LIGHTING A BUILDING WITH A SINGLE BULB: TOWARD A SYSTEM FOR ILLUMINATION IN THE 21st C.

or

A CENTRALIZED ILLUMINATION SYSTEM FOR THE EFFICIENT DECOUPLING AND RECOVERY OF LIGHTING RELATED HEAT.

by Kurt Antony Levens

Submitted to the Department of Architecture and the Department of Civil Engineering at the Massachusetts Institute of Technology in partial fulfillment of the requirements for the degrees of

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ABSTRACT

Piping light represents the first tenable method for recovery and reutilization of lighting related heat. It can do this by preserving the energy generated at the lamp as radiative, departing from precedent and avoiding absorption of and re-emission of radiant heat as convection and conduction. Within thermodynamic limits, the radiant heat generated by an electric lamp or the sun is available for optical concentration and for reconstitution as a high thermodynamic quality power reservoir. Piping light from a large central lamp facilitates the decoupling of lighting related heat at the source, and also means that the efficiency of one central fixture can be stringently optimized instead of the multitude of fixtures it replaces in buildings. Luminous efficacy for a full-spectrum lamp decoupled of its infrared can be shown to approach theoretical limits of 250 lumens/watt. UV generated by the lamp, if coupled along with the illumination into the transport fibers, can be converted into visible radiation at the emitting end of the fiber, supplementing the light output.

Fiber optics are used to carry information over long distances (actually encoded pulses of radiative IR), but certain fiber optics can carry tremendous amounts of energy. As fiber optics become more and more plentiful in telecommunications, their prices will come down. Cost and operating expense studies included in the final chapter of this thesis indicate that a large single source with light that is efficiently coupled and piped throughout a building's interior could reduce electric light consumption to one-fourth, and that even at current fiber pricing levels some systems can be competitive in initial cost to conventional lighting. Certain aspects of centralization suggest further reductions in cost and operating expenses such as centralized, instead of localized, relamping and cleaning, and eliminated requirements for thermal, electrical, and structural hardware at room fixture locations.

The economic and technical feasibility of a central system depends on the simultaneous minimization of fiber aperture area and energy losses. Thermodynamically, the concentration of light for transport cannot surpass the energy density of the source. So such a system employs, at best, an optical process that preserves the extent of the source. That is, a high brightness source must be used to drive the system, regardless of the lamp's lumen output. High brightness lamps, then, can be viewed as an alternative to high efficacy lamps for increasing the energy performance of lighting systems in buildings. This thesis anticipates the existence of high brightness, high lumen lamps.
The sun's 10,000 footcandles in peak conditions can be a potent contributor to the energy efficacy of buildings if a collection and utilization strategy is properly devised. At 100 sq. ft of available illumination for each sq. ft of collected sunlight, a scenario including simultaneous collection and distribution of electric light and heat and sunlight and solar heat in a building could reduce to near zero the energy consumed for lighting during peak sun conditions. Studies in this thesis indicate that an economically driven future role of solar energy in the lighting, heating, and cooling of buildings could very well revolve around keeping sunlight in the form of illumination and sunheat in the form of radiative heat, instead of converting both into electricity via photovoltaics and reconversion of this electricity back into electric light.

Conventional lighting is an inefficient process, essentially using heat sources for the light they provide. Not only is lighting related electricity generating predominantly waste heat, this heat must be removed from the building's envelope by an additional input of energy. Even energy saving fluorescent lamps and fixtures produce at least 80% heat. This might serve to explain why 30% of the country's electricity is consumed by lighting.

This thesis proposes a method for decoupling and recovery of lighting related heat, and transporting light in lieu of electricity to lighting fixtures (Chapters 2 and 6). Each of the optical components that would comprise such a system is examined. Chapter 7 investigates the radiation source. Chapter 8 develops the source reflector which will direct the source's radiative output in a particular direction. Chapter 9 studies a mirror that will separate the source's radiation beam into a light beam and a heat beam for subsequent processing. Chapter 10 looks at the heat collector that will convert the heat beam into a usable high-temperature power reservoir. Chapter 11 devises the light collector/concentrator that will facilitate coupling of light energy into a fiber optic transport network. Chapter 12 assembles the constituent components into central modules.

Chapter 5 surveys the light transport media, in particular fiber optics and Prism Optical Light Guide, for suitability to building lighting applications. The exact method of solar couplature is not introduced. Sample energy efficiency comparisons, cost and payback scenarios, implementation issues and concepts for room emitters are included in chapter 13. Related concepts for a transparent concentrating solar collector for use as a window or skylight, and a solar concentrating wall are disclosed in the conclusory chapter.

Material included in this thesis has been patented by MIT. The usage of such material for any commercial means requires a licensing agreement.

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to Thomas Edison

in memory of Alexandra Tuttle
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CHAPTER 1

CONVENTIONAL LIGHTING

From the time society first used sources other than the sun for light, heat has been an unwitting accompaniment. In the centuries preceding this one, artificial light was the result of combustion: the burning of whale oil in lanterns, the burning of wood in fires. In those instances, as well as with those adopted in this century with the advent of the electric light bulb, heat is the primary constituent of the lighting process.

The electric light provided relative safety and convenience over that of the candle. It has come under scrutiny for the amount of energy it consumes commensurate with the increasing appetites of the modern lighting user. Lamps that provide relatively high energy efficiency lighting require ballasts to properly regulate current flow. Ballasts contribute their own energy losses in the electricity to light conversion process, subtracting from the efficiency of light production. Typically about 3 to 7% of input power is converted to waste heat at the ballast.

Furthermore, for stable operation, mechanical and thermal hardware is introduced into higher power fixtures to dissipate waste energy. These fixture components can require sizeable structural support, consuming space above (or below) the ceiling and influencing building form via story-to-story height by requiring above-the-ceiling plenum space. Expensive fire-safety electrical wiring and installation procedures for ensuring long term operational safety underlie much of the National Electric Building Code (NEC).

The fixture is further encumbered by reflectors, lenses, louvers, and baffles necessary to convey the light away from the lamp, beyond the ceiling, and into the space. These accoutrements, while improving comfort through better design of the visual environment, reduce further the lighting efficiency of the lamp/fixture combination and increase the heat build-up in the fixture. Conversely, a general consequence of many measures taken to improve the energy efficiency of lighting fixtures, or the efficiency of utilization of light in the space, is the introduction of glare into the visual environment. Lamps with improved efficacy generally introduce a compromised rendering of colors, making skin tones appear (and making us feel) less healthy than if outdoors.

**Efficacy and Efficiency**

Lamps convert electricity into heat and light. The process is described by the product of two terms: 1) the luminous efficacy, expressed in lumens/watt, quantifies the rate at which a lamp converts electrical energy into visible light, and 2) the luminous efficiency (or efficiency) of the fixture, which is a percentage of light leaving the fixture in relation to the amount of light that is generated inside of it by the lamp. Efficacies have shown considerable improvement over the last
few years due to the emphasis placed on improving the energy performance in buildings, but efficacy decreases naturally as a lamp ages. Lighting fixture efficiencies, while attaining values approaching 95% in optimum situations, are characteristically 50 - 65% in commercial installations or lower due to dust buildup over time and the necessity of controlling glare. Deterioration of lamps and fixtures has also spawned economic incentives for cleaning and group relamping regimens for maintaining lamp light output, but these efforts entail high labor costs due to the decentralized nature of current lighting systems.

**Lamps are heat sources**

Despite recent and proposed improvements in electric lighting, lighting energy losses are still high. As illustrated in the following diagram, high luminous efficacy energy saving fluorescent lamps generating 2800 lumens at 32 watts are contributing roughly 26 watts of heat (77%) to the environment through conduction, convection, and radiation losses. Ballasts contribute further heat losses to this process. These energy shortcomings are further exacerbated by the additive electrical cooling loads required for the removal from the inhabited space of heat generated by these lamps.

Waste heat in buildings is generated by people, computers, lighting, and building equipment. The amount of heat removal required in buildings varies throughout the year and with respect to climate and building type. In colder climates some of this heat would be used to provide warmth in the space, and excess heat removal could be accomplished with ventilation and without the need for mechanical cooling. In hot sun-intense climates buildings may be mechanically cooled all year long. Two cases can be used to bound the quantitative problem with regard to lighting efficiency and the removal of light-related heat: no air conditioning penalty, coupled with new lamps and new 90% efficient fixtures; and air conditioning with a coefficient of performance (the ratio of thermal output over electrical input) of 3.5, combined with considerable lamp aging and dust accumulation. Overall lighting system performance for converting electricity into illumination lies somewhere between 5 and 18% [i.e. $2.1w/(2w + 32w + 10w)$ or $6.3w/(2w + 32w)$] depending on efficiency conditions and air-conditioning needs (Figure 1.1).
Compact fluorescent lamps are a popular alternative to energy saving tube fluorescent lamps. Their popularity stems from their convenience as an energy saving substitute for the standard incandescent light bulb. Although less efficacious than energy saving fluorescent tubes, they provide many times more light than their filament lamp counterparts in terms of lumen output and longevity. Improved incandescent lamps, on the other hand, handily compete for installations requiring aesthetic sensitivity, because the compactness of their light source accommodates very precise beam control for installations where a heightened degree of visual contrast is desired. Incandescent lamps (such as the widely used tungsten-halogen PAR and mini-reflector lamps) consuming 150 watts of energy are contributing 130 watts of heat directly to the environment for every 1850 lumens of light they produce (12.3 lm/w). Bounding the problem as before, the system delivers between 3 and 12% of its input energy as illumination [6w/(150w + 43w) or 18w/(150w)].

It is evident that conventional methods for illumination are characterized by an inefficient conversion of electricity into illumination. Fixture efficiency improvements of 5% or even 10% will not affect the overall system performance by more than a percent or two. Industry's painstakingly attained efficacy and efficiency gains are readily reversed by dust and dirt accumulation ubiquitous to commercial and industrial building interiors (in instances, ironically, brought about by avoidance of expensive group relamping and cleaning regimens due to economic restrictions imposed by the purchase of improved energy saving lamps, fixtures, and ballasts).
Summary

An understanding of how energy is consumed in the illumination process helps to clarify the shortcomings of conventional illumination systems:

- 60 - 92% of lighting energy dissipated as heat at the lamp.

- fixtures typically reduce the amount of light actually entering the space by another 15 - 50%, or more.

- an additional load of 35% of lighting load is required for removal of lighting related thermal energy generated by illumination system, for the general case in which excess heat is produced within building interiors (this load is customarily neglected when evaluating illumination system performance).

- luminaire dirt depreciation from dust and dirt deposited on the bulb and reflector surfaces, prompted in part by avoidance of expensive cleaning and relamping regimens, constitutes a reduction in system efficiency of 20% over a two-year period in a clean environment.

- lamp lumen depreciation is the result of lamp aging and is characterized by a decrease in lumen output of 8 to 20% over the lifetime of the lamp.

Emphasis being placed on reducing energy consumption in buildings creates a favorable environment for effecting changes to reduce the number of stages and multiplicity of losses in the lighting process. Developments in lamp and fiber technology may eventually enable a revising of the general approach taken toward the illumination of building interiors. Just as the centralization of other building systems (i.e. power distribution, water, HVAC) can represent a higher order of evolution in building technology, this thesis will attempt to establish that centralization of illumination can enhance the visual quality of the lighted environment while significantly improving the energy performance of illumination systems.
CHAPTER 2

INTRODUCTION TO CENTRALIZED ILLUMINATION IN BUILDINGS

This thesis proposes a system for illumination to cut in half the lighting related electrical energy consumed by a building. In addition to being more efficient than a typical energy saving fluorescent system, a centralized illumination system could solve many of the problems associated with conventional lighting by: 1) providing full-spectrum light close in characteristics to that of sunlight, 2) eliminating the entrance of lighting related heat into conditioned space, particularly heat within the light beam, 3) incorporating collected and concentrated sunlight into a distribution grid (for only a nominal additional capital expenditure) for peak load shedding of lighting electrical load, 4) reducing constraints posed by lighting related thermal and structural considerations in the architectural delineation and expression of space, 5) allowing for a reduction in cooling equipment capacity concomitant with the reduced cooling load, 6) decreasing fire and electromagnetic safety concerns by transporting light rather than electricity to lighting fixtures in walls and ceilings, 7) eliminating a fixture's thermal dissipation and structural support hardware thereby vastly simplifying room lighting fixture manufacture and installation 8) centralizing the cleaning and maintenance regimen for sustained light output and lowering maintenance and labor costs.

Background

It is a curious anomaly and testament to the inefficiency of our national energy strategy that peak electrical loads in buildings coincide with the hours of peak sunlight. This is indicative of an approach to building design in which energy considerations are not wholly integrative with building architecture, whereby energy inside of a building is used to encapsulate it from any effect of energy outside of a building. A centralized system integrating sunlight, electric light, sunheat, and electric heat could reverse this tendency, ushering in buildings that exist in a quasigenerative capacity.

Energy is expensive, not only in terms of direct dollar costs, but also in terms of the long term effects energy production casts on the closed global environment. CO₂ production for energy use in buildings amounts to 500 million tons per year in the US, or two tons of carbon for every person. Lighting in buildings competes for a majority of this percentage. Buildings consume 36% of the country's energy supply [Bevington, 1990].

Anyone familiar with electric light is aware of the heat that a lamp generates. As a thermal source, an incandescent lamp varies little from a flame. The principal output of fluorescent, microwave, and radio frequency lamps and fixtures is also heat, despite their energy saving status.
If one were to collect the light sources from within a building and assemble them in one isolated portion of that building, an immense buildup of heat in that area would reveal what the energy, lighting, and construction industries have long and arduously been grappling with: that heat is by far the largest constituent of electric lighting. Reducing lighting related heat is the target of much lighting research since it comprises the largest portion of the electrical energy used to light a building. Not only is this heat wasted, it must also be removed from the space by additional energy for air cooling. This additional A/C load is generally not referred to in illumination system performance evaluations. In actuality, despite recent advancements in electric lighting technology, illumination in buildings is still a grossly inefficient process.

Efficiency in lighting is essentially a struggle against the production of heat. In response to increasing pressure from consumers and local, state, and national agencies to improve the energy efficiency of the lighting process, most lamp manufacturers are trying to increase the energy performance of their products by suppressing the generation of the heat (IR radiation) and encouraging the production of light (visible radiation). Basically what is sought is a selective transmitter of radiation: a source that emits radiation only in the visible range. Since the lighting process customarily converts between 80 and 95 percent of its incoming electricity directly to heat, it is conceivable that the result of putting such a source to work would be reducing the lighting related energy consumption in buildings by 80 to 95 percent or to somewhere between 5 and 20 percent of its original level. However, such a product is quite contrary to the physical nature of light production. Since light and heat are both electromagnetic radiation differing only in wavelength, requiring a thermal source to produce light but not heat is like asking the sun to emit only green.

**Method**

Rather than suppressing the generation of lighting related heat, a logical, arguably natural, approach to energy savings would be to devise a means to decouple the heat at the source, and recollect it. Were this achieved, one could reduce the energy consumed in the lighting process by transporting light, rather than electricity, to light fixtures in buildings. Pre-empting heat from entering the space immediately saves in air conditioning costs. Optically collecting and concentrating the heat would increase its temperature and increase its thermodynamic quality beyond any other strategy of thermal recovery in buildings. This is akin to a solar furnace, only it is using wasted electric-light radiation instead of solar radiation as an energy source. If this centralized waste heat can be collected, concentrated (re-focused), and converted into a supplemental power source, then possible applications for the recovered waste heat would range from hot water to direct heating needs to air conditioning via heat-absorption chilling. This is in contrast to conventional approaches to heat recovery lighting fixtures which, despite some
popularity, cannot concentrate the heat and therefore accomplish very modest levels of heat removal, much less heat recovery or reutilization.

