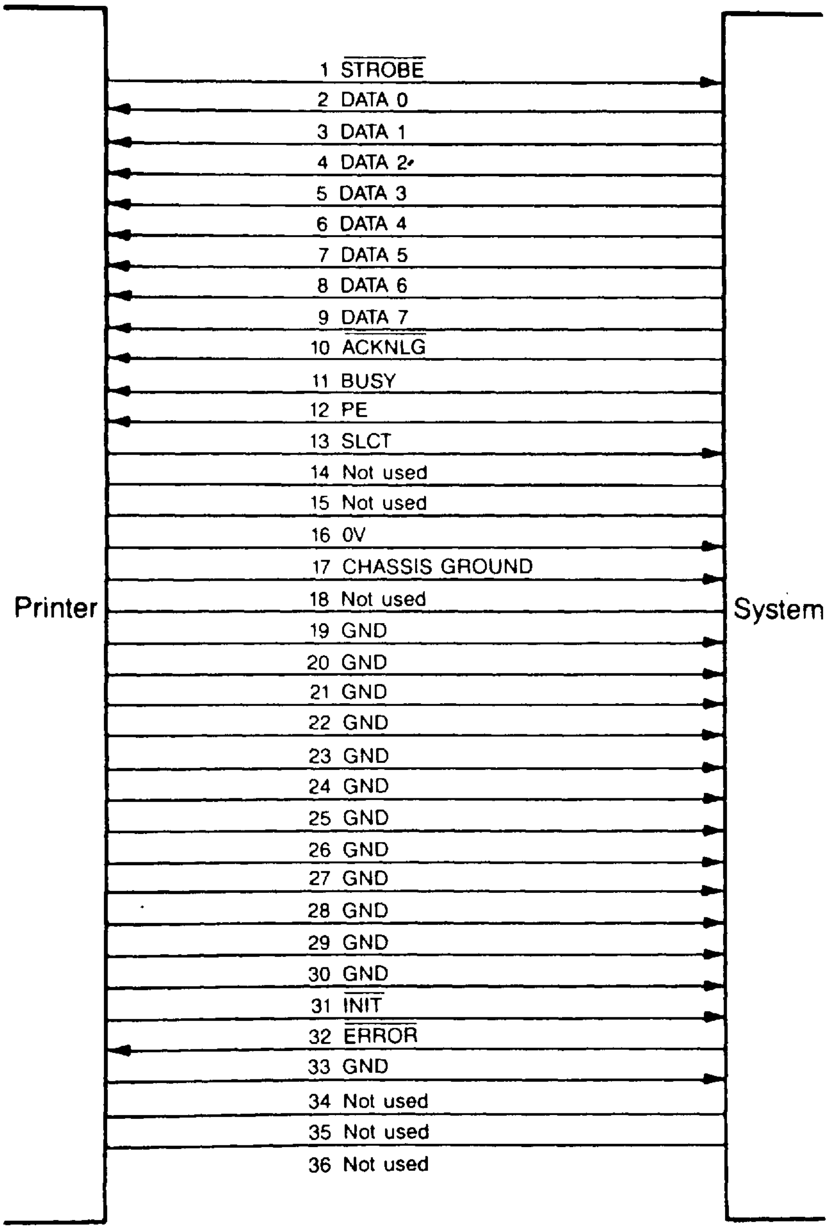
The printer used is an IBM Proprinter. This printer used is an IBM Proprinter. This dot-matrix uses a print head with nine pins (wires). The nine wires, under control of the printer, print a group of dots to form each character. For near-letter quality (NLQ) printing, the dots print closer together.

The print head takes the shortest path for the next character to print. The proprinter can print up to 200 characters per second (CPS) at a paper feed rate of 86.4 mm per second.

The printer is connected to the parallel port of the computer. The interface is shown overleaf.

Parallel Interface

Use the following chart to determine the connections your printer uses.



APPENDIX G

Batch file to sequentially execute cable design package

```
TYPE CRYSTAL.BAT
```

```
ECHO OFF
ERASE CABLE.ASC
CD ..
BASIC NLQ
CD CRYSTAL
CRASC /A200 CABLE
IF NOT EXIST CABLE.ASC GOTO CONTINUE
CD C:\DOS
MODE COM1:96,N,7,1
CD C:\CRYSTAL
COPY CABLE.ASC C:\TURBO\GRAPHIX
CD C:\TURBO\GRAPHIX
COPY CABLE.ASC CABLE.BAK
PLOT
CLS
ERASE CABLE.ASC
ECHO ON
CD C:\CRYSTAL
ERASE CABLE.ASC
CLS
:CONTINUE

C>
```

APPENDIX H

Variation of cut-off wavelength with length

Variation of Fibre Cut-off Wavelength with Length

1. Introduction

The current British Telecom (BT) specification for singlemode fibre (CW1505), requires that the cut-off wavelength shall lie in the region 1120 to 1250 nm, this is at variance with the CCITT recommendation G652 of 1100 to 1280 nm. The data which follows will show that the effective cut off wavelength of a fibre will drop between 16 and 29 nanometres within the first 10 m of propagation. This effect does not take account of any decrement due to cabling.

2. Experimental Procedure

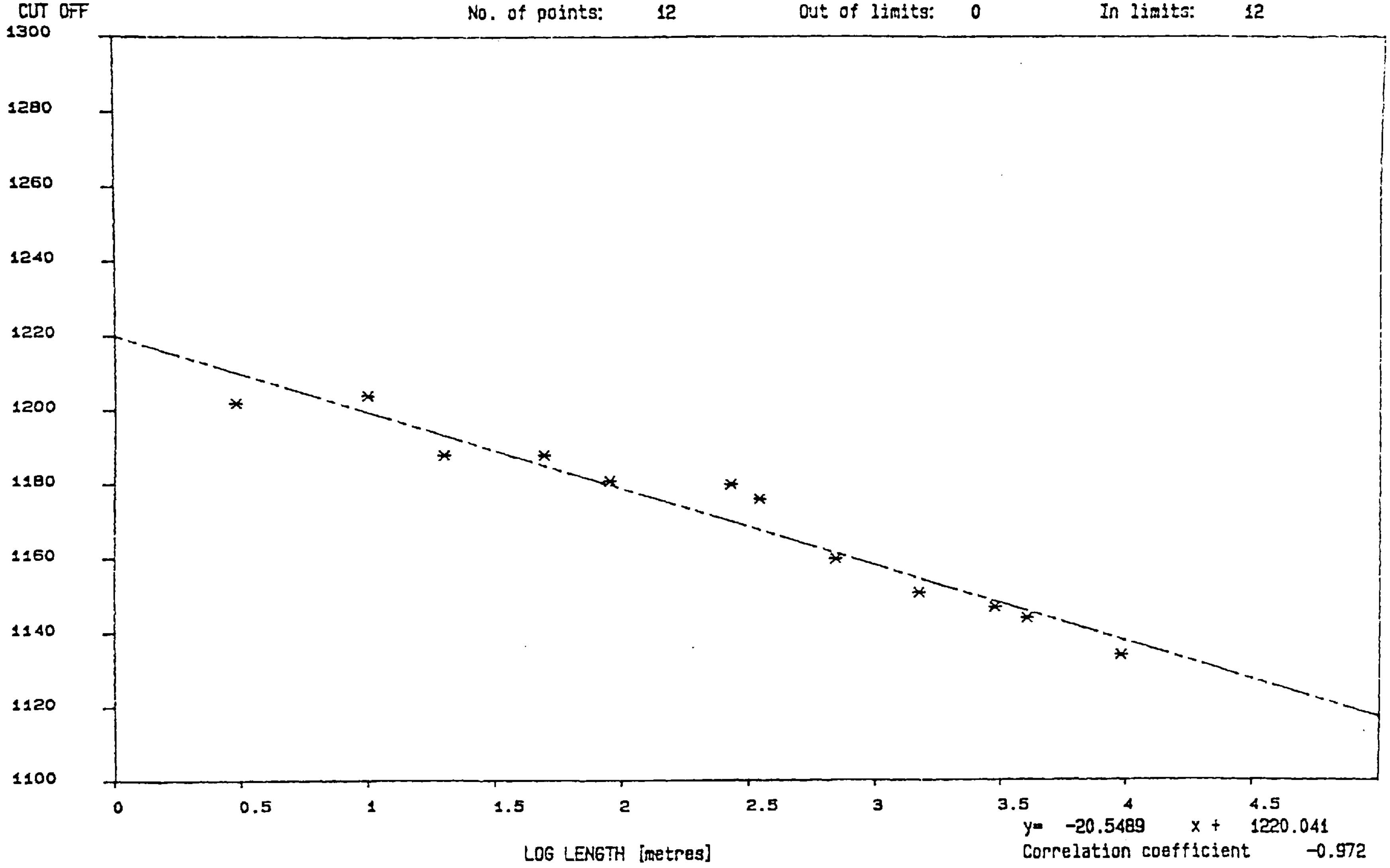
Eight fibres were chosen to have a cut-off wavelength at either end within 20 nm. (Due to the taper effect of the MCVD process, thia variation will have decreased to that of the measurement error within 2 km of the start end). The effective cut-off of these fibres were measured using the wavelength cut-off method. This method has been correlated with the BT reference technique. These fibres were then cut in half and re-measured, with the process repeated until 3m of fibre remained. (At each cutting process the 'start'end of the fibre was removed so that the most linear fibre remained).

The effective cut-off wavelength plotted against log length of the eight fibres tested are shown in the following graphs.

