USE OF PRISMATIC FILMS TO CONTROL LIGHT DISTRIBUTION

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INTRODUCTION

Piping light for illumination purposes is a concept which has been around for a long time. In fact, it was the subject of a 1881 United States patent[1] which proposed the use of mirrors inside a tube to reflect light from wall to wall down the tube. The use of conventional mirrors for this purpose, however, has not worked because mirrors do not reflect well enough. The best conventional mirrors[2] are about ninety-five percent reflective. The rest of the light is lost through absorption. So, if a light ray traveling down a tube strikes a mirror surface ten or twenty times, and loses five percent with each "bounce," little light is left by the time it reaches the end of the tube. On the other hand, optical fibers composed of certain glasses or plastics are known to transport light much more efficiently. The light that enters is reflected back and forth within the walls of the fiber until it reaches the other end. This is possible by means of a principle known as "total internal reflection." No light escapes through the walls and very little is absorbed in the bulk of the fiber. However, while optical fibers are very efficient in transporting light, they are impractical for transporting large quantities of light. This would require large solid fibers which would be very heavy, difficult to install in many applications, and exceedingly expensive.

Lorne Whitehead, as a student at the University of British Columbia, recognized that prismatic materials could be used to create a "prism light guide," a hollow structure that can efficiently transport large quantities of light. The prism light guide was patented in 1981[3], exactly one hundred years after the first patent on "piping" light appeared! This invention is a pipe whose transparent walls are formed on the outside into precise prismatic facets. The facets are efficient total internal reflection mirrors which prevent light traveling down the guide from escaping. Very little light is absorbed by the pipe because light travels primarily in the air space within the hollow guide. And, because the guide is hollow, weight and cost factors are much more favorable than would be the case with very large solid fibers.

The early history of the development of the concept of the prism light guide has been described.[4] In 1983, Whitehead founded TIR Systems Ltd., a company in suburban Vancouver, Canada to design, develop, optimize, and manufacture prism light guides. The first guides were

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[1] W. Wheeler, U. S. Patent 247,229, *Apparatus for Lighting Dwellings or Other Structures,* September 20, 1881.

[2] For example, Silverlux™ film produced by 3M Company.

[3] L. A. Whitehead, U.S. Patent 4,260,220, *Prism Light Guide Having Surfaces which are in Octature,* April 7, 1981.

[4] *Popular Science,* May, 1988, page 76.

constructed as rectangular rigid acrylic pipes with molded-in prisms, and, as shown in Figure 1, each side of the 1/4 inch thick rigid panel was flat. While the original concept was born from the early dream of piping sunlight to the interiors of artificially lit buildings, it quickly became clear that prism light guides had applicability in a variety of diverse applications and markets.

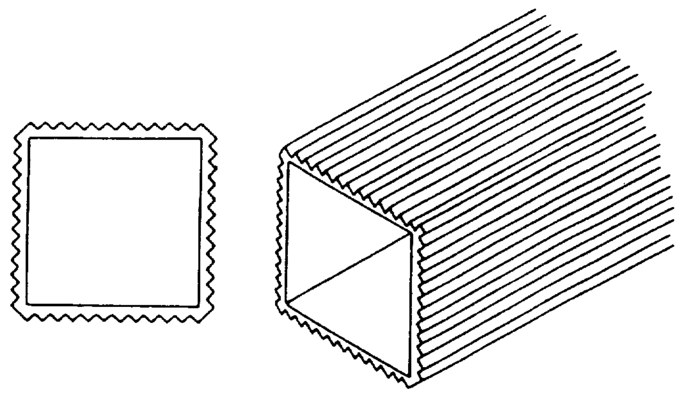

Fig. 1. Rectangular rigid hollow light guide

3M BRAND OPTICAL LIGHTING FILM

In 1983, 3M recognized that the macro-prism structure which existed in the first thick walled rigid acrylic panels could be made as a continuous thin film incorporating microscopic prisms with the same 90° geometry. The geometry of this film, known as 3M Brand Optical Lighting Film (abbreviated OLF), is shown in Figure 2.