The light source of the building is, in essence, broken into two subordinate energy systems: light system and heat system. Since source heat is recovered and used for power it can be seen that luminous efficacy of the illumination system is directly related to only that portion of the total wattage converted into light. Luminous efficacy values are, therefore, raised to more accurately reflect the actual wattage consumed in the production of light, independent of the efficacy in which the radiation source produces heat.

For a source with a high percentage of radiative output, such as a compact metal halide lamp, recovery of its radiant IR (50% of total energy) at 80% efficiency results in luminous efficacy increasing from 100 lm/w to 166.7 lm/w (an increase of 100/(1 - 0.5 x 0.8)).

Similarly, recovery of heat from an incandescent halogen source at 20 lm/w (90% of total energy) at 80% efficiency could result in luminous efficacy increasing to 250 lm/w (20/((1 - 0.9) x 0.8)). Neither of these examples take into account the additive energy savings of eliminated lighting related cooling load.
The proposed system as a whole has no direct precedence, however, elements of the system have precedents spanning many fields. It is the experienced opinion of the writer that no system for illumination as comprehensive as that being proposed has ever been justified or attempted.

Fiber optic lighting remains very small in its application type and in its impact on the lighting market (showcase lighting, predominantly). There are many fiber optic illuminators on the market, each essentially doing the same thing and of approximately the same size (topping out in the 400 watt range). Integration problems, lamp problems, and thermal problems that accompany increasing light handling capacity can't be resolved at the small end of the application scale because they require added hardware which the energy savings over time do not justify the expense of. It is only when large amounts of energy are conveyed by small optics that the addition of an optical element for increasing energy efficiency is warranted. The copious use of optical thin films for maximizing reflection and spectral separation will ameliorate some of the thermal problems and increase system efficiency by 20%. They too are only justifiable at higher energy density levels. As discussed in chapters 3 and 9 there are standard thin film products, although this application would require some modification to manufacturing methods since larger coverage areas are needed than the fabricators are currently supplying to the laser-using scientific community.

Another area of precedent is the Himawari sunlighting system (chapter 5) sold in Japan. Energy savings offered by transient sunlight doesn't offset initial cost in the long run. Japanese acceptance of the technology is driven by cultural acclimation to interior sunlight. The Himawari doesn't integrate electric light, and loses incumbent radiative heat and UV to the environment. Also discussed in chapter 5, hollow light guide transporters can be used in conjunction with fibers, or in lieu of fiber in special circumstances.

Optics for energy management lie solely within the realm of solar energy, a very narrow subset of optical systems. As developed in Chapter 4 and 10, optical systems for recovering the radiant heat from the source, and for subsequent high temperature reutilization, are based on Roland Winston's high collection nonimaging optics.

This thesis is basically a theoretical engineering project, identifying suitable optical techniques where appropriate and extrapolating from them the design of a system that comprehensively manages the radiation from its source (electric initially, eventually including the sun). The conceptual process of radiative heat recovery from a central light source is an invention of the author and patented. The reflector system and method of interstitial void elimination are patent pending. Furthermore, as will be explored in chapters 7 and 8, the thesis recognizes the significance of two other enabling concepts: 1) the thermodynamic concentration limit posed by the energy density of the lamp can be ostensibly surpassed within a solid media [ie the transporter], 2) the source reflector concept of re-entrant light can effectively double the driving power of the lamp.
CHAPTER 3

OPTICAL COATINGS

Uncoated optics

As discussed by Hecht [Hecht, 1990], the intensity of reflected light at a simple interface between two light-propagating materials is governed by three properties:

1. Fresnel reflection losses described by:

   \[ R = \left( \frac{1 - \frac{n_1}{n_2}}{1 + \frac{n_1}{n_2}} \right)^2 \]

   (3-1)

   where \( n_1 \) is the refractive index of the incident medium, \( n_2 \) is the index of the refractive medium, and \( R \) the proportional intensity of reflected light.

2. Polarization of incident light
3. Angle of incidence

As can be deduced from equation (3-1), the amount of reflected light increases with the disparity between the two refractive indices. For example, at a simple air-glass interface where air has a refractive index of 1.0 and glass has a refractive index of 1.5, 4% of incident light is reflected. This concurs with our everyday experience of seeing the ghost of a reflected image when looking into or out of a glass window.

A system of 10 surfaces (e.g. 5 lenses or 5 rear surface mirrors) will transmit an absolute maximum of 66% of original flux, according to:

\[ T = (1 - R)^n \]

(3-2)

where \( n \) is the number of surfaces and \( R \) is the fresnel reflection loss at each face as determined by equation (3-1).

These fresnel energy losses at the interface of uncoated optical elements subjected early attempts to optically convey sunlight into building interiors to low throughput efficiency. An
example of such a sunlighting application was the University of Minnesota Civil and Mineral Engineering building (UM). The optical elements were placed along a light transport path that descended 110' underground. Despite the efficiency shortcomings of UM's design, the installation remains a solar optic demonstration center (optical coatings can reduce fresnel reflection losses from 8% to -0.5% in a lens and would improve the throughput efficiency of such a system significantly).

The optical efficiency of coated, and especially uncoated, optics is further degraded by absorption and scattering of light resulting from adherence of dust to optical surfaces deposited by localized convection. This increases hazard of fire due to localized, uncontrolled high-temperature zones in applications with high flux concentrations.

Introduction to optical thin films

Thin film coatings modify the reflection/transmission properties at the surfaces of optical elements and are usually described by reflectance and transmittance values (and occasionally absorptance). Five types of reflective/antireflective optical coatings will be used by the system designed in this thesis: 1) reflective across the entire visible (VIS) and infrared (IR) spectra, 2) reflective across just the IR, 3) reflective across just VIS, 4) transparent to VIS and reflective to IR, 5) transparent to VIS.

Optical coatings change basic fresnel reflection characteristics by introducing a thin intermediary layer with a desired refractive index to serve as the incident or refracting medium. These films will be examined for applicability to the proposed lighting method with a view to how well frequencies of light may be separated from frequencies of heat, and with an interest in attaining the maximum reflection and transmission capability of optical elements. In laser light applications, where the light beam is barely divergent, thin film behavior with regard to angular divergence is important in only specialized applications. Strict collimation of electric light, on the other hand, is patently difficult and would severely compromise optical efficiency, and hence energy efficiency of the entire system. So sensitivity of films to angle of incidence is important. The effects of, and possible relevance of, polarization is left to future inquiry.

To what extent will these films facilitate the centralization of illumination production? Can adequate separation of light and heat by frequency be obtained? Could the density of energy upon the thin film of a particular optical component be a limiting factor in the power transport capability of an entire system? Would high flux densities cause imperfections in thin film layers that would lead to scattering, absorption, and thermal stresses? Would films break down under the thermal strains of the optical substrates? Will longevity of films be compromised under the types of duress posed by the concentrated radiation? Are films capable of improving optical performance over a
range of angles to accommodate diverging light emanating from a central source? How much improvement to optical efficiency can be expected by the addition of thin films? If technically feasible, can the energy saved through the usage of thin films pay for their cost? This chapter seeks to provide a basis for addressing these fundamental questions and, where specific information is unknown, to establish that these concerns are within the scope of the attainable.

The following discussion uses statistics published by Melles Griot and is typical of other optical coatings manufacturers. All figures in this chapter are taken from Optics Guide 5 [Melles Griot, 1990].

High reflectance coatings

High reflectance coatings are thin films that may be adhered to the outside of a substrate to produce a frontal surface mirror. There are two basic types: metallic coatings and dielectric coatings. Metallic coatings are reflective materials that rely on the optical properties of the material to attain reflectance. Dielectric coatings are thin films, applied to opaque substrates, that rely on constructive interference for reflectance.

Metallic Coatings

Metallic coatings have a wide range of reflectivity values. Metallic coatings are often overcoated with dielectric thin films to increase reflectance over a desired range of wavelengths or angles of incidence. In these cases the metallic coatings are said to be enhanced. An additional protective dielectric layer (half wave optical thickness) may be added to resist the abrasion and the tarnish that plague exposed metallic coatings. This additional layer contributes negligible optical losses. Overcoated metals are referred to as durable, protected, or hard coated depending upon which type of additional protective coating is added. Routine high reflectance coatings such as aluminum, protected aluminum, enhanced aluminum, gold, and silver are commercially available (Figures 3.1 - 6).
Figure 3.1. ALUMINUM is the most widely used metal for reflecting films. It is characterized by consistently high reflectance throughout the visible, near IR, and near UV regions of the spectrum. Aluminum is also characterized by a much slower oxidation rate than some of the higher reflectivity metal coatings. Consequently aluminum may display better reflectivity over time when compared with higher reflectivity materials.

Figure 3.2. PROTECTED ALUMINUM is the best general purpose metallic coating for use as an external reflector in the visible and near infrared. Protected aluminum is overcoated with a dielectric film of disodium trioxide of half wave optical thickness at 550 nm. The protective film arrests oxidation and helps to maintain initial high reflectance.
Figure 3.3. ENHANCED ALUMINUM may be overcoated with a multilayer dielectric film to increase reflectance over a range of wavelengths.

Figure 3.4. UV ENHANCED ALUMINUM
Figure 3.5. SILVER has higher reflectivity than aluminum across the entire visible and near infrared spectrum. However, it tarnishes so easily it can’t be exposed.

Figure 3.6. GOLD demonstrates exceptional reflectivity in the near, middle, and far infrared. While it is possible to construct multilayer films that exceed gold’s reflectance at specific wavelengths, gold’s consistently high reflectivity across such a broad spectrum is unparalleled. Consequently, it is the most widely used reflective material for the control of thermal radiation. Gold is also extremely soft and scratches easily.

Dielectric Coatings

High reflectance dielectric coatings rely on principles of interference to attain reflectance. Quarterwave thicknesses of various metals are applied to a substrate to form a dielectric multilayer. By choosing materials of appropriate refractive indices, various reflected wavefronts can be made to interfere constructively in order to produce a highly efficient reflector.

The basic element and building block of high reflectance, and partial reflectance, dielectric coatings is the quarterwave stack. The quarterwave stack is a stack of alternate high and low
refractive index films, each one having the optical thickness of a quarterwavelength (QW), Figure 3-7.

Figure 3.7. Quarterwave high reflectance coatings are fabricated by alternating high index and low index materials of quarterwave optical thickness. High reflectance is attained through constructive interference at each dielectric boundary.

QW stacks achieve a very high reflectance in a narrow wavelength for which the optical thickness for both layers is exactly quarterwave. The high reflectance is a result of all wavelengths being reflected in phase with each other, undergoing only constructive interference. The width of the reflectance curve is determined by the film index ratio. If the difference in the refractive indices of the two materials is large then the spectral region over which high reflectance is attained is increased. In such a case a quarterwave stack consisting of only a few layers will have a very high reflectance over a broad range of spectral values.

The reflectivity characteristics of reflective dielectric coatings can be modified by several different design procedures. The two most common design procedures are 1) using two or more stacks at slightly shifted design wavelengths and 2) perturbing layer thicknesses within a stack. The reflectances of these dielectric coatings can be made to exceed the highest metallic reflectances over very large wavelength intervals: spanning almost the entire visible spectrum, for example.
In the modified stack each layer is characterized by a different optical thickness. The reflectivity of a stack for any wavelength will be at least that of the most reflective component layer. For a broad band of reflection, optical layer thicknesses are discrete regions between the ends of the anticipated bandwidth for reflection. The optical thicknesses generally follow simple arithmetic or geometric progression. Multilayer broadband high reflectance coatings of this type typically demonstrate reflectances in excess of 99% over several hundred nanometers.
The change in the spectral composition of light reflected at high angles of incidence (as shown in the 45° incidence angle curves) would be perceived as a color shift. The light being reflected at that angle would still be a continuous spectrum "white", but the downward shift in the curve would be perceived as an enhanced "rendering" of blue colors, and a diminished "rendering" of red (skin tones). The requisite high reflectance is still attained despite the shift in spectral character.

These reflectivity values assume a collimated incoming beam and an inclined reflective surface. Where the incoming beam has a divergence, mirror inclination should be maintained such
that extreme angular incidence does not exceed 45°. Reflectivity values fall off at excess of 45° incidence.

**Antireflection coatings**

Antireflection coatings rely on principles of interference to perform their functions. In order for a coated substrate to experience optimum transmittance, incident light reflected from the coating surface interferes destructively with the incident light transmitted by the coating but reflected by the substrate surface. The result is near zero reflection and near total overall transmission.

As opposed to reflective coatings, the exact behavior of an AR coating is a function of the refractive index of the substrate to which it is applied. Certain AR coating types are insensitive to angle of incidence over a range of up to 45°. This characteristic makes them useful for efficient coupling to high numerical aperture lenses or fibers.

The thickness of a single AR film must be an odd number of 1/4 wavelengths in order to achieve phase cancellation. In order for the beam being reflected from the outer air-thin film surface to cancel with the beam reflected from the substrate-thin film interface, the two reflected beams must also be equal in intensity. This is accomplished when the refractive index ratios are the same at both interfaces (i.e. the three indices form a geometric progression):

\[
\frac{n_{\text{air}}}{n_{\text{film}}} = \frac{n_{\text{film}}}{n_{\text{substrat}}}
\]  

(3.3)

since the refractive index of air is 1.0, the thin AR film should ideally be

\[
\sqrt[n_{\text{substrate}}]{n_{\text{film}}}
\]  

(3.4)

Optical glass is usually between 1.5 and 1.75. An ideal thin film coating would have a refractive index of approximately 1.25. The closest readily available material that can be deposited in durable thin layers is Magnesium Fluoride. Its index is 1.38.

Magnesium Flouride is the most widely used material for optical coatings. Its performance is not outstanding but is considerably better than an uncoated substrate. In contrast to an uncoated optic's 4% fresnel loss, an MgF₂ coating reduces reflection to 1.5%. As shown in Figure 3.10, a generous reduction of reflectance is achieved throughout the visible spectrum for normal and 45° incidence.
Sophisticated multilayer coatings are available for even more demanding transmission requirements. The index of refraction of MgF₂ coatings is higher than the optimal index for complete phase and intensity cancellation. This difference accounts for a reflection from the first surface that is too strong to be cancelled by reflection from the second surface. In a two layer coating, the strong first surface reflection is nullified by two subsequent weaker reflections instead of one. A quarter/quarter coating has two 1/4 wave layers centered around the frequency of interest. The outer layer has the lower index of the two. Overall coating behavior is characterized by:

$$\frac{n_{\text{substrate}} n_{\text{low index layer}}^2}{n^2} \frac{n_{\text{high index layer}}}{n_{\text{air}}} = n_{\text{air}}$$

(3.5)

Many optical systems use polychromatic light. In designing for systems of this type, transmitting optics may be coated with a broadband antireflection coating. The main technique for accomplishing antireflectivity over a broad band of spectral values is to use interspersed layers of 1/2 optical thickness, called absentee layers.
Figure 3.11. Typical performance curves for antireflecting multilayer thin films. Insensitivity to angle of incidence indicates capacity for coupling to high numerical aperture lenses and fibers.

