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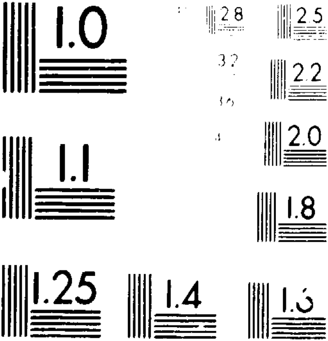

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TECHNIQUES FOR THE PRODUCTION OF OPTICAL COMMUNICATIONS FIBRE

14294

CONTENTS

A survey by :-

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ABSTRACT

This paper briefly reviews some of the key properties of modern communications fibres and relates these properties to the material and processes used in their manufacture. It then looks at the major manufacturing processes in use today and attempts to highlight the strengths and weaknesses of each. There follows a brief consideration of the world fibre market characteristics and their implications for developing countries wishing to set up manufacturing facilities.

1. GENERAL INTRODUCTION

Optical fibre now finds application in a very wide variety of communications systems. These are summarised below, in groupings based upon those used in telecommunications systems although a diverse range of other applications such as electrical power and production control systems, data systems and undersea systems can be placed among the same headings in terms of their fibre requirements.

i). Long Lines or Trunk digital communications.

Typically on routes between cities or major centres of population, with digital transmission rates spanning

34Mbit/s to more than 1 Gbit/s per fibre, according to traffic need. Route lengths of a few tens to many hundreds of kilometres. Requires fibre having high bandwidth (in excess of 500MHz.km) and very low attenuation (under 3dB/km). Repeater spacings of 10 to 50 km according to technology used.

ii). Inter-office Trunk or Junction digital communications. Used for connections between switching centres in cities or from outlying switching centres to main nodes. Data rates in the range 8 to 34 Mbit/s. System lengths from few kilometres to many tens of kilometres. Shorter systems unrepeatered. Still favours low attenuation fibre but with less bandwidth requirement. Great attraction in un-repeatered links to minimise external plant costs.

iii). Local Wideband, CATV, Video Conference etc.
Used to provide dedicated cable from customers premises to local distribution node. Range typically 0.5 to 5 kms. May use analogue FM or digital modulation. Generally assumed to require intermediate performance fibre with simple installation and termination properties. However, the over-riding constraint of low overall system cost may ultimately favour the use of a single mode "tree structure" network rather than the "switched star" network currently

favoured. The future here is very uncertain.

iv). Special Interconnects

Used for short distance (few metres to 1 km) medium data rate (0.1 to 100 Mbit/s) links of great variety, such as inter-rack connections in switching or computer systems, computer to peripheral equipment connections, data transmission between control computer computers and sensors, data concentrators or storage media etc. Fibre attenuation and bandwidth not usually critical parameters. Ease of installation, connectorisation and splicing usually key issues coupled with low cost.

v). Fibres for sensors.

A wide range of special fibre designs are now emerging for use in optical fibre sensor systems. However, a common theme in many is highly birefringent designs supporting true single mode propagation. The design of such fibres is dictated primarily by the need to maintain the state of polarisation, with low attenuation coming second. Lengths used range from a few hundred metres to a few kilometres.

Each of the above classes of applications favours a different fibre type, usually manufactured by a different process.

2. TYPES OF FIBRE

For general discussions of the various types of fibres, their properties, fabrication and use, the reader is referred to Refs.1 & 2. However, by way of introduction, we present here some brief notes on the subject.

We can discern four broad classes of fibre types, each of which finds its major application in one or two of the above application categories. In all designs, light is guided by total internal reflection in the dielectric waveguide formed by a high refractive index glass core surrounded by lower refractive index cladding. The radius of the core is designated by the symbol "a" and the maximum angle at which light can propagate is given by the angle A as shown in Fig.1. This angle is related to the refractive index of the core glass, n(core) and that of the cladding glass, n(clad) by the following relationship:-

$$\sin(A) = \sqrt{n(\text{core})^2 - n(\text{clad})^2}$$

$$= \sqrt{2\, n(\text{core})^2 . \Delta}$$

$$= \text{Numerical Aperture (NA)}$$

where Δ is the fractional index difference defined as

$$\Delta = (n(core) - n(clad)) / n(core)$$

The term Numerical Aperture is widely used in describing fibre types. The range of values for these two parameters is as follows:-

Core radius a.	3 to 80 microns
Cladding outer diameter	125 to 200 microns
Numerical Aperture	0.01 to 0.6

The glass refractive index usually lies in the range 1.45 to 1.6.

The categories of fibre of interest are as follows:-

i). Single mode fibre.

Cross section shown in Fig.2. Core radius in range 2 to 5 microns. Outer diameter 125 microns. Usually designed for operation at 1300nm, 1500nm or both wavelengths. The fibre offers the highest performance in terms of very low dispersion, huge bandwidth and very low attenuation and is becoming standard for category 1.i type applications above. Some design variants of current interest are shown in Fig.2 also.

ii). Graded index fibre.

Cross section shown in Fig.3 The refractive index versus radius in the core region varies roughly parabolically. The fibre supports multiple guided modes, all of which carry light. Typically, the number of modes is given by

$$M = (a.n(core).k)^2 \Delta / 2$$

where $k = 2\pi / \lambda$

This fibre was the first design used for telecommunications systems. It was initially designed for use at wavelengths between 850 and 900nm but has recently found increasing application at 1300nm wavelength. It offers less performance than the single mode fibre, is easier to splice or connectorise by virtue of its larger core diameter, may be more sensitive to induced cabling attenuation and requires exceptionally good production control of the core refractive index profile if good bandwidth is to be obtained (ie greater than 300 MHz.km). Manufacturers typically offer as their highest grade product a fibre with in excess of 1GHz.km bandwidth with lower bandwidth products accounting for the majority of the plant production. The wide spread represents the uncontrolled variation arising from the fluctuations in the production process. The fibre is the most common choice at present for applications categories 1.ii. and 1.iii.

iii). Step-index fibre.

The term is used to describe a fibre that superficially resembles the single mode fibre but which has a larger core diameter and probably also larger index difference. Typical values for core radius might be 30 to 80 microns and with values of NA from 0.2 to 0.6. The number of modes in such a fibre is just twice that of a parabolic core fibre with similar a and Δ. This type of fibre is used for short distance links where low cost Light Emitting Diodes are used for sources and where simple connecto isation is important. Such applications fall in Category 1.iv.

iv). Polarisation holding fibre.

These fibres are of similar dimensions to the single mode fibre described in 2.i. However, that fibre actually supported two degenerate guided modes polarised at 90 degrees to each other. In the Polarisation holding fibre, the circular symmetry of the core is broken either by the use of an elliptical cross section or by the inclusions of glass structures that generate very high strains at right across one diameter. In such fibres, the two propagating modes "see" different refractive indices, travel at different group and phase velocities and hence do not couple to one another readily. A variety of cross sections for such fibres are shown in Fig.4. (see Ref.3 for further information). Such fibres find application in a variety of fibre sensors, fibre gyros and special fibre devices such as polarisers.

3. PRIMARY DESIGN CONSTRAINTS

A study of the mechanisms whereby light becomes attenuated in glasses shows a number of important separate effects. They fall into two broad categories, intrinsic and extrinsic. The intrinsic effects are those that arise from the basic glass constituents, assumed to be 100% pure, whilst the extrinisic effects arise from contaminating impurities or process defects.

i). Intrinsic attenuation mechanisms

The intrinsic effects are shown in Fig. 5 for pure silica glass, SiO . They include absorption from the "band edge" of the silica material which increases rapidly towards very short wavelength in the ultra-violet spectral region and a similarly rapidly rising absorption edge as wavelengths longer than 1600nm are reached which arises from the infra-red absorption peaking at 9000nm (9 microns) of the

Si-O bond vibration. In between these effects, Rayleigh scattering from the disordered glass structure contributes about 0.6 dB/km. at 1000nm (1 micron) wavelength and varying as wavelength to the minus fourth power. These effects give rise to fundamental minumum attenuation centred at about 1550nm of about 0.14 to 0.2 dB/km. At the time of writing, silica is firmly established as the preferred base material for communication fibre.

To produce a guiding structure, a second glass material is required of higher or lower refractive index. These are normally obtained by using silica with some dopant species in concentrations of a few weight percent. These dopants can be split into two classes, those which raise the index above silica and those which depress it. The commonly used dopants are as follows:-

Increasing Index

GeO_2 and P_2O_5

Decreasing Index

B_2O_3 and Fl

Adding such dopants usually increases the Rayleigh scattering a little and may change the Infra-Red absorption characteristics. For lowest possible attenuation, particularly in the 1500-1600nm wavelength window, it is generally best to avoid Phosphorous in the core and Boron in the cladding.

Many other considerations enter into the detailed planning of the production process. For example, the deposition rate varies with composition (Phosphorous doping favour high deposition, pure Silica giving very low rates). The relative thermal expansion coefficients of different compositions are important since low strain preforms are less likely to shatter mechanically while the different fictive (solidification) temperatures of different glasses must be considered, since a very stiff material surrounded by low viscosity material during the collapse phase can lead to severe instability and mechanical distortion. This can lead to very complex detailed process optimisation considerations for particular fibre designs.

ii). Extrinsic attenuation effects

Extrinsic effects can be very broad ranging. For example, the mechanical perfection of the fibre itself is important, in terms of a smooth core/cladding interface and freedom from gas bubbles or other inclusions in the light guiding material. The fibre must also be cabled without the mechanical deformations induced by the cabling process which scatter light out of the fibre. This imposes tough design contraints on both the cable and the fibre.

