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16. Abstract
This report provides the results from a study to determine possible uses of fiber optical light guides for remote source lighting for the Texas Department of Transportation. Fiber light guides are currently used within the Department for changeable message signs and signal heads. The investigation primarily considered its use for street, tunnel, and navigation lighting. The information in the report could help the designer for specific lighting configurations. The study as will be discussed in the report, has basically concluded that fiber optics for remote source lighting has many possibilities for transportation related needs and in fact are currently being implemented for changeable message signs and signal heads. However, the technology still requires additional improvements or break-throughs for efficient usage before the full extent of the technology can be realized for the specific application areas investigated.

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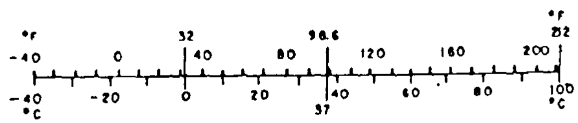
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



Implementation Statement

This report provides results from a study to determine the use of the fiber light guide for remote source lighting in the Texas Department of Transportation. Such technology is currently being implemented for changeable message signs and in signal heads. The study investigated its use for street, tunnel, and navigation lighting. The study concluded that, although it might soon be possible for practical usage of fiber lighting for these application areas, it didn't appear practical at this time. Thus no implementation recommendations are provided. On the other hand, the report can provide the lighting engineer with useful information regarding this new technology, and aid in following the rapidly changing advances in this field. Thus, as such advances occur, Texas Department personnel will be in a position to implement this technology for these areas in a timely manner.

Author's Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

Patent Disclaimer

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patented under the patent laws of the United States of America or any foreign country.

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Table of Contents

List of Illustrations

CHAPTER 1

INTRODUCTION

Replacement of bulbs for traffic signal and other highway illumination systems is time consuming, hazardous, and requires heavy equipment. Bulbs require replacement either because of failure or scheduled replacement. For example, in some locations traffic signal bulbs are routinely replaced at predetermined intervals. The primary problem with these illumination systems is that the bulbs are located over active lanes of traffic. To change bulbs, a truck with a lift system is generally parked in an active lane of traffic while a crew member is elevated in the lift basket into a position from which bulb replacement can be accomplished. This problem of interfering with traffic causes problems for the traveling public, as well as, exposes crew members to hazardous situations.

This report provide the results of a study for the Texas Department of Transportation to investigate the usage of remote source lighting using fiber light guides for various Texas Department of Transportation lighting applications. The study as will be discussed in the report, has basically concluded that fiber optics for remote source lighting has many possibilities for transportation related needs and in fact are currently being implemented for changeable message signs and signal heads. However, the technology still requires additional improvements or breakthroughs for efficient usage before the full extent of the technology can be realized for the specific application areas investigated. The two main problems found limiting its usage for these applications are the attenuation losses and the problems of sending large amounts of luminous flux. For example, 50 percent attenuation in a 10 meter fiber light guide is typical, not including losses in coupling the light source to the light guide, and extracting this light from the guide at the other end, etc. On the other hand, remote source lighting has many advantages over conventional lighting and when these problems are solved, this technology would be useful for many transportation lighting applications. The technology is changing very rapidly and should thus be closely followed for possible usage in the many Texas Department of Transportation lighting applications.

It is the purpose of this report to discuss the findings of the investigation and also provide the traffic lighting engineer the advantage and limitations of current remote source lighting methods.

BACKGROUND:

During this past decade, many advancements have occurred in the electronic, laser, and optic fields. Although remote source lighting had been introduced much earlier, it has only been in the last few years that it has become a practical lighting methodology. The use of methods for the transmitting light rays has been around for many years. Details of the history of remote source lighting can be found in most libraries and is also included in several of the references in this report.

The early light guides were never very practical although there were a number of systems developed. In 1983 Lome Whitehead of the University of British Columbia in Vancouver, Canada and his colleague, Roy Nodwell founded TIR System, Ltd which began to first offer a prism light guide using total internal reflection. TIR sold a number of such systems in North America, Japan, and Europe. In 1985, 3M developed a technology known as microreplication which further enhanced the manufacturing of practical hollow light pipes for remote source lighting. With the introduction of the 3M prism light guide film the usage of the light pipe has increased for remote source lighting applications. The light pipe uses an open tube or a box which is surrounded by this special material and is able to transmit light inside the tube.

In the transportation field there are several applications of using the light pipe for tunnel and navigation lighting. Whereas the light pipe can transmit large amount of luminous flux, for applications such as room lighting, etc., it has a major problem in not being able to easily go around bends without considerable losses.

FIBER OPTICS:

Fiber optics are now being used in most new telecommunication networks. Such systems are used for transferring millions of bits of digital information for various voice, video, and computer networks applications. These communication applications are able to share the same facilities by the use of wide bandwidth channels and time division multiplexing. The infrared light source and silicon fiber provides a means for sending information at relatively little attenuation, noise interference, and cable weight. By the use of a similar type of fiber optic light guides, it is now possible to transmit light sources to remote locations for lighting applications. Although telecommunications can efficiently use fiber optics for transmission, requirements for remote source lighting are very different.

Remote source lighting using the fiber light guides are commonly found in many applications. Some typical applications include:

- swimming-pool lighting,
- indoor lighting for buildings (office, conference room, or hotel secondary lighting),

- museum and other decorative lighting,
- auditorium lighting,
- side-emitting fibers for continuous areas in pathways,
- outside building and/or decorative effects,
- roadway signs,
- medical uses (optical-fiber inspection devices),
- automobile instrument displays,
- hazard lighting.

Similar to the light pipe these applications continue to increase at a rapid pace and their possible uses in transportation related lighting is no exception. The technology is already commonly found in changeable message signs and signal heads. An advantage of this lighting for these two application is that the light pixels required for each of the letters in signs can more easily be controlled and distributed.

The major disadvantage of fiber light guides is the transmission light losses. For instance, for the changeable message signs, light is typically only transferred a few feet at most. For usage in roadway illumination or light signals with the light source located at the bottom of the pole, many feet of the fiber medium would be required to provide any significant maintenance advantage.

From a geometrical consideration, optical fibers have an advantage over the light pipe as light can more easily be routed to the various remote locations. The light pipe has a similar attenuation problem as the fiber light guide. However, because of it's diameter, it is easier to couple large amounts of light into the entrance for transmission and is thus more practical for large scale remote source lighting applications. The reasons for the use of light pipes instead of fiber light guides in many applications is noted in a recent CIE report. As stated in this report (CIE Technical Committee TC 3-30, Volume 1, March 1995.):

> "With the recent improvements of optical fibers, many more researchers have considered the possibility of using them for efficient distribution of light for illumination, and several specialized applications of this type have evolved. However, such applications are limited to a rather small size scale, because these guides are generally too expensive to carry the large luminous flux required for conventional illumination."

This statement seems to hold true in the investigations performed.

SCOPE AND REPORT OUTLINE:

Early in the project, after discussing possible uses within the Department of fiber light guides with the Department's research committee, the committee specified that the study should be directed toward the use of fiber optics for street, navigation and tunnel lighting. The usage of fiber optics for changeable message signs was currently being implemented, and at the time, LED display devices appeared to be the most likely candidate for traffic signal lights. A comprehensive study underway was being conducted for the National Cooperative Highway Research Program to investigate the usage of the Light Emitting Diodes (LEDs) for traffic control signals. It was thought by the committee that the successful usage of LEDs would likely preclude most of the advantages of remote source lighting for traffic signals using fiber optics. Although, the study found that orange and red light could be used, it indicated problems with green and yellow. Thus it is still unclear if LED's could be used for the red-yellow-green signal heads. The final report for this study is summarized in [Ref 75]. During discussions with various manufacturers and transportation engineers, there was reference made on several occasions regarding existing signal heads using LED's for traffic lights.

The basic concepts used in remote source lighting as they are related to fiber light guides are described in Chapter 2. This chapter also discusses the concepts of total internal reflection followed by other light characteristics which effect successful light transmission.

Two of the tasks originally planned in the investigation work plan were to actually obtain some fiber light guides and equipment to evaluate one or more of the applications considered. During the latter part of the first year of the project it became apparent that a modification should be made in the work plan as initial investigations indicated that for the applications areas being considered, it would probably not be practical for implementation at this time. Thus it did not appear to be appropriate to purchase fiber guides and instrumentation as originally planned until more information could be obtained. This activity had been included in the research plan in order to purchase and test possible fiber light guide candidates for the lighting needs of the Texas Department of Transportation. It appeared that the results of such purchases would not provide much more information than could be obtained then by consulting the specifications, since the attenuation limitations were well specified by many of the manufacturers and in the literature. Also a number of laboratories across the country were already performing and reporting similar measurements. Thus with the current state of the technology, it was determined that the same results could essentially be achieved at less cost to the Texas Department of Transportation by consulting the specifications and modeling the fiber light guide. Furthermore, with the rapid changes in lighting sources, such as the electrodeless lamp, improvements in light guides, coupling, etc., the manufacturers were probably better qualified to initially perform such test, or at least until a configuration could be established with some potential of success for evaluation.

In reviewing the literature it was found that a fiber optic mathematical model had been developed by a group of researchers [Ref 31] for the study of the amount of light losses for various fiber configurations. Such a model could be beneficial for establishing what could be expected in the use for fiber light guides for various fiber parameters. It was hopeful that this model would be useful in supplementing the manufacturers specifications. It was found though that the model was not available for general public use. So, after reviewing the published material by the authors of the model, a similar model, limited to straight fiber analysis, was made during the last months of the project and is reported in Chapter 3.

Chapter 4 will discuss various configuration considerations for remote source lighting for some possible applications within the Department, along with costs and limitations.

Chapter 5 provides a summary of the study and possible future study topics.

CHAPTER 2

REMOTE SOURCE LIGHTING CONCEPTS

As noted in Chapter 1, considerable research has occurred over the past few years in the development of low loss fibers, primarily for communication applications. Typical telecommunication applications are concerned with low power signaling. Remote source lighting is concerned with transferring large amounts of luminous flux. Light losses are often what determines the success of such systems. These losses are small for telecommunication systems as the wavelength of the light used is in the infrared region where there is low loss. The wavelength of visible light is in a high loss region. These losses along with light coupling currently limit the successful usage of these systems for the applications considered within the Department. However, there are many successful uses of fiber light guides for remote source lighting, several of which are in transportation related fields as discussed in Chapter 1. Also noted in Chapter 1, the hollow light pipe, another form of remote source lighting, is being successfully used in many applications, a number of which are in the transportation field.