The energy density capacity is on the order of 10 kW/cm², although it will vary for each film. The usage of thin reflective film on the inside of the bulb jacket on GE's recent IR lamp attests to the radiation intensity such films can tolerate. Such precedent suggests the likelihood that

1 Communication with Melles Griot, Irvine, CA.
flux density limits will not impose constraints on the realization of centralized illumination, although this will be discussed in more detail in following chapters.

The use of thin films in extended term high power applications shows no fundamental limitation, with optical properties remaining fairly consistent over time. A thin film's 1) stability over time, 2) color shift characteristics especially where incident at an oblique angle, and 3) continued minimization of absorption are areas relevant to further inquiry.

Optical coatings will be employed in many places throughout a centralized system to maximize efficiency by minimizing energy losses at the interfaces of optical elements. This is critical to the economic performance of a centralized system. Engineering for the optimization of components in a single central module instead of a components in a multitude of fixtures affords wider use of thin films, which are recent innovations and consequently expensive. Thin film technology allows the optical components to approach their maximum throughput efficiency.

The next chapter examines the optics of solar energy collection and conversion, with a view to devising an optical system that would accommodate a centralized production and distribution of light.
CHAPTER 4

SOLAR PRECEDENCE

Introduction to Solar Energy Collection Systems

At peak daylight conditions, the power density of sunlight/heat radiation is 1 kw/m² at the Earth's surface [IES 1990]. It is comprised of roughly half light and half heat. The 1 kw/m² of radiant energy corresponds to about 60,000 to 120,000 lumens in peak conditions, or to a luminous efficacy of sunlight at about 60 to 120 lumens / watt. But when absorbed all of the light and heat constitute heat. If this energy were incumbent upon a perfect absorber, assuming no conductive / convective heat transfer (i.e. absorber in space), the equilibrium temperature of the absorber would be 364°K (91°C, just below the boiling point of water) according to the Stephan-Boltzmann equation

$$\beta T^4 = S,$$

(4-1)

where $\beta$ is constant $5.67 \cdot 10^{-8}$ w/m².K and $S$ is the power density of the incident radiation. There are some practical applications of solar energy where temperatures in this range are adequate, but most require higher temperatures for conversion into useful work. 364°K is a low temperature by thermodynamic standards. Higher temperatures would mean potential for higher efficiency in the generated work. Concentrators are needed for solar power applications requiring heat at temperatures above 90°C. One would increase the temperature by increasing the power density $S$ on the absorbing blackbody by a factor $C$ of about 6 to garner a temperature of 300°C, from equation (4-1). Such temperatures could be useful for both domestic and industrial applications.

It is interesting to note that the luminous efficacy can be effectively doubled to between 120 and 240 lumens / watt by stripping away the heat constituent of the solar radiation. In this case, 60,000 to 120,000 lumens is provided by 0.5 kw/m² of solar radiation, with only the solar heat being concentrated and absorbed for conversion into work.

The potential of this available energy as a resource for reducing the power consumption in buildings has stimulated research into daylighting and sunlighting systems for capturing and utilizing this light and heat [Whitehead, 1986, Smart, 1983, Eijadi, 1983]. The most efficient methods for harnessing solar energy are generally associated with some sort of electromechanical sun tracking device (Figure 4.1), which have characteristically long payback periods because of frequent maintenance and regular cleaning for maintaining performance. The sizeable initial costs and operating expenses of solar tracking are in large part responsible for the dirth of wide-scale installations, and to some extent, the demise of the solar industry in general. In such sun intense
areas as the American southwest, technological pioneers and solar advocates have maintained a toe-
hold during the topsy turvy solar funding cycles of the 1970’s and 1980’s, but the systems they
advocate have long payback periods. In uses unrelated to building interiors, NREL, Golden Colo.
is using heliotracking and concentrated sunlight to detoxify chemical pollutants in groundwater (see
Photo 4.1).

Figure 4.1. Heliotracking device -
*simple schematic using a tracking, concentrating lens instead of reflecting mirror.*

Photo 4.1. NREL detoxification plant using heliotracking and solar concentration to detoxify chemical pollutants in
groundwater. [photo K2 product literature]
Nonimaging optic solar heat collectors

Recent advances in solar optics simplify and improve the way in which standard solar heating systems operate. With nonimaging optics, pioneered by Roland Winston at the University of Chicago and Argonne National Lab, a stationary optic collects almost as much solar energy as a tracking optical collector. "Nonimaging optics has come to signify a systematic study and development of design techniques that optimize angular acceptance and throughput efficiency for a given flux concentration" [Winston, 1989].

For a stationary collimated source like the sun, nonimaging optical concentrators can recreate the luminance of the source: the thermodynamic limit. Nonimaging optics achieve higher radiation concentrations than conventional imaging optical systems by a factor of 4. Imaging optical concentrators have not been able to surpass 1/4 of the thermodynamic concentration level. Nonimaging optics is a class of high aberration optics. For this reason they are frequently referred to as energy transfer (as opposed to image transfer) optics because in the limit all image information is lost in the concentration process. The use of passive nonimaging optics for solar collection and concentration may have economic advantages over heliotracking since they are less prone to break down, much simpler to build, and easier to maintain. The reasons that nonimaging optics aren't used in heliotracking applications are complicated and explored later in this thesis.

A nonimaging optic collector is comprised of an opaque substrate cast into a non-imaging optical form, to which is adhered a thin reflective film to improve reflectivity. Cheap versions use a specular substrate material itself for reflectivity. There are mega-installations such as Solaras, in Phoenix, which drives a Rankine engine; the Holiday Inn, Virgin islands, which uses solar arrays for cooling and desalination; or the Illinois Dept of Agriculture HQ which uses solar arrays for heating and cooling (see Photo 4.2).
Figure 4.2 A non-imaging optical collector reflects all solar radiation within its acceptance angle onto a collection device, e.g., heat transfer tube.

The concentration attained by a solar concentrator is the ratio of entrance aperture area to heat transfer tube surface area, or more generally the ratio of entrance to exit aperture areas. The input a beam of light of certain diameter and of angular extent $2\phi$ (Figure 4.3). The concentrator consists of a lens of diameter $2a$ and angular extent $2\phi$ to accept the beam. These two can be combined as a product usually without the factor 4, giving $\phi a$, an optical quantity known variously as extent, etendue, acceptance, LaGrange invariant, etc. It is a quantity invariant through the optical system, neglecting any obstruction of the light beam and ignoring material losses such as absorption and scattering. In dealing with 3D systems it is convenient to deal with the square of this identity, $a^2 \phi^2$, as a measure of the power flow passing through the system, where $a$ is a measure of the entrance aperture and $\phi$ is the semiangle of the beam. If one is considering a medium of refractive index differing from unity then this invariant becomes $n^2 a^2 \phi^2$.

![Figure 4.3. An image forming concentrator](image)

In a concentrating optical system [Winston, 1989]:

$$\text{ansin}\phi = a'n'sin\phi'$$  \hspace{1cm} (4-2)

where $a'$ is the diameter of the exit aperture large enough to permit any ray that reaches it to pass, and $\phi'$ is the largest angle of all emergent rays. Clearly, $\phi'$ cannot exceed $\pi/2$, so the maximum theoretical concentration ratio is

$$C_{\text{max}} = a/a' = n'/n \sin\phi$$  \hspace{1cm} (4-3)

for a two dimensional case. And when $n=n'$

p.36
\[ C_{\text{max}} = \frac{1}{\sin \phi} \quad (4-4) \]

Similarly, the three dimensional case can be shown to be

\[ C_{\text{max}} = \left( \frac{n'}{n \sin \phi} \right)^2 \]

\[ = \left( \frac{1}{\sin \phi} \right)^2 \quad (4-6) \]

provided that all rays inside the collecting angle actually emerge from the exit aperture. For the more general case when \( \phi' \neq 90^\circ \), in two dimensions

\[ C_{\text{max}} = \frac{n' \sin \phi'}{n \sin \phi} \quad (4-7) \]

and for the three dimensional case

\[ C_{\text{max}} = \left( \frac{n' \sin \phi'}{n \sin \phi} \right)^2 \quad (4-8) \]

The 3D optic has multiple reflections and these can actually turn back some of the skew rays that enter within the maximum acceptance angle. Nevertheless, the transmission angle curves calculated by ray tracing approach very closely the ideal. Transmission curves for 2D and 3D optics are shown in Figure 4.4. Transmission is nearly perfect with cut-off occurring over a range of 1°.

![Figure 4.4. Left - transmission angle curve for a 2D Compound Parabolic Concentrator CPC with an acceptance angle of 16°. The cut-off occurs over a range of 1°. Right - transmission angle curves for 3D CPC’s with \( \phi_{\text{max}} \) from 2° to 60° [Winston, 1989, p.65].]

The concentrator collects rays over 2\( \phi_{\text{max}} \) and no rays inside the maximum collecting angle are turned back (Figure 4.5). As the sun moves across the acceptance region, a collapsed image of
the sun moves across the focal plane in the opposite direction. Unfortunately, the depth of these concentrators can be excessive. The overall length is

\[ L = a'(1+\sin \phi)\cos \phi / \sin^2 \phi, \text{ where } \phi = \phi_{\text{max}}. \quad (4-9) \]

Concentrators can be shortened somewhat at the entrance aperture end with negligible decrease in performance. Parameters for accomplishing this are described in Chapter 11, Light Collector.

![Diagram](image)

*Figure 4.5. Focal point moves across absorber plate as solar angle changes throughout the course of the day.*

The Edge Ray principle is a convenient technique for determining the shape of the nonimaging optic collector that will result in concentration of the incident radiation to its near thermodynamic maximum. A concentrating optical system that preserves the image of the sun would be able to attain only 1/4 of this concentration.
The Edge Ray principle requires that the extreme incident rays at the entrance aperture also be the extreme rays at the exit aperture. The solution for a flat plate absorber consists of two parabolic segments, each with its axis tilted at an angle relative to the collecting aperture normal, and its focus at the lower edge of the opposite mirror (Figure 4.6). The device, frequently referred to as a compound parabolic concentrator CPC, collects radiation entering the aperture of diameter d1 (2D or 3D) within the angle $\pm \varphi_{\text{max}}$ and directs it to the smaller diameter aperture d2.
Collectors for wider incidence angles are shorter and concentrate less, Figure 4.7. As depth increases so does concentration potential.

*Figure 4.7. Depth of optical trough affects angular acceptance and therefore, concentration level. Exit apertures are equal in diameter.*

Edge Ray principles that are extended to other absorber plate configurations result in uniform irradiation on absorbers, Figure 4.8 [Winston, Hinterberger, 1975]. Assumptions are made regarding the profile of the device. The absorber is convex everywhere, and symmetric about the optic axis. Rays entering at the maximum $\phi$ shall be tangent to the absorber surface after one reflection. $P_o$ is the point at which the extreme reflected ray meets the absorber surface. Past $P_o$, the reflector is continued as an involute of the absorber surface [its normal is tangent to the parent curve (the absorber), for proof see Winston, 1989, chapter 6.2]. All rays within $\pm \phi_{\text{max}}$ meet the absorber.
In air, maximum concentration of sunlight is a function of angle subtended by the sun, $\theta = 0.267^\circ$. When substituted into equation (4-6), one obtains the maximum theoretical concentration of sunlight

$$1/\sin^2\theta = 46000.$$
By concentrating within media of differing index of refraction values, \(n\), Winston has attained solar concentrations of 100,000, exceeding the intensity at the surface of the sun. Using, for example, a concentrator filled with fused silica having index of refraction \(n = 1.5\), and substituting into equation (4-8) one attains the theoretical maximum concentration of sunlight in fused silica:

\[
\frac{n^2}{\sin^2 \phi} = 103,500.
\]

**Summary**

There are three types of nonimaging optical collectors for solar applications: nontracking, unidirectional tracking for line focusing, and bidirectional tracking for point focusing. Maximum concentration values are not necessarily achievable values. In practice, light is always lost inside the optic. Some of the incident rays at precisely the maximum acceptance angle are actually turned back by internal reflections at the exit aperture. Some light is lost by absorption, imperfect reflection, etc. The formulas provide upper theoretical bounds.

Although this theory was originally developed for passive optics, nonimaging optics is extended to active tracking systems. If high temperatures are desirable, then nonimaging optics should be evaluated with the intention of limiting the acceptance angle in order to maximize concentration. This would accommodate heliotracking. Low concentration, nontracking two-dimensional troughs properly aligned can achieve moderate concentrations of about 2 to 10 [de Winter, 1990].

With modifications to their form, nonimaging CPC's can emit radiation at a maximum angle less than \(\pi/2\) (See Equation (4.7, 4.8)), but restrictions upon angular exitance reduce concentration potential of the optical system if other parameters remain the same.

**Sunlighting**

There is a wide breadth of theory and application for illuminating the perimeters of buildings with sunlight. Prominent among the techniques for peripheral light penetration are light shelves and even holographic films for the bringing of perimeter sunlight deeper into building interiors. A key reference to sunlighting techniques for architectural applications is Bill Lam's book "Sunlighting as a Formgiver for Architecture".

The luminous efficacy of sunlight can reach 120 lumens/watt. Each square meter of roof or window or solar collector area projected toward the sun receives 120,000 lumens of light in peak conditions. Each square meter of admitted sunlight could illuminate 120 m\(^2\) of interior office space to 100 footcandles if transported and distributed without loss. Despite this potential benefit, researchers in solar collection generally absorb solar radiation and convert it to heat or electricity, with disregard for the direct transport of light. The scenario of collecting solar energy by
photovoltaics for the generation of electricity for interior illumination is most ironic. In this relatively common application type, direct sunlight usage peak solar conditions could provide between 60 and 300 times more illumination for the same solar collection surface area, as shown in Figure 4.9.

Figure 4.9. Energy comparison of two approaches to using solar energy to provide lighting during periods of peak solar intensity. For each square meter of surface collector A) conversion of solar energy to electricity with photovoltaics at 10% efficiency, and back into light at another 10% for total energy performance of 1%. B) Direct usage of sunlight provides between 60 and 300 times more light, and usable as opposed to wasted power.

In only a few select investigations have technologists sought to retain sunlight as light [Fraas, 1983, Smith, 1986, Bennett, 1980, Smart, 1983, Whitehead, 1986]. The first successful investigation was the installation of a solar optic sunlighting system at the University of Minnesota's Civil/Mineral Engineering Building, 1983. This system uses a tracking device that holds a mirror to reflect, concentrate, and direct the solar energy (both light and heat) along a narrow corridor (through a series of lenses) into an underground space (see Chapter 5 for discussion).

Also of note is also is a simple system devised by Sandia National Labs in Albuquerque, N.M., 1977 (refer to Chapter 5). In this preliminary experiment, Duguay and Edgar first articulated favorable payback scenarios for light collection and transport, even with heliotracking, for supplanting electric light and reducing lighting related electricity costs directly [Duguay, 1977]. Their system demonstrated a dielectric filter for separating out the sunlight's IR component, and
collected this heat for conversion to electricity with a photovoltaic cell. The researchers found that revenue from sunlighting was over four times higher than the combined revenue available from systems converting solar radiation to both usable heat and electricity. "In situations where incandescent lighting (at 10% efficiency) is preferred because of its color rendition and/or directionality (reflector lamps), a sunlighting system would result in annual savings of 220 $/m² of collector" (1977 $).