Impurities in the fibre cause serious attenuation. The first-row Transition Metals in the Periodic Table of Elements are well known for the coloration they produce in glasses and trace amounts (order parts per million) of such elements (Fe, Cu, Mn, Ni, Co, etc) lead to broad absorption bands. These must be rigorously excluded. The presence of water within the glass, in the form of an Si-O-H bond also gives rise to significant absorption as shown in Fig.6. The fundamental absorption line arising from the O-H bond is centred at about 2800nm. However, the first and second harmonics occur at about 1370 and 960 nm with other associated bands arsing from the Si-O-H interactions at 1230, 880nm and other wavelengths. Thus it is also critically important to hold water levels at part-per-million levels in low attenuation fibres.

iii). Mechanical control

Both the graded index and single mode fibres require exceptionally close control of the dimensional tolerances and the distribution of the refractive index of the glass versus radius. In the graded-index fibre, the most difficult task is to control the refractive index profile so as to maintain it close to a nearly parabolic, theoretically generated ideal shape whilst in the single mode fibre, close control of diameter, concentricity and index difference are important to maintian the guiding properties of the fibre and low splice losses.

iv). Summary

The above design considerations have led virtually all fibre manufacturers to the following conclusions:-

a). Silica is the best basic design material, linked with some combinations of the dopants listed above.

b). The starting materials must be exceptionally pure and must be maintained so throughout manufacture.

c). This strongly favours using starting materials in volatile liquid form, allowing for purification by distillation and transport of the material within the sealed production apparatus in vapour form.

d). Deposition of glass from the vapour phase is relatively slow. However, computer control of the vapour flows using mass flow controllers makes possible the precision control of the glass composition aat any given time or place.

Thus, the commonly used starting materials for such a fibre process are as follows:-

Glass Constituent	Starting Material
SiO_2	$SiCl_4$
GeO_2	$GeCl_4$
B_2O_3	BCl_3
P_2O_5	$POCl_3$
Fl	CCl_3F

In each case, Oxygen is used, possibly with another inert gases, as the carrier to transport the vapour to the reaction zone. The oxygen is then reacted with the halides to form the appropriate oxide material. The detailed techniques for this process vary widely. The materials are generally available in "semiconductor grade" purity.

All the production processes to be discussed here consist of two stages, a preform production stage followed by a preform pulling stage. The preform production stage involves building up a solid circular preform, typically of length in the range 10cm to 1 metre and diameter from 1 to 5 cms and having the cross sectional structure of the desired fibre. This preform is then pulled (stretched!) so that it becomes a continuous length of fibre, of as little as 1km in length to as much as 100km. Taking the standard fibre diameter used for telecommunications systems of 125 microns so that 1km of fibre contains 12.3 cubic centimetres of glass, we find the following :-

Preform Size (length x diameter in cms.)	Fibre Length * (in kms.)
10 x 1	0.64
50 x 2	12.8
100 x 4	102.

* This assumes 100% yield which will not be achieved in practice.

4. BASIC PREFORM PRODUCTION TECHNIQUES

i). Introduction

All the techniques that we will discuss start with their pure materials in liquid form as discussed above. They are stored in sealed temperature controlled flasks through which the carrier gases are bubbled in order to carry the vapours to the reaction zone (see Fig.7). The carrier gas will include oxygen to generate the oxide glass on reaction, but may also include other gases such as He or Cl to increase flow rate and sweep away impurities.

The gases must be dried and their flow rate controlled. This is usually done using mass-flow control valves under computer control. The individual vapour streams are mixed and pass into the reaction hot zone where the oxidation takes place to produce the oxides in very fine particulate form. These are then deposited and compacted to form a glass. The details of how that is achieved largely distinguish the different processes.

ii). Modified Chemical Vapour Deposition Technique (MCVD).

This technique is the most widely used for preform fabrication, has been studied by numerous laboratories and is probably used in more production plants than any other, e.g by Bell Telephone Laboratories and Western Electric in the USA and by BTRL in the UK. The process is one of the easiest to set up with limited technical resources, although may not be the best suited to high volume production.

The basis of the technique is shown in <u>Fig.8</u>. A silica tube is mounted in a glass working lathe between the headstock and tailstock and rotated at constant speed, typically about 1 revolution per second. The headstock end of the tube is connected via a rotating gas seal to feed system which provides the mixed vapours and carrier gases. The tailstock end is connected to an exhaust system which removes waste products, unreacted gases and undeposited glass powder. The waste gases are passed through a scrubbing system to prevent toxic materials escaping.

On the moveable saddle of the lathe, there is mounted one or more gas burners, usually based upon oxygen and hydrogen, which heat the outside wall of the silica tube. The saddle is traversed slowly forwards down the tube, rapidly returning to the start end to commence another traverse. The reactants combine in the hot zone to deposit the glass powder as a fine "soot" on the inside wall of the tube. However, since the hot zone passes by this material, it fuses to form a succession of thin, transparent layers on the inside of the tube. Also on the saddle, there is usually an infra-red pyrometer which is used to measure the silica tube wall temperature and, via the control computer, to control the gas flow to the gas burners. It is also common to maintain the lathe saddle motion under computer control so that all aspects of the process can be optimised easily.

In <u>Fig.9</u>, we show a schematic view of the reaction zone, indicating that the fine powder material is driven towards the tube wall by thermo-phoresis, movement down the temperature gradient. Hence, the deposition efficiency can be improved by increasing the temperature gradient. One technique for doing this is to spray cold water onto the tube wall ahead of the hot zone.

The material that will thus guide the light is built up layer by layer, with perhaps 100 layers being deposited for a graded-index fibre, including some pure cladding material followed by successive layers of core material. The composition is varied from layer to layer under computer control in order to provide a close approximation to the desired profile.

When sufficient layers have been deposited, the tube is collapsed in-situ by increasing the heat of the burner on the lathe saddle to soften the silica tube wall. In this way, the deposited layers coalesce to form a solid core, totally enclosed within the original silica jacket, so forming a preform.

Typical parameters for this process (Ref.4) for the manufacture of single mode fibre are as follows:-

Starting support tube dimensions	
Internal diameter	19mm
External diameter	25mm
Deposition rates	
Cladding material	0.25 to 0.75 gm/min
Core material	0.05 to 0.1 gm/min

Final Preform cross section

Before collapse

Thickness of deposit	1.15 mm approx

After collapse

Core radius	0.56mm
Deposited cladding radius	3.9mm
Overall radius	9mm

Using a mean density figure (for silica) of 2.7gm/ml, we see that such a 1 metre long preform weighs approximately 690 gms, of which about 20% has been deposited from the vapour phase. Taking a mean deposition rate of 0.5 gm/min, this corresponds to a deposition time of 4 to 6 hours according to the detailed design of the core and cladding materials.

The figures for a graded-index fibre would be broadly similar although for the typical 50 micron core diameter, 125 micron outside diameter fibre, something like 60 to 65 micron in diameter would need to be vapour deposited, some 27 to 30%, with a corresponding increase in deposition time.

A variety of problems arise in the MCVD deposition which become more serious as the size of preform sought increases and production pressure demands higher deposition rates.

Larger preforms require thicker deposited layers and would imply thicker wall tubes, yet high deposition efficiency requires a large temperature gradient from the reaction region to the deposition point. High reaction temperature encourages rapid reaction, yet also leads to softening of the tube wall and problems with deformation. Large diameter, thin walled tubes allow rapid deposition but would initially imply a need to deposit a greater volume of cladding material and also require greater control of the collapse process. One simple approach that leads to rapid deposition but uses the maximum volume of silica in tube form is to sleeve the collapsed preform with a second tube.

Examination of real preform or fibre index profiles shows the presence in MCVD fibres of a large central dip in the dopant concentration in the popular Germania doped Silica core fibres. This arises during the collapse process because volatile germania is lost from the innermost layers before they finally close up on each other. This can be combated partially by maintaining a high partial vapour pressure of Germanium Tetrachloride inside the preform during collapse or by gas phase etching the innermost layers of material away altogether just before final closure.

To prevent the premature collapse of the preform during the deposition phase, it is often necessary to maintain some back pressure of gas inside it to counteract the forces of surface tension on the tube wall. Indeed, servo control of such back-pressure has been used to correct fluctuation in preform diameter in conjuction with a diameter monitor system on the lathe saddle.

A further complication in MCVD preform processes concerns the fact that deposition is assymetrical, with the gas flow always commencing from one end. Accordingly, it is often found that the resulting preforms are tapered. Such problems can be corrected in principle through suitable programming of the control computer but any attempt to do so rapidly complicate the process.

The complexity of the process therefore very much depends upon the needs of the user. A simple MCVD preform system is rdily established and will quickly give short lengths (1km) of reasonable fibre (say 3-5dB/km at 850nm, 100-300 MHz.km bandwidth in graded-index). To obtain world class in 10 to 30 km lengths per preform with precision control of dimensions requires great sophistication. The process this offers great attraction for a first time user who start simply and develop over time as his needs become more sophistiated.

iii). Plasma assisted Chemical Vapour Deposition (PCVD)

This technique can be considered as a major variant of the MCVD technique. The process has been extensively studied by the Philips company in Europe. The apparatus is essentially identical, except that an RF coil is mounted on the lathe saddle in addition to the burners to produce a RF excited plasma discharge in the reaction zone. Thus the reaction process is "heated" much more efficiently and more complete reaction occurs. Furthermore, the temperature gradient is larger so that somewhat higher deposition efficiency is generally obtained, with figures very close to 100% being reported (Ref.5). On the other hand, to maintain a stable plasma discharge, it is normally necessary to maintain a reduced vapour pressure within the preform tube, so that actual material flow rates to the reaction zone are reduced and glass deposition rate is lower. Using high pressure discharges, however, deposition rates close to those found in the competing processes are believed to have been achieved. The detailed design trade-offs involved here are no known to this author.

Because it is not necessary to supply heat through the wall of the support tube, it is possible to scan the reaction zone back and forth along the preform length very rapidly, so that the deposition is composed of a very large number of discrete layers, perhaps 1000. This coupled with the high deposition efficiency means that exceptional good profile control is obtained, leading to good yields of very high bandwidth graded-index fibres.

iv). Outside Vapour Deposition process (OVD)

This process, which was developed by the Corning Glass Works, is fundamentally different to the MCVD and PCVD processes in several respects and is shown schematically in Fig.10. In place of a silica tube and internal layer deposition, it uses a solid ceramic mandrel on to which material is sprayed from the side, thus building up a preform from the innermost layers first to the outermost last. Usually, all the cladding material is deposited by the flame fusion burner, as well as the various core and special cladding layers. The process shares with the MCVD process the cylindrical coaxial-layer symmetry with the glass composition being controlled by changing the composition of the vapours supplied to the burner. It has proved to be capable of delivering good control of both the mechanical dimensions and the refractive index profile.