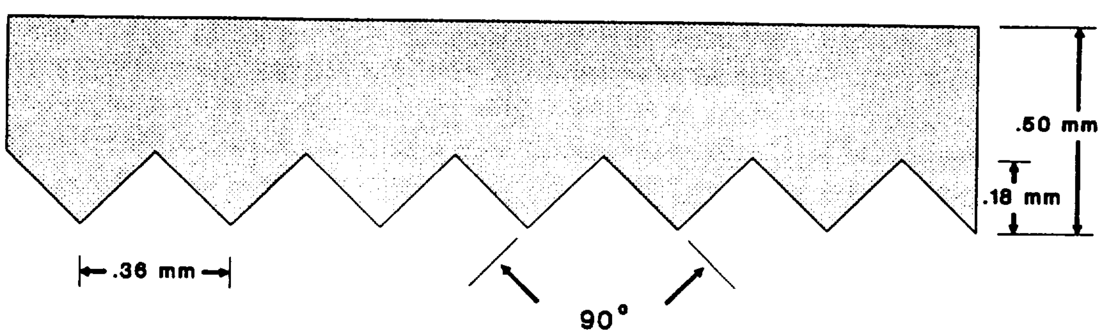

Fig. 2. 3M Brand Optical Lighting Film Cross-section

3M's goals in the development of this new film were the advantages of flexibility in cross-section shape, lower material costs, and potential for economical high volume production. The material is made from either acrylic or polycarbonate polymer resins which have been especially selected for their physical and optical properties. The acrylic film is more stable in certain adverse environments. Polycarbonate films, on the other hand, are tougher, can operate at higher temperatures, and have better handling properties. Very low light absorption in both materials is the critical feature which allows the film to transport and distribute light efficiently.

The degree to which the film's prisms shown in Figure 2 deviate from perfect prisms also affects the efficiency of the total internal reflection process, and, therefore, the effectiveness of the film in transporting and distributing light. Of course, the prisms will not be absolutely perfect, so reflectance of the film will not be 100%. Absorption and transmission will occur. Absorption, as was mentioned above, is due to bulk absorptivity of the resin used to produce the film, and is an irretrievable loss from the optical system. Transmission results from imperfections in the form of the surfaces. Examples of these imperfections include 90° corners which are not precise, surfaces which are not optically flat or which deviate from the correct angle, optical inhomogeneities in the material, etc. Transmission, while generally undesirable if not controlled, can be used to advantage if one goal of the application is light distribution. With the typical losses due to absorption and transmission, the reflectance efficiency of OLF has been calculated as approaching 99%.[5] Using OLF, circular hollow light guides, as show in Figure 3, can be produced in a variety of sizes which may be required for specific applications.

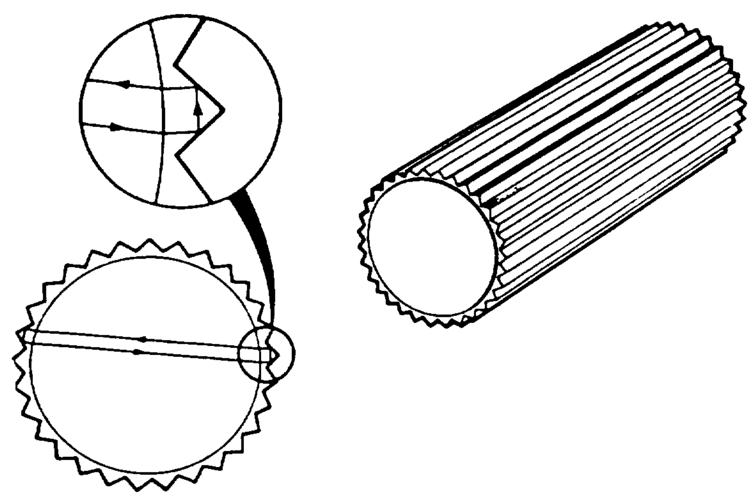

Fig. 3. Circular hollow light guide

Because of a need to protect our proprietary position, little can be said of the process which 3M uses to manufacture OLF with the precision required to produce this very high level of reflectance efficiency. Recent advances in precision micromachining, polymer processing, and certain other manufacturing technologies have made the development of OLF possible. The process is referred to within 3M as "microreplication" and has been found to have broad applicability in a number of diverse product areas.[6]