In a more accomplished vein, the Himawari unit of La Foret Engineering, Japan, collects sunlight for interior illumination. It is the world’s only commercially available centralized sunlighting system using fiber optics for light transport.

The Himawari is still premature technologically, never supplanting enough electric light to offer payback period incentives, and consequently not getting far beyond the decorative stage in architectural lighting. Although the Himawari does preempt solar heat from entering the lighted space, it utilizes conventional imaging optics and is not concerned with efficient energy management. See Chapter 5 for more detailed discussion.
Electric light analog

This thesis introduces the concept centralized electric illumination. By centralizing the production of light and piping light through a distribution network, the concept is analogous to that practiced by Himawari. However, there are some very fundamental differences between collecting energy from the sun and from an electric source: the sun has inherent collimation and high brightness whereas an electric source inside a reflector is likely to have neither. And the sun is outside the Earth's envelope so we don't have to worry about energy losses in production, only in collection. Even sunlight collection systems are largely external to the building envelope so energy losses are not within the building and can be removed with a nominal input of additional energy.

The distribution network is the largest portion of either system's total cost. If electric light and sunlight share a distribution network each would carry a portion of the cost burden, effectively decreasing the expense relative to either. In fact, it will be found that the electric portion of the system can economically sustain the cost of the entire distribution network, if carefully derived. This is attributable to a number of factors, the most notable of which are 1) the reconsitution potential of all lighting related heat, 2) the reduction of A/C cost owing to the preemption of waste light heat from entering the habitable space, 3) engineering for the energy efficiency of one source reflector instead of the multitude of reflectors it replaces. For reasons explained in a later chapter, solar energy supplementation to a building's energy profile could then become simply a matter of adding a rooftop collector only, making solar supplementation much more feasible.

This thesis suggests the use of solar collection optics for electrically induced radiative applications. Since the generation of light is largely within the building's envelope energy losses have to be managed if it's not to be a hot spot within the building interior. Centralization is feasible if energy losses can be minimized so that energy consumption is competitive with conventional illumination. Therefore, both technical and economic feasibility depend on the minimization of energy losses. This thesis will show that centralization's visual attributes are compelling: excellent potential for visual comfort, architectural flexibility, color renditioning. If managed properly, waste heat does not constitute energy losses. Centralized illumination uses the highest quality optical components to form a theoretical system level management of all energy.

By placing an electric source within the solar acceptance angle of the collection optic, its radiative energy can be collected and concentrated in a manner analogous to solar collection (Figure 4.10). This is fundamental to centralized electric illumination.
Figure 4.10. This thesis investigates an approach to centralized illumination that incorporates electric light by positioning the electric source such that its radiative output can be directed to within a solar collector's acceptance etendue.

Although sunlight is collimated, light emitted from an electric source is not. It emits in all directions. Reflectors can be placed around the source to send its emittance in a desired direction. But the more controlled the divergence, the greater is the amount of light inevitably lost due to practical rather than theoretical considerations. This in effect reduces the efficacy of the source. In short, the optical solution is not trivial. Can radiation losses be managed to such a degree that a centralized illumination system can feasibly exist? The following chapters examine this possibility.
CHAPTER 5

Transporter

This chapter explores the precedence in optical light conveyance, and examines components that would be assembled in the creation of a delivery system. Light conveyance, or transport, is related to but wholly separate from solar collection for energy use. Examples are cited in this chapter to illustrate concepts and techniques, which are considered here with a view to include electric light, energy (radiative light, heat, and UV) management, and solar energy.

There have been many methods proposed and studied for directing concentrated sunlight deep into building interiors. Reflective systems used lenses and mirror guides, and internally silvered metal ducts. Because of inherent limitations to their energy effectiveness, these early approaches are essentially obsolete except in the most special of cases. Solid and hollow core refractive light pipes on the other hand show considerable promise, if utilized correctly.

This chapter will discuss two emerging types of transporters: fiber optics and Prism Optical Light Guide (PLG). It will also look at their most direct light-conveyance precedents: internally silvered ducts, and lens and mirror light guides. Novel technologies such as fluid filled fibers are discussed briefly at the end of the chapter. Holographic films are considered a technology more suitable for perimeter sunlighting penetration and are not examined.

Internally silvered light guides

The earliest method for piping light is the hollow guide with internally reflecting walls. Specularly reflective films are available commercially. They can be adhered to the inside surface of a pipe to create a hollow guide. These films are usually aluminum, silver, or chromium sputtered or vapor deposited on a plastic substrate.

Guide transmittance is a function of the cross-sectional shape of the guide, and the polarization state and directional and spectral distribution of the incoming light [Spear, 1986]. If sunlight is used as the light medium then it is reasonable to assume that the spectral composition of the incoming light will closely resemble sunlight. One might also assume that the incoming light will be randomly polarized, as is the light produced by the sun and by most lamps. Within these restrictions, guide transmittance depends only on directional distribution of the input light [Spear, 1986].
Silverlux film (3M) has high reflectivity in the visible range. Using it, Spear determined transmittance of a guide for any directional distribution of incoming light by weighted integration of directional data. He defines a set of two angular coordinates $\alpha, \beta$ to specify the direction of any incoming ray. These are the angles between the longitudinal axis of the guide and the projection of the incoming ray on the horizontal and vertical walls of the guide. One can show that the average number of reflections encountered by a ray on the vertical walls of the guide is $L/D \tan \alpha$, where $L$ is the length of the guide and $D$ is the distance between the two walls. Similarly, $L/D \tan \beta$ is the number of reflections on the horizontal walls. The overall number of reflections can be approximated by

$$n = \frac{L}{D} (\tan \alpha + \tan \beta)$$

(5-1)

Spear finds that the simplest way of estimating the transmittance of a guide is to assume a single value of optical reflectance, $R$, that is independent of wavelength, polarization, and incident angle. The transmissivity is then a function of that reflectivity and the number of overall reflections, $n$:

$$T = R^n$$

(5-2)

Transmission measurements corroborate an aspect ratio dependence (Figure 5.1). If incoming rays are confined to within $25^\circ$, then the guide would be restricted to an aspect ratio not to exceed 11 in order to pass 80% of the light.
Internally silvered light guides are are likely to experience high loss from absorption in the visible range because of the multiplicity of reflections that would occur in any type of large scale piping network. A beam of tolerable divergence, say 20° or 30°, would encounter an excessive number of reflections if pipe diameter is to remain within dimensions that do not pose a major imposition to the amount of or quality of interior space. Significant improvement to the internal metallic film could be realized with a stacked dielectric reflector film sprayed along the interior walls of the pipe, but this would be expensive, difficult to make, and probably unfeasible economically.

Even with improvement in reflectivity, the light loss per bounce becomes the fundamental shortcoming of reflective lightpiping. The manifestation of this shortcoming is its sensitivity to reduction in pipe diameter. Reflective light piping therefore presents itself as most tenable in larger scale core dominated office buildings where >1 meter pipe diameter could be accommodated within the building core. However, in such core dominated high-rises, sacrificing habitable floor space to accommodate light piping aperture area may be of direct economic consequence.
**Lens and mirror guides**

Like the internally silvered duct, lenses and mirrors can be used to centralize the collection and distribution of sunlighting. Again like the duct, lens and mirror guide light piping systems are susceptible to an aspect ratio dependence. As a collimated sunbeam is optically concentrated so that maximum energy transfer for a given collector surface area can be conveyed with lenses and mirrors of smallest diameter and least cost, its angular divergence expands commensurate to minimizing this diameter. In order to optically match the source to the transporter, either the shaft diameter will have to grow or more lenses will have to be placed within the beam to continually offset the divergence.

Each lens or mirror surface introduces loss. Fresnel reflection accounts for 4% loss at each lens surface, for 92% transmission through each lens. Therefore, light is reduced to 50% of its original intensity after passage through 8 lenses. Transmission efficiency is categorically limited by the number of components in system. Light is susceptible to backscattering and absorption by dust if mirrors, lenses, and passageways (if not sealed) are not kept clean, and as these systems are likely to be relegated to core areas this is an imminent concern. Sealing such a system from dust intrusion along its entire routing length would be a significant undertaking. Furthermore, absorption of energy resulting from dust accumulation causes thermalization. Thermalization, and its associated fire risk, is compounded by not removing heat from the system prior to transmission. Misalignment resulting from vibration induced by a building's mechanical equipment, wind load, etc.) is another tangible setback, especially for "short" (short focal length) optics. Periodic realignment is assumed for maintaining performance, and would coincide with periodic cleaning. Without regular maintenance throughput will diminish significantly.

Technological improvements over the past twenty years in thin film antireflection coatings, synthetic bushings for vibration and alignment stability, optical component clarity, and fresnel lens accuracy could offer sizeable improvements over the most recent experimental systems. Frontal surface mirrors, judiciously employed in this application, would reduce losses at each mirror interface significantly, but they would still be susceptible to dust accumulation and alignment instability.

Duguay and Edgar, of Sandia National Laboratories, first proposed the use of controlled sunbeams for interior illumination (in areas other than atrium shafts) as potentially more competitive than coal or nuclear generated energy by applying light directly to end-use. A system of lenses and mirrors and suntracking concentrators was devised in 1977 [Duguay, 1977]. Duguay and Edgar used a series of lenses and mirrors to bring a concentrated beam of light through a hole in the roof, decoupling and recovering low-grade heat, and siphoning off light along its path for diffusion into the space. Working with direct
and indirect illumination methods, they attained illuminance levels and compared them with those arrived at with conventional illumination, tabulating that a sunlighting system would result in annual savings of $220/m² of collector (1977 $). Light lost while passing through a lens could be utilized by fitting the lens with some type of diffuser, whereby recouping some of the system's inefficiency by doubling as a luminaire (Figure 5.2). Variations of this idea were investigated by [Ngai, 1983].

![Diagram of sunlighting system](image)

*Figure 5.2. Proposed solar energy management scenario tested by Duguay and Edgar [Duguay, 1977]. Mirror F passes heat onto a solar cell. Mirrors M1 - M4 collect and concentrate sunrays, siphon off light from the solar beam for direct and indirect distribution of illumination in the space, and transport the remaining solar light into the story below. Despite optical losses, system is 11 times more efficient than solar generated electrical light.*

The annual savings determined above account for solar light supplanting electric light, and neglect the available heat energy in its revenue calculations (which it assumes is converted into electricity and back into electric light at an overall 2.8% efficiency, and hence negligible contribution). The revenue potentially available from converting this solar IR into heat could be upwardly adjusted if efficient methods for collecting and harnessing it were applied: i.e. nonimaging optical concentration instead of PV's, for improving thermodynamic quality, etc. Measurements showed that 66% of the solar power incident on the sun tracking concentrators entered the room. Revenue calculations assume 45% of entering solar power is in the visible range, accounting for a system efficiency of about 30% instead of 66%. Revenue calculations disregard the solar heat constituent entirely.
Building from Duguay and Edgar’s effort, Bennett and Eijadi of BRW Architects, St. Paul, MN., developed a heliotracking system intended as a solar optics demonstration project at the University of Minnesota Civil and Mineral Engineering building (UMM). UMM is the most celebrated installation of a lens and mirror guide light piping system, however, the UMM installation falls prey to numerous technical shortcomings in collecting, transporting, and distributing sunlight (and its constituent heat) into laboratory space 110 feet underground. This is a result of the standard low grade optical quality of the components in the light path that were feasible and available at the time of construction. UMM is still widely regarded as successful, but more for reasons of novelty and the light tectonic that the architecture expresses, than the actual energy savings realized by adopting a light conveyance paradigm into the building’s architecture.

Prism optical light guide

Prism optical light guide (PLG) is a large diameter hollow-tube-like fiber. PLG was invented with the expressed interest of introducing core sunlighting to buildings. The first major installation using this technology was in Toronto 1986 (Photo 5.3). The invention of PLG is attributed to Lorne Whitehead, formerly with the University of British Columbia, now with TIR Systems, Ltd., Canada. U.S. patent rights have been licensed to 3M for film manufacture. 3M refers to PLG as Scotch Optical Lighting Film, SOLF. Advancements in the microreplication process allow for fairly precise manufacture of the film in 0.020" thick plastic sheets. Losses are due to microscopic flaws in the material. As of this writing, TIR Systems of Canada manufactures the only lighting components based solely on the transport capabilities of the film. Although intended originally as a transport device, it is being marketed more successfully as a lighting diffuser.

As discussed subsequently, linear PLG light piping systems using solar and electric sources have demonstrated efficiencies of 30 - 40%, which makes them comparable to, but generally less efficient than, conventional lighting fixtures with similar distribution characteristics (Figure 5.6)[Saxe, 1986]. When used for illumination, a mirror is placed at one end of a PLG tube and a light source at the other. As light reflects back and forth along the length of the tube, some of it is diffused through the walls of the tube with each pass, creating a uniform glow.

The predominant use of PLG is in applications that specifically identify a need to remove a source of light and heat away from proximity of lighted space. This design method has been selected in instances of very difficult relamping access such as over large swimming pools, hazardous environments where sparks from a malfunctioning lamp or ballast could ignite an explosion, temperature controlled areas like a blast freezer where heat introduced into the area must immediately be removed again, and in installations sensitive to magnetic or radio interference generated by ballasts and by discharge sources. The installation of PLG in the atrium of 3M's headquarters office in Minneapolis, Minn. (Photo 5.2) deviates significantly from precedent and marks the first recognized architectural application of piped electric light.

The next few sections examine the underlying physical principles of the PLG medium for transporting light. Armed with the theory, we will then be in a position to evaluate the merits and pitfalls of this visually intriguing installation.
Properties

Prism Light Guide uses refraction as its transport mechanism. Light incident upon properly oriented film is reflected if its incidence is within the film's acceptance angle of about 27°. Light incident at angles greater than the acceptance angle are passed through. PLG demonstrates 0.12 - 0.5% absorption per reflection within the acceptance angle. This level of absorption is an order of magnitude less than a typical
metallic reflector. However, if the 1.2 - 2.0% diffusion loss per bounce is not utilized along the entire length of the tube the reflectivity, hence efficiency, is effectively reduced from 99.5+% to 97.5%. This level of optical efficiency relegates it comparable to, yet still superior to, the methods of light transport discussed in the previous sections. The multiplicity of bounces likely encountered in a piping situation suggests the need for still higher reflectivity versions to be implemented for light transport applications if centralized systems are to offer improved efficiencies over conventional lighting systems, or over PLG's predecessors in centralized sunlighting. Sources at 3M have indicated that higher reflectivity can be accomplished through improving the purity of the polystyrene substrate.

If incoming light exceeds a critical angle all of it passes through the film. If incoming light falls within the critical angle then 98% is reflected and two percent is dissipated.

Figure 5.3. PLG prismatic refractive film for attaining total internal reflection in light guides.
by rolling the film into a tube and putting a mirror at the other end, the light reflects back and forth until all of it is diffused. The causes the tube to glow. Light pipe is used in special installations. 

by removing the mirror it behaves like a light pipe. The more narrowly the incoming beam of light is confined, the fewer bounces the light will undergo and more will emerge out the other end.

**PLG as transporter**

By treating the tube as a light transporter, and allowing light to emerge at one end of the tube instead of being reflected back and forth along its length, much higher fixture efficiency can be attained than is currently being utilized from diffusion of illumination through the side walls of the tube (Figure 5.4). Since light entering and exiting the PLG has divergence within the material’s acceptance angle, luminaires placed at the open end of the tube, regardless of whether they are surface...
mounted, recessed, or pendant mounted, could attain nearly 100% efficiency in their redistribution of the emitted light.