THE LIGHT PIPE:

At present, the light pipe (also sometimes referred to as the hollow light guide) is the most practical method for light transfer for applications requiring large amounts of luminous flux, such as room and building lighting. It has the advantage of carrying large amounts of light flux, and because of it's entry size, makes it easier to couple light from the source into the transmission medium. It has a major disadvantage in that it cannot easily transmit light around bends or corners without significant light losses by the usage of mirrors, etc. Thus it is typically configured in a straight path. 3M, currently manufactures the material most often found in the light pipe, the Scotch™ Optical Lighting Film (SOLF). The theory of using this product in the light pipe is described in an Application Bulletin, by this name, Scotch™ Optical Lighting Film, November 1988. The SOLF is a clear plastic film, approximately 0.5mm (0.02 in) in width and manufactured by a special 3M process called microreplication. This process provides prisms grooves on one side and a smooth surface on the other. A cylindrical ‘pipe’ (other shapes are possible) is then formed, with the smooth side in and the grooves outside and parallel to the length of the pipe. The SOLF will act as a mirror or a window depending on how the angle of the light (which is placed at one end of the pipe), strikes the material. An extractor can be added to send the light out along the length of the tube, which is the method employed for room lighting (both ends could be equipped with a light source). Or, the light can simply be transported to the far end. For this method the amount of light which is sent down the length of a simple round SOLF is specified as a function of the aspect ratio of the light pipe.

The aspect ratio is defined as the ratio of the tube length to the tube diameter, or thus, the larger the diameter of the tube, the more light which can be sent for an equivalent distant. This relationship, which is given in the 3M application bulletin previously referenced is illustrated in Fig. 2-1.

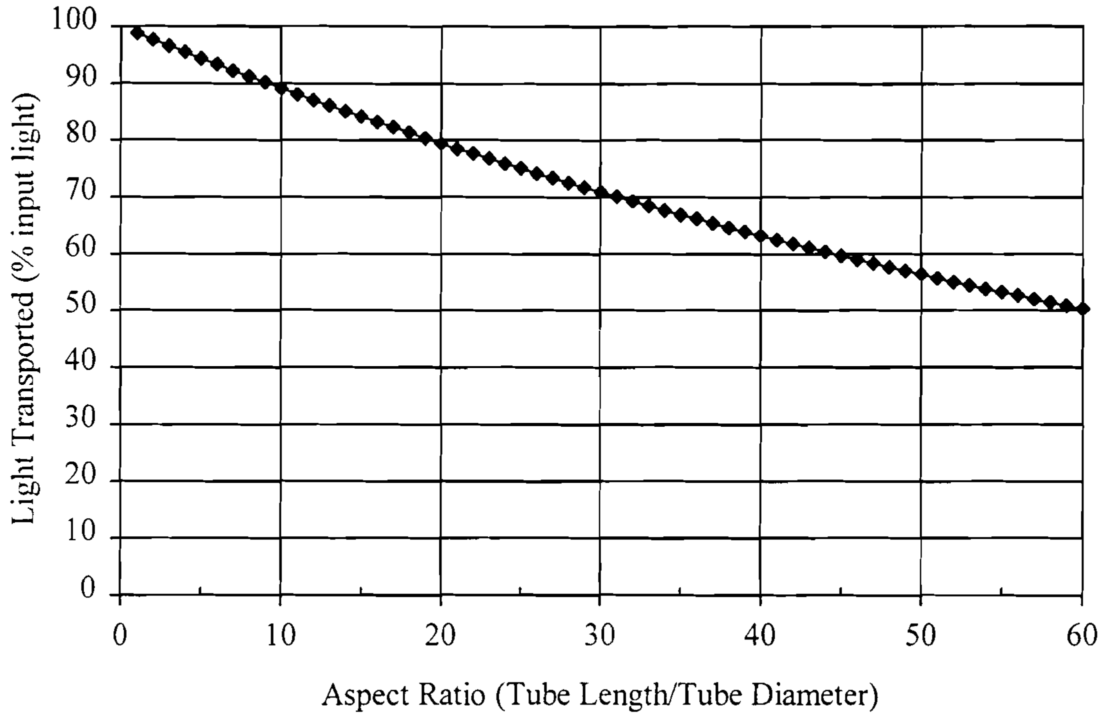

Figure 2-1. Light Transport VS Aspect Ratio for a Light Pipe

Although the light pipe is not specifically addressed in this project, it is mentioned in both this and the previous Chapter because of the numerous current and possible future applications using this concept for remote source lighting. Also, it was found during the investigation that some undocumented sources describing uses of remote source lighting with fiber light guide technology were actually referring to ones using the light pipe. A good description of many hollow light guide applications can be found in the International Lighting Review, [Ref. 36] and the Hollow Light Guide Applications Report published by the CIE Technical Committee, referenced in Chapter 1. Following are a list of the various hollow light guide applications described in this latter reference.

- Building Lighting,
- Display and Advertising Lighting,
- Hazardous Area Lighting,
- Pole Lighting,
- Roadway Lighting,

- Tunnel Lighting,
- Vehicular Lighting, and
- Walkway Lighting.

The fiber light guide is much smaller in diameter then the light pipe and at present typically cannot carry the same amounts of light flux. However, it does have the advantage of being able to direct the light around bends or other non straight paths. Both the hollow and fiber light guides transport light by means of total internal reflection.

TOTAL INTERNAL REFLECTION:

The concept of total internal reflection is well known by many and can be found in most basic physics books, thus it will only briefly be discussed.

Light passing through a medium can be represented as a ray of an infinitely small narrow beam traveling along a specific path. One of the more important laws for light transmission through a medium is Snell's law which defines this path. When light strikes the interface between any two mediums, such as air and water, as shown in Figure 2-2, part of the light wave is reflected back into the first medium and the other part is transmitted into the second medium.

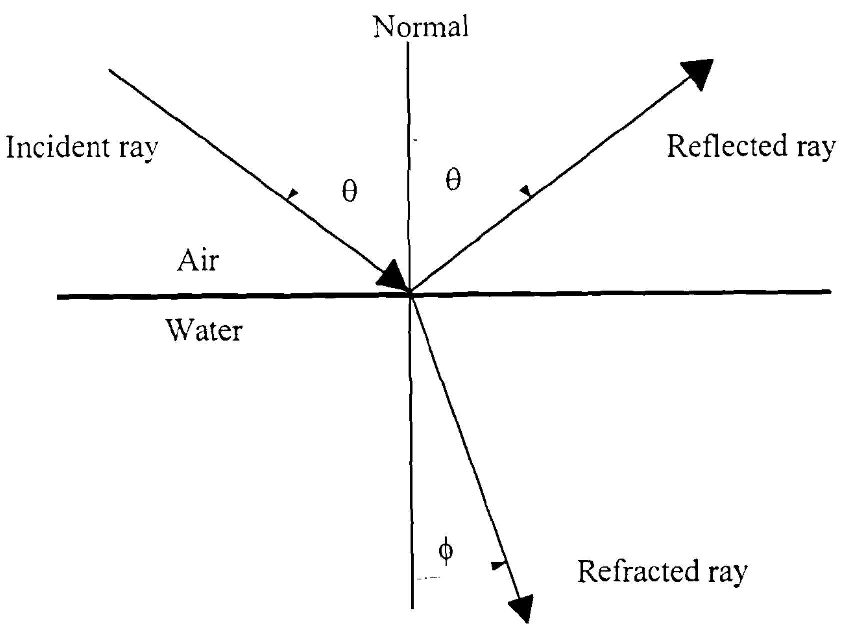

Figure 2-2. A Light Ray Incident Upon the Surface of Water is Bent Toward the Normal.

In Figure 2-2 the ray which is bent into the water away from the normal to the interface is said to be refracted, where the normal to the interface is a line perpendicular to the surface. For rays reflected, the angle of the incidence ray with respect to the normal (θ) is equal to the angle of the reflection ray. For refraction, the angle of refraction is bent toward the normal. The second medium's index of refraction, denoted by n, determines the angle of bending to the normal. The refraction index is the ratio of the speed of light in a vacuum, c, to the speed of light in the given medium, v, and is defined by the equation:

$$n = c/v \qquad (1)$$

A list for the index of refraction for several common materials [Ref. 73] is provided below:

Medium	Index of refraction
Vacuum	1.0
Air	1.0003
Water	1.33
Optical Fiber	1.6
Diamond	2.2

Snell's law is defined by the equation:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad (2)$$

where

n_1 = refractive index of medium 1,
θ_1 = angle of incidence to the normal,
n_2 = refractive index of medium 2,
θ_2 = angle of refraction to the normal.

When $\sin\theta_2$ is equal to 1, the phenomenon known as total internal reflection occurs, and θ_1 is called the critical angle, θ_c. For optic fibers, light is sent through a silicon or plastic fiber surrounded by a special cladding material. The index of refraction of the cladding with respect to the core is selected so that it is less than the fiber core at a ratio which will cause total reflection. A jacket surrounding the cladding absorbs all of the rays except the total reflection rays. This is illustrated in Figure 2-3.

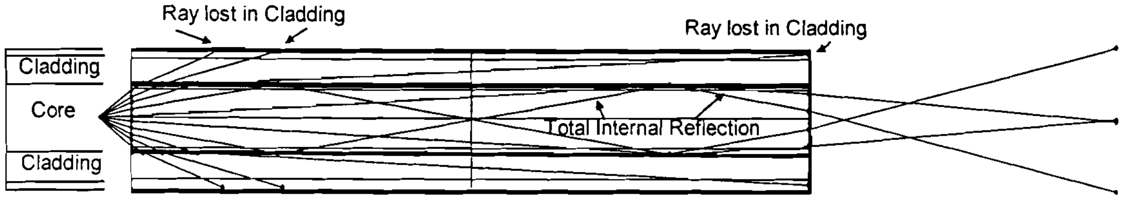

Figure 2-3. Total Internal Reflection in a Fiber Cable

In order for the light to be sent through the face of the fiber, the ray must enter within the critical angle. The numerical aperture (NA) is used to specify the light-gathering capability of a fiber. This number is defined as the sine of half the angle of a fiber's acceptance cone. The acceptance cone and angle is illustrated in Figure 2-4 and is related to the index of refraction of the fiber core and the cladding.

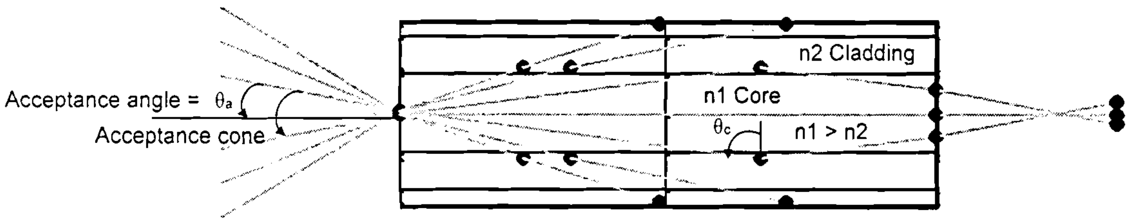

Figure 2-4. Acceptance Cone and Angle of a Fiber

Or, mathematically,

$$NA = \sin \theta_a$$

which is equivalent to:

$$NA = \sqrt{n_1^2 - n_2^2}$$

where n_1 and n_2 are the refractive indexes of the core and cladding respectively.