CONSTRUCTION AND OPERATION OF HOLLOW LIGHT GUIDES

OLF will act as either a nearly perfect mirror or transparent window depending upon the angle

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[5] S. G. Saxe, L. A. Whitehead, and S. Cobb, Jr., SPIE Volume 692, *Materials and Optics for Solar Energy Conversion and Advanced Lighting Technology*, p. 235, 1986.

[6] R. H. Appeldorn, *Nano-Technology Applied to Surfaces,* The Royal Society American Lecture, London, April 2, 1992.

that light strikes the material. For example, the path of a light ray in a typical hollow prism light guide is shown in Figure 4. Light enters the tube from an external source, shown as a lamp with accompanying reflector. It first strikes the smooth, unstructured side of the OLF film, is refracted according to Snell's law, and passes through the smooth side to strike one of the prism surfaces. If the ray strikes the surface at an angle greater than the critical angle, it reflects by total internal reflection, and heads for the other prism face. If it reflects again, it returns to the interior of the tube for further propagation. This light ray path is also shown in Figure 3. Note that the ray spends relatively little time in the OLF plastic bulk, especially if the film is thin, and benefits from the low absorption of propagation through air.

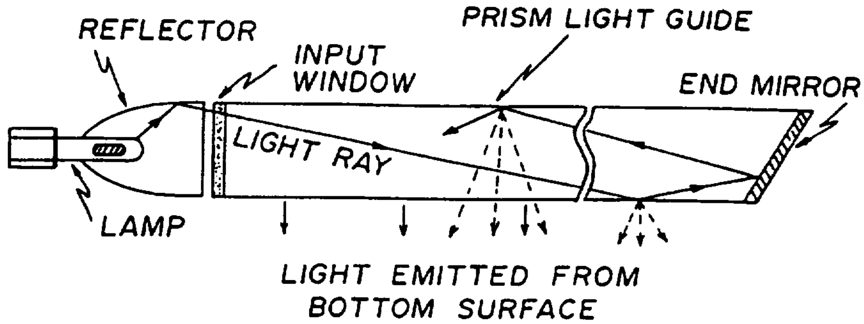

Fig. 4. Typical hollow prism light guide

Since the reflectivity of the film depends directly upon the angle at which the light rays strike the prism surface, it is obvious that the characteristics of the light source and reflector used to collimate the light are critical to the performance of a prism light guide. For the plastic materials used in OLF, light must enter the guide at an angle of 27.6° or less from the axis of the guide. This is shown in Figure 5. In other words, the cone of light from the source should form a 55.2° angle. In general, this means that very narrow spot light sources are used.