Total fixture efficiency (transporter and luminaire) for sunlighting is a combination of transport and distribution efficiencies. Efficiency in transport would be improved by restricting the angle of divergence.

A rule of thumb for determining the transport efficiency of an open ended tube is

\[
T = 0.985 \left( \frac{L}{D} \right)
\]

(5-3)

where the coefficient is the reflectivity per bounce (between 0.95 and 0.99). The currently available transporter/diffuser grade PLG exhibits 80% efficiency at a length to aperture aspect ratio of 20, when utilized solely as a transport device at the maximum acceptance angle (highest number of internal bounces). This limits the variety of applications in which commercially available PLG can be applied because over a length of transport of only 40 meters the 2 meter diameter tube would become a gross architectural imposition if a reasonable level of transport efficiency is to be attained (unless doubling as an HVAC duct, which would introduce light loss from dust accumulation). Higher reflectivity grade PLG would improve light transport feasibility by reducing necessary aperture diameters (reducing aspect ratio dependence), increasing transport length, and increasing transport efficiency. Although transport grade PLG has long been considered a logical derivative of commercial grade PLG, the manufacturer is waiting for demand that economically warrants its full scale production. However, Lorne Whitehead contends that the prism ridges in the optical film would have to be smaller than the wavelength of light for this to happen, and as such is why it hasn't been manufactured. In any event, optical lighting designers will strive for collimation when efficient long length transport is desired.

**PLG as diffuser**

PLG film is used in TIR Systems' light pipes, which illuminate via diffusion along the length of pipe. The units are 8' long. According to the manufacturer, 83% of the lamp's light output is contained within the required 27° acceptance cone and launched into the cylindrical tube. Another 2% is lost to the UV glass window that protects the tube interior from UV emitted by the source, 6% is absorbed by PLG wall prior to diffusion, 3% absorbed by reflecting mirror at end of tube, 7% returns to

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2 Communication with Sandy Cobb, 3M. 3-92
3 Communication with Lorne Whitehead, UBC. 9-92

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the source and is lost in the source reflector's cavity, 13% is absorbed by PLG and emitting surface, leaving 52% to be emitted as illumination to the surfaces below.

Figure 5.5. Luminaire efficiency (initial) for 8' PLG tube.

An initial efficiency of 52% is too low to compete favorably with conventional illumination in general cases. Efficiencies in actuality have been found to be lower. A reflector efficiency of 83% is very high for a single port fixture, although reflector efficiency could be as high as reflector reflectivity through the use of noimaging optics. Further compromise in efficiency would result from the usage of square tube (for easier installation into conventional ceilings). The system is subjected to all the light loss characteristics of conventional illumination, which over time would drive maintained efficiency down to within the 30 - 40% range, if not lower.

The use of an extraction film placed along the inside face of the PLG opposite to the desired direction of exitance provides improved directional control and a higher diffusion rate. It is effectively a low absorption diffuse reflector. Light incident on it is within the film's angular acceptance angle. Reflected light that exceeds this angle diffuses through the walls of the tube in the direction away from the extraction film and becomes usable illumination. The extraction film causes nonuniformity of emission along the length of the tube. This could be ameliorated somewhat by tapering the strip of extraction film (i.e. narrow near the source end, broad nearer the opposite end).

**PLG in buildings** Applying light pipe technology to buildings would require that the pipe negotiate turns. How would this be accomplished? What types of losses would be incurred? What lengths and diameters of pipe could be utilized?
A standard piping network would consist of T-junctions and L-junctions as illustrated below. Branches could lead to individual or multiple lighting fixtures.

![Diagram of a simple PLG branching network](image)

**Figure 5.6. Schematic of a simple PLG branching network.**

**Negotiating Turns** One would be inclined to place a 45° mirror at the bend, as has been done in all applications requiring turns to date (including the 3M atrium). However, it is readily apparent that light is not completely transported. Only axial rays make the turn (Figure 5.7 A). An exit pipe of equal diameter results in leakage at the branching junction for any rays along the periphery that are not axially aligned. So all rays within the film's acceptance angle don't make the turn. Rays deviating from the normal will miss the mirror and hit the side of the branch tube at an angle exceeding the maximum internally reflecting angle, and pass right through (Figure 5.7 B,C).
So, in order to collect all light at the junction for correct branching, the pipe diameter must grow in relation to the degree of collimation of the principal beam according to the following equation:

\[
    d_2 = \frac{d_1}{1 - \tan \phi_i} \left[ \frac{(\cos \phi_i \sin \phi_i + \sin^2 \phi_i)}{\sin (90 - 2\phi_i)} + 1 \right]
\]

(5-4)

For example, a 23° collimation standard for earlier versions of the PLG film would result in a 30" branch arising from a 10" trunk. The 27° acceptance angle that the newer improved version of the film can tolerate would result in even greater branch sizes.
In order to collect all light rays at the film's maximum TIR angle and direct them around a 90° corner the pipe diameter must increase (Figure 5.8). 2nd or 3rd order branching could lead to untenable aperture areas. The more confined the beamspread in the primary trunk, the lower the beam divergence in the junction and the smaller the secondary branch that will be required to collect all light rays. However, as described in the source reflector section of this thesis (Chapter 8), a high degree of collimation in the source beam can result in higher energy losses due to the difficulties inherent in collimating a beam of light from an adirectional source. Furthermore, in the limiting case, a perfectly collimated beam renders the film moot: reducing the system to a lens and mirror guide with no reflection at wall surfaces. So, for reflection, pipe diameter enlargement is a natural consequence of the medium. If reflection is utilized as a means to turn light around bends, axial divergence will effectively limit the number of turns a particular routing will be able to sustain. This may pose an undue design constraint: the routing of fixtures along a single floor could easily take 4 or 6 turns. As will be introduced in a later chapter, an alternative method for taking turns would employ a solid, internally reflective device. These are expensive owing the large diameter of the PLG transporter that it would couple to.
Multiple Branching

To some extent, the technical shortcomings of PLG could be ameliorated through finesse in application: simultaneously optimizing the medium's full capacity as transporter and diffuser. In cases with diffusion en route, the lighting design challenge may become more architectural than technical.

For a light piping design to accommodate specified luminous distribution, multiple branching from a central trunk would be a basic design requirement. Circular cross-sections offer the best transport efficiency, but circle to multiple circle transitions present very difficult geometric problems if large light losses are to be avoided. Circular cross-sections could be transformed to square cross-sectional devices at junctions. So long as the square side equals the diameter of the circular section, branching of 1:4, 1:9, or any squared subset branching could be accomplished easily, without any loss of energy. After the branch node, the square sections transform back into circular ones, with the diagonal of the square now equal to the diameter of the circle. This lowers the energy density in subsequent branches, but could keep the overall diameter of distributed branches from becoming unwieldy.

Optical extent is not preserved with such a technique. Overall cross-sectional area increases. As will be explored in subsequent chapters, this will negatively affect launching of light from a PLG tube into multiple fibers. Branching arrays of other than a squared integer will even more negatively affect material requirements and energy losses downstream.

Where extent preservation and aperture area isn't of concern, circle to circle branching networks can be devised, as shown in Figure 5.9.
Figure 5.9. Cross-section of hypothetical 1:2 branch

**3M atrium**  The light piping network in the 3M atrium uses inclined 45° mirrors at horizontal/vertical junctions. Opaque sections mask the light losses there. Unutilized light losses not only reduce efficiency, they cause localized heating and possible locations of glare. Linear sources could have been used in this installation with better energy efficiency than piped point sources. The visual differences would have been nominal if not imperceptible.

3M's atrium doesn't capitalize on the potential of PLG for improving lighting efficacy via simultaneous introduction of sunlight, nor does it pipe "cool" electric light. If sunlight had been brought in through the top end of the pipe, then the lamps could be selectively dimmed to offer an energy saving incentive regardless of the overall optical efficiency of the system. But this system was not designed with this in mind. The system's apparent intention was to demonstrate the visual attributes of spreading out a point source in a linear space, only.

By garnering a number of architectural awards it has attracted the imagination of creative architects and engineers, perhaps some of those capable of applying an improved understanding of the optical principles of light flow toward the evolution of a tectonic of light. Because of the low efficiency that improperly devised systems demonstrate beside comparable linear lamp systems, designers will need to adopt an optical engineers
vocabulary if light piping is to be used to its potential for energy savings and avoid being relegated gimickry.

**Toronto**

The first sunlighting application of PLG was in the top floor of a 5 story office building in Toronto (Photo 5.3)[Whitehead, 1986]. Eight identical sun trackers are coupled into eight horizontally mounted 25' long Prism Light Guides. The light guide tubes are designed to disperse light through their bottom surface to illuminate the space below. The underside of the light guide tubes take the form of the fluorescent luminaire troffers that they are replacing. The architectural intention was to use sunlight to replace electric light, without the inhabitants sensing any difference. In that concern it succeeded. More importantly it served as an introduction to piping sunlight into building interiors with PLG film. Two 400 watt metal halide lamps couple into each light guide for delivering light during periods of cloudcover or nightfall. During these times 800 watts per prism light guide provide approximately 88 FC to the surfaces below. The total 6400 watts lighting energy is distributed over 2000 ft², corresponding to 3.2 watt/ft², an excessive lighting load indicative of a low efficiency optical system.

*Photo 5.3. PLG used in the top floor of a five storey office building in Toronto.*
Future Developments

At present, 3M is developing a refractive fresnel lens for directing light around a 90° turn. Prototypes show efficiency of 80 - 90%, which render PLG light pipes comparable to lens and mirror guide systems in efficiency. Antireflection coatings may reduce the fresnel losses at each face of the lens, however, the discontinuous surface features of fresnel lenses, while suitable for optical control of collimated sunlight, are at odds with the divergent nature of uncollimated electric light. This refractive fresnel would help to contain branching diameter growth in instances where stringent collimation of the light beam is not feasible.
Fiber Optics

The rapidly expanding use of fiber optics in telecommunications is not only bringing the price of fiber down, it is motivating research into improving fiber transmissivity in the visible and IR regions. Centralized illumination as proposed in this thesis is positioned to utilize the improvements reached by research in telecommunications. Fibers used for carrying light have very large diameters by telecommunications standards but the material constituency is the same. High energy capacity fibers are currently used in industrial welding applications, and in optics research, for directing light from high power lasers.

This chapter examines the characteristics of plastic optical fibers and fused silica optical fibers. These two general types are extremes, with very little in common except that they are both identifiable as fiber optics. Plastic core fibers transport light over very limited distances, with energy being absorbed or scattered en route. Fused silica core fibers permit much longer runs, but are so expensive that very high energy densities must be carried if any kind of economic justification for piping light in this manner can be formulated.

Why haven't fiber optics carried so much light before? As we shall see, some can carry the light if it can be gotten in, but for sources other than lasers it couldn't be gotten in. That is, it is the lamp not the fiber that determines the amount of light a selected fiber optic can carry. As we shall see in a later chapter, the optical system has only limited usefulness in this regard. This chapter looks into the energy density capacity of selected optical fibers, and into techniques that could be used to allow the fiber to reach energy densities within appreciable margin of that threshold, assuming that the desired optical concentration level can be achieved. Also, the spectral characteristics of the fiber's absorption bands are examined to see how the color of the transported light might be affected. In the course of this inquiry, we shall see that it is not the fused silica fiber core that fails in instances of extremely high energy density, but the surrounding materials.

When a bundle of fibers is placed in an optic's focal zone, light lost within the intersticial voids between individual fibers is not transported along the length of the fiber. It is absorbed within the discontinuous surface of the void area. This lost light energy is absorbed and turns into heat. Consequently, if high energy density light is directed toward the entrance of a fiber bundle, the light lost in the interstitial voids can rapidly lead to fiber failure. Any method of couplature then must absolutely minimize the energy losses at this interface.

This chapter also examines aspects of the processing of fiber optics to provide a basis for understanding how the material for a system with as much as 1 linear foot of fiber per square foot of interior space might be assembled. These include the techniques of
splicing, connecting, polishing, cleaving, and antireflection coating of fiber ends. Emission at the end of a fiber optic transport system is evaluated for visual comfort in Chapter 13, System. A couple of simple fixture types are recommended then as well.

**Background**

The materials constituting the fibers—glass, silica, or plastic—have been developed to provide minimum absorptance around 0.8µm, because of the particular near-IR wavelengths used by light emitting devices in optical communications [Cariou, 1982]. Despite their optimization for IR transmission, many fibers, in particular fused silica, demonstrate very high transmissivity across the visible spectrum.

Basically, all fibers are made up of a core material and an outer jacket. A fiber core has a higher index of refraction than its cladding. It accommodates total internal reflection as defined by Snell’s law:

\[ n_1 \sin \phi_1 = n_2 \sin \phi_2 \]  

(5-5)

where \( n_1 \) is the index of refraction of the core and \( n_2 \) is index of refraction of the cladding. The geometry of launching illumination into a fiber is governed by

\[ n_0 \sin \phi < \sqrt{(n_1)^2 -(n_2)^2} \]  

(5-6)

which establishes a critical angle of entering light, in an exterior medium \( n_0 \), not to be exceeded for total internal reflection. The left hand side of the equation, \( n_0 \sin \phi \), is the fiber’s numerical aperture, NA. The higher the fiber’s NA the greater the fiber’s cone of acceptance.

As long as the fiber’s diameter is much greater than the wavelengths of energy being propagated through the fiber, the fiber diameter has no effect upon transmissivity (unlike PLG, lens and mirror systems, and reflective light pipes whose transmissivities are aspect ratio dependent). Since reflection at the dielectric interface exceeds 0.9995, fiber
transmissivity is dependent upon the actual length of dielectric medium that a ray passes through, not the number of internal reflections. Therefore light entering at the critical entrance angle experiences greatest attenuation since it transverses the greatest length over a given fiber run.

**Optical coupling**

Prior to the advent of nonimaging optics for solar energy concentration, Cariou et al. carried out investigations with a view to "conveying concentrated solar energy in fibers" [Cariou, 1982]. Working from Kato's findings [1976], Cariou devised an efficient method, and theoretical optimization design criteria, for launching illumination into fiber. Cariou articulated the need for inexpensive, large diameter fibers because standard small diameter fibers would have to be clustered, and subjected to associated packing fraction losses, in order to admit the relatively large focal spot of light generated by commercially available mirrors.

He established coupling to a fiber with conventional imaging optics, as shown in Figure 5.11. By placing the core of a fiber end precisely at the focus of a concentrator an image of the sun appears across the cross-section of the fiber.

![Image](image.png)

*Figure 5.11. Solar coupling to fiber.*

Cariou's investigation called for a parabolic mirror to reflect and concentrate sunlight onto the fiber end. A parabolic mirror gives the focal spot of radius \( r_g = f \epsilon \), where \( f \) is the focal length of the mirror and \( \epsilon \) is the angle subtended by the source.
Parabolic mirrors usually have a large $f$ so the $r_g$ value is much larger than than the usual radii of fibers. So, efficiently capturing light requires a larger diameter fiber which will not have the flexibility or cost economy that characterizes smaller diameter fibers. Using a fiber much wider than required for transmission of a specified level of illumination would render the entire technology too expensive to implement or too inefficient to justify.