FIBER LIGHT GUIDES:

When using either the hollow light guide or the fiber light guide for remote source lighting, four components are required: the light source, the coupling mechanism, the light transmission medium or light guide, and the output optics. The fiber light guides have an important advantage over the light pipe in that they can be bent, and thus directed toward individual targets or pixels. However, the bend radius is important as there is obviously a limit on how far the fiber can be bent. The bend radius is usually provided by the manufacturer and related to the diameter of the fiber. The rule of thumb that is often used is that the radius of the bend should be no smaller than ten times the fiber's diameter. One light source can distribute individual light points to a number of targets. This is one of the reasons they are used in many various displays and ornament lighting applications, and in transportation related applications such as the changeable message signs.

There are two types of fiber guides, silicon based, and plastic. Between the plastic and silicon light guides, the silicon guides have the best light transfer characteristics or lower light attenuation. However, because of their size (50 to 150 micro meter), they are not as practical for many common applications. Because the silicon guide is only a few micrometers in diameter, a number of these fibers would need to be bundled together to transfer the same amount of luminous flux as the larger plastic guides. Thus, the cost of using these guides for the same or approximate size wave guide is considerable more. Figure 2-5 illustrates a bundled fiber guide.

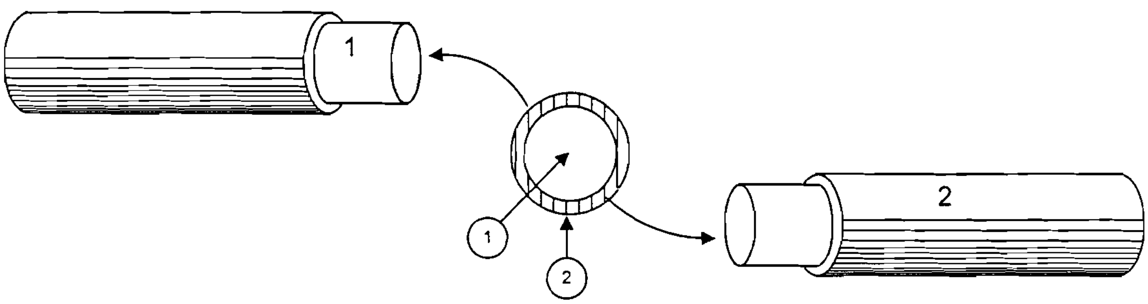

Figure 2-5. Bundled Fiber Guide

In this figure, the individually bundled fibers are illustrated by 1. The cladding surrounding the bundle of the individual fiber guides is illustrated by 2. Plastic fiber guides are usually referred to as small core plastic optical fibers, SCPOF, with diameters from 125 to 3000 micrometers , or the bigger, large core plastic optical fibers, LCPOF with diameters to 18 millimeters. The smaller diameter plastic guides are also often bundled to increase the entry aperture to cables of 1 to 10 millimeters in diameter. As in the case of the silicon guide, this further increases costs. The LCPOF are the most efficient because they have a larger optically active area even when bundled to a cable of the same size.

The plastic guides can be constructed for either side or end lighting. For side lighting, the light is extracted along the fiber instead of at the end, as the case for the end lighting fibers. For the side lighting fibers, a reflective surface is often provided at the end to provide more light on the sides by reflecting the light back.

The costs of optical fibers varying considerably, depending on the size and quality of the materials used in the manufacturing process. The silicon fiber typically cost much more, but not only having the better transmission characteristics, but greater life. The silicon fibers are generally less affected by environmental conditions. Plastic fibers tend to become brittle and yellow over time. They do not last as long as the silicon when in close proximity to high temperatures, as can be the case when coupling the light source to the fiber.

COUPLING:

For both the silicon and plastic light guides it is difficult to couple light from the light source (often referred to as the light engine) into the light guide without significant light losses. For light transfer, there is light loss at any junction or interface (e.g., plastic to air, plastic to plastic, etc.) as some of the light is transmitted, some is absorbed and some will be reflected as discussed earlier. The larger diameter plastic fiber makes it easier to couple the source. Manufacturers or companies distributing fiber light guides will typically offer some device to couple the light into the fiber. These can range from no coupling device to devices specifically designed for efficient coupling, such as the GE Lighting "integrating coupler" [Ref. 76]. Appropriately designed couplers provide thermal isolation, reduce UV light, and provide for a more uniform light intensity into the fiber.

When no special coupling device is provided the light is typically coupled by the insertion of the fiber tube into the case containing the light source and aligning it to the focal point of the reflector. This configuration usually results in the greatest losses. For such coupling, although adequate for many applications, the designer must give consideration to heat from the light source which can damage the plastic fiber tube. An installation can include a small fan in the source enclosure to help cool the fiber.

The following formula given in [Ref. 35] provides an estimate of the maximum fraction, x, of the flux from a lamp with luminous surface area A_s coupled into a fiber bundle of aperture area A_f and an acceptance half-angle α (NA).

$$x = A_f / A_s \sin^2 \alpha \quad \text{(x smaller than one)} \qquad (5)$$

As observed, for the same numerical aperture, the formula indicates that the efficiency is only a function of the ratio of the areas and does not depend on the optical system. This relationship, along with that for an elliptical reflector is illustrated in Figure 2-6 below.

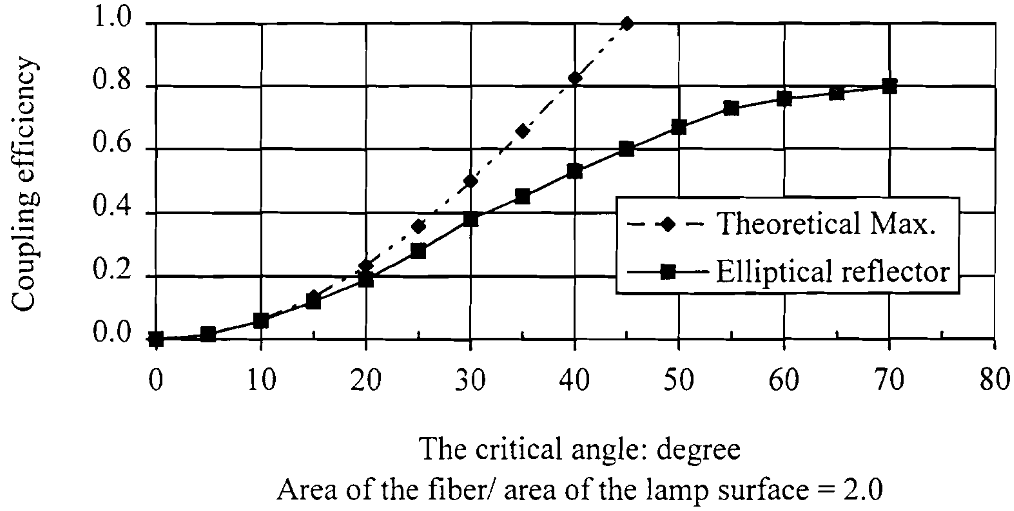

Figure 2-6. Coupling Efficiency Versus Acceptance Half Angle

Thus from this relation it is illustrated that the best way to couple light into a small fiber aperture is to use a source with a high flux and a small luminous surface area. The figure and relation shows that an elliptical reflector with an axially-mounted discharge lamp approaches this efficiency if properly designed. This is illustrated in the figure. An example of a well designed lamp is the GE Lighting Xenon Halide Lamp, specifically designed for fiber cables. The GE SMH60 lamp and reflector system , a 60 watt lamp, emits a total of 4200 lumens. For this lighting system, 2000 lumens can be collected by a 12 mm diameter aperture placed at the focal point. The reflector has been optimized for use with fibers with acceptance half-angles of 30 degrees.

Once the light is coupled to the surface of the light guide, the concentration of the light as it is introduced into the light guide must also be considered. For instance, if the light source is a laser beam, the light will be highly concentrated or focused to the aperture surface. The typical light source does not have such a concentration factor. The importance of the concentration of the light to the aperture is discussed in Chapter 3.

MODE AND PROPAGATION CONSIDERATIONS:

The propagation characteristics of an electromagnetic wave as it travels in a fiber is determined by its mode. When the ray is along the center axis the fiber is referred to as a single-mode fiber. With more than one path, the fiber is referred to as a multi-mode fiber. Single mode fibers are common in telecommunication systems. For these systems, it is important that the light ray maintain the characteristics of the signal, which it won't if part of the light travels a longer path, as occurs with multi-mode fibers. This is illustrated in Figure 2-7 for the single mode fiber and Figure 2-8 for the multi-mode fiber.

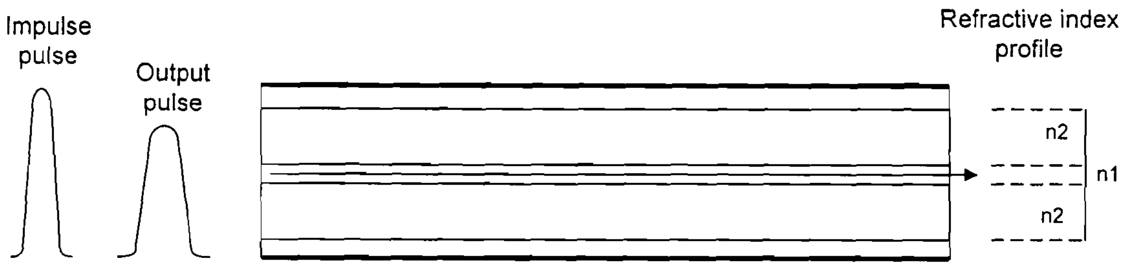

Figure 2-7.
Single Mode Fiber

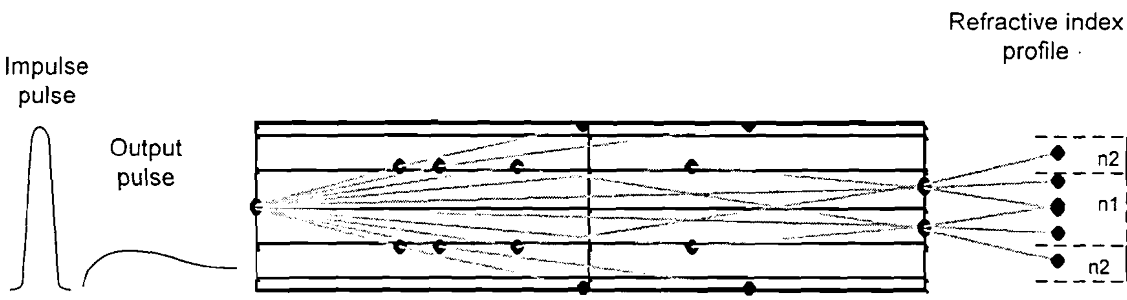

Figure 2-8.
Multi-mode Fiber

The multi-mode fiber is used for remote source lighting as it makes little difference if the individual light rays to not reach the end of the fiber at the same time, as long as they at least get there.