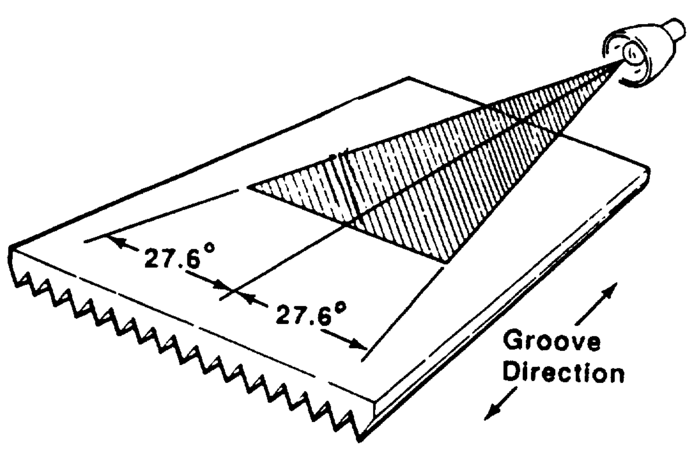

Fig. 5. Angular distribution of light rays entering hollow light guide

A "perfect" prism light guide would reflect all rays that entered within that 55.2° cone. However, as discussed above, imperfections in the film cause some of the light to be transmitted through the film and escape from the guide, making it glow and illuminating the space around the guide. Generally, in the case of hollow light guides, one attempts to "manage" the rate at which light leaks from the tube, and create uniformity of light escaping along the entire length. One of the most efficient ways to get light out of the tube is to place an additional film (referred to as an "extractor" film) inside the tube to "interrupt" light ray propagation and create uniform light escape from the tube. This extractor film is typically a matte white vinyl material, such as 3M Scotchcal™ Series 7725-20 ElectroCut™ film. Another method is to simply cut holes in the prismatic film.

Details of the construction of hollow prism light guides, including predicted performance resulting from various light sources, tube sizes, and extractor configurations are given in previously published 3M Application Bulletins.[7] [8] [9] Many of the practical issues which must be addressed for the successful performance of such fixtures, such as protection from heat, dirt, UV, etc., are discussed later.

APPLICATIONS

The interesting combination of light transmission and reflection capabilities of OLF has made it possible to produce lighting products with unique properties. For example, a point light source can appear as an area source. Light can also be distributed uniformly to avoid "hot spots" which are often associated with point light sources. In addition, light can be transported from the location of the light source to a remote location where illumination is desired. Finally, OLF can be used to provide a desired directionality to light.

The performance which is achievable with OLF often translates into significant product advantages and benefits. Several examples include the following:

Unique Features

Because the angular distribution of light exiting the prism light guide is controlled, fixtures with unique capabilities are possible for some applications.

Design Freedom

The use of point sources provides the capability for variable fixture length and diameter. The lightweight construction which is possible requires less structural support. Light intensity, uniformity, and color are usually easier to control with prism light guides than with standard fluorescent fixtures.

Improved Safety

Because it is possible to deliver light efficiently to a remote location, it is often possible to locate the lamp, ballast, electrical connections, and sources of heat outside of a hazardous or sensitive area.

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[7] 3M Optical Lighting Film Application Bulletin, *General Theory,* November, 1988.

[8] 3M Optical Lighting Film Application Bulletin, *Photometrics,* September, 1989.

[9] 3M Optical Lighting Film Application Bulletin, *Photometrics Appendix,* October, 1989.

Ease of Maintenance

Lamps placed remotely may often be positioned in locations where maintenance is more convenient to perform, safer, and less expensive.

Reduced Cost

In certain situations, the use of fewer, more efficient light sources may result from the use of an OLF-containing fixture. However, in considering overall system cost, it is important to include not only the cost of the fixture, but also the potential life-cycle cost reductions for installation, operation, and maintenance.

Over our years of experience in working with OLF, we have uncovered unique and interesting lighting applications using this film which are too numerous to mention. In fact, because the apparent opportunities for the creation of new products based on the capabilities of OLF are so large and diverse, it has sometimes been difficult to assess and manage our product development priorities. We have found it easier and quicker to invent new applications for the film than to develop and commercialize these myriad opportunities. And, as will be discussed later, there are many critical variables which must be addressed in the successful development of a new lighting product. As a result, we have recently decided to confine our development efforts to products which could find utility in a market which we in 3M know -- the traffic management market. The selection of applications for this market was not accidental. It was largely based on the recognition that 3M already has good knowledge of the traffic management market through existing sales of a wide variety of retroreflective products for marking road surfaces, vehicles, and highway signs. It is a market for which we have effective distribution around the world. As a result, we have introduced several new products for use in highway applications:[10]

3M Internally Illuminated Highway Sign

This new sign product combines the property of passive retroreflectivity with that of internal illumination. OLF is used to distribute the light evenly within the sign box and thereby provide uniform luminance of the sign face. In addition, the use of OLF allows the light sources to be placed remotely at the side of the road where they may be easily maintained. The light is efficiently transported to the sign which is over the road. Advantages, therefore, include safer and more convenient maintenance allowing for the elimination of traffic diversion and delay, improved uniformity of sign luminance, improved performance under adverse weather conditions, and preferred aesthetics.