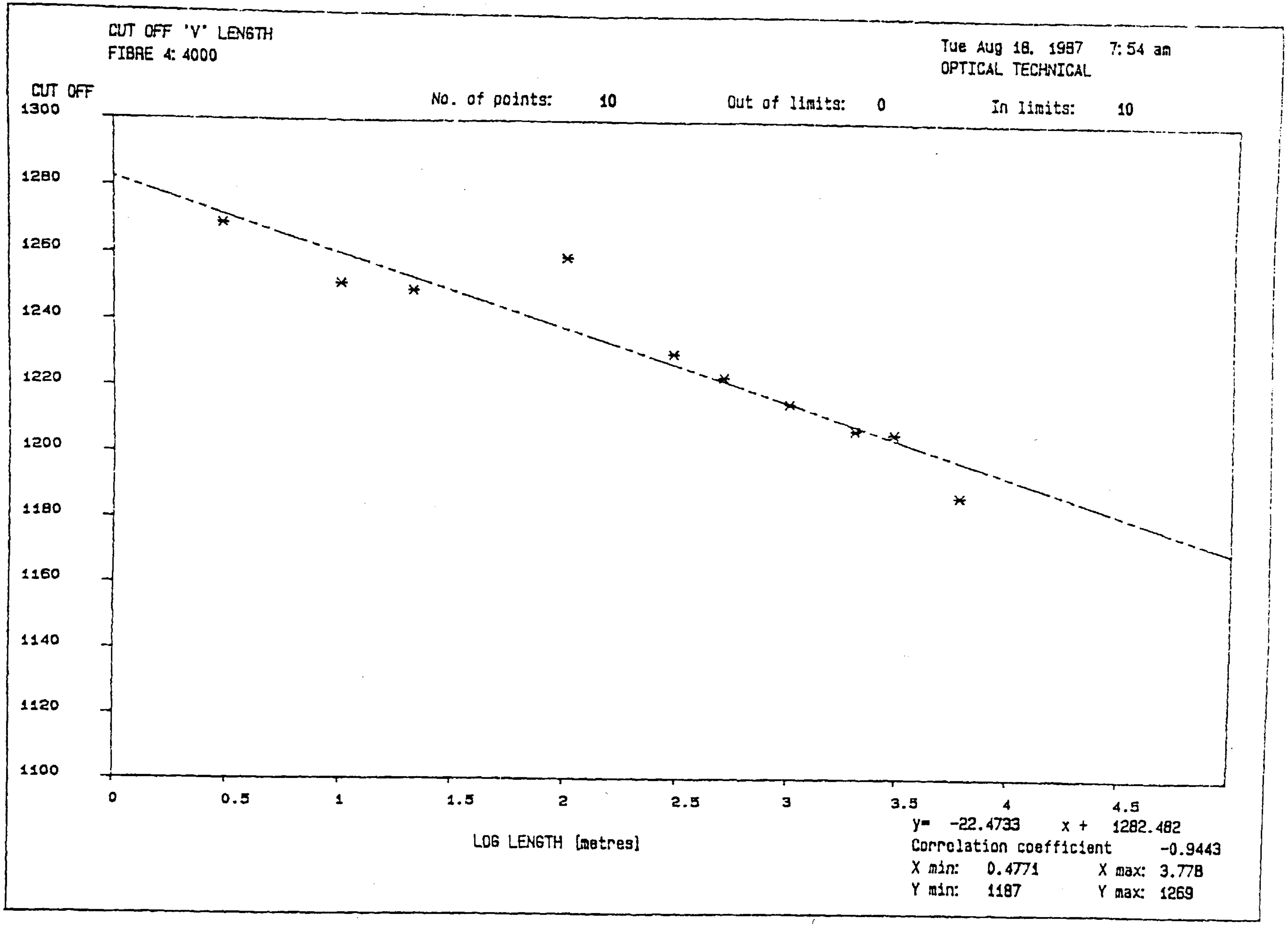
CUT OFF 'V' LENGTH
FIBRE 4: 2000

Tue Aug 18. 1987 5: 36 am
OPTICAL TECHNICAL

No. of points: 12 Out of limits: 0 In limits: 12



y= -20.5489 x + 1220.041
Correlation coefficient -0.972
X min: 0.4771 X max: 3.9823
Y min: 1134 Y max: 1204

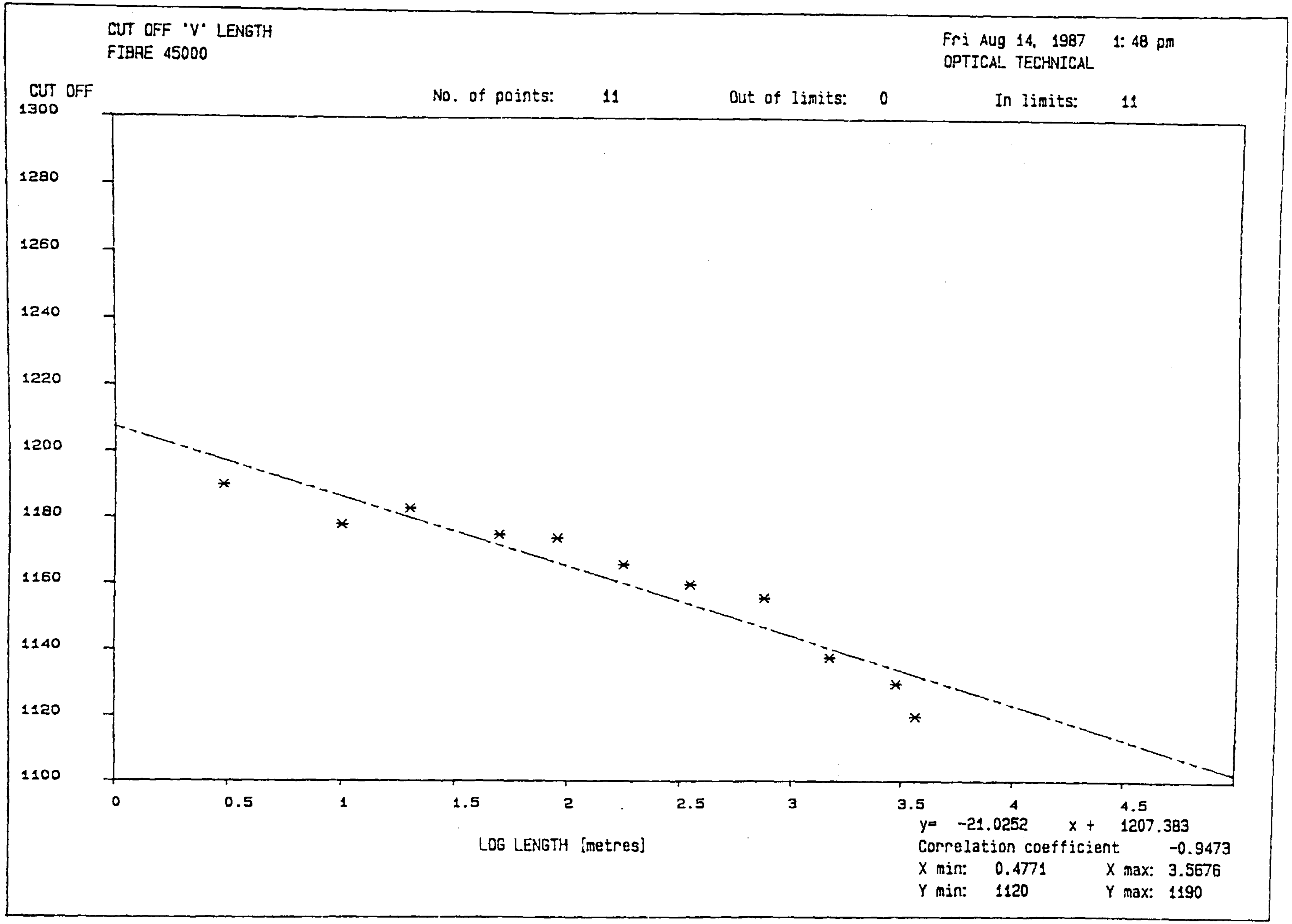


CUT OFF 'V' LENGTH
FIBRE 4: 4000

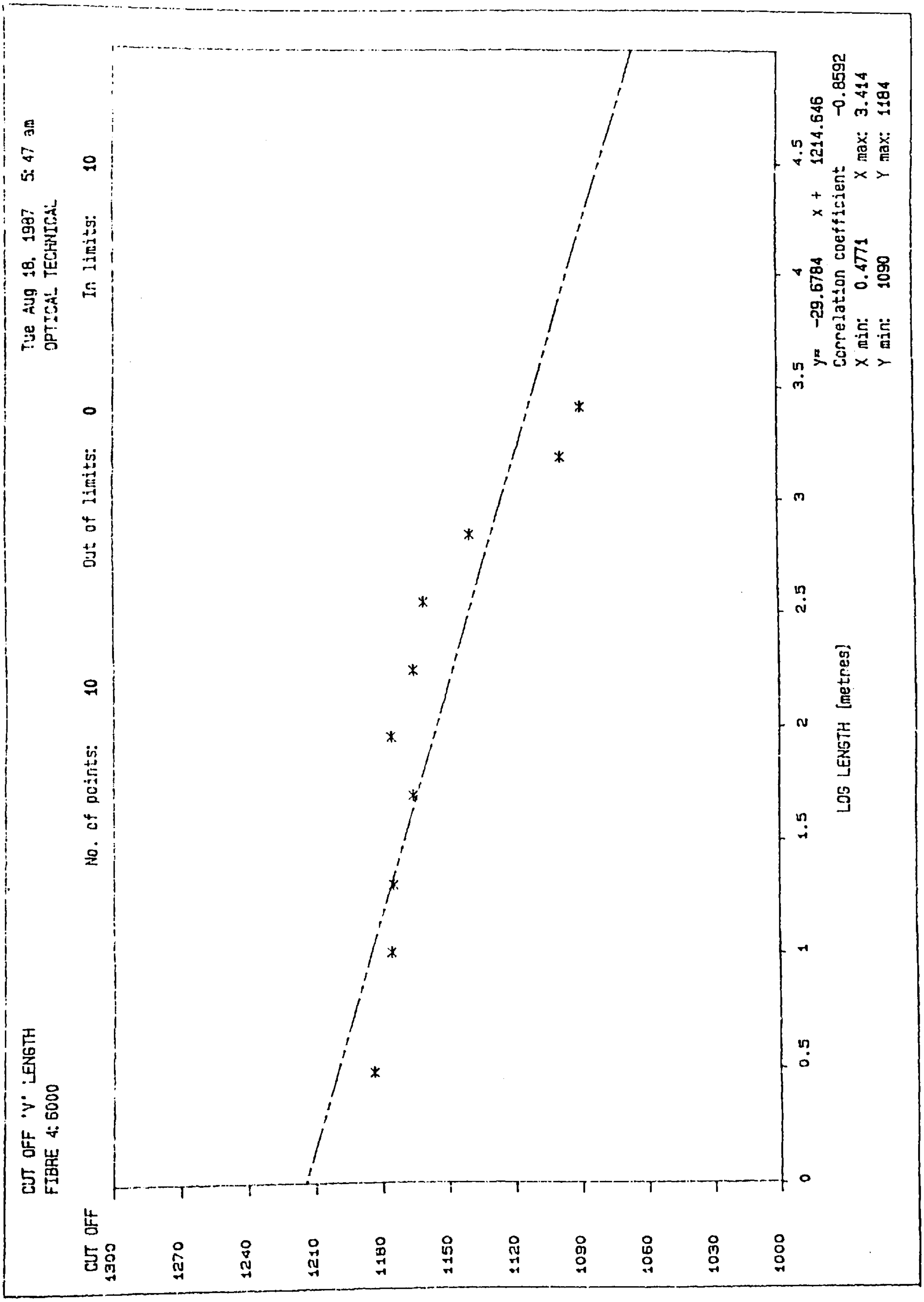
Tue Aug 18, 1987 7:54 am
OPTICAL TECHNICAL