ATTENUATION CONCEPTS:

Light traveling through a fiber medium is attenuated in accordance to both the material type and its wavelength. Visible light is between the wavelength bandwidths of 450 to 700 nanometers. (Figure 2-9). On the other hand, telecommunications use light sources in the infrared regions, above the 700 nanometers.

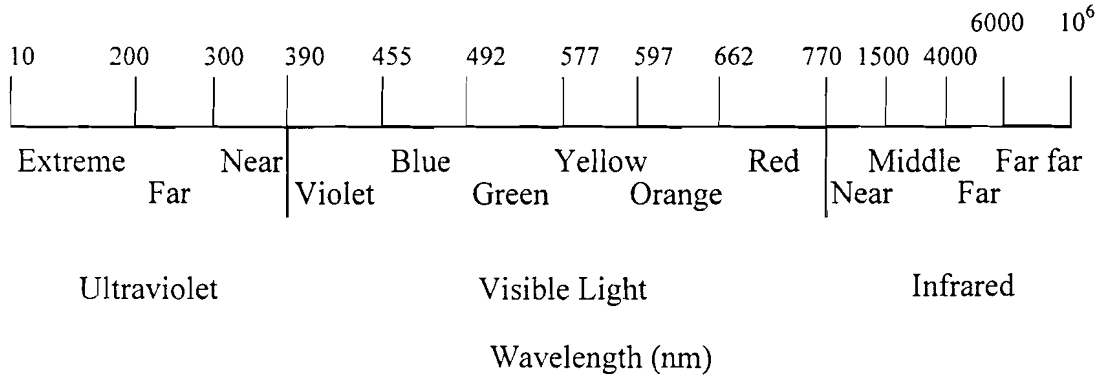

Figure 2-9. Electromagnetic Spectrum Showing the Approximate Boundaries Between Spectral Regions Used for Optic Fiber.

The transmission loss in fibers is further attenuated by several processes, one of which is known as Rayleigh scattering at the shorter wavelength, and another, the umltiphonon absorption at the longer wavelength regions. Chapter 3 discusses these attenuation or losses in greater detail.

The transmission characteristics of a typical silicon and plastic fiber as a function of wavelengths is illustrated in Figure 2-10. As can be noted in the figure, much less attenuation occurs in the wavelengths in the infrared range, and as noted, this is the range used in the telecommunication field. However, for visible light, the wavelength are much more affected by the attenuation of the fiber material. Notice also from this figure that silicon or glass fibers typically have better characteristics or less losses than do plastic fibers.

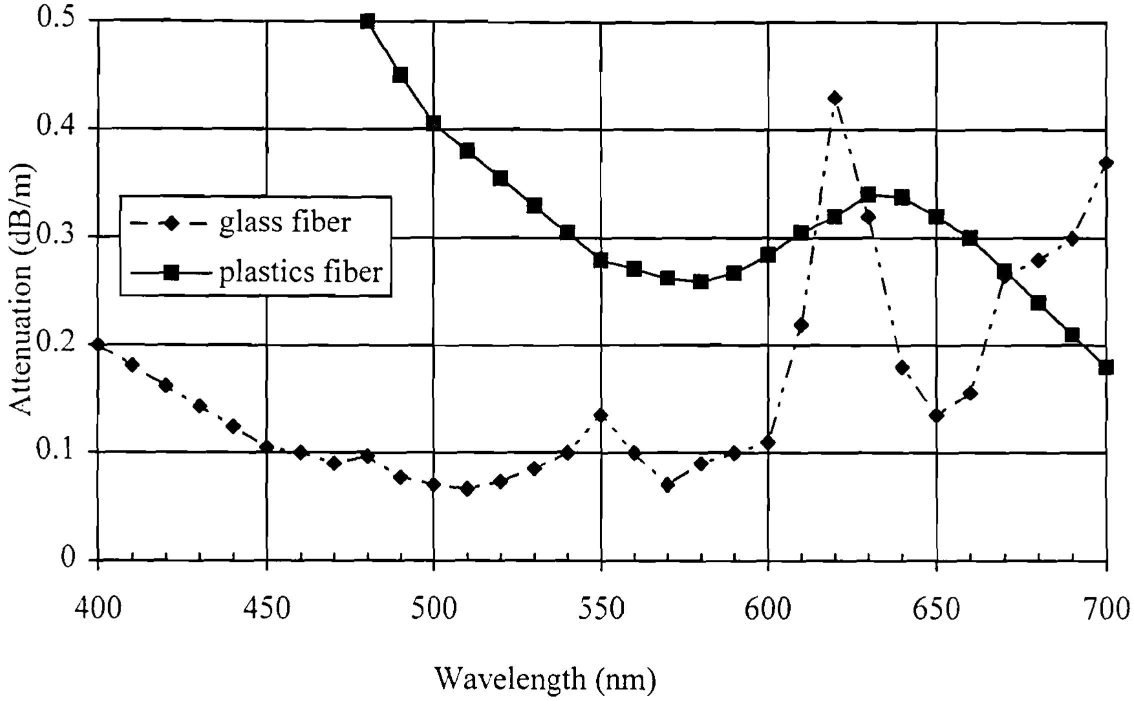

Figure 2-10. Typical Attenuation Characteristics of Light as it Travels through Plastic and Silicon Fiber Guides.

The loss of light or its attenuation as it propagates through an optical fiber is expressed by the equation:

$$a = 10 * \log [P(0)/P(L)]$$

where a = the attenuation coefficient in dB/km

L = the fiber length in km.
P(0) = the power or intensity of the light at the source end, and
P(L) = the power or intensity of the light at the far end.

If for example, a light is attenuated by 3 dB it is attenuated by about 50 percent. Single-mode fibers are typically found with attenuations of 0.2dB or less per kilometer at a wavelength of say 1550 nm. That is for light at 1550 nm, only about 4.5 percent of optical power is lost over one kilometer. Contrasting this with visible light at say 700 nm, losses of 50 percent in just 10 meters, or a little more than 30 feet, is common for many plastic fibers.

Since light sources typically provide light with many wavelengths, and since the light intensity of each of these wavelengths are affected differently by the fiber light guide, it is possible that the original light will not only be attenuated in overall or average intensity, but also the colors will be somewhat different. The distribution of the intensity of light for a typical light source is illustrated in Figure 2-11. The resulting light distribution after it propagates through a light guide, could be somewhat different.

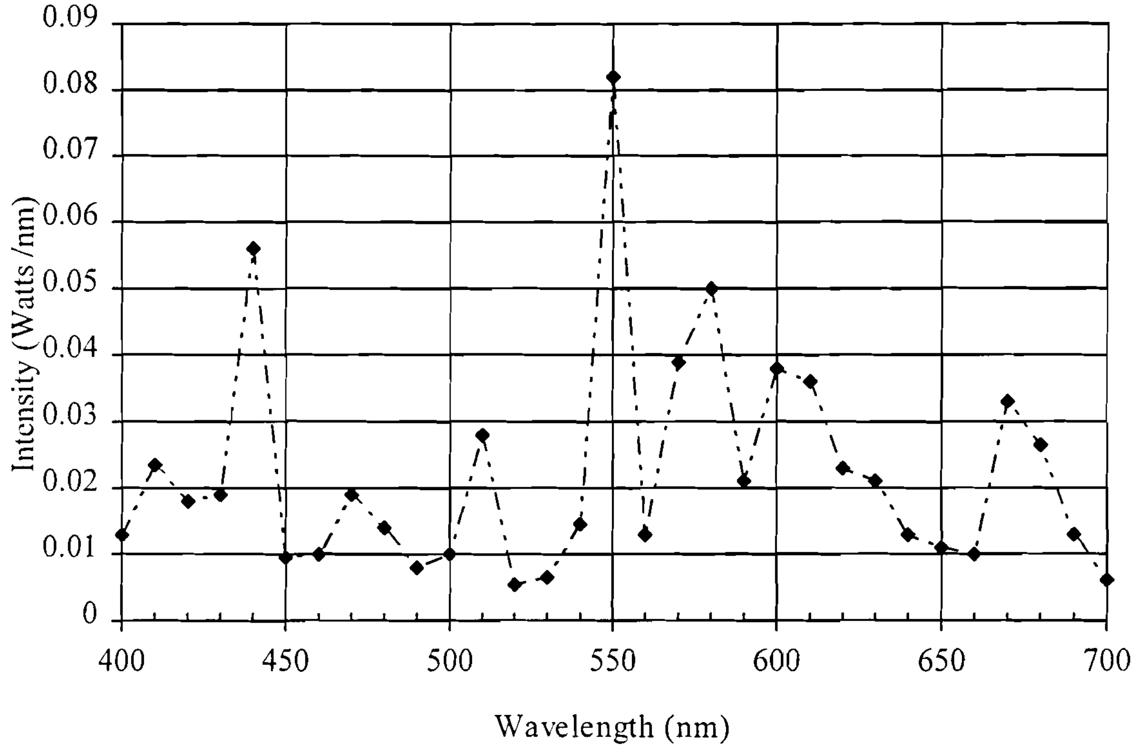

Figure 2-11. Spectral Distribution of the Light Source [Ref. 76]

Chapter 3 will discuss a model for investigating these attenuation characteristics. The model will then be applied to various possible applications of fiber light guides which will be useful in discussing the implementation issues in Chapter 4.

CHAPTER 3

FIBER LIGHT GUIDE MODEL

A fiber light guide model for straight fibers is described in this Chapter. The model was developed similar to the one developed by Nader et al. [Ref. 31]. The model described in this Chapter is for straight fibers. The model in the Reference also includes bent fibers. The model by Nader et al was not available for general use at the time of this investigation so the model described in this Chapter was developed so that the various conditions discussed in the previous and next Chapters could be investigated. To verify the model, the parameters for the fibers described in [Ref. 31] were used and similar results were obtained. The model, as will be discussed in Chapter 4, was also found to provide similar results to some of the manufacturers specifications and is thus useful for determining an estimate of the expected attenuation results for various applications.