3M Lighted Guidance Tube

This product is a linear illumination system which provides positive guidance to motorists traveling along hazardous or unfamiliar roadway locations or during conditions of adverse visibility. This system utilizes small low-voltage light sources located approximately every 30 meters to illuminate a continuous polycarbonate tube mounted atop concrete barriers or steel guard rails. The effect of providing a continuous line of light is made possible by the light

[10] D. L. Strand and K. G. Kneipp, XII International Road Federation World Meeting, Madrid, *Novel Uses of 3M Optical Lighting Film in Roadway Applications,* May, 1993.

transport properties of OLF. In addition, because of the directionality of the light which exits, it is possible to provide different colors to the light exiting the tube when viewed from either direction.

3M Pole Light

The 3M Pole Light uses OLF to transport light from a lamp located at the base of the pole to the top where it is redirected back to the ground in the desired "footprint" by a unique reflector. This product is also made possible by the efficient light transport properties of OLF, and provides advantages of easy and convenient light source maintenance and improved safety due to the location of all electrical components at the base of the pole or below grade.

In addition to these product applications being pursued directly by 3M, a number of other light fixture manufacturers purchase OLF and fabricate an array of novel fixtures which capitalize on the film's benefits. The following summary of selected applications is not intended to be a complete listing, but rather a sampling which shows the wide variety of products which have been developed based on this technology:

Thin Light Boxes

Thin boxes for backlit advertising and graphics display applications have been built by several manufacturers. The use of OLF permits uniform luminance of detailed sign graphics with a thinner box profile than would be possible using standard construction techniques. It allows for lamps to be located in positions where they may be easily maintained. Typical techniques for construction have been described.[11]

Explosion Environment/Hazardous Lighting

The light transport properties of OLF permit the construction of fixtures where the lamp, ballast, wiring, and associated electrical components may be safely located outside of hazardous or sensitive areas. All maintenance of the fixture is done in easily accessible, safe locations, and the light is delivered into the room where it is needed. This type of fixture has been used in solvent rooms and other similar environments, in food processing plants, health care MRI rooms, and over swimming pools where lamp maintenance is difficult and expensive or where elimination of electrical components is necessary.

Tunnel Lights

OLF fixtures for application in tunnels offer the advantage of greatly reduced number of lamps compared to fluorescent fixtures which they typically replace. Reduced and easier maintenance in these difficult-to-access locations are major benefits to the end-user or maintaining authority.

Building Highlighting

Long lines of light located atop buildings have been used to highlight the building design and create desired architectural effects. With OLF, it has been possible to design such fixtures with

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[11] 3M Optical Lighting Film Application Bulletin, *Thin Light Box,* March, 1990.

the light source located inside the building for ease of maintenance. In addition, changing colors or creating other desired visual effects is made easier than with other lighting designs. Buildings which incorporate such lighting systems may be found in several locations in North America, Europe, and Japan.

Emergency Vehicle Interior Lighting

OLF fixtures create more uniform illumination and eliminate the glare often associated with point sources. Because light sources which provide better color rendition may be used, patient care, as well as comfort, is improved.

Workstation Task Lighting

The use of OLF in fixtures located over workstation or desk areas allows the light to be directed so that undesirable glare and reflections from shiny surfaces are eliminated. This improves worker comfort and productivity.

The products which have been briefly mentioned here all capitalize on the unique light transport and distribution properties of OLF. These properties have led to a variety of benefits, including fixtures with unique designs, improved safety, reduced operation cost, and improved maintenance due to the use of longer-life lamps and the ability to locate them for ease of replacement.