### Packing Fraction and Core/Clad Ratios

Common to all coupling methods for bundles of fibers are the energy losses associated with 1) spaces between fibers and 2) energy incident on the clad rather than the core. This effect is particularly relevant if fibers are used for propogation of IR as well as visible radiation. At higher energy densities, light and heat trapped within the intersticial voids between fibers cause localized thermal breakdown of the cladding material. Borosilicate spheres between 1 and 100 um in diameter are one suggested technique for diffusing concentrated heat incumbent on the end of a fiber bundle$^4$.

The fractional area occupied by cores is given by [Allan, 1973]:

$$F = \frac{\pi d^2}{2 \sqrt{3} D^2}$$  \hspace{1cm} (5-7)

This is known as packing fraction, which refers to the actual amount of energy reaching the fiber core as a fraction of the total energy incumbent upon the end of the fiber. It may be approximated by

$^4$ Communication with DeHart, 3M Specialty Optical Fibers Division.
\[ F = 0.91 \frac{d^2}{D^2}, \]

where \( d \) is the interior diameter of the core and \( D \) is the exterior diameter of the cladding material. A typical fiber would have a \( d/D \) ratio of 0.88 which gives a value for \( F \) of 0.70. Only 70% of the incident light strikes the fiber core. The light accepted by the fiber is the core packing fraction less the fresnel reflection losses (Equation 3-1). Fibers considered for centralized light transmission will have maximized core to cladding area ratios.

Like Cariou, one can associate one fiber with one collector. But to simplify the coupling situation by avoiding the packing fraction dilemma is to place greater demands on the precision of the concentration method. Single fiber coupling has been adopted by Himawari (refer to subsequent discussion of Himawari). It has been suggested that rods or fibers of square cross-section at the coupling juncture would improve light loss associated with the problems of voids in bundled fibers [Ruck, 1988]. Fibers with square cross-sections are not currently manufactured. However, fibers tapering from square to circular in cross-section can be fabricated.

The square coupler is a simple technique for eliminating interstitial void losses. As shown in Figure 5.13, the side of the square equals the diameter of the focal zone. Each square rod is then subdivided into a squared integer of short square fibers which can be bent and positioned to abut circular fibers. The diameter of each circular fiber is set equal to the diagonal of each square fiber. There will be no energy losses if these dimensions are observed. By varying the coupler's length, it can also serve to uniformize the cross-section of the energy at the focal zone (to some degree) so that the fiber entrances receive an average irradiance. Hot spots will cause the fiber to fail locally at levels lower than energy capacity throughput. The example of Figure 5.13 shows 25 short square fibers abutted to the exit of the coupler.
The use of the square coupler, or any other method for the elimination of interstitial voids, increases the optical extent of the source, and therefore requires a larger fiber cross-sectional area to transport the increased quantity of light. The elimination of interstitial voids does not increase brightness of the side emission or end emission fiber. It merely makes the integration process more efficient. The coupler may be doped with a UV or IR inhibitor.

The governing relationship for transmission through a length of fiber is:

\[ T = \frac{I_o}{I_i} = e^{-kL} \]  

(5-8)

where \( k \) is the attenuation coefficient of the fiber material, \( L \) is the fiber's total length, and \( I_i \) and \( I_o \) are respective input and output radiant energy levels. \( I_i \) inclusive of (Equation 5-7) would be:

\[ T = \frac{I_o}{I_i} = 0.91 \frac{d^2}{D^2} e^{-kL} \]  

(5-9)

**Fused Silica**

Low loss fiber optical waveguides are designed principally for information transmission systems. Kato [1976] investigated the feasibility of transmitting very broad spectrum light (blackbody radiation) through two types of core material: pure fused silica and high-silica-content glass. His investigation sought the
"intrinsic attenuation characteristics of optimal fiber materials which yield the probable upper limit of transmission of solar radiation in optical fibers."

While the spectral range that Kato studied, 200nm to 1000nm, extends below and above the visible spectrum, the findings obtained support efficient transportation of concentrated light from a central source (or sun). Fused silica was found to be highly transmissive, demonstrating attenuation of 25 db/km or only a 6% drop after 10m. Using a mean attenuation coefficient K, an average transmittance of more than 80% of solar radiation over at 40m (or even longer) has been attained using fused silica core optical fibers (Figure 5.14).

![Figure 5.14](image)

*Figure 5.14. Calculated transmission T(L) through fused silica and soda lime silicate glass fibers as functions of transmission length for the wavelength interval 200nm - 1000nm. (Kato)*
Fiber characteristics

Fused silica core fibers are available in numerous diameters and grades. A specific manufacturer's line, 3M, is taken as typical for all manufacturers. Fused silica or hybrid silica/polymer claddings offer the lowest attenuation of all cladding types, but the workability of plastic and composite claddings is generally superior, providing less brittleness, higher ductility, and better resilience to abrasion and fracture during installation.

For centralized illumination it is necessary to minimize cladding thickness in order to maximize core/cladding ratio. The buffer layer will be stripped back at the microcollector junction, so its cross-sectional area is not of consequence to efficiency of light coupling. There are two grades of fibers to be considered here. One with NA 0.39 and the other with NA 0.48 (A 0.61 NA fiber currently being developed by 3M is left to future consideration). Greater concentrations could be coupled into the the fiber with higher NA.

The peak optical power capability is between 16 and 64 MW for the desired fiber diameters (pulsed power). This is governed by the core material properties and assumes ideal launching efficiency (none into cladding). Minimum bend radii are generally >10(fiber diameter). Commercially available lengths are adequate for investigations into building applications. Shorter lengths might be coupled together to form a longer run.

A 3M fiber with a TECS hard clad and a 0.48 NA fiber, for example, has many ideal features but one specific drawback: its attenuation of 280db/km at 400 nm (Figure 5.15. Calculated spectral changes of blackbody radiation after the transmission of a fused silica core fiber for several lengths. The transmission lengths are given by L. (Kato)
5.16). This significantly lowers peak power capacity for full spectrum illumination due to the potential for core material failure at the lower end of the VIS spectrum. As can be seen from the attenuation curve, UV is not carried well. If the selective mirror in the central module is tuned to pre-empt the entrance of light in the lower range of the visible spectrum then power density capacity of the fiber may actually be higher than that presented. If so, pre-emption or absorption of the blue light directly affects the spectral quality of the central system's light output in correlation to the spectral efficiency curve of the human eye (Figure 7.1). Since the eye is not as sensitive to light below 475 nm, it is conceivable that the change in spectral character of fiber piped light decoupled of energy below 475 nm may be imperceptible to the average observer regardless of the change of CIE coordinates. At least over shorter distances.

![Figure 5.16. 3M large diameter core fused silica fibers in 125,200,400,600, 1000um have NA =0.48, higher than desirable attenuation at the low end of the visible spectrum, power density capacity of 0.6 to 64 MW, good core / cladding diameter ratios, and acceptable lengths and bend radii for building applications.](image)

Hard clad low OH fiber with NA = 0.40 has a lower acceptance angle range but much better attenuation characteristics. At 40 db/km at 400 nm (99% transmittance/meter, minimum) bulk material failure of the core becomes less likely within the desirable power ranges. Average attenuation in the visible is about 10 db/km (99.8% transmittance/ meter) which is pretty close to ideal. All fused silica fibers demonstrate better transmittance at the red end of the spectrum than at the blue end.

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5 Communication with DeHart, 3M Specialty Optical Fibers Division. Curve is incorrect and at 400nm does not coincide with 3M data.
Plastic optical fibers

The fiber optic manufacturing industry has experienced recent advances in the transparency of plastic optical fibers (POF), promoting their use for the transmission of illumination. Further advantages are high NA and lower price than fused silica. Polystyrene (PS) or polymethyl methacrylate (PMMA) are used as a core material. PMMA is superior to PS in transmission efficiency and mechanical properties.

Low loss plastic optical fibers with PMMA core are described by Kaino (1983). In it he established a frequency dependent transmission curve with attenuation of 89db/km at 520 and 570nm, low enough for use in fiber-optic signal transmission systems. Refractive indices of core and cladding are 1.49 and 1.41, respectively; leading to NA = 0.48, corresponding to 29° acceptance half-angle.

The energy density capacity of plastic fiber is low, so a much larger diameter fiber would have to be used for a given projected illuminance than with fused silica.
The optical attenuation of plastic fibers is mainly due to the intrinsic carbon-hydrogen (C-H) vibrational absorption, intrinsic electronic transition absorption, scattering due to dust and microvoids in the materials, and geometrical imperfections in the waveguide structure (such as variation in the core diameter and microbending of the fiber axis both of which are generated during the fiber drawing process (Kaino)). The visible spectrum of the PMMA core fiber is dominated by the absorption from the high harmonics of the C-H stretching vibration at 740, 622, and 544nm. These spectral absorption peaks are inherent in the material, they do not arise from impurities [Kaino].

The scattering loss before fiber drawing is 13.5 db/km at 633 nm. This Rayleigh scattering is inversely proportional to the fourth power of the wavelength. The loss of a fiber at an arbitrary wavelength is calculated by applying the value at 633nm to the following equation:

$$k_{(\text{db/km})} = 13.5 \left(\frac{633}{\delta}\right)^4$$  \hspace{1cm} (5-10)

A summary of PMMA’s actual and theoretical losses are shown in Table 5.1.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Total Loss (dB/km)</th>
<th>Intrinsic Loss (dB/km)</th>
<th>Scattering Absorption</th>
<th>Imbalance (dB/km)</th>
<th>Waveguide Imperfection (dB/km)</th>
<th>Loss Limits (dB/km)</th>
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</thead>
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<tr>
<td>522</td>
<td>89</td>
<td>28</td>
<td>1-4</td>
<td>57-60</td>
<td>29-32</td>
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<td>570</td>
<td>89</td>
<td>20</td>
<td>16-19</td>
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<tr>
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<td>178</td>
<td>12</td>
<td>121-124</td>
<td>42-45</td>
<td>133-136</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1. Loss factors and loss limits of PMMA core plastic optical fibers.
The UV absorption tails resulting from electron transitions within the fiber are not recognizable >500nm. Any excess loss is believed to be the result of imperfections in the waveguide structure. The loss limits of plastic optical fibers are composed of the intrinsic absorption loss and the Rayleigh scattering loss, so it is assumed that the loss limit of PMMA core fibers is @ 30 db/km at 522 nm and @ 40 db/km at 570 nm (Table 5.1).

Similarly, the scattering loss of a PS before fiber drawing is 55 db/km at 633 nm. PS core fibers have refractive indices of 1.59 and 1.485, with an NA = 0.58, corresponding to a critical angle of 34.6°.

![Figure 5.19. PS spectral characteristics](image)

The equation governing Rayleigh scattering is:

\[ k \left( \frac{db}{km} \right) = 55 \left( \frac{633}{\delta} \right)^4 \]  

(5-11)

A summary of the fiber's actual and theoretical losses are shown in Table 5.2.

<table>
<thead>
<tr>
<th>wavelength (nm)</th>
<th>total loss (db/km)</th>
<th>intrinsic loss (db/km)</th>
<th>loss due to waveguide imperfection (db/km)</th>
<th>loss limits (db/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>552</td>
<td>162</td>
<td>95</td>
<td>45</td>
<td>117</td>
</tr>
<tr>
<td>580</td>
<td>138</td>
<td>78</td>
<td>45</td>
<td>93</td>
</tr>
<tr>
<td>624</td>
<td>129</td>
<td>78</td>
<td>45</td>
<td>84</td>
</tr>
<tr>
<td>672</td>
<td>114</td>
<td>43</td>
<td>45</td>
<td>69</td>
</tr>
<tr>
<td>734</td>
<td>466</td>
<td>30</td>
<td>45</td>
<td>421</td>
</tr>
</tbody>
</table>

Table 5.2. Loss factors and loss limits of PS core plastic optical fibers
**Power Capacity**

The economic justification for the use of fiber optics in a large central system depends on the power handling capacity of 1mm+ diameter fused silica core fiber optics. What is the minimum diameter fiber that can carry enough light to serve a lighting fixture? Is it small enough in diameter to permit centralized illumination to be economically competitive with conventional illumination systems?

Generally the breakdown of a fused silica fiber optic has less to do with fiber core material than with fiber mounting technique. Mount location is critical to power handling capacity and is the major cause of premature fiber breakdown in fiber power applications [deHart, Photonics, 10/92]. The squeezing of a fiber, as brought about by shrinkage of curing epoxy used for mounting, drops fiber NA in that area. Light at or near the maximum NA leaks from the core and into the cladding, where it is absorbed or passed into the epoxy potting mount. Consequently, mounting location should not coincide with areas of extreme energy density. If energy/area is high enough cladding, buffer, or epoxy mount will fail. Mounting epoxies have variable shrink rates and remain a major cause of coupling failures at high power densities.

There are numerous examples of industrial high power laser applications coupling into fiber optics. 3M's Specialty Optical Fiber Division is currently involved in two such applications: 3 kw continuously into a 300um core fiber, and 5k continuously into a 550um core fiber. In neither case has prolonged radiation from a continuous wave laser done any damage to the material core. Depending on the wavelength, the damage threshold of fused silica is approximately 1 to 5 GW/cm² (350 - 1750 watts for a 200u core).

There are three prominent fiber failure modes for most connector designs involving high energy densities: 1st bounce, 1st focal point, face of fiber. Normally, the epoxy mount is within the first bounce. The first internal focal point has the highest energy density of any location along the length of the fiber. It occurs at approximately twice the first bounce distance. It is slightly larger in diameter than the beam waist outside the fiber. The low and high light frequencies share the same space at this internal focusing point and the energy per area can cause bulk material failure. Bulk material failure rarely occurs after the first focal point unless fiber impurities are present or high stresses are applied.
After about one meter the output of a fiber has roughly a Gaussian profile, and modes are well mixed. Chips, fractures, dust, impurities, or a poorly polished or cleaved surface at the exit end of the fiber could result in failure due to increased absorption or reflection sites.

Liquid light guides  Liquid light guides are just becoming available. They show promise of improvement over plastic for the transport of concentrated illumination, but fall far short of fused silica's transmissivity. Fluid filled fibers such as those manufactured by Lumatec GmbH Munchen, are available in 3, 5, and 8 mm core diamters. They have very high numerical aperture (0.76), for half-angle acceptance cone of 49°. Factory specifications indicate 70% transmission in the VIS for a 2 meter length. It is unclear whether this includes the anticipated 8% fresnel loss. As of this writing, information on ultimate power handling capacity is unavailable.

Conventional fiber optic illumination devices  There is a wide variety of commercially available fiber optic illumination devices. Using parabolic or ellipsoidal reflectors, they utilize conventional imaging optical techniques to reflect and focus a portion of a lamp's output onto the end of a fiber optic or bundle. The lamp's direct (unreflected) component is siphoned off, absorbed, and/or convected away as heat. Ambient temperature is stabilized with passive or forced air cooling. Three principle application areas are 1) medical imaging (endoscopy), 2) automotive applications, 3) architectural applications.