Apart from the deposition geometry, there are some further major differences in the OVD process. The use of an external flame-fusion burner means that very high rates of material deposition can be achieved. However, the material is not deposited in clear glass form but in the form of a porous ceramic structure that looks like unglazed pottery. The material has low density and normally contains high levels of water, trapped from that formed when the Oxygen and Hydrogen burned in the torch. Thus it is necessary to follow the deposition phase by two additional ones, drying the preform by purging it in a suitable gas atmosphere such as Chlorine at high temperature and then compacting it by heating it until the porous material softens and collapses under surface tension to form a clear glass. At some stage in this processing, it is also necessary to remove the original support mandrel and then to collapse the hollow preform. These additional operations add considerably to the overall processing load although the process compensates for this by making it relatively easy to make large preforms with good control and high deposition rate, with figures of up to 4.0 gm/min reported. (Ref.6). As in the MCVD and PCVD processes, the OVD process builds up a given index-profile in concentric layers and thus allows almost any desired profile to be made to a good approximation. The process has been heavily developed by Corning Glass Works and to the authors knowledge has not been successfully reproduced elsewhere other than under licene. Intending users are therefore advised to seek a technology transfer agreement with the developers.

v). Vapour Axial Deposition method (VAD)

This process has been developed primarily in Japan by NTT in collaboration with the Japanese Industry, probably as a competitor to the OVD process. It shares with the OVD process the use of external flame-fusion burners to deposit material at a high rate onto a revolving form. However, as shown in Fig.11, it differs in its use of a seed or bait rod on which core and cladding are built by longitudinal growth along the rod axis. Hence, the preform grows in much the same way that many crystals are grown, for example Ruby in the Verneuil method. The core may be deposited alone, leaving a solid form that must later be sleeved with silica tube to provide a cladding. Alternatively, the cladding can be deposited using a second and/or third flame fusion burner, with each providing a different composition of material. As in the case of the OVD process, the preform is initially of low density material and must be dehydrated and sintered to form a clear, low OH content glass preform.

Several major differences seperate the VAD process from the preceeding processes. For graded-index fibres, the control of the fibre profile is not done by building up a layered structure in a step-wise approximation to the desired profile but instead, is achieved by maintaining a controlled temperature gradient across the end of the growing preform so that various amounts of dopant diffuse away from different radii, leaving the desired profile.

This appears to be extremely difficult to control. In the case of single mode fibre, the same basic control mechanism means that some of the more complex W, triangular or depressed cladding designs are virtually impossible to make.

The lack of the layered, cylindrical deposition symmetry introduces a further control problem in that parallelism and accurate preform control must be produced by precision control rather than by occuring almost naturally as in the the MCVD,PCVD and OVD processes. It is clear from many reports that this can lead to extreme difficulty in obtaining precise dimensional control on VAD fibre and it may mean that, prior to sleeving the compacted core preform, it must be processed by pulling or machining to obtain parallel sides. However, the process has given some very long continuous lengths of fibre and some very low OH content material. Production plants using the process appear to face tough yield and control problems but may be compensated by their ability to make large preforms yielding 50-100kms or more of fibre. As with the OVD process, high deposition rates should be obtained but unlike the OVD process, much of the cladding is often obtained by sleeving with a silica tube. In a recent reference (Ref.7), a double burner deposition system was reported which deposited 4.5 gm/min/burner with 55% deposition efficiency which led to preforms for graded index fibre of up to 2500gm in weight. The process is generally regarded as a difficult one to bring into production, so that the intending user is advised to seek a technology transfer agreement with the developers.

vi). Other techniques.

A number of variants on the above techniques have been proposed, mainly to provide ways of making very large quantities of low cost fibre for the application listed under 1.iii. Generally, these are based upon the concept of procing very large "boules" of uniform composition material at very high rates with a technique akin to the VAD process. Large in this context might be 10cm diameter by 500cm long. Such boules would then be drawn down to more "conventional" size (2 x 100 cm), sleeved with suitable tubing and then drawn into fibre. Such processes are still under investigation, yield inferior performance fibre but may offer the possibility of very low cost fibre.

Another altogether different technique for the manufacture of intermediate performance fibre is the "double crucible" process which uses glass rods, formed by melting powder materials, to feed two concentric cricbles with nozzles located in their bases so that an inner and outer glass stream extrude concentrically and can be drawn into fibre.

This is shown in cross-section in Fig.12. The process has attracted some attention for high NA, large core diameter fibre but is little used at present. It has been discussed in some detail in Ref.1. It has proved to be extremely difficult to achieve attenuations below about 10dB/km in a production environment since the purity of the fibre is at best the purity of the powder starting materials. The process may find attraction where this is not a problem.

5. PREFORM PULLING

The basic apparatus for preform pulling is shown schematically in Fig.13. The preform is fed vertically downwards into a graphite or zirconia lined furnace held at a temperature in the range 1900 to 2100 deg.C. The tip softens and falls away, bringing with it a fine filament of glass. The "gob" is removed and the filament fed into a winding system to maintain a constant pulling speed and to wind the fibre so formed onto a suitable take up drum.

The early furnaces were heated by passing an electric current through a suitably formed graphite element. This had to be purged with a Nitrogen or Argon atmosphere to prevent it burning away too rapidly. A thermocouple or pyrometer is used to monitor the element temperature and to control the drive current through a servo loop.

More recently, Zirconia lined furnaces have become popular, primarily because the graphite material sputters off the element and on to the preform or fibre, leading to micro cracks that weaken the fibre mechanically. The Zirconia lined furnace makes it possible to seal the element better from atmosphere but can also be used as the susceptor in a direct Radio Frequency heating system. An operational problem with the Zirconia lined furnace is the extreme sensitivity of such liners to thermal shock, requiring the furnace to be keep hot at all times or to be temperature cycled with extreme care.

After the furnace, the fibre diameter is usually monitored using some form of optical device that passively measures its dimensions. Most designs rely upon monitoring the far field diffraction pattern from a HeNe laser beam shone at right angles to the moving fibre. The control signal from this monitor can then be used to vary the preform feed rate or the fibre pull rate to provide diameter correction.

The fibre take up is done in one of two ways, either using a capstan to provide constant pulling rate and a separate constant tension take-up drum and winder, or by using the drum itself to provide the take up. The latter approach suffers from the problem that on long fibre pulls, multilayer winding may change the effective drum diameter so that constant angular speed does not give constant linear speed. It also presupposes the use of precision drums and does not allow fibre from a single preform to be wound onto several separate drums, presenting a measurement problem when very large preforms are to be pulled.

The key components for fibre drawing are available from a number of commercial suppliers in the UK and USA. However, most production systems use a combination of bought-in and custom designed equipment. The major variations tend to occur in the coating technology (see next section) where the coating apparatus may vary considerably in size, according to the type and number of coatings and the pulling speeds planned. For low speed pulling (1m/s) pulling towers vary from 3m to 6m in height. For high speed pulling (up to 10m/s), pulling towers may extend to 10m or greater height.

6. COATING AND STRENGTH

i). Strength considerations.

A factor of major importance in the production of optical fibre for telecommunications is its mechanical strength. Being made of glass, when stretched, it elongates elastically until it breaks, unlike metals which undergo a small elastic extension followed by a large non-elastic extension during which the metal flows prior to breakage. It is for this reason that glasses are generally regarded as weak materials.

However, examination of the detailed properties of glass (see Ref.1) shows that glass can be exceptionally strong, stronger on a weight basis than steel. However, to demonstrate such strength, samples must have exceptionally good surfaces. This is becuase the normal glass surface contains huge number of micro-scopic cracks (micro-cracks), generally so small that they are invisible under an optical microscope. When the sample is tensioned, stress is concentrated at the crack tip leading to local failure which then propagates throughout the sample. Surface quality and protection is thus vital.

ii). Strength precautions

To manufacture high strength fibre, a number of discrete steps must be carried through.

a). The preform support tube must be free of inclusions that might nucleate crack growth and its surface must be maintained as pristine as possible.

b). After deposition aıd collapse, the preform must handled with great care to avoid surface damage.

c). Prior to pulling, the preform surface should chemically cleaned and flame polished (heated with a oxy-hydrogen flame to soften the surface layer only).

d). The Pulling apparatus must be kept dust free, with particular care being taken to suppress the transfer of refractory dust from the furnace liner to the heated preform.

e). Immediately after pulling, the glass fibre should be coated with a protective coating.

f). Care should be taken during winding and storage that the fibre is not maintained under high tension since this encourages crack growth and also mechanical damage by abrasion to the protective coatings must avoided.

iii). Coating materials

The choice of coating materials is a matter for the manufacturer, each preferring his own proprietary material. However, some general comments may be helpful.

a). The thick (100 micron) primary coating is usually a soft polymeric material. Silicone resins have proved to be very popular, usually of the heat or ultra-violet polymerisation/curing type. They are applied by passing the fibre vertically downwards through a funnel shaped container whose monomer liquid level is continuously maintained. The coating thickness is controlled by the nozzle size & liquid viscosity (see Ref.1). The fibre then passes through an oven or UV light bath typically 1-2m in length. These materials provide a soft spongy layer to cushion the fibre against locally applied deformation and also provide an excellent protection for the pristine glass surface. However, they are high friction materials which make cabling or handling difficult unless secondary coated.

b). The thin secondary coating (optional) is then applied in similar manner. A popular material is UV cured epoxy-acrylate which provides a hard low friction coating. Such a coating may also be colour coded for identification purposes.

c). The final packaging or coating often takes the form of a thick extruded polymer coating such as Nylon to make up the total package to 1-1.5 mm diameter. The use of such final extrusions is strongly favoured in Japan but less so in Europe, where simpler cable designs have been evolved to accept fibres without the extruded coating. This reduces fabrication and installation cost and appears to present no performance penalty but rather offers some advantage (lower attenuation frequently).

iv). Strength assurance

It is common practice to ensure that all fibre has some minimum strength value after manufacture by on-line testing. This is susually done by interposing between the pulling capstan and the final take up drum two capstan drums, one of which runs at typically 1% greater speed than the other. In passing round the slow one followed by the faster one, the fibre is thus stretched by 1%. If there are faults in the fibre above a given size, the fibre then breaks. Whilst this test is destructive, it is much cheaper for breakage to occur at this early stage than at the cabling or installation stage and is thus widely used. The detailed thinking and design behind such testing is discussed in greater detail in Ref.1.

v). Lifetime assurance

The user of the fibre should then be aware of the effects of stress corrosion. The fact that micro-cracks grow when subjected simultaneously to stress and moisture means that in any operational cable environment, if the fibre is under tension either during installation or afterwards, cracks will grow. The evaluation of this effect is too complex to detail here. However, in general it may be said that if the operational stress level in the fibre is always significantly less than the proof stress level, failure should be extremely unlikely. The reader is referred to Ref.1 for detailed discussion.