IN-USE FIXTURE DESIGN AND PERFORMANCE CONSIDERATIONS

The environment in which a light fixture is to be used dictates many of the details of its design. For example, fixtures which are intended to be used in exterior locations must meet design and performance criteria which do not apply to interior fixtures. Exterior fixtures are usually constructed to different specifications using different materials than fixtures which will not be subjected to harsh exterior environments. The fact that fixtures intended for use in specific applications must each be designed and constructed to meet the unique requirements of that application has been a key factor limiting the number and types of widely different fixture designs and end-use applications which we in 3M have elected to pursue. We recognize that the effort to produce an effective fixture design, and the investment required to prove that the design functions acceptably in the intended environment, are often substantial. Some of the factors which must be considered in the design and operation of any new OLF-containing prism light guide are outlined below:

Service Access

The design freedom which often results in OLF fixtures can make maintenance of the light sources much easier and more convenient. It is important to design the fixture so that optimum advantage may be taken of this benefit by designing the proper location and type of service access for ease of lamp replacement and electrical maintenance.

Effect of Heat

OLF-containing fixtures often incorporate HID sources which provide light which is properly collimated for use in a prism light guide. However, these source also produce heat, which, if not properly dissipated, can result in fixture overheating and ultimate destruction of certain components. Plastic components are susceptible to damage from excessive heat. For example, polycarbonate OLF will suffer film distortion at temperatures above about 265°F; acrylic OLF will be damaged at temperatures above about 190° F. It is necessary, therefore, to place hot sources in appropriate locations and to use suitable venting and cooling techniques to insure that these films and other heat sensitive components will not be damaged.

Effect of UV

Plastic resins, such as polycarbonates or acrylic materials, are often stabilized to the damaging effects of UV radiation by the use of certain additives. The polycarbonate and acrylic polymers used to produce OLF, however, do not incorporate such stabilizers. This is because stabilizing additives also absorb sufficient light in the visible portion of the spectrum such that the optical efficiency of the resulting film will be too low. As a result, because UV radiation will cause undesired resin yellowing, crazing, and cracking, it is necessary to use a filter between the light source and OLF material. While the acrylic film is less susceptible to damage from UV exposure, unstabilized polycarbonate is known to yellow when exposed to radiation of less than 337 nm.[12] An effective filter glass for use with polycarbonate is UVILEX 390 (Schott Glass).

Weatherability

While it is necessary to protect the OLF from the damaging effects of UV radiation, prism light guides which are used outdoors will be subject to the effects of sunlight. The OLF must be contained in a housing which does not allow sunlight to shine directly on the film. This may be done by using metal or stabilized plastic components for the outer housings.

Effects of Dirt and Moisture

In addition to protection from sunlight, the optical components must be protected from excessive dirt and condensing moisture, both of which will destroy the optical performance. Thus, fixtures containing OLF are often sealed to eliminate concerns from dirt and moisture. In some cases, where sealing is impractical, such as in the case of a large sign, it is necessary for the entire structure to breathe. Filters to keep out dust, insects, or other debris, are often used at the breathing ports.

Hostile Environments

While any fixture which is used outdoors is subject to the effects of sunlight, temperature extremes, and moisture, certain environments are particularly hostile and deserve separate mention. For example, products such as the 3M Lighted Guidance Tube, tunnel lights, and certain other outdoor fixtures are subjected to occasional high pressure water, detergent, or even steam cleaning. It is important that the actual operating environment be considered in fixture design and selection of components.

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[12] C. A. Pryde, ACS Polymer Preprints, Volume 25, Number 1, *Weathering of Polycarbonates - a Survey of the Variables Involved,* p. 52-53, April, 1984.