Most of the research that is being conducted today in the area of fiber optic lighting is within the automotive industry. The automotive industry's research environment contrasts that of the commercial lighting industry. Commercial lighting's low-margin, high-volume business, supports little or no infrastructure for extensive R&D, regardless of the size of the potential market. The automotive industry, on the other hand, supports

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considerable work in the interest of adopting fiber optic lighting to automobiles. Ford, GM
(through its subsidiaries Hughes, Packard Electric, Inland Fisher Guide, and its advanced
lighting division) have longstanding interest in centralizing light production in
automobiles. Attenuation and efficiency are not of predominant concern in automotive
applications, as they are for interior lighting systems for buildings. The lighting load of an
automobile is a negligible portion of its operating load. The auto industry is more
concerned with maintenance and styling advantages. The auto maker's efforts are in three
categories: headlighting, taillighting, and interior lighting. The US Department of
Transportation's requirement that redundant systems be installed in vehicles so that in the
event of a central lamp failure at least some of the auto's lights remain functional was a
hearty blow to the industry's efforts. This redundancy negates much of the incentive of
using remote source lighting for automobiles because of its impact upon basic economic
and technical advantages: 1) fiber is expensive and doubling of the material doubles the
cost, 2) thin film coatings, or other precision techniques, for low loss energy throughput
are beyond the reach of researched systems because of their expense, 3) doubling of the
number of sources doubles the number of ballasts, lamps, and reflectors. The automotive
industry seeks the absolute in minimal cost: cheap fibers, cheap connections, adequate
performance. Maybe such is why fiber lighting has not made significant headway into
automobiles despite the auto makers having fascination with the subject for 20 years.

Interestingly, the fibers making inroads into today's architectural lighting market do
not transport light. They scatter it. Architectural side lighting is a decorative usage of
scattered light, like neon. Fibers function as long low luminance luminaires, principally for
exterior illumination. Fibers used in these architectural lighting applications are
manufactured of plastic, usually acrylic or polystyrene, by any of a number of domestic
and foreign manufacturing concerns. Their losses are high @300db/km. A listing of plastic
fiber sizes, properties, and prices is included in the Appendix. Owing to its relatively large
diameter, it is much easier to launch illumination into a plastic fibers than a fused silica
fiber. However, the larger diameter adversely affects the fiber's bending radius. A 3mm
silica or plastic fiber is as rigid as a glass rod.

The large backscattering component of fiber optic illumination devices is
characteristic of high attenuation fiber and is the cause of the fibers luminance. Companies
interested in the end-lighting attributes of their products wrap the fiber in an opaque buffer,
which absorbs the escaping light and converts it to heat. Since the escaping light is diffuse
in nature, an internally reflective fiber coating would do nothing to improve the end-lighting
efficiency of the device.
Light conveyance systems using higher efficacy HID lamps are entering the commercial electric lighting market to compete with installations normally requiring a multitude of lower efficacy incandescent point sources. The efficiency of these novel systems is so low that they can compete with only incandescents in energy performance despite their higher efficacy sources. This is due to the issues previously addressed: 1) core/clad and interstitial void losses, 2) the use of only a small portion of the lamp’s luminous output. Their optical inefficiency elevates thermal considerations to a design governing status, and limits the source's magnitude. At present, utilizing more of the lamp’s output would actually have a reverse effect. It could 1) require a fundamentally different optical system; 2) aggravate an already tenuous thermal condition; and 3) increase the focal diameter (and fiber diameter) to the point that it would overprice the competition.

One of the more successful fiber optic illuminator manufacturers whose niche market is architectural interior lighting is Fiber Light, of Essex England, who offers a system using 3mm+ diameter PMMA fibers. They have a repertoire of interior lighting fixture designs that can be used in architectural applications.

Lumenyte, which has a similar product, originated its niche market in the lighting of swimming pools. Lumenyte manufactures its own plastic fibers, which GE has tested for use in the Light Engine. Attenuation is stated as 2% per foot. Both side lighting and end lighting fiber systems are available, but there is no single standard by which fiber attenuation is determined. A manufacturer who states a low attenuation may be launching collimated light, whereas a more accurate estimation would fill the fiber's NA.

GE's Light Engine is the most widely recognized fiber optic illuminator. The product uses a 60 watt instant start xenon-metal-halide lamp. It is passively cooled and has about 40% luminous efficiency (generated IR is wasted). The Light Engine accommodates a fiber or fiber bundle diameter of 1/2 to 3/4". The stated module efficacy of 41.7 lm/w is up to the point of fiber coupling, and does therefore not include the core packing fraction or fresnel reflection losses of the fibers, which reduces the effective efficacy to roughly the 30 lumens/watt range. The luminous energy density at the focal point 14.1 lm/mm². This is not high enough to justify the general use of AR coatings. Energy density could be increased by shortening the focal length of the concentration optic, but this would increase the divergence of the emitted beam. The bulk of the Light Engine's body is thermal hardware for the dissipation of absorbed light/energy, and the ballast. The GE Light Engine conducts away the radiative heat energy generated by the source. As of this writing, the unit is priced at $2000 and delivers about 2500 lumens. Considering that a central system would use one lamp to replace a multitude, GE may also be in the distinct position of
having disincentive to accelerate research, the success of which would compete with their principle line of business: a highly stable and profitable light bulb division.

This thesis intends to provide the basis for formulating an efficient fiber optic illuminator for building interior use, through: 1) the use of non-imaging optics for maximum energy throughput and minimization of optical extent; 2) decoupling and retaining the lamp's (and sun's) large component of waste heat as radiative energy for subsequent reutilization as a power source; 3) managing, instead of dissipating, the lamp's (and sun's) large component of waste heat as a means to reduce thermal stresses, 4) increasing the length and transport efficiency of the fiber runs by using smaller diameter silica core fibers, and 5) devising an appropriate optical system for efficiently accomplishing the above. As we shall see in subsequent chapters, such an optical system is feasible, however, there may be no lamp capable of driving it.

NiOptics Corp, Evanston, Ill., holds patents for the use of nonimaging optics developed by Roland Winston and closely monitors all products utilizing nonimaging optical technology.

**Himawari**

The Himawari is the first commercially available centralized sunlighting system. This product draws much from Cariou's original work in the concentration of solar radiation and launching into fiber optics.

As discussed, Cariou devised a method of launching solar energy into a fiber by focusing sunlight to within a focal region in which a fiber end was placed. Cariou asserts that it is best to "associate only one fiber with a concentrator". This is exactly what Himawari has done. Consequently, the small size of the fiber maintains that the concentrating lens is also small. Hexagonal fresnel lenses are used in place of standard lenses for coupling illumination into a fiber. They are 105 mm each, in diameter. Heat and UV are decoupled by chromatic aberration (Figure 5.21). The visible focus of the fresnel is at the fiber's aperture. In this optical system, the decoupled heat is successfully pre-empting from entering the space. It is dissipated outside of the building's envelope.

As in other solar applications, the heat constitutes one-half of the collected energy. The sun's heat energy is disregarded. Himawari's optical system is subjected to fresnel reflection losses of 4% at each end of fiber, 4% at each surface of the converging lens, and losses in excess of 20% at each fiber to fiber connection. The Himawari delivers 11% of the energy incumbent upon its face to the lighted space (22% of the light, 0% of the heat). While there is some loss of efficiency in light coupling, most of the lost light energy is dissipated en route by attenuation in the fiber. The fiber used is synthetic quartz with 1mm diameter. Future developments might include 1) the collection and use of solar heat to
enhance the overall energy performance of the unit, 2) central electric source supplementation to justify cost of device. As of this writing only one has been sold in the United States: Penn State University purchased one for research pursuant to a NASA contract.

Figure 5.21. Himawari fresnel array for launching into fiber optics.
Fiber manufacture and assemblage

Centralization would take advantage of technologies just becoming available for fiber processing. For the first time there is: 1) a commercially viable AR coating for fibers, 2) a fairly good cleaving process for larger diameter core fibers. Still, much of what is required for optimum system performance remains undeveloped. For example, fiber branching networks with highly efficient power throughput do not exist, since uniformity of output, not energy efficiency, is the objective for information coupling systems. Such might permit vast reduction in the amount of fiber required for any commercial building application by eliminating the "spaghetti" approach proposed in this thesis. Furthermore, for reasons discussed previously, high NA fused silica core fiber is an adequate but not optimal fiber. Improvements to fiber could take many forms: 1) cheaper, 2) square fiber tapering to circular without transmission degradation (maintaining same NA), 3) thinner cladding for tighter packing, 4) a completely different fiber core material that is designed specifically for visible light transfer instead of information (IR). Current levels of transmissivity are largely the result of massive research investment by Corning Glass Inc. and AT&T into improving the purity of the fiber drawing process.

The following discussion covers the practical fiber optic terms and techniques necessary for fabrication and installation of a fiber optic transporter from a central source. It is intended as an introduction, to provide a designer enough of a platform to conduct his/her own inquiry. Actual techniques will vary by manufacturer, size, core material, cladding material, and application.

Drawing process

The fiber drawing process is basically a gravity induced extrusion. For fused silica, a 25mm fused silica rod is drawn into a fiber core of any smaller diameter. Draw speed determines diameter. Varying of draw speed results in taper: short and long length tapers are made. Light is not lost along taper length unless NA of the thinner section is exceeded. Laser scanners continuously monitor and feedback fiber diameter to micro-vary extrusion speed to maintain uniform cross-sectional dimensions. Cladding goes on within seconds of core cooling. The cooled core is passed through a bath of cladding material. As the cladding material congeals about the core surface it is passed through an aperture that trims off cladding excesses. The core is kept free from oxygen contact during the small time interval between cooling and cladding adherence.

Cutting

Fiber generally comes on reels, which for 1mm diameter fiber might contain a single strand 1000 meters long. Fiber must be cut to an appropriate length before processing of its end faces can begin. A fiber cutter is basically a standard, high-grade,
honed, surgical knife. Every cutter leaves an impression of its stone carved face on the face of the fiber. The secret to good cutting is doing it quickly, and with a very sharp knife. It is important to minimize squashing of the core material.6

Polishing Fiber polishing is a multistage scoring process. A first pass rough polish is accomplished with a 3 - 9u silicon carbide rough grit mylar film. The second stage refines the grit size to 1u. The third and final stage uses a 0.3u aluminum oxide mylar for the best finish. Water is used to wash fiber ends between polishing stages so that heavier grit is not deposited on subsequent finer mylars. At 0.3u the particulate size is smaller than the wavelength of light and the fiber end is therefore completely transparent to it. The scored channels are <0.3u in gauge depending on the depth to which the circulating particle is submerged. A diamond grit is available for even smaller grit size. At 0.3u, however, the polishing finish is already so small that it can not be inspected with a visible microscope, regardless of power. Serium Oxide, a mild solvent for glass, is sometimes used as the final polishing stage where maintaining wavefront integrity in the UV is required. Quality of polish is measured by scattered reflection. That is, there should be no visible scattering at <0.3u. The fiber end should appear black.

Polishing of fibers is not cost effective unless done in bundles. 3M and other manufacturers offer services for polishing bundles of fibers. 3M can polish 1000 fibers of 600u at a time or 3000 - 4000 of 200u. The process requires one hour of labor and about 7 hours of machine time. Polishing is best done in bundles because bundling provides a support mechanism against chipping and abrasion caused by rocking of fibers against the circulating polisher if not kept absolutely perpendicular to the rotating disk. Stripping off of buffer and cladding after, instead of before, polishing would provide for added stability during the polishing process. Polishing leaves impurities that are present embedded in surface.

Cleaving Fiber cleaving is a possible alternative to standard cutting and polishing. There are many organizations capable of cleaving 125u or smaller (telecommunications) fiber. As core diameter increases, however, cleaving becomes much more difficult. It is quick to do, but frequently cleaving leaves a cross-sectional lip that would affect illumination launching as NA would vary across diameter of fiber. Cleaving is done with diamond or sapphire blade.

6 Communication with Andrew Bigley, Rohm & Haas Company, Bristol, PA.
Pioneer Optics, Hartford, CT., specifications claim <5% scribe chip from the outer surface into the core (Figure 5.22). For a 600u fiber this would correspond to less than 30u. Normally, the scribe chip is much smaller than specification at about 10u. A small amount of scattered light will be introduced relative to the area of the scribe chip in relation to the overall core area of the fiber. An average 10u x 10u scribe chip over a 600u diameter fiber corresponds to 0.35% scattering loss (100 \text{um}^2 / 282,743 \text{um}^2).

![Figure 5.22. Scribe chip resulting from cleave results in 0.35% scattering loss.](image)

Cleave angle flatness is <3° on either side of normal, so wavering of the cleave across fiber face will affect acceptance of illumination at the NA. Beam collimation should be contained to within 3° of NA (6° overall), if possible. Smoothness of the cleave face (exclusive of scribe chip) matches or exceeds that obtained through polishing. Cleaving creates the near perfect polish, probably better than 0.3u grit and without the polish marks. In batches of 200, 800u core fibers would be cleaved for $1.75 per end and would be done at a much lower cost for high volumes [Pioneer Optics, Hartford, CT.].

**Stripping**

Fiber strippers range from $50 hobbyist versions to $7000 automatic cutters. There are basically two parameters by which to judge the suitability of a splicer for a specific fiber:

1. blade size - just cuts buffer, not cladding or core
2. guide tube - for holding fiber very steady and perpendicular to cutting edge

Stripping back of buffer to expose cladding and core near the fiber end would allow tighter fitting of fiber end to collection optics. The buffer will most certainly be highly absorptive since it does not contribute to light transport. The buffer layer is generally thick.

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7 Communication with Ron Hille, Pioneer Optics, Hartford, CT.
and would consume a large percentage of available aperture area, leading to thermal breakdown from absorption.

3M, and other manufacturers, recommend values for blade size and guide tube size for each size fiber that it manufactures (refer to Appendix). When stripping, care must be taken to not penetrate cladding or to drag blades along core as any scraping could easily chafe away the 15μ cladding and damage the core. Any damage to core would result in light leakage due to microscopic angular deviations created at the point of contact, as well as introducing an eventual fracture point in tension.

**Acetone**

An acetone bath will dissolve the cladding to leave only the core. This could eliminate the cladding surface area at the location of fiber coupling. The tip of each fiber could be an exposed core. As long as the bare core is not in contact with any substances that have a lower NA, total internal reflection will be sustained (angular acceptance in the exposed core region would actually be higher than the rest of the fiber’s run). The core would be highly susceptible to damage as oxidation would render it extremely brittle. This may be tolerable as long as it is isolated from any mechanical stress.

**Antireflection coat (AR coat)**

AR coatings would be applied to any inline optical component of a central lighting system where there is a change in light transport media. The point of initial fiber launching is critical, as is both faces of each fiber to fiber connection (if an air gap exists), and the fiber end/room luminaire interface.

The lack of AR coatings for high power laser applications has long been a technical shortcoming. The standard 4% fresnel loss at air-glass interface affects the performance of resonators, and other such instruments for high power laser investigations. AR coatings were first applied for butt coupling of laser diodes, and are still problematic to manufacture with contamination resulting from outgasing of the plastic cladding at the fiber’s tip. ECI is one company capable of providing a process.

The AR coating at each end of a fiber should increase the transmissivity of the system for illumination by up to 8% by eliminating (or nearly eliminating) the 4% fresnel reflection losses at each fiber end. This 8% improvement in system efficiency is critical to the long range performance and energy payback of high energy density light transport. The AR coating should be highly transmissive across the visible range (430u to 680u), able to withstand the necessary power densities, and highly transmissive without color shift for all angles up to the fiber’s critical angle. It is assumed that radiation reaching these fibers is
almost entirely within the visible range, other frequencies being decoupled prior to reaching
the point of initial fiber coupling.

The available technology for spraying optical coatings directly onto fiber optic ends
is limited. Two parameters governing coating selection for this application are 1) sensitivity
to angular divergence and 2) visible transmissivity, and to some degree durability. A
multilayer film is more highly transmissive across a broader spectral range than a single
layer film like MgF2, yet it is also more sensitive to angular divergence and might perform
poorly for rays falling outside of tight collimation. If angular divergence is kept to within
20° (either side of normal) then the reflection loss of the multilayer coating will be lower.
The best (and most expensive) multilayer coatings offer better transmissivity for up to 35 -
40°.