MONTE CARLO METHOD:

The Monte Carlo simulation method [Ref. 77] is used for simulation of light through an optical fiber. The method is common for static simulation techniques to solve problems where analytical solutions are not possible or easily obtained. Basically using this method provides a means to determine an estimate of the light loss or attenuated from entry to exit of an optical fiber. The concept of the simulation method is to first determine the path of a light ray as it transverses through the fiber. If the light ray is parallel to the axis of the fiber, and if the fiber is straight, then the ray entering will exit with only extinction or energy losses (loses due to the characteristics of the fiber's molecular structure). If the ray is not parallel to the axis, then it will, at some point, strike the cladding and thus be reflected, or refractive as described in Chapter 2. The refracted ray is loss in the cladding. The reflective ray is then followed to the next intersection with the fiber wall. This process is continued for the ray until it is either lost or exits the fiber. A similar process is performed for each ray for a sample set of rays. The accuracy of the simulation process depends on the sample size and how representative the ray characteristics and fiber characteristics are to actual rays. A representative sample is obtained by selecting unbiased ray characteristics.

To obtain such characteristics, the Monte Carlo method involves selecting random characteristics which permits all possible characteristics of a ray to be equally likely to be selected. Thus, the more samples so randomly selected, the more representative the sample and the closer the sample characteristics represent the population of all rays which would transverse the fiber. This chapter describes how a path is defined, the various options for each path and finally, how a sample of such rays are used to estimate the losses in the fiber for various fiber characteristics.

OPTIC FIBERS:

As discussed in the previous Chapter, the fiber light guide consists of the core, the cladding, and the jacket. First the analysis of straight lines of fiber optic illumination systems is performed.

For light passing through a transparent medium, the light can be represented as a ray of an infinite small narrow beam. The radius of the fiber is much larger than the wavelength, and ray theory can be applied to uniform core optical fibers with good accuracy for large values of the V number. The V number is defined as:

$$V = 2\pi R_f \sqrt{n_1^2 - n_2^2} \Big/ \lambda$$

where R_f is the fiber core radius; n_1 and n_2 are the refractive indices of the core, and cladding respectively, and λ is the wavelength.

As discussed in the previous chapter, Snell's law specifies the relationship of the incident light ray to the reflected and refracted wave. Thus as long as the incident angle is less than the critical angle, the phenomenon known as total internal reflection occurs, and the light rays are transmitted through the wave guide. For optic fibers, the cladding index is less than the core so as to permit total reflection. The jacket absorbs all of the rays except the total reflection rays.

The Monte Carlo method is used to solve this simulation of the fiber optics. This method, as in all simulation methods using random variables, only provides an estimate of the actual solution, but is used when analytical methods are not obtainable. The problems involved in this and other simulation procedures using random variables can be found in [Ref. 77].

THE DENSITY FUNCTION:

Assuming a uniform input on the surface of the optical fiber, the point position of flux input on a ring can be obtained with a position vector r from the ring center and an azimuthal angle ϕ with respect to the x-axis. Both of the random numbers, R_ϕ related to ϕ , and R_r related to the position r , can be obtained:

$$R_\phi = \int_0^\phi d\phi \Big/ \int_0^{2\pi} d\phi \qquad (3)$$

and

$$R_r = \int_{r_i}^{r} rdr \Big/ \int_{r_i}^{r_o} rdr \quad . \tag{4}$$

For an azimuthally symmetric input, an azimuthal angle can be obtained from:

$$\phi = 2\pi R_\phi \ . \tag{5}$$

For r_i=0, the position vector can be obtained from:

$$r = R_f \sqrt{R_r} \tag{6}$$

where R_f is defined above.

The direction of flux input on the fiber can be obtained by knowing the source distribution. For the point source the total flux on the surface is:

$$\phi_T = \int_0^{2\pi} \int_0^{\pi/2} I(\theta, \psi) \sin\theta \, d\theta \, d\psi \quad , \tag{7}$$

where

I : the luminous intensity of the luminaries,
θ: the zenith angle with respect to the normal of the surface at the point,
ψ: the azimuthal angle with respect to the tangent at the point.

If I is independent of ψ, the total flux ϕ_T is:

$$\phi_T = 2\pi \int_0^{\pi/2} I(\theta) \sin\theta \, d\theta \quad , \tag{8}$$

the distribution function would then be

$$\phi_T = \frac{1}{\phi_T} \int_0^{\psi} \int_0^{\pi/2} I(\theta) \sin\theta \, d\theta \, d\psi = \frac{\psi}{2\pi} \quad . \tag{9}$$

In the similar way, the azimuthal angle can be related to the random number by

$$\psi = 2\pi R_\psi \ . \tag{10}$$

The zenith angle θ at a particular ψ can be related to the random number by

$$R_\theta = \int_0^{\theta} I(\theta) \ \sin\theta \ d\theta \Big/ \int_0^{\pi/2} I(\theta) \ \sin\theta \ d\theta \quad . \tag{11}$$

If the flux input to the fiber can be found by

$$I(\theta) = I_n \cos^M(\theta) \tag{12}$$

where M is a concentration parameter, and the larger the M value the narrower the beam spread is, then

$$\theta = \cos^{-1}\left(1 - R_\theta\right)^{1/(M+1)} \quad . \tag{13}$$

All four parameters shown above will be incorporated into the modeling of straight fibers to simulate the light transferring through the transmission line of optic fibers.

THE MODELING OF STRAIGHT FIBERS:

The geometric description of ray tracing through a straight fiber will be presented. The detail of the geometry of a straight fiber and the light traveling is shown in Figure 3-1. The heavy lines in the Figure 3-1 indicate the ray tracing through the fiber. All surfaces are modeled by the coordinated, x, y, and z, or the unit vectors, $\hat{i}$, $\hat{j}$, and $\hat{k}$, and their local coordinates with two unit tangents and a normal as follows:

$$\hat{t}_1 = \frac{d\bar{r}/du_1}{\left|d\bar{r}/du_1\right|} \tag{14}$$

$$\hat{t}_2 = \frac{d\bar{r}/du_2}{\left|d\bar{r}/du_2\right|} \tag{15}$$

$$\hat{n} = \frac{\hat{t}_1 \times \hat{t}_2}{\left|\hat{t}_1 \times \hat{t}_2\right|} \tag{16}$$

where $\hat{t}_1$ and $\hat{t}_2$ are unit vectors tangent to the surface and perpendicular to each other, and $\hat{n}$ is a unit vector normal to the surface. $\bar{r}$ is a position vector pointing from the center of the ring of the fiber to a point on the surface. u_1 and u_2 are two surface parameters.

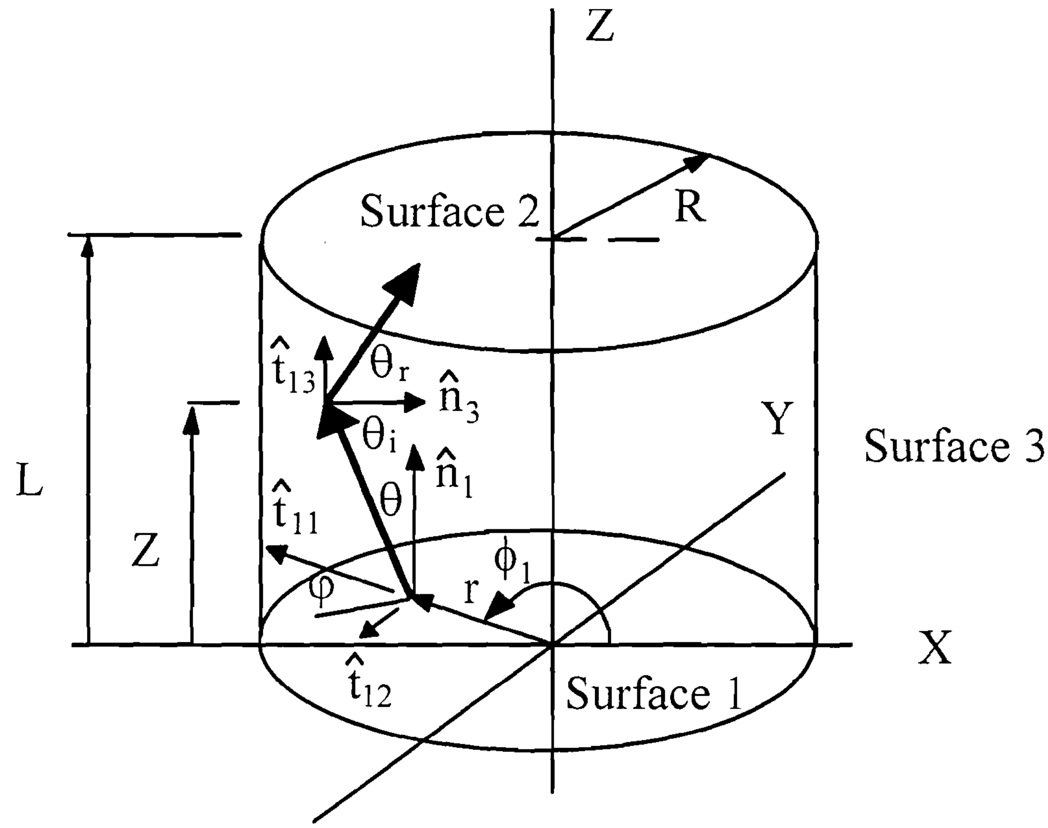

Figure 3-1. Surface Description of the Core of a Fiber

For surface 1 in Figure 3-1, the position vector of the flux input on the base is

$$\bar{r}_1 = r_1 \cos\phi_1 \hat{i} + r_1 \sin\phi_1 \hat{j} \tag{17}$$

where ϕ_1 is the azimuthal angle with respect to the x-axis measured counterclockwise as shown in Figure 3-1. The tangents and the normal vector can be found as:

$$\hat{t}_{11} = \frac{d\bar{r}/dr}{|d\bar{r}/dr|} = \cos\phi_1 \hat{i} + \sin\phi_1 \hat{j} \tag{18}$$

$$\hat{t}_{21} = \frac{d\bar{r}/d\phi}{|d\bar{r}/d\phi|} = -\sin\phi_1 \hat{i} + \cos\phi_1 \hat{j} \tag{19}$$

$$\hat{n}_1 = \hat{k} \tag{20}$$

where $\hat{t}_{11}$ is tangent number 1 on surface 1, $\hat{t}_{21}$ is tangent number 2 on surface 1, and $\hat{n}_1$ is normal to the surface 1.