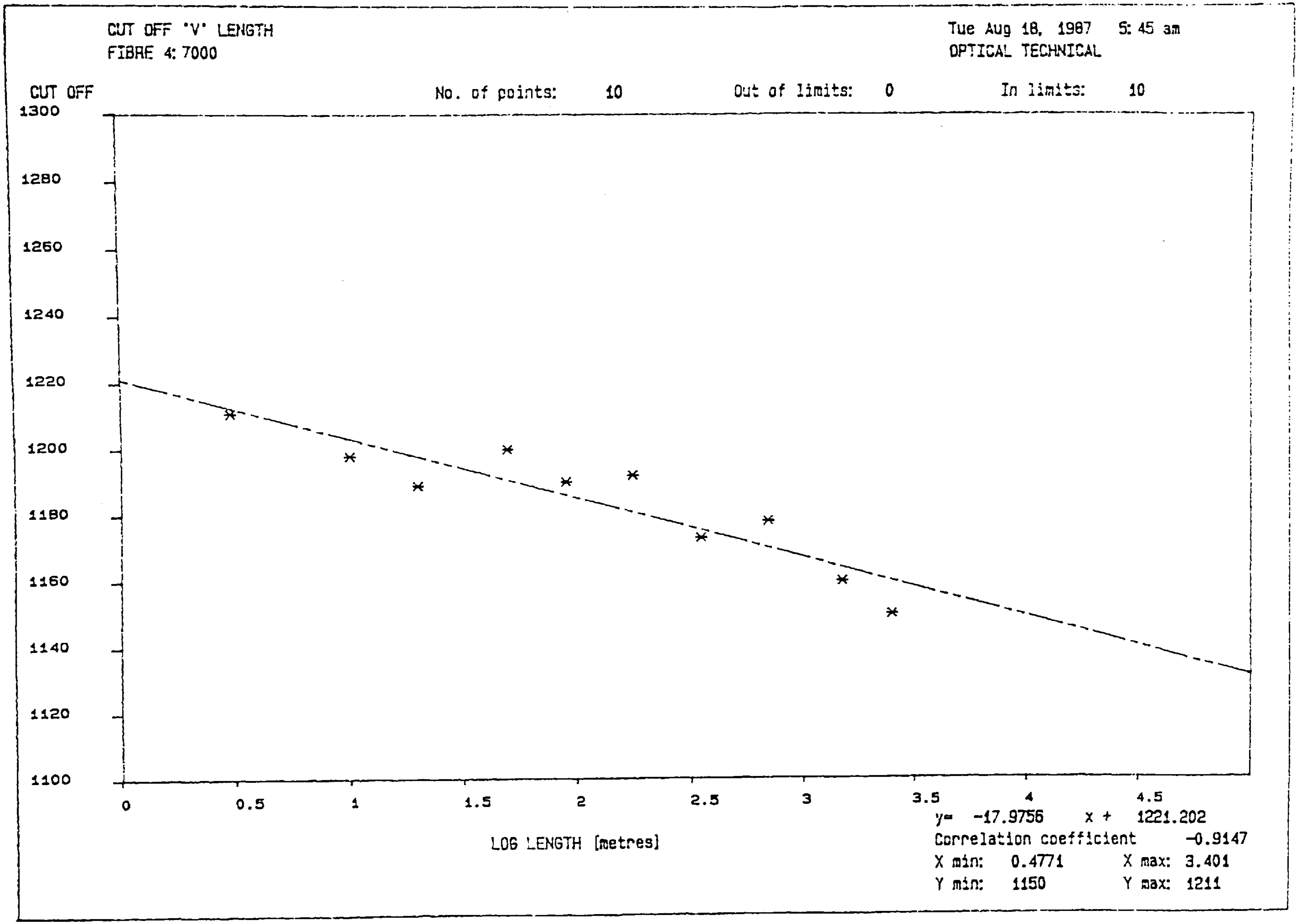
No. of points: 10
Out of limits: 0
In limits: 10

y= -22.4733 x + 1282.482
Correlation coefficient -0.9443
X min: 0.4771
X max: 3.778
Y min: 1187
Y max: 1269


CUT OFF 'V' LENGTH
FIBRE 45000
Fri Aug 14, 1987 1: 48 pm
OPTICAL TECHNICAL
No. of points: 11
Out of limits: 0
In limits: 11
CUT OFF
1300
1280
1260
1240
1220
1200
1180
1160
1140
1120
1100
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
LOG LENGTH [metres]
y= -21.0252 x + 1207.383
Correlation coefficient -0.9473
X min: 0.4771 X max: 3.5676
Y min: 1120 Y max: 1190

Lxxxx


CUT OFF 'Y' LENGTH
FIBRE 4: 6000
No. of points: 10
Out of limits: 0
In limits: 10
Tue Aug 18, 1987 5:47 am
OPTICAL TECHNICAL
CUT OFF
1300
1270
1240
1210
1180
1150
1120
1090
1060
1030
1000
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
LOG LENGTH (metres)
y= -29.6784 x + 1214.646
Correlation coefficient -0.8592
X min: 0.4771 X max: 3.414
Y min: 1090 Y max: 1184