7. FUTURE DEVELOPMENTS

At present we find the following processes in high volume production (circa 50 to 500 thousand fibre km/annum). In the USA, Western Electric is believed to use the MCVD process and Corning Glass is believed to use the OVD process predominatly. A number of other manufacturers use the MCVD process. In Japan, the MCVD process has been used widely but following an intensive R&D programme involving NTT, Fujikura, Furukawa and Sumitomo, it is believed that the VAD process is now being widely used although this author knows of no firm production figures. Within Europe, there is an OVD plant operational in the UK with another reputedly under construction in another country as well as numerous MCVD plants. Philips are assumed to use the PCVD process for their own fibre. There is also a large scale development of the silica rod-in-tube process in France aimed at local network application.

Most volume users of fibre now buy to performance specifications that are close to CCITT or other International Standards, placing their order with the lowest bidder since fibre has become a high volume standard product. We have discussed above the ability of the individual processes to meet operating specifications and noted that most are capable of doing so although yields may vary substantially. It should be noted that actual numerical yield data for a given plant or process is virtually unobtainable since it is of great commercial significance.

Since all processes use essentially identical starting materials and their cost is a small part of the finished product, there remains room for considerable cost reduction. Hence, during the remainder of the present decade (to 1990), it seems certain that the price of fibre will continue to fall as the volume installed increases and the processes become steadily more refined. As this happens, factors such as deposition and pulling rates, start material costs (including silica tubing where used), yield of fibre to the required specification and the need for screening individual fibres will become key issues in deciding which process will be best equipped to meet the market. Strategic considerations may also have an impact, for example the supply of suitable tubing or a material such as Germanium Tetra-chloride.

The nature of wages structures in the Western Industrial countries has led to a great deal of development effort being expended on achieving higher productivity (fibre.km) per industrial man-hour as a major part of the cost reduction process, since wages make a substantial contribution to cost of the finished product. In an economy with lower wage rates, this balance will obviously change and may allow them to undercut the prices of fibre manufactured in Europe, North America or Japan.

A second trend that is already apparent will be an increasing switch from graded-index fibre to single mode. Already, the price of single mode fibre has fallen close to or below that for good graded-index fibre whilst offering much superior performance. However, its use in a system is probably still higher becuase of the additional cost of connectors, splicing and sources (single mode pigtail lasers). Once again, volume production will reduce these component costs so that the cost/performance advantage of single mode fibre will further increase.

The largest potential future market in the West is for wideband TV distributuon over fibre, optical CATV or Pay TV systems. However, in general, the system specification for such an application is still so incomplete that it is not clear what type of fibre, if any, will be used. The only large scale programme announced is that for France for which the fibre is expected to be made internally. There is great controversy within Europe about the programme and no concensus that it represents the correct route to follow.

Fibre for under-sea systems will undoubtedly remain the silica single mode type this decade. The major change that can be anticipated is the extension of repeater spacings to, perhaps, 250km. This would make many routes repeaterless; a development that seems likley to greatly and favourably affect their economics and perhaps generate more traffic.

In the longer term, there is speculation that trans-oceanic repeaterless submarine systems might be possible, operating at wavelengths of 3 to 10 microns in non-oxide glass fibres, (ie halides, chalcogenides etc). Whilst there is some theoretical evidence that suggests that losses as low as 0.001dB/km might be achievable, it remains a matter for speculation as to what will be achieved. Values of about 10dB/km have been achieved in the laboratory and the remaining problems appear formidable. Furthermore, the market is limited and very specialist and such systems would need completely new transmitters and receivers for the longer wavelength operation.

8. PATENT CONSIDERATIONS

This author is not qualified to advise on the legal aspects of Patents. However, within the context of this report it seems advisable to point out that within Europe, North America and Japan, there have already been a number of major legal battles over infringement of Patents on fibre processes. Generally speaking, problems have arisen as soon as a given company has started to gain a major fraction of a given market. Patent Law has then been used by competitors to improve their competitive position by seeking royalty payments from another for infringement.

Thus, any manufacturer proposing to set up fibre manufacture using any of the processes described above should be aware that they are heavily protected by Patents and he is accordingly advised to seek legal advice from a professional lawyer. The detailed position varies from country to country so that no other general statements seem appropriate.

9. MARKETS FOR DEVELOPING COUNTRIES

At present, the largest single market for fibre is North America, probably followed by Europe and Japan in that order. The sizes of these markets are estimated to be (order of magnitude) 1 million and 100 thousand fibre km/annum for North America and Europe/Japan respectively. Whilst these are large markets, it is questionable to what extent they are open. The North American market appears to be largely closed to imported fibre, with several large contracts reputedly awarded to North American suppliers as opposed to overseas suppliers, not on grounds of cost but of National Security. However, some Japanese companies are known to have sold fibre, cable and systems into both

Canada and the USA and one Japanese manufacturer (Sumitomo) has recently been reported to be building a fibre manufacturing plant in the USA.

In Europe, the telecommunications administrations have traditionally required European based manufacture for most key components and systems and that does not appear to be changing significantly although there have been some moves towards liberalisation, notably in the UK. Likewise in Japan, NTT has traditionally bought only from within Japan although as a result of external trade pressure, has indicated a willingness to purchase from overseas sources. The extent to which these markets will be truly open is a matter for speculation.

The above markets arise from the conversion of the existing networks from analogue to digital operation coupled with the growth of traffic on major routes. In less industrialised countries, the markets are more likely to arise as a result of the expansion and imporovement of an old and overloaded network. Many countries in South America and Asia provide good examples. Here, the major problem facing the would-be importer is that such countries can easily set up their own home-based manufacture, typically using the MCVD process or a minor variant. Whilst they may not achieve the levels of precision control and productivity demanded in Europe, North America and Japan, their system demands are often less stringent and cost structures so different that little impediment arises. Furthermore, such countries are frequently short of foreign currency. Thus it seems certain that countries such as India, China, or Brazil will rely almost exclusively on home based manufacture although they may well be interested in inward investment in terms of both production plant and technology.

Market opportunities within the Eastern bloc, Russia and its associated nations, are unknown to this author. Within the scientific press, there has been little evidence of activity in the field although it is well known that a number of systems have been built, typically for 34Mbit/s operation over graded-index fibres.

The remaining countries where market opportunities may exist are those which for special reasons find themselves rich yet lacking a developed industrial infrastructure. Examples are the oil rich states of Arabia and Africa. Here, large scale plans for rapid modernisation tend to lead to large "turn key" contracts for complete imported systems. These favour the telecommunications system company that can offer a complete package of fibre, cable, terminal and perhaps switching equipment.

In short, it is this authors view that large open export markets for fibre do not generally exist although there are many markets for small numbers of fibre cables for special purposes outside the mainstream telecommunications market. The nature of the manufacturing process is such that it is ideally suited to any country having a minimal industrial infra-structure that wishes to modernise its own network provided that it does not set out to produce immediately the most sophisticated product.

For those countries having very large home markets and a need for rapid industrialisation, there may well be advantage in buying in Western manufacturing equipment and perhaps backing it with licences to some of the high volume protected production technology. There appears to be little incentive for such countries to import the finished fibre product for anything other than trial purposes.

10. RECOMMENDATIONS FOR DEVELOPING COUNTRIES.

i). Analyse your home relecommunications market carefully to establish the bit rate and length of systems that are best suited to it.

ii). Identify the simplest fibre design that will meet this requirement.

iii). Estimate the volume requirement in fibre.km per annum (f.km/a).

iv). For low volume, (up to 50 000 f.km/a) the MCVD or a variant is almost certainly the cheapest and easiest to establish and operate. (But note Section 8 above).

v). For very high volumes, (several 100 000 f.km/a) it is generally claimed that a process such as the OVD or VAD is the most economic although the detailed case for such claims is sensitively dependent upon the relative cost of capital and wages. If such a process is sought, then licencing it is likely to be best route.

vi). If a very high performance fibre is required (0.2-0.3 dB/km single mode for example) then a sophisticated version of the MCVD apparatus is likely to be best. Again, it may be cheaper to licence the key technology rather than to develop it since the number of parameters to be individually monitored and controlled is large and the process optimisation is likely to consume a great deal of time and skill.

vii). Having developed a manufacturing base using a home market, export opportunities may develop. Clear evidence of systems achievement and tight production control will be necessary. Furthermore, many National communications equipment markets appear to be virtually closed to imports although detailed exceptions exist. (see Section 9 above).

11). REFERENCES

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2. S E Miller & A G Chynoweth "Optical Fiber Communications" Pub. Academic Press, New York, 1979

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7. H Suda, S Shibata, M Nakahara, T Miya, "Double flame VAD process for high rate deposition", European Conference on Optical Communication ECOC-84, Stuttgart, West Germany, 3-6 Sept 1984

8). Based on work by D B Keck, R D Maurer & P C Schultz, Applied Physics Letters Vol.22, p.307 (1973)

9). For a general review of the latest and future applications of fibres, particularly single mode fibres, see J E Midwinter, "Optical Communications, Present & Future", Proc.Roy.Soc.Lond. Vol.A.392, pp247-277, (1984)

12). FIGURE CAPTIONS

1). Schematic design of an optical fibre, defining terms.