OTHER PRISMATIC MATERIALS AND THEIR APPLICATION

In addition to OLF, 3M has developed other prismatic film materials for redirecting light. An important example of such a product is a film which we call "2370" polycarbonate prismatic film. The structure of this film is similar to that of OLF shown in Figure 2, except that the prism angles are 70° instead of 90°. The way in which this film interacts with incident light is quite different. When the film is positioned so that the groove direction is perpendicular to the direction that the light is traveling within a hollow light guide, light which strikes the groove side of the film at a grazing angle (less than about 20°) will be bent 90°. The 2370 film has found use in helping to achieve uniform light extraction from our internally illuminated signs, as well as in redirecting light in a preferred direction from other hollow light guides. OLF and 2370 are often used together in order to achieve desired light control. The 2370 film is manufactured in a microreplication process similar to OLF.

Another important prismatic material is the 3M Solar Optical Products Daylighting Panel which incorporates a Fresnel lens system to collect light energy from the brightest area of the sky and redirect it vertically into the interior of a building. The bulk of available natural light varies with the time of the day as well as time of year. Conventional skylights and windows are only partially effective since they cannot constantly redirect the brightest portion of the sky into the desired areas of the building. 3M Daylighting Panels also soften direct sunlight without reducing reflective efficiency while still providing unique light collimation properties. Energy requirements for heating and cooling are substantially reduced.

In a typical installation, such as the one at the 3M Austin, Texas Center, the panels are mounted in the roof area of the building. A primary panel collects and concentrates direct solar radiation and redirects the light to a secondary panel. The secondary panel is positioned such that sunlight is directed vertically downward into the building regardless of the time of year. Due to its large collection efficiency, the system works well even on cloudy or hazy days. The construction and performance of the 3M Austin Center installation has been previously reviewed.[13]

Another application example for daylighting panels is at the Minnesota Zoo Tropics Building. The building previously utilized ordinary skylights to provide natural light for plants and animals located between 9 and 23 meters below the roof's surface. During the winter months, plants were being lost because most of the light did not transmit through the skylight due to the low sun angle. 3M installed daylighting panels on the north side of each skylight to capture the low angle sun and reflect it down into the building. This made the distribution of sunlight more uniform throughout the year, and provided light required for greater plant growth during the winter.

The ability to make the level of light delivered to the interior of a building more uniform throughout the year has been demonstrated by placing daylighting panel louvers on a greenhouse in Flagstaff, AZ. In the winter, low angle sunlight will be captured by one section of the louver and directed through the roof into the greenhouse. When the sun's altitude increases during the summer, the resultant sun's rays will reflect off a second section of the louver to reduce the transmitted sunlight. Use of these daylighting panel louvers will provide greater growing capacity for a conventional greenhouse throughout the year and reduce winter time heating and

[13] *Architecture,* August, 1990, p. 90.

summer time cooling energy requirements.[14] Details on these daylighting installations may be obtained from 3M.[15]

Still another application of the Fresnel lens technology is in prismatic materials for solar concentrator applications. Using the 3M lens film, sunlight is focused on a strip of active solar material. This increases the efficiency of the overall collection system, reduces the amount of active cell material required, thereby eliminating the need for broad flat plates of active cells. The performance of a system which has been installed atop the parking garage at the 3M Austin Center has been described.[16]

SUMMARY

3M prismatic films are finding increasing utility in the construction of new hollow light guide fixtures which capitalize on the unique ways in which these novel materials interact with light. Often, the resulting systems provide features and end-user benefits which are difficult or impossible to achieve by alternative design or construction methods. It is apparent that the benefits may be applied to a wide variety of end-uses, and that the resulting products being developed will find utility in many diverse market areas.

With the recognition that creating hollow light guide products and systems requires a substantial resource investment, and because of an existing prominent position in the traffic management market, 3M has decided to focus its current efforts in the development, manufacture, and distribution of value-added products for this market.

However, through the sale of these prismatic films, a variety of companies have developed and are manufacturing and distributing other unrelated hollow light guide products which capitalize on the unique capabilities of these films in controlling and distributing light. There appears to be little doubt that the potential applications of this technology will grow both in numbers as well as in diversity.

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