Following the same procedure for surface 2 and surface 3, the position vector, the tangents, and the normal are:

$$\bar{r}_2 = r_2 \cos\phi_2 \hat{i} + r_2 \sin\phi_2 \hat{j} + L\hat{k} \qquad 0 \le r_2 \le R_f \,,\ 0 \le \phi_2 \le 2\pi \tag{21}$$

$$\hat{t}_{12} = -\sin\phi_2 \hat{i} + \cos\phi_2 \hat{j} \tag{22}$$

$$\hat{t}_{22} = \cos\phi_2 \hat{i} + \sin\phi_2 \hat{j} \tag{23}$$

$$\hat{n}_2 = -\hat{k} \tag{24}$$

$$\bar{r}_3 = R_f \cos\phi_3 \hat{i} + R_f \sin\phi_3 \hat{j} + z\hat{k} \qquad 0 \le z \le L \,,\ 0 \le \phi_3 \le 2\pi \tag{25}$$

$$\hat{t}_{13} = \hat{k} \tag{26}$$

$$\hat{t}_{23} = -\sin\phi_3 \hat{i} + \cos\phi_3 \hat{j} \tag{27}$$

$$\hat{n}_3 = -\cos\phi_3 \hat{i} - \sin\phi_3 \hat{j} \tag{28}$$

where L is the length of the cylinder, and R_f is its radius of the fiber.

If a ray comes from the surface 1, the point of intersection with surface 3 can calculated as:

$$\bar{r} = \bar{r}_1 + D\hat{S}_e = (x_1 + DS_{ex})\hat{i} + (y_1 + DS_{ey})\hat{j} + (z_1 + DS_{ez})\hat{k} \tag{29}$$

where D is the distance from the point of flux input to the point of reflection. The unit vector of the ray can be found from:

$$\hat{S}_e = \sin\theta \cos\psi \hat{i} + \sin\theta \sin\psi \hat{j} + \cos\theta \hat{k} \tag{30}$$

where θ and ψ are the zenith and azimuthal angles with respect to $\hat{n}$ and $\hat{t}_1$ respectively. We obtain three equations with three unknowns D, z, and ϕ_3.

From Figure 3-1 and the equations shown above, we know

$$\bar{r} = \bar{r}_2, \tag{31}$$

and find

$$\left(\frac{r_{1x} + DS_{ex}}{R}\right)^2 + \left(\frac{r_{1y} + DS_{ey}}{R}\right)^2 = 1 \quad . \tag{32}$$

Expand the equation above, and we define

$$a = S_{ex}^2 + S_{ey}^2 \tag{33}$$

$$b = 2\left(S_{ey} r_{1y} + S_{ex} r_{1x}\right) \tag{34}$$

$$c = r_{1x}^2 + r_{1y}^2 - R^2 \tag{35}$$

and we find the three known relations:

$$D = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad D > 0, \tag{36}$$

$$z_3 = \left(DS_{ez} + r_{1z}\right), \tag{37}$$

$$\phi_3 = \cos^{-1}\left(\frac{r_{1x} + DS_{ex}}{R}\right) \quad . \tag{38}$$

The incident angle is calculated as:

$$\theta_i = \cos^{-1}\left(-\bar{S}_i \bullet \hat{n}_3\right) \quad . \tag{39}$$

For the total reflection (i.e. the incident angle is larger than a critical value) the reflected ray vector can be found:

$$\bar{S}_r = \bar{S}_i + 2\left|\bar{S}_i \bullet \hat{n}\right|\hat{n} \quad . \tag{40}$$

As the light ray travels into the air from the optical fiber, the difference in the index of refraction between the air and the core causes the ray to refract. The angle of refraction can be obtained from Snell's law.

RESULTS AND DISCUSSION:

With the Monte Carlo method the trace flux transfer through optical fibers can be simulated. The optical fiber configuration for the straight optical fiber is defined similar to that in [Ref. 31]. After calculating the critical angle, we can repeat the loop for each ray, and then through the number of sub-samples. The angle of refraction is calculated. If the ray goes straight to the output of the fiber, we can then repeat for the next ray. If not, the ray must strike the fiber/cladding interface. We then find the incident angle to the normal of the interface, and compare it to the critical angle. If the incident angle is less than the critical value, the ray is lost. The ray is followed until it reaches the output of the fiber. The total effective length traveled by all rays that is not lost are calculated. The process is then repeated over for next sub-sample. The average critical angle losses are found along with an average effective length and a confidence interval. The efficiency of the fiber due to the total losses is the ratio of the output flux of the fiber to the input flux of the source:

$$\varepsilon = \eta_c \tau_f \left(1 - \rho_f\right) e^{-\beta S} \tag{41}$$

where

$$\eta_c = \tau_c \varepsilon_A, \tag{41a}$$

$$\tau_c = 1 - N_{rc} / N_T, \tag{41b}$$

$$\tau_f = 1 - N_{rf} / \left(N_T - N_{rc}\right) \tag{41c}$$

ε_A is the efficiency of the coupling between the source and the fiber, τ_c is the transmittance of critical angle losses, N_{rc} is the number of rays lost due to critical angle, N_T is the total number of rays, τ_f is the transmittance of Fresnel losses, N_{rf} is the number of rays lost due to total Fresnel reflections, β is the extinction coefficient per unit length within the fiber core such as absorption of water, and S is the effective length. As shown in Figure 3-2, if a ray hits the interface at the end of the fiber, and if it is not totally reflected, it is partially reflected. The reflectivity ρ_f is equal to the value of the percentage of rays reflected.

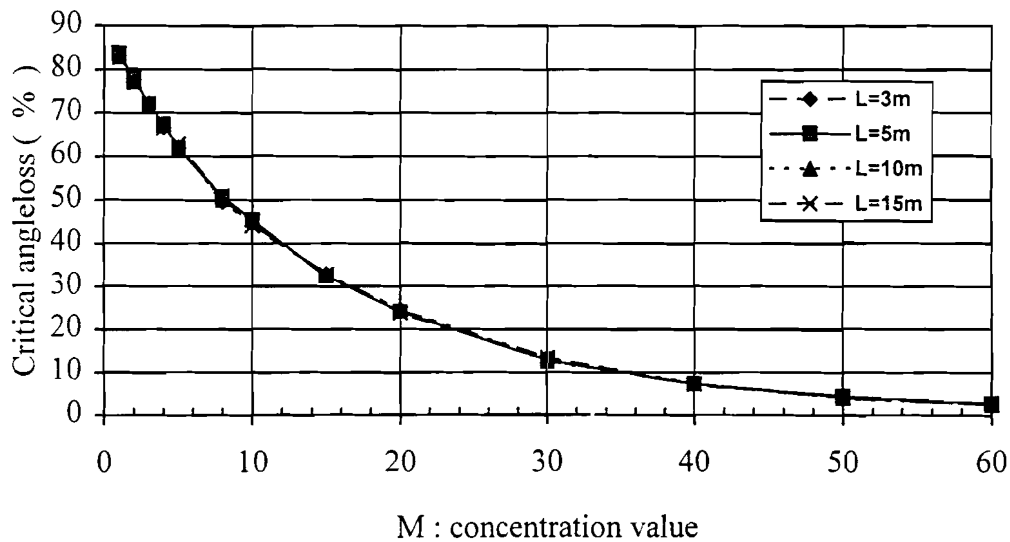

Figure 3-2. Critical Angle Losses for a Sample Plastic Optical Fiber

The calculation method described above was used to simulate the behavior of straight fibers with different input flux. Simulation parameters for Figure 3-2 to 3-4 are:

1000 random numbers with uniform distribution generated, 10 samples of the 1000 random numbers calculated for confidence interval, the radius of the fiber = 0.0015, the index of the core = 1.491, the index of the cladding = 1.419, and the extinction coefficient = 0.03 m^{-1}. The unit for the length of the fiber is in meters. The concentration value, M, is used as the value of the x-axis of those figures. The angle of sine of the indexes is 1.258759 radius, or 72.121597 degrees.

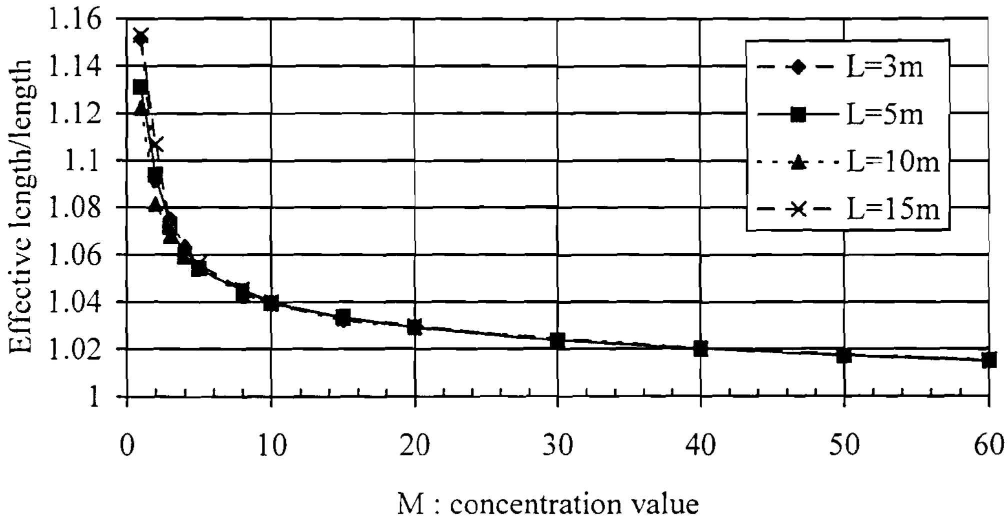

Figure 3-3. Effective Length for a Cladded Plastic Optical Fiber

The critical angle losses for various flux inputs are shown in Figure 3-2. Figure 3-3 shows the effect of the value of the concentration parameter on the effective length of the fiber. From these figures, we can see that both losses are not related to the length of the fiber.

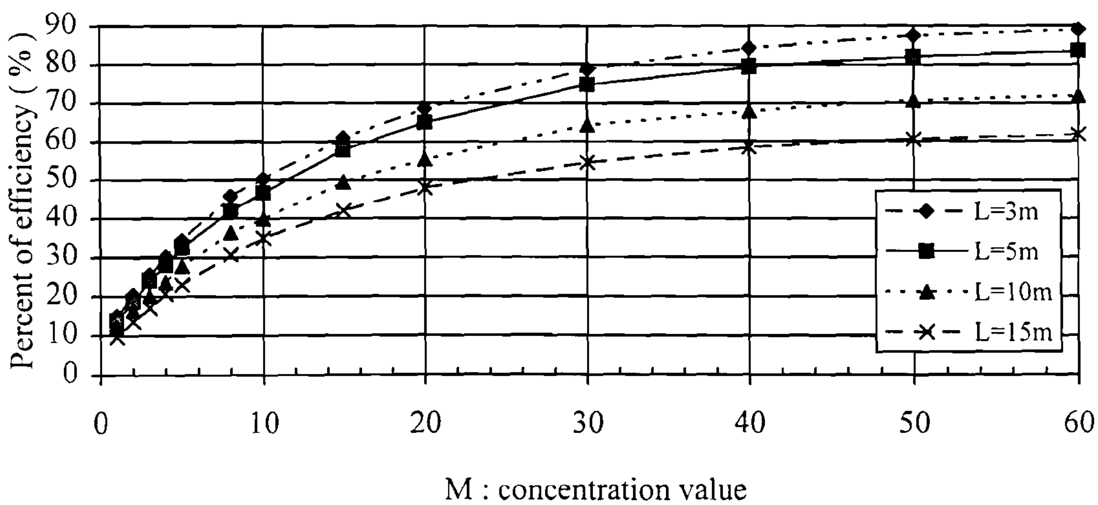

Figure 3-4. Efficiency of a Plastic Optical Fiber
Considering Critical Angle, Fresnel, and Extinction Losses

We can compute the effect of the concentration parameter on the total efficiency of the fiber for critical angle losses as well as extinction losses. Figure 3-4 shows the efficiency of total losses of a fiber with an extinction coefficient of 0.03 m^{-1} with different geometric configurations and values of concentration, M. From Figure 3-4 it is noted that reducing the beam spread beyond a certain point does not significantly increase the efficiency.