2). Some specific designs of single mode fibre.
a). A design optimised for use at 1300nm wavelength
b & c). Designs optimised for use at 1500nm wavelength

3). The design of graded-index fibre.

4). Some designs of polarisation maintaining fibres.
a). NTT Panda fibre
b). Southampton Bow-Tie fibre
c). Bell Labs. Ribbon fibre
In each, birefrringence is produced highly asymmetric strain.

5). Fundamental attenuation effects in silica based fibres. (see Ref.8)

6). The absorption spectrum due to water in silica based fibre. (see Ref.9)

7). Schematic layout of vapour supply system for a silica fibre preform preparation system.

8). The basic MCVD preform process.

9). A more detailed schematic of the MCVD reaction zone.

10).The basic OVD preform process in schematic layout.

11).The basic VAD preform process in schematic layout.

12). Cross section details of a double crucible. (see Ref.1)

13).A silica preform puller.

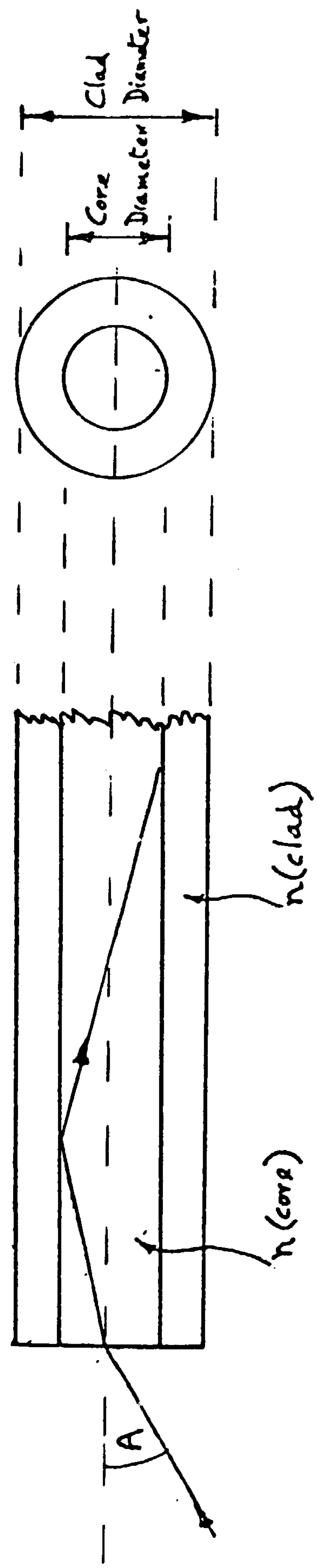
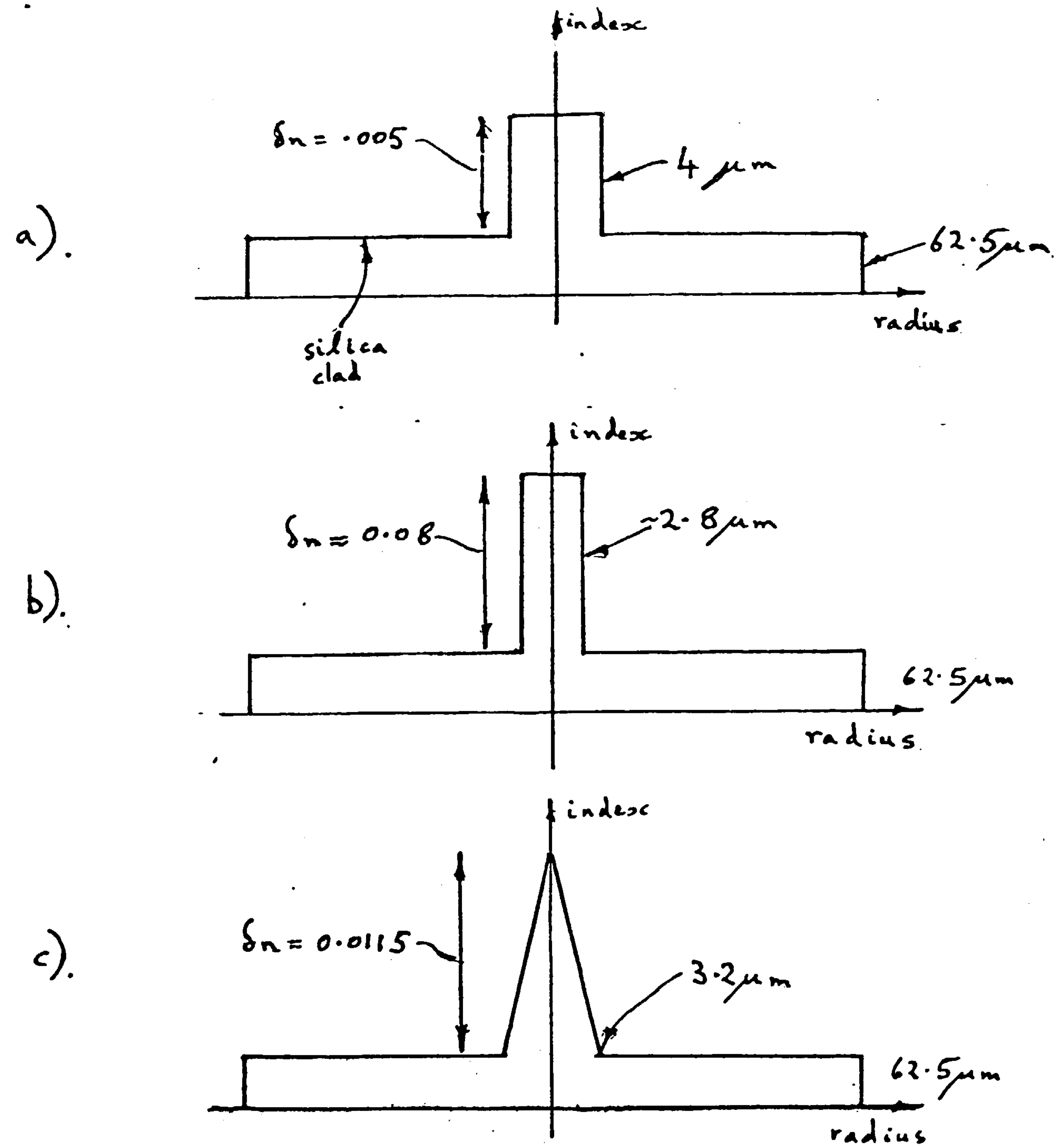


Fig. 1



index
δn = ·005
4 μm
a).
62·5μm
radius
silica clad
index
δn = 0·08
~2·8μm
b).
62·5μm
radius
index
δn = 0·0115
3·2μm
c).
62·5μm
radius