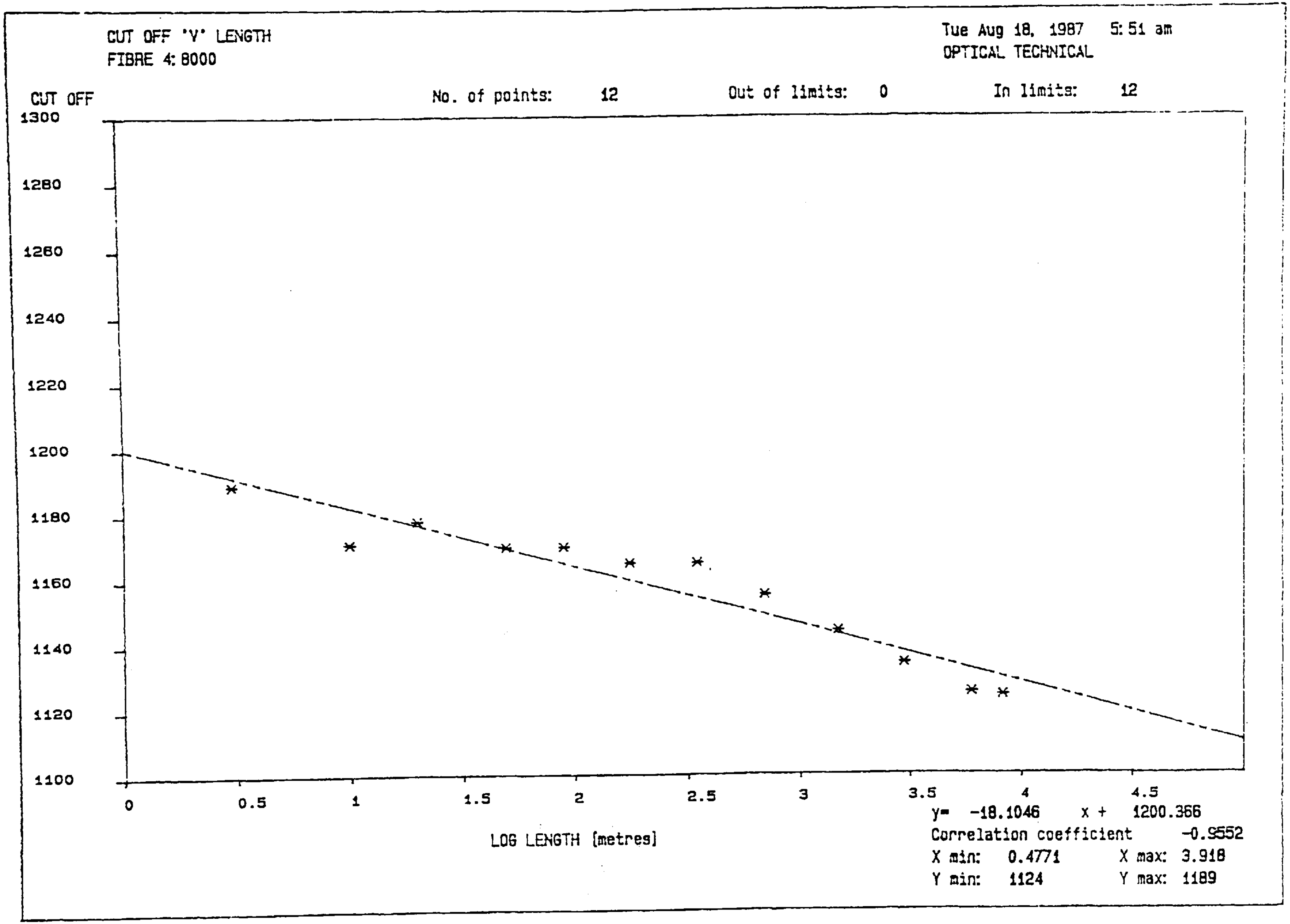


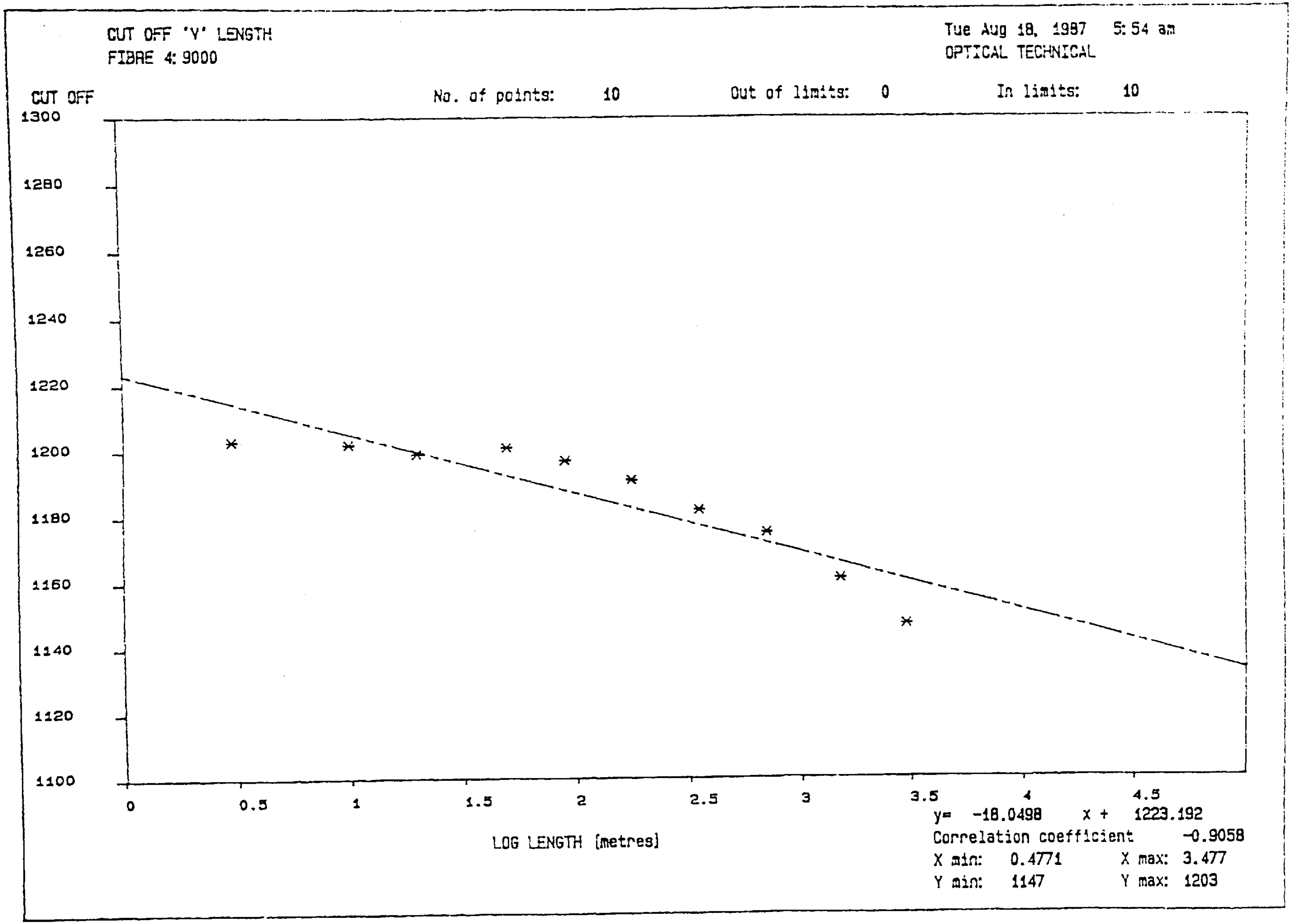
CUT OFF 'V' LENGTH
FIBRE 4: 7000

Tue Aug 18, 1987 5: 45 am
OPTICAL TECHNICAL

No. of points: 10 Out of limits: 0 In limits: 10

y= -17.9756 x + 1221.202
Correlation coefficient -0.9147
X min: 0.4771 X max: 3.401
Y min: 1150 Y max: 1211

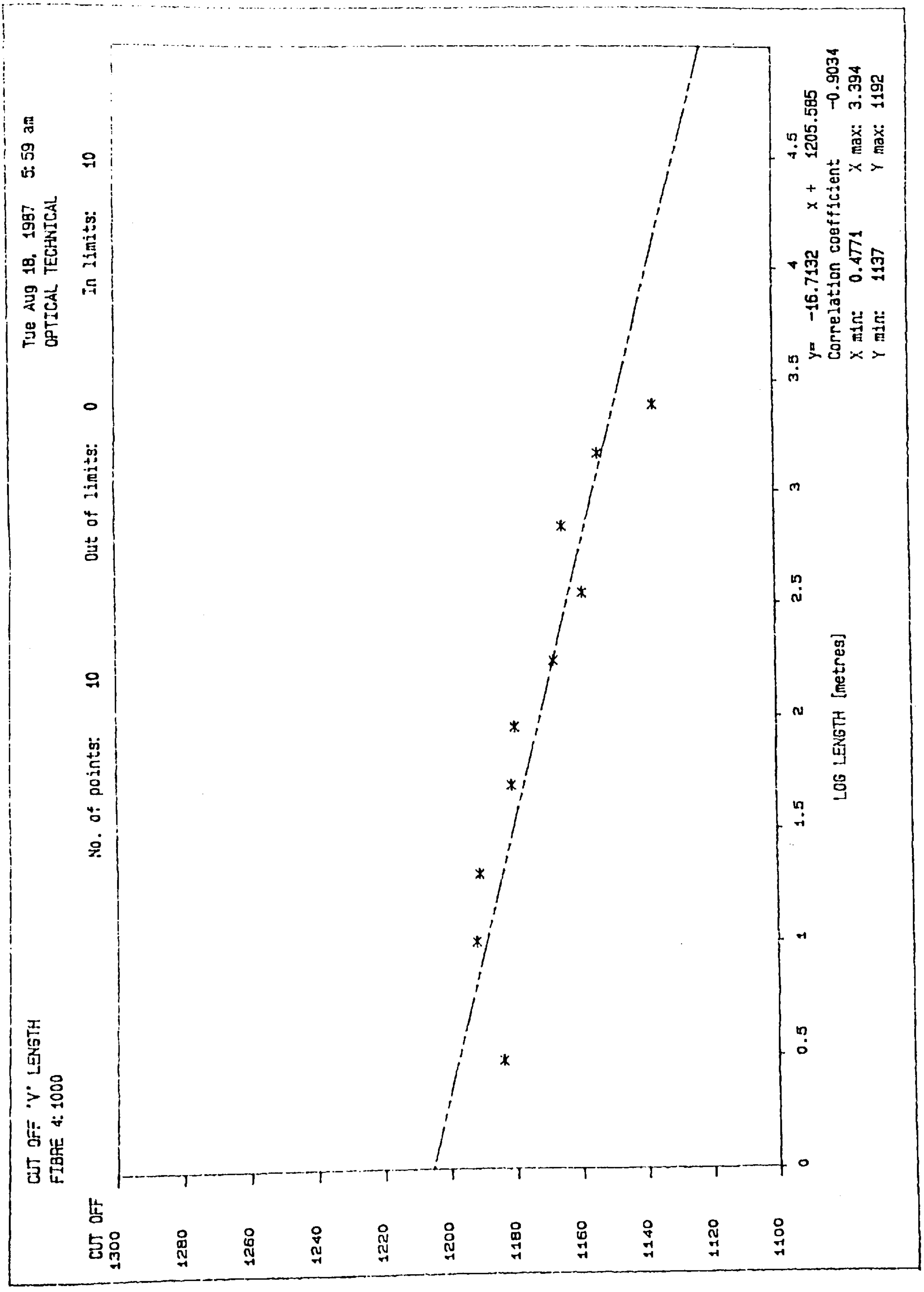

CUT OFF 'Y' LENGTH
FIBRE 4: 8000
Tue Aug 18, 1987 5: 51 am
OPTICAL TECHNICAL
No. of points: 12
Out of limits: 0
In limits: 12
CUT OFF
1300
1280
1260
1240
1220
1200
1180
1160
1140
1120
1100
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
LOG LENGTH (metres)
y= -18.1046 x + 1200.366
Correlation coefficient -0.9552
X min: 0.4771
X max: 3.918
Y min: 1124
Y max: 1189


CUT OFF 'Y' LENGTH
FIBRE 4: 9000

Tue Aug 18, 1987 5:54 am
OPTICAL TECHNICAL

No. of points: 10 Out of limits: 0 In limits: 10

y= -18.0498 x + 1223.192
Correlation coefficient -0.9058
X min: 0.4771 X max: 3.477
Y min: 1147 Y max: 1203


CUT OFF 'Y' LENGTH
FIBRE 4:1000
Tue Aug 18, 1987 5:59 am
OPTICAL TECHNICAL
No. of points: 10
Out of limits: 0
In limits: 10
CUT OFF
1300
1280
1260
1240
1220
1200
1180
1160
1140
1120
1100
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
LOG LENGTH [metres]
y= -16.7132 x + 1205.585
Correlation coefficient -0.9034
X min: 0.4771 X max: 3.394
Y min: 1137 Y max: 1192

3. Results

The tabulated results are shown overleaf, the decrement per decade for each fibre is shown below.

1. 16.7 nm
2. 20.5 nm
3. 18.0 nm
4. 22.5 nm
5. 21.0 nm
6. 29.7 nm
7. 18.0 nm
8. 18.1 nm

$$\overline{X} = 20.56 \text{ nm}$$

$$\sigma n - 1 = 4.17 \text{ nm}$$

Over 100 metres of fibre, the cut-off would therefore have dropped by approximately 40 nm. The mean drop in cutoff (expressed as a log) is plotted against log of length, and the resulting relationship is:

$$\text{Log}(\delta\lambda co) = 0.3846 \log (L) + 0.4337$$

$$\text{for } L \geqslant 10 \text{ metres.}$$

4. Conclusions

The effective cut-off wavelength as measured on long fibre lengths has a value up to 29 nm/decade less than the unit value (reference test on 3m sample). The minimum decrement/decade was 16.7 nm.

From the above data there is 99% confidence that a fibre's effective cut-off will be 8.1 nm below that of the 3 metre measurement, within the first 10 metres.