CHAPTER 4

ECONOMICAL AND IMPLEMENTATTION CONSIDERATIONS

Various economical and implementation issues will be discussed in this chapter for remote source lighting using fiber light guides. In particular, first some general characteristics of various fibers will be discussed. Then each of three application areas specified earlier, that is, street, tunnel and navigation lighting will be examined. Some discussions on other possible application areas will then be included, followed by a brief discussion of the new electrodeless sulfur lamp offered by Fusion Lighting Inc. This lamp is mentioned as it could aid the efforts of remote source lighting.

The Ideal Fiber Guide:

In a visit to the lighting group at 3M Corporation, the characteristics of an ideal optical plastic fiber using current manufacturing processes were specified as follows:

- Spectral Transmission range of 300-800 nm
- Acceptance angle of 40 degrees or higher
- Core Refractive Index of 1.48 or higher
- Cladding refractive index of 1.34 or lower
- Transmission loss less than 2 percent per foot at 550 nm (250db/km)
- Light extraction element efficiency approaching 80%

One of the problems in manufacturers' specifications is that often the attenuation is given as an average over a frequency range. the actual characteristics throughout the visible light range, or an attenuation level is specified for a particular frequency, as in the above. As noted from the Figure 2-10, some frequencies have less light losses than others. Additionally, there are other losses involved as noted in Chapters 2 and 3. Finally, one must insure that the type of fiber guide is considered. The silicon fiber guides have much better light transmission characteristics, but are also much smaller. For example, the transmission loss per meter shown in one specification is around 0.4 percent at 550nm. The size of the silicon fibers range from 100 to 800 micro-meter. Thus clearly, many of these would have to be bundled for usage in the application areas considered.

The bottom line losses should be determined from the amount of light actually coupled to the light guide, the amount of light loss due to the critical angle, and the extinction losses. This will be discussed next for street lighting.

Street Lighting:

As noted earlier, although fiber optics are currently being used in changeable message signs, it doesn't appear that it is yet practical for the applications involving the transfer of large amounts of luminous flux for distances associated with street lighting, etc. Figure 4-1 illustrates the losses involved for a typical system using a light source designed specifically for remote source lighting, or the GE Xenon Metal Halide System. For this system the light source provides 4200 lumens of which approximately, 2000 is available for a fiber with a diameter of 18 mm. This figure also includes a coupler, which can add additional losses, the fiber cable, using the characteristics of the 'ideal' fiber given above, and the output lens. Recall that losses of up to 8 percent can be expected when going from one medium to another, although for the calculations to follow, only 8 percent will be included for the extraction at the output or distribution head. From this figure and using the simulation of Chapter 3, a cable of 15 meters can result in a total loss of up to 74 percent. Thus the lamp with 4200 lumens, projecting about 2000 lumens to the fiber surface results in a total output from the other end of this fiber system of 2000*0.26*0.92 or 478 lumens. Special couplers provide for averaging of the light intensity, color, and thermal isolation but can also result in additional losses as described in Chapter 2.

Now let us consider similar loses for a street lighting system. Assume a street light with the dimension characteristics of Figure 4-2. Assume a High Pressure Sodium (HPS) lamp 250 watts is used which generates 26,000 lumens. Since the 15 meter length required for Figure 4-1 would be appropriate for Figure 4-2, a lamp generating 26,000/(0.26*0.92) or 108,695 lumens would be required for an equivalent output. This factor 4.18,1/(0.26*09.2), would probably in practice be much greater as no coupler loss was assumed. A coupler of same type would probably be need to prevent heating problems on the fiber for such a light source.

In addition to the light source and lens, the coupling (special coupling to insure no heat damage to the fibers) and bending angle could also add additional losses. These are some of the reasons optical fiber lighting have not yet been used in street lighting.

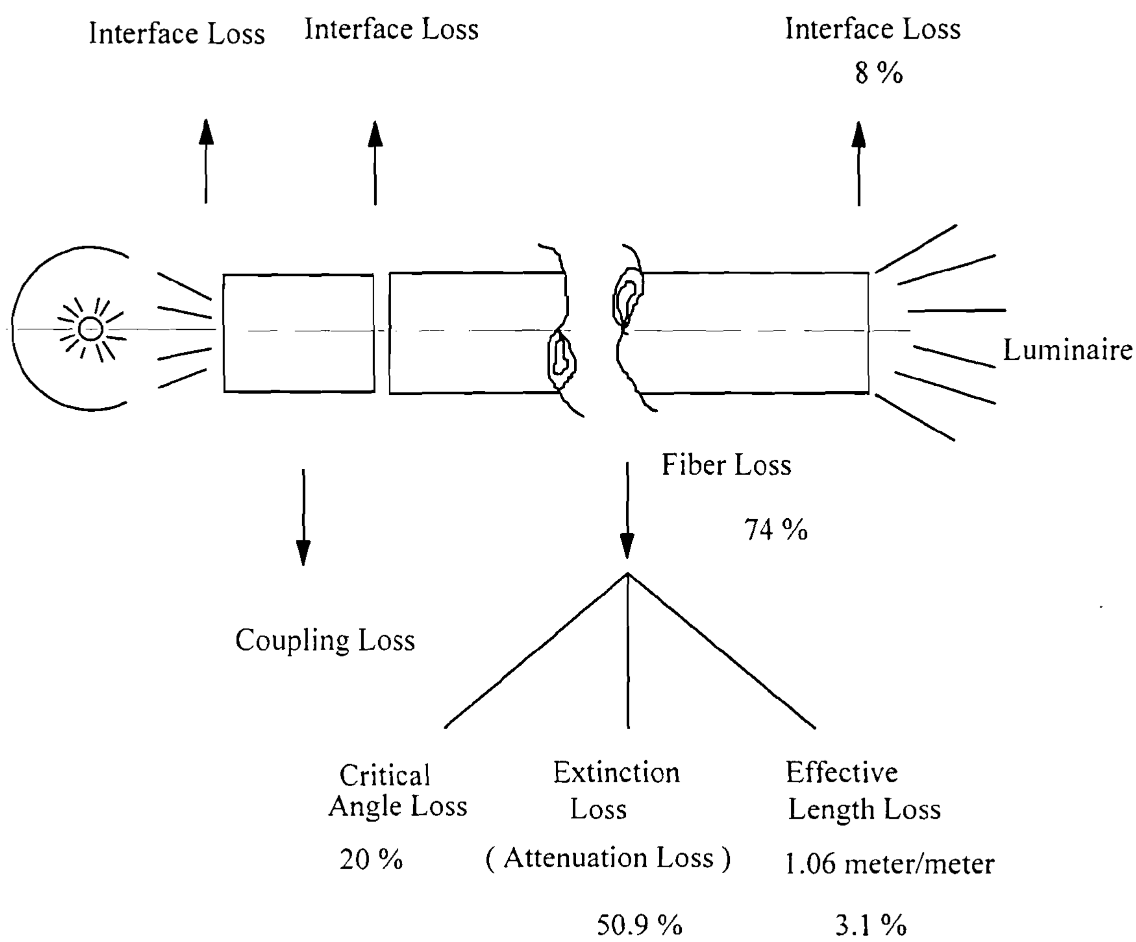

Figure 4.1. The Loss for a Coupling Fiber Optical System
M =10, Extinction Loss= 0.05/meter,
Critical Angle = 64.88 degree, n_1 =1.48, n_2=1.34, Optical length = 15 meter.

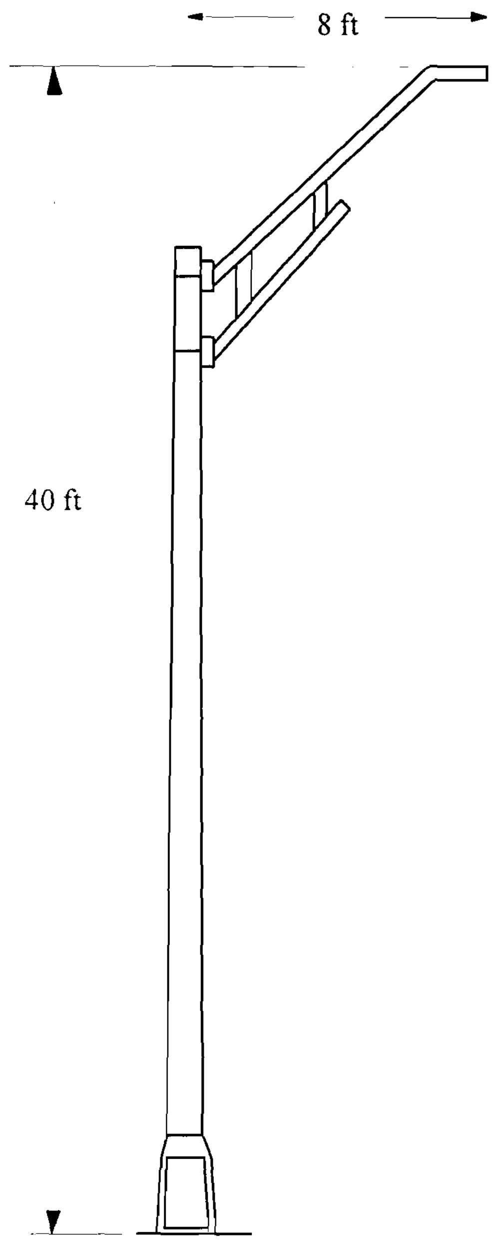

Figure 4-2 Typical Street Lighting Configuration

TUNNEL LIGHTING

As noted earlier, remote source lighting is being implemented for tunnel lighting at several sites including the Callahan Tunnel in Boston, Massachusetts and can also be found in Japan. The lighting systems are using the hollow light guide or light pipe. For the Callahan System (Ref. 71), the number of hollow light tube sections and the light sources are provided as follows:

Length of Sections	Lamp Wattage	Total Footage	# of Sections
9.75m (32 ft) Sections	250W	3092m(10,138ft)	317
9.75m (32 ft) Sections	400W	88m(260ft)	9
3.29m (10.8ft) Sections	400W	323m (1,060ft)	98

The lighting along the tunnel is accomplished using the light tubes and extractors to provide the side lighting required. In the primary run on each wall of the tunnel, the 9.75m light pipes with the 250W luminares maintain a light level of 80.73 lux (7.5fc). In the threshold transition zones, the 3.29m (10.8ft) sections and 400W lamps provide increased light levels up to 1292 lux (120fc). The Light pipes are 12.25mm (6 inch) diameter impact-resistance acrylic.