Fig. 2

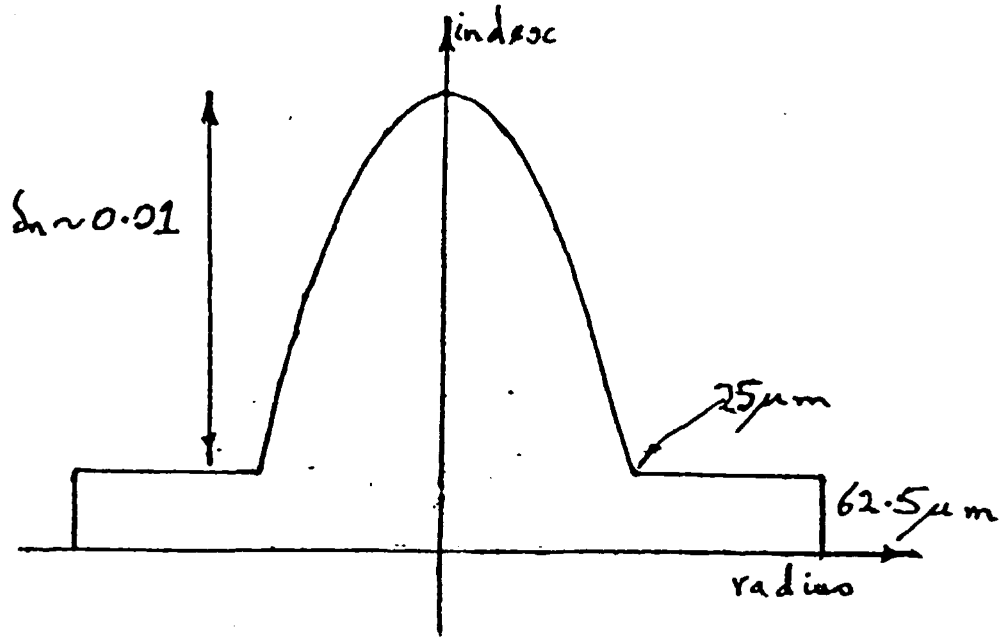


Fig. 3

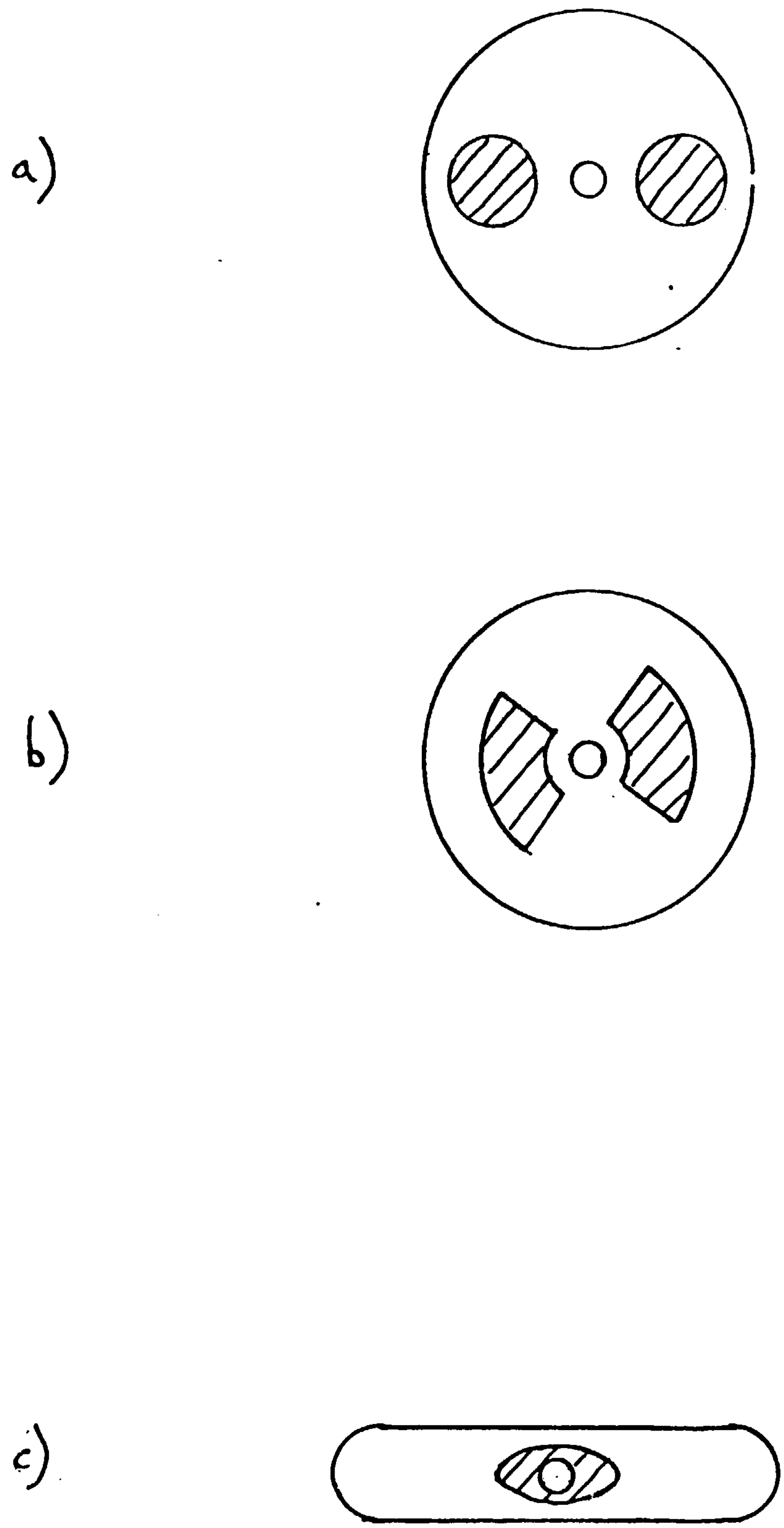


Fig. 4

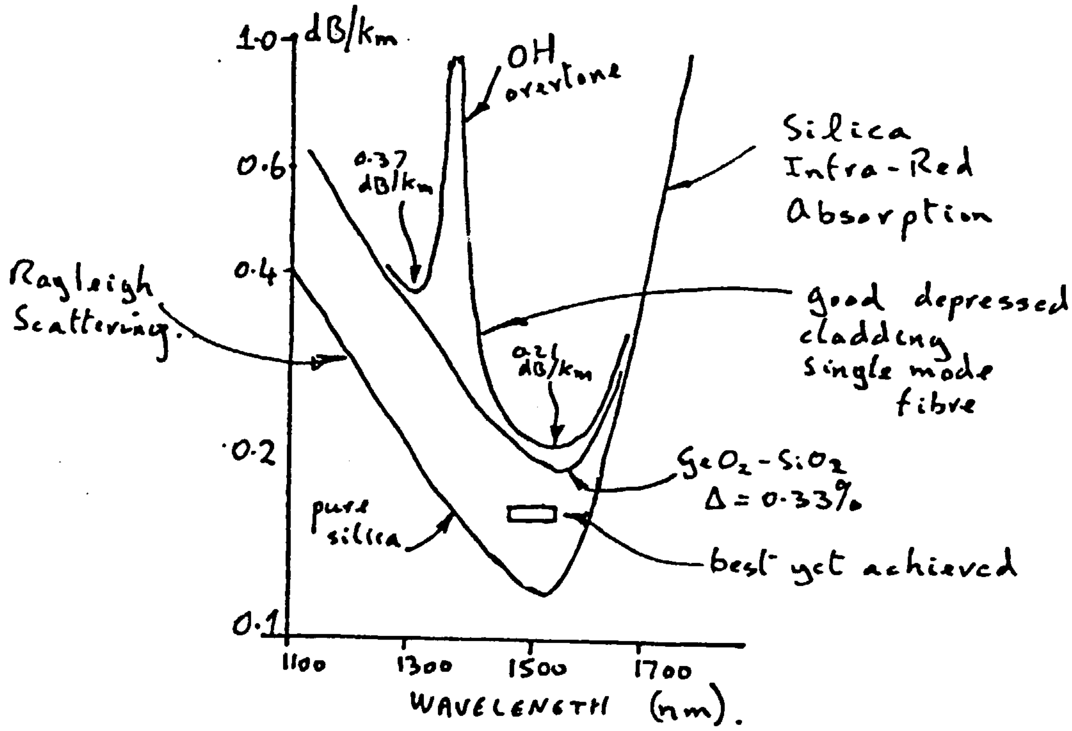
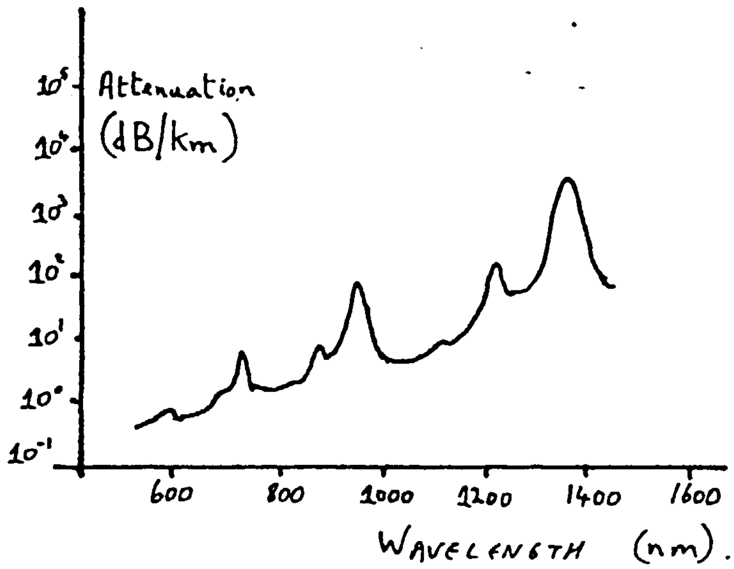
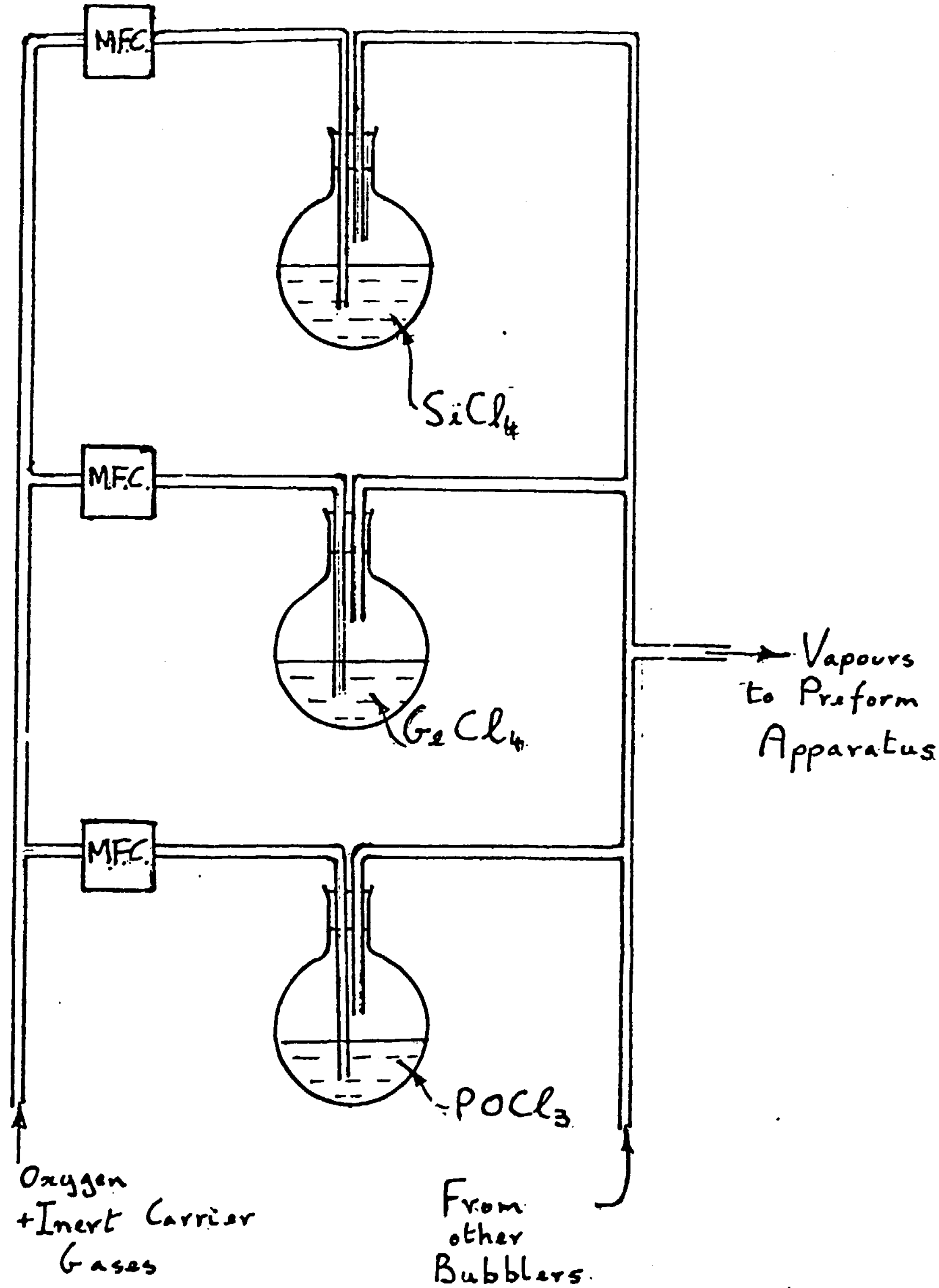

1.0 dB/km
0.6
0.4
0.2
0.1
OH overtone
0.37 dB/km
Silica Infra-Red Absorption
Rayleigh Scattering.
good depressed cladding single mode fibre
0.21 dB/km
$GeO_2 - SiO_2$
$\Delta = 0.33\%$
pure silica
best yet achieved
1100
1300
1500
1700
WAVELENGTH (nm).