Fibre no: 47000

Length		effective cut off	Change
3	0.4771	1211	
10	1.0000	1198	13
20	1.301	1189	22
50	1.699	1200	11
90	1.954	1190	21
175	2.243	1192	19
350	2.544	1173	38
700	2.845	1178	33
1500	3.176	1160	51
2520	3.4014	1150	61

Fibre no: 49000

3	0.4771	1203	
10	1.000	1202	1
20	1.301	1199	4
50	1.699	1201	2
90	1.954	1197	6
175	2.243	1191	12
350	2.544	1182	21
700	2.845	1175	28
1500	3.176	1161	42
3000	3.4771	1147	56

Fibre no: 41000

3	0.4771	1184	
10	1.000	1192	-8
20	1.301	1191	-7
50	1.699	1181	3
90	1.954	1180	4
175	2.243	1168	16
350	2.544	1159	25
700	2.845	1165	19
1500	3.176	1154	30
2475	3.394	1137	47

Fibre no: 48000

3	0.477	1189	
10	1.000	1171	18
20	1.301	1178	11
50	1.699	1170	19
90	1.954	1175	14
175	2.243	1165	24
350	2.544	1165	24
700	2.845	1155	34
1500	3.176	1144	45
3000	3.4771	1134	55
6000	3.778	1125	64
8288	3.9184	1124	65

Fibre no: 44000

Length		effective cut off	Change
3	0.4771	1269	
10	1.000	1251	18
21	1.3222	1249	20
100	2.000	1259	10
200	2.301	1230	39
300	2.4771	1230	39
500	2.699	1223	46
1000	3.000	1215	54
2000	3.301	1207	62
3000	3.4771	1206	63
6000	3.7781	1187	82

Fibre no: 42000

3	0.4771	1202	
10	1.000	1204	-2
20	1.301	1188	14
50	1.699	1188	14
90	1.954	1181	21
175	2.243	1180	22
350	2.544	1176	26
700	2.845	1160	42
1500	3.176	1151	57
3000	3.4771	1147	55
4043	3.607	1144	58
9602	3.982	1134	68

Fibre: 46000

3	0.771	1184	
10	1.000	1176	8
20	1.301	1175	9
50	1.699	1166	18
90	1.954	1176	8
175	2.243	1166	18
350	2.544	1161	23
700	2.845	1140	44
1500	3.176	1099	85
2597	3.4144	1090	94

Fibre no: 45000

3	0.4771	1190	
10	1.000	1178	12
20	1.301	1183	7
50	1.699	1175	15
90	1.954	1174	16
175	2.243	1166	24
350	2.544	1160	30
750	2.875	1156	34
1500	3.176	1138	52
3000	3.4771	1130	60
3695	3.568	1120	70

APPENDIX I

Publications

OPTICAL FIBRE CABLE DESIGN USING AN "EXPERT SYSTEM"

by

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ABSTRACT

The paper describes the development of an expert system to design Loose Tube optical fibre cables. It shows its advantages both in terms of financial gains and as a training tool.

1. INTRODUCTION

STC Cable Products Division has been engaged in the manufacture of optical fibre cables for four years. Over the past year the demand for optic cables has increased dramatically, thus placing a great burden on engineers to quickly produce new designs for specific applications. This has highlighted the need for some form of computer program to harness the knowledge and experience of cable design built up over this period. Such a program would automate the standard design procedure, thus freeing engineers to concentrate on future developments.

The expertise required in the design of optical cables is a mixture of geometrical mathematics, knowledge of materials, and practical experience. To incorporate these three areas in a computer program using conventional software would be very laborious, in terms of emboding the various design rules used in cable design. Therefore clearly, another solution is needed, one which would allow the basic construction of such a program and then allow quick and efficient entry of additional information.

An expert system approach seemed to offer most promise in that engineers experience and heuristic design principles could be embodied within a computer program in a straight forward manner. Rather than write an inference engine from scratch, a proprietary expert system builder, or "shell" was employed, namely Crystal by Intelligent Environments, a package written in the ´C´ language (1). It proved very flexible since each rule can be reduced to a hierarchy of sub-rules, an essential requirement in the design of optical fibre cables.

2. BACKGROUND

Optical fibres (2) are inherently brittle and fragile but have to be made into cable that will withstand installation and the often hostile environments in which they must operate reliably. Working environments that have been met range from the almost constant 2-4°C of the sea bed for deep-sea submarine cables to rapid changes from -55 C to +155 C for some avionic applications; from normal pressures up to 70 MN/m ; from ambient air to hot corrosive liquids. The number of fibres in a cable may vary from one in rack wiring to several thousand in distribution cables now being proposed. The cable may be all-dielectric containing only fibres or may incorporate numerous conductors or other more complex elements.

Such diversity can only be met with a wide variety of cable designs and the state-of-the-art is such that even some straightforward applications can be met by several alternative designs. However, all optical fibre cables can be judged by their success in meeting two basic criteria. First, they must not significantly degrade the transmission properties of the fibre and second, they must maintain the integrity of the fibre during manufacture, installation and service.

The cabling engineer therefore has two main tasks:-

(i) to minimise optical attenuation increments associated with manufacture and use of cables, and

(ii) to maintain the physical integrity of the fibre during the cabling process and in service.

The main type of optical cable manufactured by STC Cable Products Division is of the Loose Tube variety, with over 90% of the total output being of this kind. For this reason it was decided to concentrate on developing an expert system to aid the design of cables of this type.

3. DESIGN PROCEDURES

Loose Tube cables consist of either single or multiple fibres loosely contained within tubes which may be filled with a special compound to prevent the ingress and transportation of gases and liquids. These tubes are laid around a central strength member, wrapped with tape and then sheathed to form a cable. The cable interstices may also be filled with special compound to provide a genuinely fully filled cable.

Cable variants to suit customers specifications include steel or dielectric central strain members, aluminium moisture barrier, steel tape and/or wire armouring, polyethylene, PVC or low fire risk sheathing compounds. Copper pairs may also be incorporated.

Figure 1 shows an armoured cable as used in the trunk network and installed buried beneath the ground. This particular design incorporates 12 optical fibres, with two fibres located in each tube. The cable consists of a strength member of compacted steel strand, coated with low density polyethylene. Six tubes and four fillers are stranded helically around the central member and wrapped with paper tape. The tubes are of extruded polybutylteraphthelate, whilst the fillers are of extruded polyethylene. An aluminium/plastic laminated moisture barrier is applied over the whole cable. To provide the crush resistant armouring required by buried cables, galvanised steel wires are stranded over the inner sheath. A final outer sheath is then extruded over the armour.

4. EXPERT SYSTEM IMPLEMENTATION

The expert system must handle routine mathematical calculations from a cable design specification, together with a sequence of empirical design decisions that influence the final construction of the cable. A user, not necessarily a fibre optic cable designer is expected to work interactively with the Crystal generated expert system.

The method of designing cables is to fit the required number of tubes and copper pairs around a central member. Then, to apply layers of certain materials which act as protection against all hazards. The cable strength is determined by the size of central member, or the number of galvanised steel wires if the cable is so armoured. The strength of cables is usually quoted by their strength to weight ratio. Cables armoured with galvanised wire are dramatically heavier than those without, but their strength to weight ratio is maintained at a high level, due to the added tensile strength of the armouring itself. Therefore cables with galvanised steel wire armouring rarely require fillers in between the tubes and/or copper pairs to expand the size of central member.

Unarmoured cables do not follow the same pattern and often require one or more fillers amongst the tubes and/or coppers. Larger central members are permissible therefore, to strengthen the cable. Doing this results in an increase in both the tensile strength and weight of the cable. The net effect on the cable´s strength to weight ratio is only a minor change. There will be a slight increase however, since the strength of steel or GRP increases proportionally to the square of its radius. An indefinite number of fillers cannot be added since the cost of the cable would rise accordingly, also its diameter may be out of specification especially if the cable were to be installed in ducts where space is a major constraint.

Therefore there is a fine discrimination drawn between cables which pass or fail a particular specification. It is not uncommon for an engineer to re-iterate a design three or four times for different central member dimensions.

An expert system to perform the equivalent function required a total of 680 rules. The complete implementation from learning Crystal to training system users took approximately 6 months. Much of the time was spent collating cable design aspects from records and design staff. As expected, several conflicting viewpoints on certain ´grey areas´ were apparent. Thus a number of ´best approach´ decisions were taken before incorporating these rules within the knowledge base.

The expert system was written so that interaction with the user led to the progressive solution of rules. The questions asked were designed to allow a non-technical user to run the package. Obviously some expertise in cable requirements and materials is necessary, but all the mathematical calculations are performed by the system. The output of results is a three page description of the cable requirements in terms of weights and dimensions, proceeded by the title and summary sheet (Fig. 2).

A cross-sectional view of the finished cable design must accompany all specifications issued by the fibre optic cable section, traditionally drawn by hand with stencils and compasses. Crystal itself is not capable of producing a graphical plot of the cable. A data transfer utility was thus used to input cable dimensions to a program written in Turbo Pascal which generated, on a plotter, a fully labelled cross-sectional diagram of the cable designed (Fig. 3).

5. OPERATIONAL ASPECTS/BENEFITS

Running Crystal takes approximately five minutes. This compares with anything up to three hours for a manual design. In addition, a fully labelled diagram on the plotter may take another five minutes, whilst to physically draw and label a diagram can take two hours. Therefore resulting in a total time difference of ten minutes against five hours (i.e. 4 hrs 50 mins).

With a total of three design engineers in the department, each performing approximately one design per day, there is therefore a total time saving of 14 hours/day where those engineers can be working on development projects etc. If an engineers time is measured at £20/hour (salary and overheads) the cost saving per day is £290, which amount to £72,500 per year.

As previously mentioned it is possible for a non-technical person, with a broad idea of his requirements, to use the system and obtain a valid design. The system could therefore be used to quickly educate new engineers within the department on the basic principles of cable design and their configurations. They could quickly learn how the variation of one or more parameters affects the cable. This procedure without the expert system could take several weeks.

6. CONCLUSIONS

The expert system was successfully implemented and has now been fully operational for six months. It is recognised as an invaluable design tool which relieves engineers from laborious, repetetive, time consuming calculations. In the future, no doubt new concepts and materials will have to be added to the expert system to keep it in line with technological advances. In addition to this it is envisaged to extend the scope of the expert system to embrace the parameters that affect the manufacture of the fibre itself. The flexibility of Crystal allows this with minimal effort, thus giving STC a system of designing Loose Tube optical fibre cables for the duration of current telecommunications technology.