Next consider the fiber light guide. The average luminance along a 1.524m (5 ft) length of 12mm optic cable using a 150 watt metal halide lamp at one end of the fiber is given by the one manufacturer as follows:

Distance from the Lamp	Lux	Foot Candles
0.1524m (.5ft)	310	30
0.3048m (1ft)	180	18
0.4572m (1.5ft)	115	12
0.6096m (2ft)	73	7.5
1.524m (5ft)	21	2.1

Consider using a number of these optical fiber guides in place of the light pipe. If we assume that the coupling arrangement can provide adequate protection from heating, we can project the usage of an equivalent size fiber light guide by bundling a number of 12mm (1/2") cables and using a 250W light source as follows:

First the illumination of a 4.877 m (16 ft), one half the pipe length, will be considered. The light pipe is 9.75m (32 ft) and there is a lamp at both ends of this section. Assuming the same general losses given above, we can project the light at 4.877 m (16 ft) for the optical fiber as 1.67 lux (0.416 fc).

Next, assume we can increase the light output by 1.67 by going to the 250 watt light. We will bundle the fibers vertically to get 12 mm, that is put 12 of the 12 mm cables together. The light pipe uses a light in each end. Assume we can do this and that the light output is doubled for the fiber cable by using some type of a similar configuration. No such light illuminator systems was mentioned in the manufacturer's literature, but we will assume that one could be constructed. This gives us a light at 4.877 m (16 ft) of 0.17 * 2 * 12 *1.67 or 6.81 fc.

This also assumes that the system would maintain the same light level as the ones for the Callahan tunnel as specified above. This is likely a bad assumption as the specifications for the fiber are probably less than those specified for the measurement zones for the tunnel. Since the distance from the guide for the measurements were not given in the manufacturers information, we will give the optical fiber guide the benefit of the doubt. Additionally, not considered would be the package situation. The coupling of the light source into the fiber could also be difficult unless, two light sources or illuminator systems are used between each section, thus doubling the number of lights over the light pipe configuration. The cost for the fiber cables would have to include the package costs, bundling costs, as well as the coupling problems and the long range heating problems for the fiber could likely affect the life of the fiber cable. This simple analysis helps in understanding the reason why the light pipe was probably used as opposed to the fiber light guide.

NAVIGATION LIGHTING

There are a number of possibilities of using fiber light guides for navigation and/or bridge lighting. Such lighting applications would benefit by minimizing the exposure of the electricity or power sources from the water. As noted in Chapter 1, one of the first application areas of fiber light guides were for swimming pool lighting. Once again the main limitation to consider would be the attenuation or light losses. Since the distance problems and implementation issues were previously covered, a few additional comments will be offered. Both side and end lighting guides could be considered for this application. The typical light output for side lighting was already specified in the section on tunnel lighting. In this previous section it was noted that using the side lighting fibers, a 150 Metal Halide lamp produced about 310 lux (30 fc) from 0.1524 meters (0.5 ft) to 21 lux (2.1fc) at 1.524 meters (5 ft). Thus the problems of locating each of the light sources along the bridge at specified interval would still have to be considered.

Some typical costs for fiber systems include side lighting cables 12mm (1/2 in) diameter are about nine to ten dollars per foot. The end lighting 12 mm diameter cables can range from seven to eight dollars per foot. The installation extrusions, clips, etc could further increase the cost by $0.85 to $3.00 per foot. Finally, the light source and simple coupling systems can range from around $175 for the standard illuminators with 150 watt bulbs up to $500 for the heavier duty systems at 250 watts. These illuminators can provide lighting and coupling for several cables. Prices on light guide bundling for such a system are difficult to estimate as a particular contractor would need to be specified and because there are no such existing systems. The "GE Lighting Optical Fiber Illumination System - A Basic Guide" provides instructions on how to create a simple bundle, which could be helpful in understanding what is required for the process. As noted earlier, G.E. also provides a source for an efficient light coupling device.

The light pipe is currently used for navigation lighting applications and are commercially available.

OTHER POSSIBLE USES:

As noted in previous chapters, there are many transportation related uses of fiber light guides. During a visit to the Minnesota DOT, it was noted that fiber light guides were being evaluated for use for hazard or warning signals for their snow plows. Several advantages were noted including only one light source and that source being located in the van or cab as opposed to being outside in the weather.

In a report by GE Lighting (Ref. 74), reference is made to the use of the Xenon-metal-halide light source and plastic optical light guides for use on the new Miata automobile head lights. They are currently being used in the instrument panels of several other automobile types. In these and other such applications, the main differences between them and the three primary areas investigated is of course the length of the fibers.

It could be possible to use the fiber light guides for traffic signal lights, particularly if the light source was located at the top of the pole, sending the light output to the signals in the center of the street. This particular application is where a phototype could be built and tested. Placing the source at the bottom of the pole would result in the same problems outlined for street lighting.

The use of the fiber light guide was also briefly considered for truck weighing systems. For these systems, it would be desirable to locate the light source some distance from the truck bays to prevent any hazards due to chemical spill, etc. If side lighting fibers were considered, the fiber characteristics listed above for tunnel lighting and used for this case would be questionable at best. However, the situation is further complicated as this would assume the light source would still be in the bays where the inspectors would work while examining the under carriage of the trucks. What would be needed, assuming the side lighting output would be sufficient, is an additional end lighting fiber which could extend the distance of the side lighting fibers from the source. No fiber systems or couplers were found which could splice an end lighting fiber to a side lighting fiber.

Many advances will undoubtedly occur in the near future, and remote source lighting using the fiber optic cables could soon be the norm in the transportation field. On the other hand, with the new sulfur lamps, many of the advantages offered by remote source lighting could be minimized as will be discussed next.

THE ELECTRODELESS SULFUR LAMP:

As noted earlier (Chapters 1 and 2), the light pipe is often found in many applications (including transportation related) for remote source lighting. Although not practical yet for many other applications it could become so with the introduction and improvements to the new electrodeless sulfur lamp [Ref. 29]. This lamp can deliver a large amount a illumination and with the light pipe, it could be possible to replace many current lighting systems. The current 1000 watt sulfur lighting system now offered by Fusion Lighting, Inc., provides about 135,000 lumens. It currently sells for about $1500.00. As this new lighting technology improves and longer life is obtained with the various components of this light, it is possible that bulb replacement and other maintenance considerations will no longer be as much of a concern as the bulb essentially doesn't burn out. Currently the weak link is the magnetron, which generates the microwave energy for the light. Other advantage of this lamp include long life and stable lumen output and color.

In a visit to the Lighting Systems Research Group at Lawrence Berkeley Laboratory, there was research interest in developing a high efficient roadway lighting system using a linear light guide and a high efficiency sulfur lamp. By new designs for the lamp, light tube, and fiber coupling, it might be possible to achieve street and high mask lighting with the light source located at the foot of the pole.

The new electrodeless bulbs, however, could well offer yet another improvement in conventional light sources which could negate some of the advantages of remote source lighting. That is, if a new light source lasts for great lengths of time, then there may not be a great advantage of having the remote lighting source for street lighting or other applications where maintenance is a problem. Of course, this wouldn't necessarily be the case for applications such as tunnel or navigation lighting.

CHAPTER 5

CONCLUSIONS

This report provides results from a study to determine possible uses of the fiber optical light guide for remote source lighting in the Texas Department of Transportation. Fiber light guides are currently used within the Department for changeable message signs and signal heads. The investigation primarily considered its use for street, tunnel, and navigation lighting. The study concluded that it didn't appear practical at this time for street or tunnel lighting, although it could possibility be used for navigation lighting, particularly in conjunction with conventional lighting. Even for this latter case, it appears only a possibility for these situations for short distances and for electrical hazard considerations. The information in the report could help the designer for specific lighting configurations.

The major disadvantages of fiber light guides for the applications considered are the transmission light losses and the difficulty of transferring large amounts of luminous flux. For the changeable message signs, where the fiber light guides are often found in the Department, light is typically only transferred a few feet at most. For usage in roadway illumination or light signals with the light source located at the bottom of the pole, many meters of the fiber medium would be required to provide any significant maintenance advantage. There are significant losses for these situations.

There are two types commonly used light delivery systems which could be considered for TxDOT lighting requirements, the hollow light guides and the fiber light guides. The hollow light guides are used, particularly in new building designs and solar systems. There are several experimental sites where they are being used in transportation related applications for roadway illumination and tunnel lighting. The light pipe has a similar attenuation problem as the fiber light guide. However, because of it's diameter, it is easier to couple large amounts of light into the light guide for transmission and is thus more practical for large scale remote source lighting applications. Remote source lighting has many advantages over conventional lighting and when the problems discussed are or are partially solved, this technology could be useful for many transportation lighting applications.

Because of these findings, no implementation recommendations are provided. However, the technology is changing very rapidly and should be closely followed. The report can provide the lighting engineer with useful information regarding this new technology, and aid in following the advances in this field.

Since traffic signal lights have somewhat different lighting requirements then street lighting, it could be possible as the technology improves, to use the technology in experimental sites. This is made even more likely if the light source can be located at the top of the pole. At least the maintenance trucks would not be required to go out to the middle of the street for bulb changes, etc. References were made by one person to such an existing system. However, this could never be confirmed. If continued research is desired, the development of such a light system for experimental studies could be one possible area for such continuation. This could be done by the Department, one of the Universities, one of the traffic light manufacturing companies, or a combination of these entities.

The effort was hampered in that many manufacturers only wanted to give general information. On one occasion, when inquiring about attenuation and amount of losses for possible configurations, it was stated that we should actually purchase the appropriate material and test to determine these characteristics. This was initially considered in the proposal as discussed in Chapter 1. However, it didn't appear practicable during the first year of the project, and is still somewhat questionable. The next step in this effort, if the Department wants to be involved in developing a system, would be to perform such an evaluation for perhaps the traffic signal light.

The electrodeless sulfur lamp should be closely followed as it could provide a source for usage in street lighting, either with optical fibers or simply to replace existing light sources.

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