Fig. 5



Attenuation (dB/km)
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
600
800
1000
1200
1400
1600
Wavelength (nm).

Fig. 6.



M.F.C = Mass Flow Controller

Fig. 7

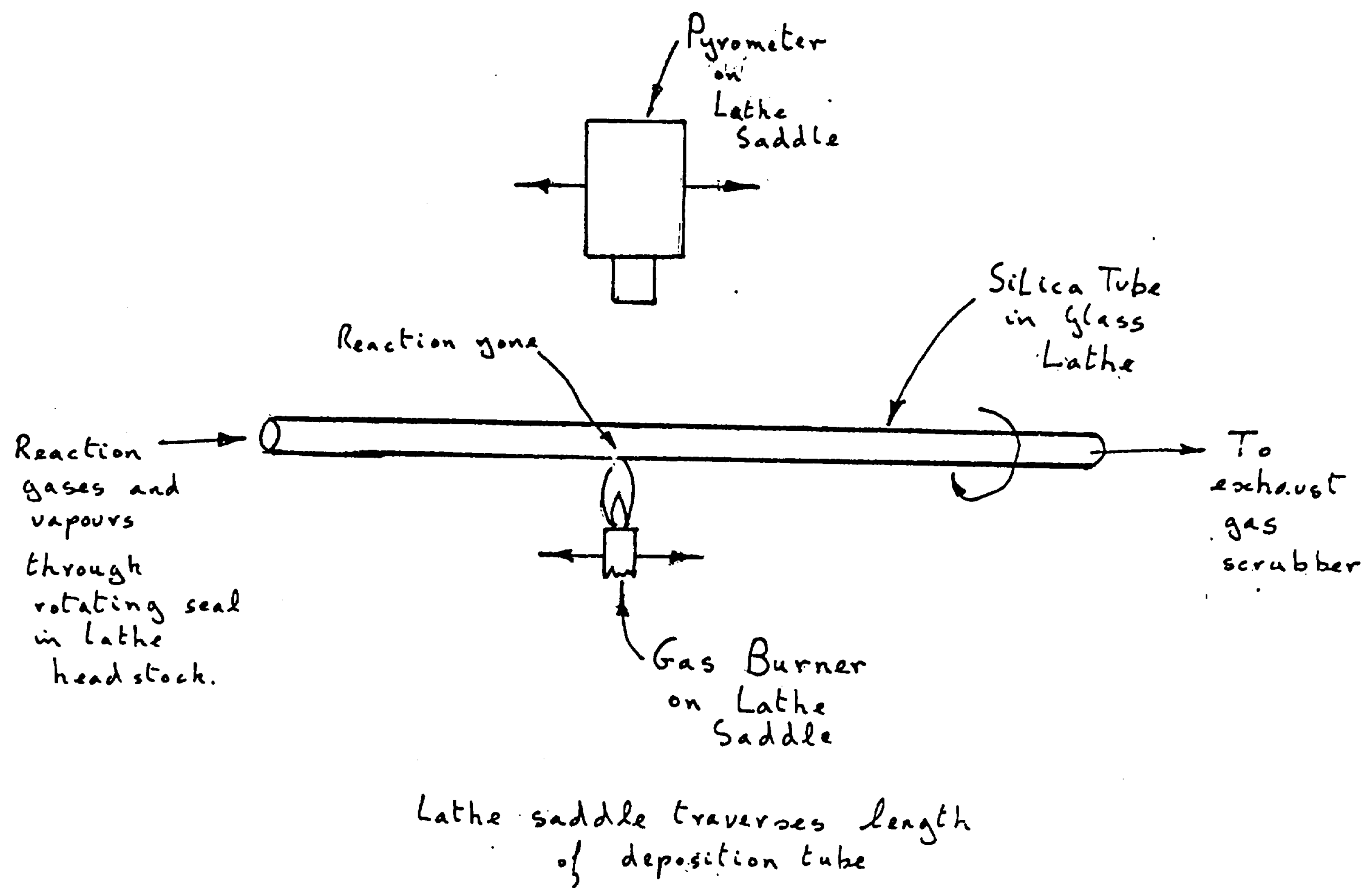

Pyrometer on Lathe Saddle
Silica Tube in Glass Lathe
Reaction zone
Reaction gases and vapours through rotating seal in lathe headstock.
To exhaust gas scrubber
Gas Burner on Lathe Saddle
Lathe saddle traverses length of deposition tube

Fig. 8.

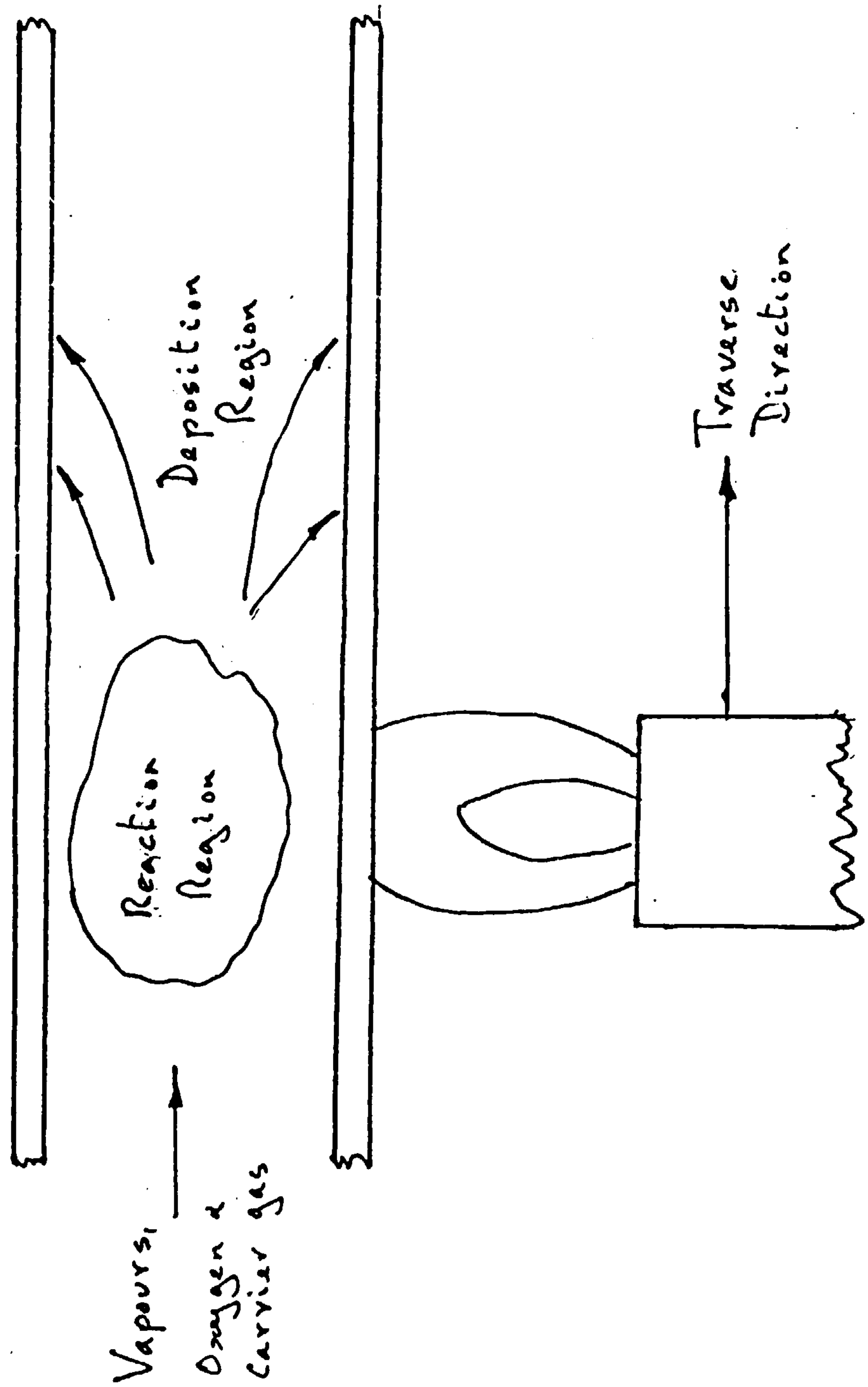

Vapours, Oxygen & Carrier gas
Reaction Region
Deposition Region
Traverse Direction