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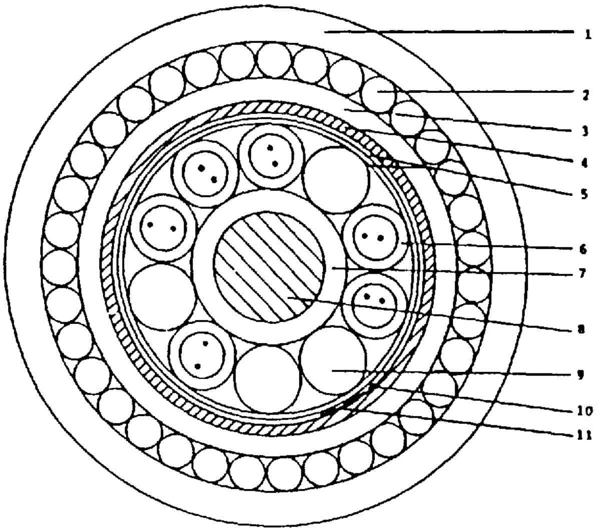


1. Outer Sheath
2. Galvanised Steel Wire
3. Inner Sheath
4. Aluminium/Plastic Tape
5. Paper Tape
6. Loose Tube
7. Strength Member Coating
8. Steel Strength Member
9. Filler
10. Rip Cord
11. Manufacturer's I.D. Tape

Fig.1 Armoured Main Cable
12 Fibre Version

DATE : / / 19

LOOSE TUBE CABLE - EXPERT SYSTEM

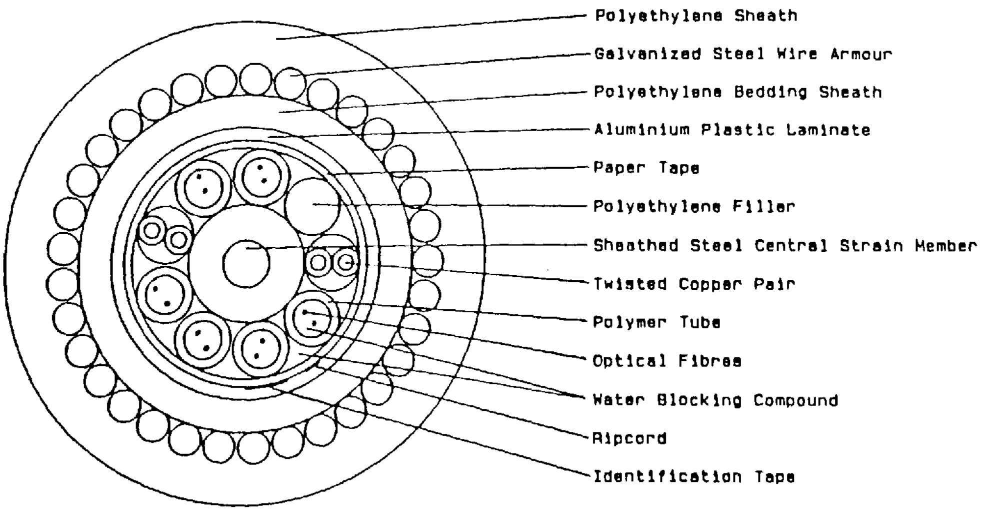
CABLE DESCRIPTION FOR A 12 FIBRE CABLE

SUMMARY

CONSTRUCTION : LOOSE TUBE	NUMBER OF ELEMENTS : 9
NUMBER OF TUBES : 6	NUMBER OF FILLERS : 1
NUMBER OF COPPER PAIRS : 2	INSTALLATION : BURIED
FILLED : YES	METALLIC : YES
ARMOURED : YES	FIBREMODE : SINGLEMODE
CUSTOMER : COMPANY X	REFERENCE NUMBER : RA00164

Fig.2 Title and Summary Sheet
from Expert System

12 Fibre Buried Cable for Company X - RA00164



Cable Diameter 18.9mm
Min Bend Diameter 378mm
Cable Weight 545kgs/km
Tensile Strength 31386N

Fig.3 Typical Graphical Output
from Expert System

2.5 Bend Characteristics of Fibres Manufactured by CVD, OVD and VAD Techniques

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ABSTRACT

Optical fibres manufactured by CVD, OVD and VAD techniques are noticeably different in terms of their index profiles as a consequence of the variations in processing techniques. This difference leads to significantly differing micro and macro bending characteristics for nominally similar ESI normalised frequency (V-number) values. This paper describes macro bending tests carried out on each type of fibre, with resulting bend performances compared and related to the fibre refractive index profiles.

1. INTRODUCTION

Optical fibre cables have many advantages over coaxial and copper paired cables. These include light weight, small diameter, and excellent transmission characteristics. However, optical waveguides are sensitive to mechanical and environmental influences, and their conservation is a major challenge in cabling. The main cable type manufactured by STC is of Loose Tube construction. These cables consist of either single or multiple fibres loosely contained within tubes. The tubes are then laid around a central strength member, wrapped with tape and then sheathed to form a cable. Longitudinal freedom and cushioning within the tubes ensures the fibres are protected against stresses applied to the cables during handling and installation operations.

The degree of longitudinal freedom depends on the amount of excess fibre placed within the tubes during manufacture. Fibres located in tubes follow a helical path (1) with a greater excess resulting in smaller bend diameters, i.e. more helical revolutions per unit distance. The actual bend diameter experienced by a fibre in a tube, which is subsequently helically laid around a central member (fibre is in a double helix) depends upon several parameters, e.g. central member diameter, tube inner and outer diameters, fibre diameter etc. The calculation of this bend diameter is a complex integral (2) whose solution relies on detailed knowledge of fibre and cable dimensions.

It is an inherent feature within the majority of optical fibres that when they are bent beyond a critical radius, light is radiated from the cladding thus causing a significant power reduction. The value of the critical radius depends upon the dimensions and shape of the fibre refractive index profile, which itself depends on the fibre manufacturing process.

It is essential to be able to fully characterise the performance of optical fibres when curved under cabled conditions. With this knowledge the cable design can be optimised so that bend radii which induce losses greater than a pre-defined limit can be removed. To manufacture a fibre of particular index profile, the type of process involved is a major influence. It is also important to note that the three major manufacturing processes CVD, OVD and VAD all contribute a particular design quirk to the index profile, i.e. central dip in CVD process, ill defined boundary at core-clad interface in OVD and VAD processes.

The macro bend tests were carried out on each of the fibre types, in an attempt to find out which fibre manufacturing process gives the best optical waveguide in terms of bend performance. The ultimate objective of the study was to empirically derive a relationship between fibre bend performance and refractive index profile, to increase the yield of optical fibre cables from failures due to bend loss.

2. MEASUREMENT EQUIPMENT/TECHNIQUES

2.1

Where possible measurement techniques compatible with CCITT Recommendations G652 (Red Book, Oct.84) were used. The equipment repeatability has been fully characterised and so a tolerance has been stated for each parameter, this is of particular significance in the case of the Refractive index profile where "state of the art" measurement equipment does not have as high a resolution as would be ideal.

2.2

Technique	Parameters	Tolerance
Fibre refractive index by the refractive near field technique	Core diameter Core delta N. Deposited cladding level	0.053 um 0.118×10^{-3} 0.034×10^{-3}
Mode cut off wavelength	LP11 cut off wavelength	7.25 nm

Papers presented at EFOC/LAN 88, the Sixth European Fibre Optic Communications & Local Area Networks Exposition, held June 29–July 1, 1988 at the International Congrescentrum RAI, Amsterdam, The Netherlands. Sponsored by IGI Europe Inc., a Division of Information Gatekeepers, Inc., 214 Harvard Avenue, Boston, MA 02134 USA. Telephone: (617) 232-3111, Telex: 499-6088 Iiber, Fax: (617) 734-8562.

Technique (Cont'd.)	Parameters	Tolerance
Mode field radius by far field technique.	Diameter of normalised field @ 1/e	.058 um
Attenuation	Increment due to macrobending @ 1300 nm & 1550 nm	0.009 dB 0.007 dB

2.3

The first three techniques mentioned are standard practice for fibre manufacturers and as such are well documented. With regard to the macrobending, however, although the "cut back" attenuation equipment is widely used and documented, the measurement of macrobending performance is very dependent upon technique and conditions, and so a brief description is warranted.

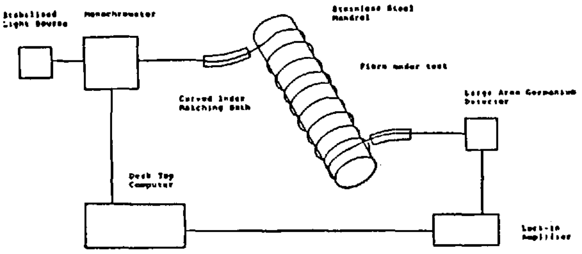

FIG. 21 TEST ARRANGEMENT FOR MACROBEND MEASUREMENTS

2.4

A 6 metre length of fibre is set up on a standard spectral attenuation rig (Fig. 2.1) - care being taken to ensure that the minimum bend radius seen by the fibre is less than 150 mm. Under these conditions a reference power level is taken at the wavelength of interest, or a scan across a wavelength window. Controlled bends are then introduced into the sample; a range of stainless steel polished mandrels are used for this, with radii ranging from 5 mm to 30 mm. Tension is kept to a minimum to ensure that microbending effects do not effect the results. It is estimated that the tension during winding is below 30 grammes. Under these conditions a second power reading is taken (or spectral scan), the macrobending loss being defined as:

$$\text{Macrobending loss} \quad (\text{dB}(\lambda)) = 10 \ \text{Log}_{10} \frac{\text{P1} \ (\lambda)}{\text{P2} \ (\lambda)}$$

3. CHARACTERISTICS OF CVD, OVD AND VAD FIBRES

3.1 Fabrication Processes

The underlying mechanism for all vapor-phase fibre fabrication techniques can be summarised as:

i) Generation of a gas phase flow of source compound.

ii) Direction of that flow to a zone where oxidation occurs.

iii) Deposition of the resultant oxides onto a substrate to produce a solid preform.

iv) Subsequent drawing of the preform into fibre.

Vapor - phase techniques can be broken down into two major categories: "inside" processes and "outside" processes. These labels refer to the physical relationship of the reactant - vapor stream to the substrate (3).

3.1.1 Outside Processes

The term OVD (outside vapor deposition) refers to the process whereby the reactant gas stream is fed into a fuel gas - oxygen burner, generating a stream of extremely minute glass spheres which is directed towards a rotating and traversing mandrel. The spheres collect on the target rod in a partially sintered state, forming a cylindrical preform. By programming the reactant gas stream composition appropriately the waveguide structure (core/clad ratio, refractive index profile) is built radially, layer by layer, into the soot preform. After deposition is complete, the target rod is removed and the preform is consolidated into a clear, bubble-free glass preform. Finally the preform is slowly fed into an induction or resistance furnace at approximately 2000 degrees C and waveguide fibre is drawn from its bottom end.

A modification of the OVD method is the vapor-axial deposition (VAD) process. The key difference between the two methods is that the growth of the VAD preform is in the axial direction rather than in the radial direction.

3.1.2 Inside Processes

Inside vapor deposition refers to the class of processes (MCVD, PCVD etc), whereby glass deposition occurs on the inside of a tube rather than on the outside surface of a substrate. A rotating fused silica tube is heated to about 1400 degrees C by a torch which traverses the tube's length. The reactant-gas mixture is injected into the tube, and soot formed by thermal oxidation, is deposited downstream of the burner. The moving burner sinters the newly deposited soot layer into a clear glassy film. Each pass of the burner causes a new layer of glass to be deposited and, as in the OVD process, by changing the composition of the reactant-gas stream, the desired preform structure is built up, layer by layer. The tube and deposit are then collapsed at high temperature, into a solid glass preform, from which fibre is drawn.

3.2 Refractive Index Profile Shapes

The refractive index profile shape of fibres manufactured by the CVD process is markedly different from those manufactured by the OVD and VAD processes, which are themselves nominally similar. A major difference between the CVD and OVD/VAD processes is the ability of CVD to produce under controlled conditions either a matched or depressed cladding fibre.

Differences in profile shape include the central dip seen in CVD fibres (Figs 3.1, 3.2) due to the depletion of dopant during preform collapse. Also with OVD and VAD fibres, the ill defined boundary seen at the core-clad interface, characterised by a slight grading of the index in that region, (Fig. 3.3). This is due to the diffusion of dopant from the core under high temperatures during the sintering process. This diffusion does not occur with the CVD process since the glass deposition occurs layer by layer, whereby each layer is fused before the next is applied. The OVD and VAD processes deposit all of the glass as a soot, where diffusion can occur before the glass is finally fused.

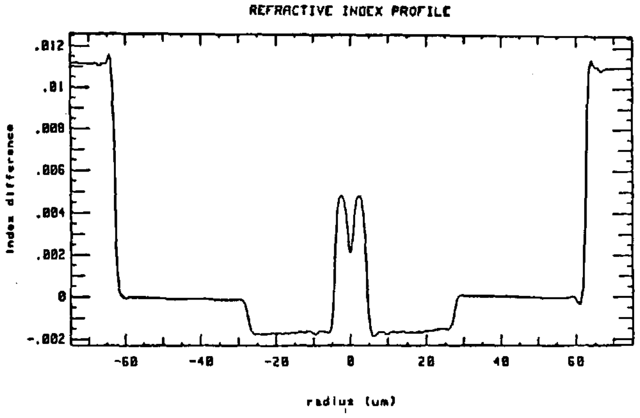

FIG. 3.1 CVD DEPRESSED CLADDING FIBRE

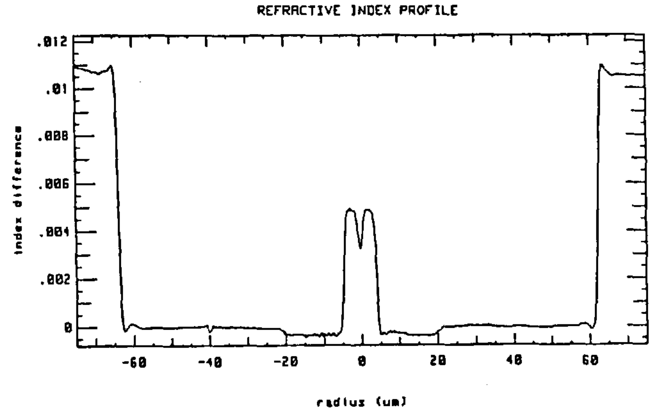

FIG. 3.2 CVD NOMINALLY MATCHED CLADDING FIBRE

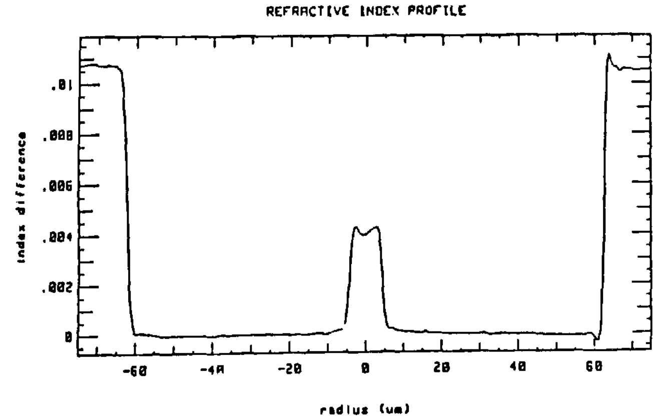

FIG. 3.3 OVD FIBRE

4. RESULTS

The macrobend characteristics of CVD, OVD and VAD fibres were only investigated at the two operating wavelengths, 1300 @ 1550nm. (Figs. 4.1, 4.2). Both graphs were plotted on a log-linear scale so that the loss region below 1dB was expanded to show the break points between two obvious regions, hence showing that the loss mechanisms are bi-functional. The relationship between loss and bend diameter for each of the fibre types tested, was found to be linear in each respective region, but the gradients of the lines in all cases was greater in the low bend diameter region.

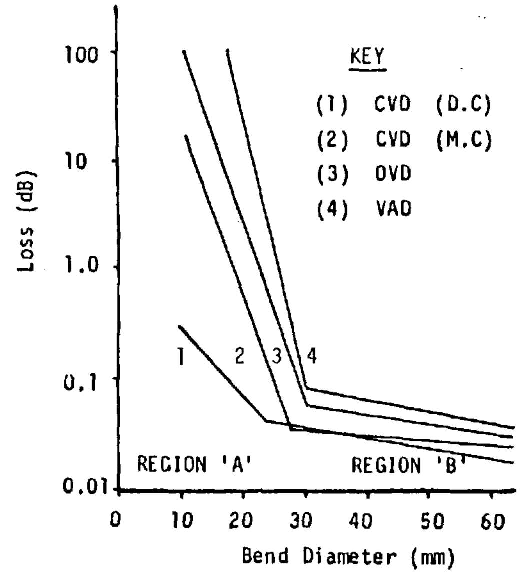

Fig. 4.1 Macrobend Characteristics of CVD, OVD and VAD Fibres at 1300nm (10 Turns)

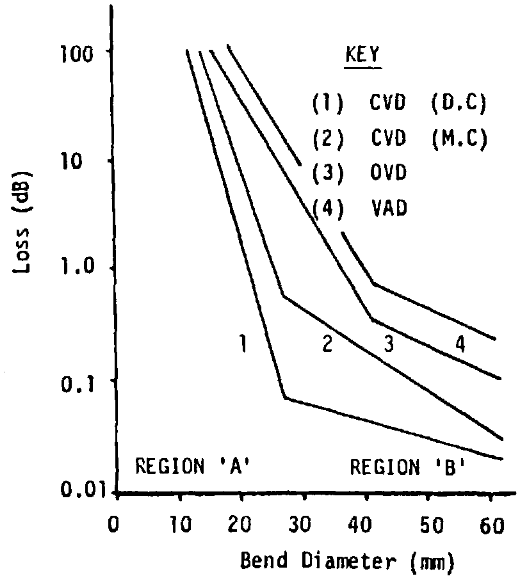

Fig. 4.2 Macrobend Characteristics of CVD, OVD and VAD Fibres at 1550nm (10 Turns)

For CVD fibres (both matched and depressed cladding), the second region, i.e. higher diameters, show 1300nm losses approaching that of experimental error. This suggests that the accuracy of the gradients are in doubt. However, the existence of this second region is confirmed by the 1550nm graph which shows significantly greater losses.

From both graphs it is clear that CVD (Depressed cladding) fibre is most bend insensitive, followed by CVD (matched cladding), OVD and VAD respectively.

It should be noted that 20 samples of each fibre were tested, with each type being nominally 8/125um fibre, step index germanium doped cores, coated up to 250um with a UV cureable urethane acrylate (doube and single layer).

In addition to the macrobend tests, each fibre was refractive index profiled and measured for spot size and cut-off. Since mode field radius and cut off wavelength tend to be indicators of bend performance, an attempt has been made to use fibres with similar values although the CVD depressed fibre had significantly higher cut off values. The distributions are shown in Table 4.1.

Fibre Type	Mode Field Radius		Mode Cut off Wavelength	
	mean	Std.dev.	mean	Std.dev.
CVD (DC)	4.48	0.06	1253	23
CVD (MC)	4.86	0.13	1171	26
OVD	5.14	0.08	1173	29
VAD	5.05	0.05	1204	19

Table 4.1 Parameter Distribution for Fibre Samples

5. ANALYSIS

This analysis attempts to provide simplified solutions to the fundamental fibre propogation characteristics by firstly, characterising the profile using an equivalent step index (ESI) algorithm and then using the ESI parameters (a and delta n) to define a value for the propogation velocity constant (V).

The ESI profile is defined:

$$Mn = \int_0^\infty (n^2(r) - n^2(a))\, r^n \, dr$$

and the propogation velocity constant V:

$$V = \frac{2\pi\ a\ (ESI)\ \ (n1\ (ESI)^2 - n2^2)^{0.5}}{\lambda}$$

The propogation velocity constant is a single parameter which is dependant upon the two basic fibre design criteria, core radius and core/cladding refractive index difference. V can now be used to characterise parameters such as Wo, λco and λo, since their dependancy upon two variables has been simplified.

The theoretical model for cut off wavelength (λco) and mode field radius (Wo) was firstly tested upon the range of samples of each manufactured type.