Fig. 9

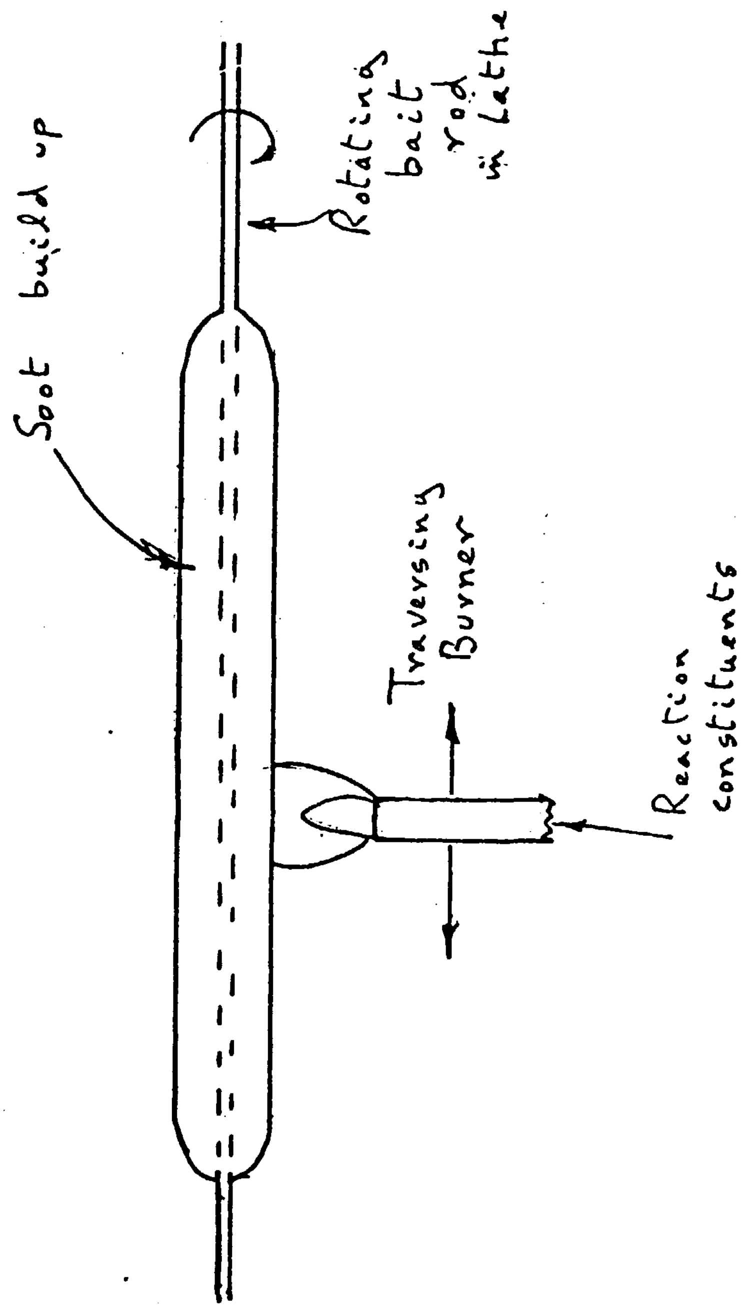

Soot build up
Rotating bait rod in lathe
Traversing Burner
Reaction constituents

Fig. 10

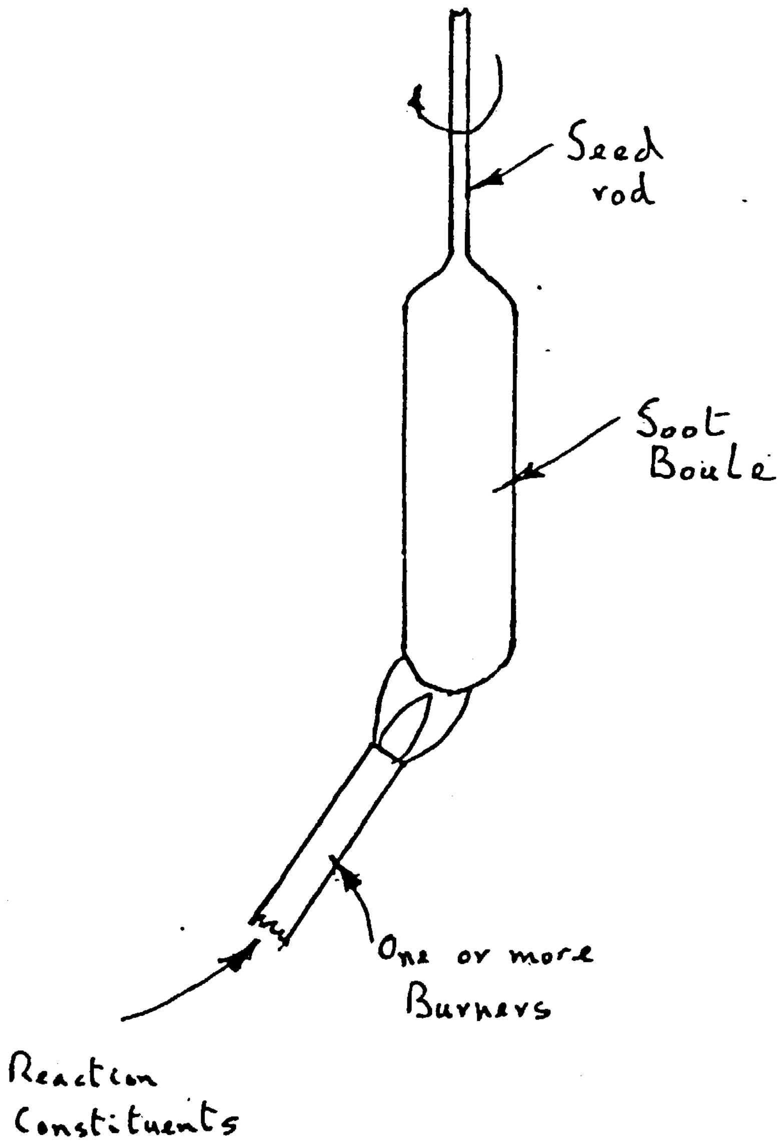

Seed rod
Soot Boule
One or more Burners
Reaction Constituents

Fig. 11

FIBER PULLING BY DOUBLE-CRUCIBLE APPARATUS

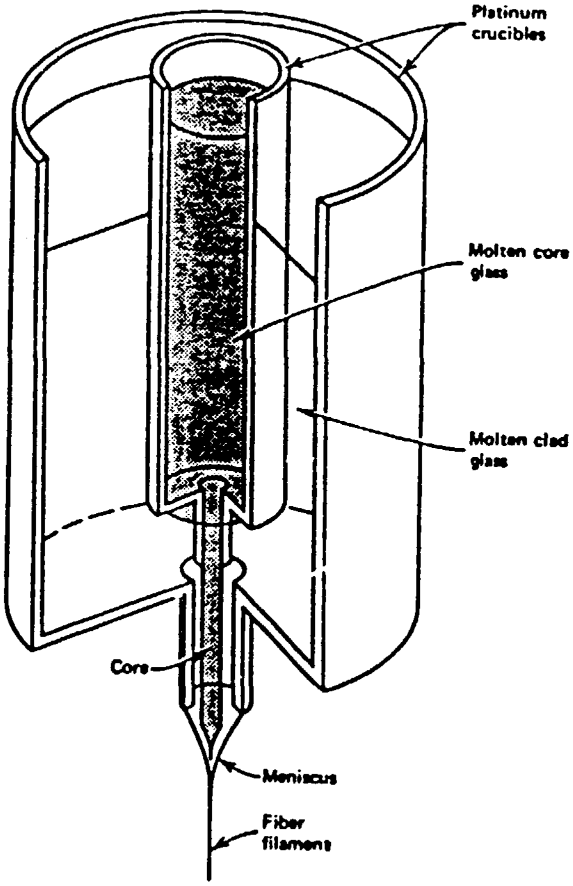


Fig 12.

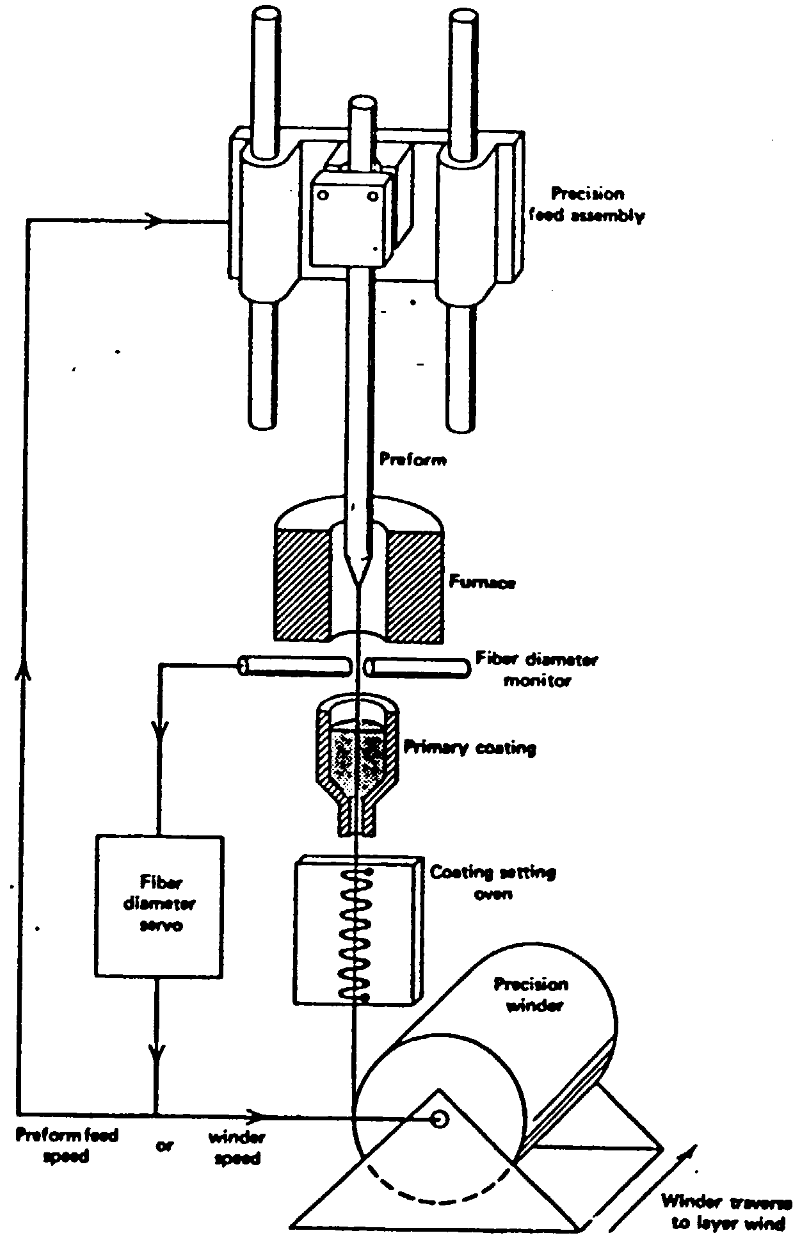

Precision feed assembly
Preform
Furnace
Fiber diameter monitor
Primary coating
Coating setting oven
Fiber diameter servo
Precision winder
Preform feed speed
or
winder speed
Winder traverse to layer wind

Fig 13.