5.1 Cut off wavelength

Cut off wavelength is traditionally a difficult parameter to measure, being extremely dependant upon sample length and fibre conditioning. Consequently comparison of a measurement of a 3 metre fibre sample with a calculation from a cross section (effectively an infinitesimaly short length) is fraught with difficulty.

Fig. 5.1 shows the measured cut off wavelength of various fibre designs against V * λ, so making the constant independant of wavelength. Regression analysis showed that good agreement existed with the straight lines for each design. The theoretical line confirms the trend and so with the exception of the offset, this method of predicting λco is reliable.

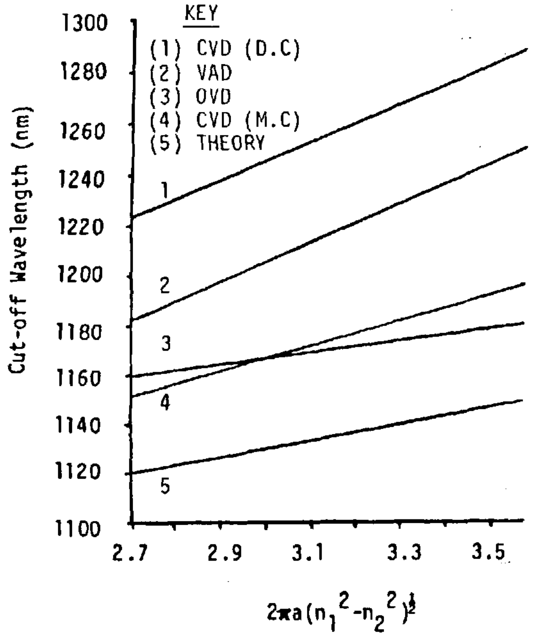

Fig. 5.1 Cut-off Wavelength Vs $2\pi a(n1^2 - n2^2)^{1/2}$

The prediction based on the profile will not take into account the fact that λco is dependant upon fibre conditioning and length. It has been shown that λco drops by up to 20nm/decade, purely as a result of the length dependance. This would suggest that the theoretical model based upon the ESI and V defines the cut off seen on long lengths of fibre (> 10 Km) or as a result of bends induced at splice housings.

5.2 Mode Field Radius

The comparison of mode field radius to theory at 1300nm provided very little correlation, in fact the trend of increasing V corresponding to a decreasing Wo(for V < 2.405) was shown to be reversed in certain cases.

Comparison of ESI based predictions with predictions based upon a finite element method (FEM) show significant discrepancies (5). Consequently it is hardly surprising that comparisons of ESI based predictions with actual measurements are very unreliable. This result shows that the profile structure cannot be ignored, as the ESI does, in the prediction of Wo.

5.3 Macrobending Performance

As can be seen from Figs. 4.1, 4.2 in all cases there are two distinct regions of loss, for the CVD fibre design the diameter at which the two regions converge is almost independant of wavelength, the VAD and OVD designs on the other hand is dependant upon wavelength.

The two regions are due to two distinct effects,

- region A due to bend loss
- region B due to transition loss

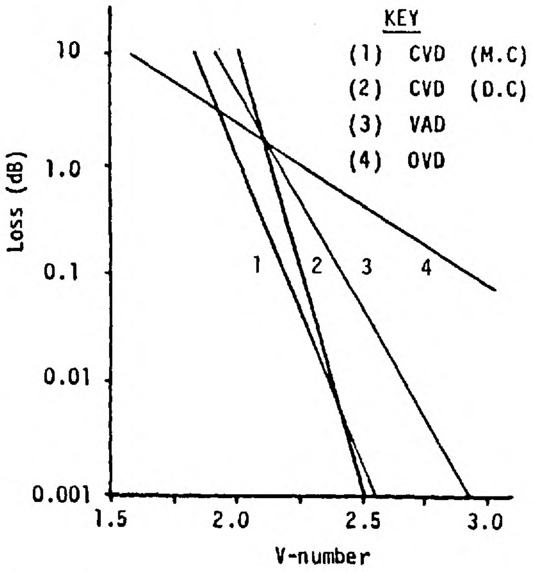

Fig. 5.2 Bend Loss Vs Normalised Frequency (V-number) Bend Diameter = 20mm; 10 turns

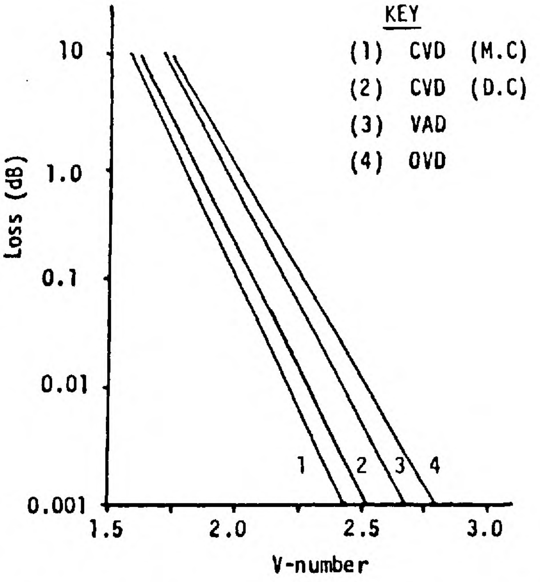

Fig. 5.3 Bend Loss Vs Normalised Frequency (V-number) Bend Diameter = 40mm; 10 turns

Figures 5.2 and 5.3 demonstrate the significant difference in performance in these two regions, generally however, although the absolute values are different the trend of decreasing 'V' producing poorer bend performance is common to all the fibres tested, in both regions. The variation in absolute values is highlighted by a comparison between figures 5.2 & 5.3 - 5.2 being 'V' against bend loss and 5.3 being 'V' against transition loss. The performance in the transition loss region is very similar from fibre to fibre, i.e. similar gradients and offsets, and since measurements in this region are of small losses it would be fair to assume that measurement errors play a significant role in these differences. The true bend loss region however, shows some more significant differences in that bend varies with 'V' to different degrees. This is more significant since its effect is greater and so contributes the most to the loss seen as a result of cabling.

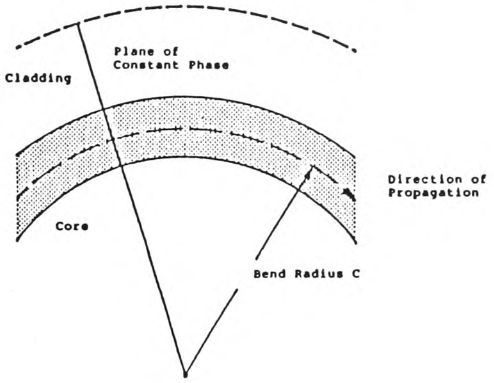

FIG. 5.4 WAVE PROPAGATION IN A UNIFORMLY BENT FIBRE

The bend loss is characterised by the different propogation characteristics for a bent to a straight fibre. In a straight fibre the primary mode (LP01) propogation can be defined as a TEM wave with the plane of constant phase being orthogonal to the direction of propogation - or Z axis. If the fibre is bent in an arc of radius C (Fig. 5.4), the phase velocity of the wave front will be required to vary depending upon its distance from the centre of the arc. The group velocity will be that of the speed of light, for this to be the case light travelling at a radius greater than that of the centre of the fibre will have to travel faster than the speed of light in this region. Since the cladding level is uniform this is impossible and so light in this region is converted into radiation modes. Attenuation due to this uniform bending is defined as the pure bending loss and is proportional to the length of the fibre bent.

A second mode of loss is experienced as a result of the effects at the interface between the straight and bent fibre. In the straight fibre the field is uniform and positioned in the centre of the fibre, just beyond the interface, the field is distorted as shown in Fig. 5.5. To achieve this the field in the straight section must excite the field that actually propogates in the curved section and radiation modes that exist on the outer edge of the bent fibre. The mismatch in power between the field propogating in the straight and bent section is defined as the transition loss and is independant of length.

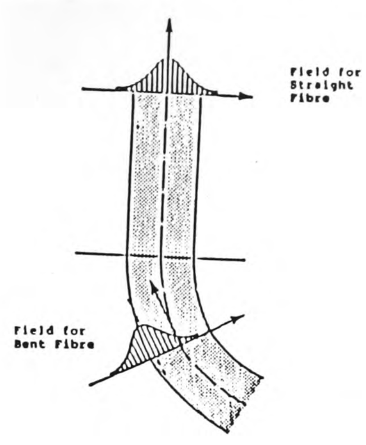

FIG. 55 BEND LOSS AS A RESULT OF TRANSITION FROM STRAIGHT TO BENT FIBRE

6. CONCLUSIONS

The relationship between the ESI profile and cut-off wavelength has been shown to be consistant, although theoretical analysis based on the ESI produces a cut-off considerably lower than the actual. This phenomena has been explained by consideration of length and bend dependancy of effective cut-off wavelength (6).

The relationship between mode field radius and ESI based predictions has been found to be unreliable, which concurs with previous work (5). Future work will incorporate a technique of finite element analysis (FEM) to take account of profile structure and processing characteristics associated with each design.

The attenuation dependence upon bend has been shown to be consistent with theoretical analysis, highlighting the bi-functional dependence upon diameter exhibited by each design. It is therefore possible to predict the performance of each fibre design under a particular bending regime. Where possible, fibres with similar performance characteristics were used, although the depressed cladding fibre samples had significantly higher cut-off wavelengths, and the OVD fibre samples had slightly higher mode field radii. By relating the bend performance to the propogation velocity constant (V), these effects are normalised.

Performance in the transition loss region is similar for all fibre designs, any differences being potentially due to measurement error. This effect, however, is considered to be of particular importance to the cabling industry and so it is proposed to investigate the phenomea further. The importance of the bend loss region is the bend diameter at which it takes effect, since as soon as this loss mechanism occurs, severe bend induced losses ensue. This is highlighted in the long wavelength region where changes in wavelength have a significant effect upon loss.

A third mode of loss has been hypothesised, occurring at relatively large bend diameters. This effect has been observed on a relatively small number of fibres. It's existence however, would have a significant effect on cabling and so it is proposed to investigate this further.

Since V is related to wavelength, the effect of increasing wavelength can be predicted using Fig.5.4. Using this figure it can be seen that the CVD based designs require lower V values to produce similar bend performances. By comparing this with the cut-off and mode field radii relationship it would appear that for similar values CVD designs provide a significantly better bend performance.

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