Coatings are applied by either of two vacuum deposition processes. Both are "line
of sight" cold processes accommodating the spraying of a bundle of fibers prior to insertion
into microcollectors (discussed Chapter 11). The standard approach to film deposition is
the electron beam gun. The second is the plasma enhanced deposition process (HDP). Both
approaches require that the end of the fiber bundle to be sprayed is planar and that fiber
diameter is less than two inches. Acetone stripping of the cladding may be impossible once
the fiber ends are AR coated. The HDP process is the more stringent of the two regarding
these sizing and plane spraying requirements. The HDP process is also more expensive. It
is intended for very high power applications.

To minimize outgasing contamination of the optical spraying chamber, the rest of
bundle is wrapped in Teflon tape and coiled into an 8” diameter of coil, with the entire
bundle wrapped in aluminum tape before fitting into chamber. Set lengths of fibers so
be sprayed. The pricing for AR coating is based on each spraying run, the cost being
independent of the number of fibers so long as the chamber’s capacity is not exceeded.
Each AR run is estimated at $4008.

Alternatively, rather than applying coatings directly to the end of fibers, one could
apply the coating to sheets of substrate which are then scribed, cut, and applied to arrayed
fiber ends. Anti-reflection cover sheets adhered to the end of each exposed fiber would
reduce scattering and fresnel losses of incoming light. Fiber would be adhered
perpendicularly to cover sheet. The use of an adhesive and cover sheet would eliminate the
need for polishing.

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8 Communication with ECI, Lowell, MA.
OCLI sells AR coated glass by the sheet and has two relevant production groups. The desired substrate thickness in this application is thinner than the standard thicknesses OCLI produces most cost effectively, as AR film laminates for computer screens. This application requires thin cover sheets since the light is not TIR as it's travelling through the cover plate. The standard thickness of the substrate material for the highest production volume of automated coating is 10-30mm, a gap which would decouple too much light. A huge cost break would occur if coated float glass could be used as the substrate material.

The size of spraying chamber has been the factor limiting production quantity of AR coatings in the past. As of this writing, the Solar Group at OCLI is currently producing sheets with up to 14"x 16" dimensions. OCLI's Solar Products Group is providing 100,000's of units per month of AR coating on microsheets, in the form of solar cell covers with thicknesses of 3/1000 to 8/1000". A 2cmx2cm at 8/1000" thickness cost $1.30 each, in substantial quantity. The most cost effective thickness is 6/1000". Thinner than that and there is an uneconomical decrease in yield from handling, cleaning and post cleaning processing errors. If OCLI's thin film laminate computer screen AR coating could be used, their multiautomatic coating machine could get cost down to 1 - 2c per cover sheet. But there are problems in that 32 x 50" pieces of float glass are coated. Anything thinner than 3mm would be prone to breakage. So if 6/1000" thickness is desired, the Solar Group's technology is all that is available. Applicable coating technology from other organizations should be investigated.

**Taper**

Fiber optics with square or hexagonal cross-sections could significantly reduce core packing fraction losses. A larger diameter core fiber can be tapered square to circular through a special forming process. The diagonal dimension of the square cross-section determines the diameter of the circular portion of the fiber. This assures that
NA will not be exceeded along the taper. Tapered fibers do not suffer the interface loss that butting square to circular fibers does.

Another taper with potential relevance is the nonimaging optical taper. A 10mm x 10mm HEA cover sheet would completely cover the larger end of a nioptic tapered 3mm fiber (Figure 5.24, with 6/1000" thickness shown) and would minimize fresnel and scattering losses at the emitter surface/air interface. The governing optical relationship is the preservation of optical extent, equation (4-8). The angular aperture of the incoming energy equals the angular aperture of the emitted energy:

\[ \text{C}_{\text{max}} = \left( \frac{\sin\phi}{\sin\phi_0} \right)^2 \]  

(4-8)

So, if more collimation is desired than that emitted from the bare fiber end, a nonimaging optical taper could be used. For example, a 3mm diameter fiber with an acceptance angle of 30° and a desired emission angle of 7.5° would have an exit aperture diameter of 10mm. Conversely, if a slightly divergent beam is available, the nonimaging optical taper could be used as an optical-extent-preserving light-launching device.

![Figure 5.24. Nonimaging optical taper as a collimation device.](image)

**Connections**

Fiber to fiber connections are prone to energy losses due to 1) misalignment, 2) fresnel losses if even a slight air gap exists between the butted fiber ends, 3) scattering losses if ends are not well polished (or if cover sheets are not used), 4) leakage of energy at or near the NA if an air gap depth greater than 1/10 the fiber diameter exists between butted fibers. Furthermore, any nonhomogeneity that is introduced in the juncture of butted fibers, such as that introduced by epoxy shrinkage (discussed subsequently), will scatter energy, tending to fill the fiber's NA. Methods for the reduction of scattering and fresnel losses have been discussed previously. In-line adhesives would
maintain a continuous medium across the juncture of butted fibers. Two methods to reduce misalignment losses across butted fiber junctures are 1) the use of a nonimaging optical tapered connector [Winston, 1989], and 2) butting a larger fiber to the emission end of the smaller fiber.

Angular losses can be circumvented with the use of a nonimaging coupler, which closely collimates radiation which is to cross the butt interface (Figure 5.25). Alignment problems are not as pronounced because a given lateral displacement of the coupler halves does not subtend as large a portion of light as the same displacement of bare fibers (the concentricity of each fiber to its half-coupler is still important).

![fusion splice](image)

*Figure 5.25. Nonimaging coupler for butting two fibers end to end.*

Butt coupling of a larger diameter fiber to the emission end of a smaller diameter fiber would reduce losses from misalignment. A properly coupled connection of this nature would not be subjected to the other loss mechanisms mentioned previously. Fiber optic connections exhibit higher than expected loss⁹. It is the position of this thesis that techniques for the coupling of fibers should improve with practiced technique.

Manufacturers (Rohm & Haas, etc.) are developing plug-on connectors for butt coupling of large core fiber optics. When disconnectability is needed, the fiber would be cut, a coupler would be slipped on, a fresh fiber end would be inserted into the other end of the coupler. This approach to disconnectability would require a minimality of special skill and reduce the labor and material costs for low loss fiber connections. Fiber ends would have to be processed appropriately such that all other loss mechanisms are reduced and the ends butt smoothly. The plastic core materials will likely fuse together over time, especially at higher energy density levels.

**Adhesives**

Adhesives serve in a triple capacity in bundled fibers, 1) to secure and maintain the alignment of fibers after end surfaces have been prepared, 2) to dissipate heat caused by absorption of stray light, and 3) to pass any stray light out of the area where

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⁹ Communication with Ben Jacobsen, NiOptics Corp., Evanston, Ill., on the prototyping of Winston’s coupler idea.

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absorption would lead to unwanted heat buildup. As discussed, adhesives also may be required when connecting fiber ends to fiber ends, connectors to fibers, cover sheets to fiber ends, etc...

There are at least two generic types of adhesives: uncrosslinked core material and epoxy. The use of epoxy as an adhesive requires prior removal UV. Epoxy is as, or more, susceptible to damage by UV than the fiber core material. Epoxy discolors rapidly under exposure to UV and would lead to increased absorption and eventually failure from thermal breakdown. Epoxy cures at low temperature. Epoxy that is black to the eye is black to visible light and will have undesirable absorption characteristics. Rohm & Haas is marketing an uncross-linked form of their core material. They claim that it will not yellow, or become hard over time10.

There are three properties that must be optimized when using adhesives. The first of these is a low coefficient of thermal expansion so that thermal strains (resulting from residual absorption) do not affect the uniformity of the material. The second is a low curing shrinkage. The Epo-Tek epoxy shrinkage is taken as spec:

\[
\text{below } T_g < 60 \times 10^{-6} \text{ in/in/ } ^\circ \text{C} \\
\text{above } T_g < 125 \times 10^{-6} \text{ in/in/ } ^\circ \text{C}
\]

The other essential criterion is a \(>97\%\) transmission in the VIS (the higher the transmission the lower the absorption and the lower the thermal strains). UV shouldn't be piped down the fiber, anyway, so the properties of the adhesive in the IR and UV are not of primary concern. The index of refraction of any adhesive used in-line should be close to that of the fiber core material.

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10 Communication with Andrew Bigley, Rohm & Haas Company, Bristol, PA.
Summary

Fused silica optical fibers have potential for the low-loss, long-distance transport of highly concentrated illumination in buildings. Plastic fibers have utility for very short length transport/diffusion en route applications, such as task/ambient lighting for office modules. The larger diameter plastic fibers can be utilized with current lamp technology. As explained in forthcoming chapters, fused silica fibers can be filled to anywhere near their capacity with currently available lamps.

The low efficiencies that conventional solar optic light systems exhibit in light collection and conveyance stymies economic incentive to stimulate further development. This is a result of the transient nature of the sun, an incomplete approach to radiation management whereby the predominant energy output (heat) is left unutilized, and inefficient methods of light capture and fiber launching.

Silica core fibers exhibit higher transmissivity in the visible spectrum than the best of light piping films. Some absorption in the blue range <470 nm will be encountered as run lengths increase. The power handling capacity of the selected fused silica fiber optic is over 1.0 GW/ cm², or about 10,000W/mm². If light decoupled of its heat is being propagated, this corresponds to between 2,000,000 and 3,000,000 lumens of light per fiber. Even at 1/1000 this level (2000 to 3000 lumens per fiber), the corresponding brightness of 3000lm/mm² is so high that shielding inhabitants from direct glare becomes an area of extreme concern.
Transport losses in fused silica fibers remain very low and isolated to specific regions across the entire visible (and IR) spectral ranges. Fiber optics could make significant contributions to the energy performance of buildings if economical central lighting systems can be devised that manage all the source's radiative output, and if the etendue of the source can be preserved by launching light into fibers with an energy transfer as opposed to image transfer optical process. Unlike PLG, fiber transmission is not aspect ratio dependent. The amount of attenuation over the length of fiber transmission is independent of the fiber's diameter.

Aspects in favor of the use of fiber over PLG in centralized lighting are ease of splicing, good ductility, adequate power density capacity, low attenuation, good light loss characteristics around corners, easy coupling to light diffusers, and much less required aperture area. A common misconception is that applications for the use of fiber transported illumination would involve cumbersome mass. The mass contribution of plastic fibers is limited by their short transport capability, the mass contribution of fused silica fibers is limited by the economic necessity of minimizing cross-sectional area.

While early explorations into lighting applications for fibers have established their suitability in special circumstances, these initial applications have strayed from the fiber's salient property: the low loss transport of illumination. These applications, motivated more by novelty than by conviction for energy conservation, have not prompted further investigations into the launching shortcomings and lamp brightness levels that limit fiber optic illumination's commercial effectiveness. Commercially successful ventures exploit backscattering by using high attenuation fibers for highlighting walkways or building exteriors (Fiberstars, Lumenyte, GE Light Engine).

High concentration of illumination in fibers will reduce the amount of fiber material required in building installations. Cost will be optimized by maximizing the amount of illumination each fiber carries, with regard for the capacity of the luminaire that it is coupled to for distributing the illumination within desired visual parameters. It will be essential to recognize that although fused silica is expensive, driving high energy densities through it can make it an economical alternative to conventional methods of illumination. This will be demonstrated in a subsequent chapter.
CHAPTER 6

CONCEPT OF CENTRALIZED ILLUMINATION

The chapter introduces the components of a central system and their physical layout within a central module. The essential properties of each optical element will be discussed. Each component requires a thin film to enhance its reflective or transmissive nature. The diagramatic model of the central module (Figure 6.1) is comprised of a source, source reflector, selective mirror, heat collector, heat transporter to mechanical system, light collector, and light coupler (device for coupling light into transporter). A light transporter carries light to room lighting fixtures. The source is contained within the source reflector (1, 2) and radiation is oriented toward a selective mirror (3). The mirror separates radiation into two beams: an illumination beam and a heat beam. A non-imaging optical heat collection trough (4) collects and concentrates the heat onto a heat absorbing power transfer tube (5) that interfaces the building's mechanical system. The light collector (6, not shown) or light coupler (7, not shown) collect or collect/concentrate light for launching into the light transport medium. Ducted forced air will remove heat from the system that has accumulated from absorption due to imperfections in the optical components within the module.

source conduction and convection losses (due in large part to filtering out UV generated by source) are recovered through secondary system of heat recovery by ducted forced air

NTS

Figure 6.1. Concept of Centralized Illumination And Heat Recovery.
envelope. This constitutes a secondary system of heat recovery.

Eventual optical configurations would work in the same way but could be smaller, more convenient to manufacture, and more precise in their radiation management, as introduced in Chapter 12, Module Configuration. In eventual systems, the source reflector may perform concentration and light collection duties. The diagrammatic version is more appropriately applicable to early stage research and feasibility study than to actual wide scale implementation. The Central Module could be modularized per floor, multifloor/lamp, or multilamp/floor for implementation.

Source

The source of the system is a lamp that is adirectionally emitting radiation (visible, UV, and IR). Although there are sources powerful enough to illuminate the interior of a building, and there are convenient improvements to efficacy and color with increases in source wattage magnitude, there are not any high efficacy sources with the appropriate density of light emission to permit optical coupling of enough of the source's light into individual fibers to drive them to lighting fixture luminance levels (this is examined in greater depth in chapter 7). This is the major current technological impediment to full realization of centralization's potential on any large scale at the time of this writing.

The method of centralization as proposed envisions source wattages of much higher than conventional levels, such as those approaching 1,000,000 watts which are being developed by private concerns for national defense agencies. At this level of luminous output, single sources can provide ambient level illumination for 70,000 m² (600,000 ft²) of interior office space. Single sources would also be used to illuminate much smaller spaces. Source luminance (brightness) is critical regardless of the scale of application. High wattage sources are essentially a larger emitting volume of same brightness chemistry. Without adequate source luminance, the source can't drive the optical system to high enough density to reduce the transport medium's material to the degree that a centralized system would compete economically with a conventional system. Once adequate source brightness is achieved, applications will arise regardless of the source's lumen output. The availability of high brightness, high lumen output lamps as an alternative to high efficacy, high lumen output lamps may set a new stage for energy efficiency in lighting. The source is discussed in Chapter 7.

Source reflector

The source reflector directs the radiation emitted from the source, controlling the divergence of the emitted beam so that it falls within the subsequent optical components acceptance zones. The performance of the overall system is maximized by engineering for the optimization of a single reflector instead of the hundreds of source reflectors it replaces in ceilings. It must absolutely
minimize energy losses in the process because any energy lost in the reflector is absorbed and converted to heat, increasing the likelihood of failure. This loss of efficiency lowers the energy competitiveness of the entire system. The reflector for this proposal is designed to reduce the number of reflections each light ray undergoes when escaping the fixture, and may also concentrate light energy, combining its duties with the light collector. The source reflector and is discussed in greater detail in Chapter 8.

**Mirror**

The beam of radiation leaving the source reflector is directed at a selective mirror, either standalone or embedded into an optical surface, which separates the heat in the beam from the light in the beam: creating two beams, one of light and one of heat. This separation can be achieved at efficiencies exceeding 98%. For the diagrammatic version of the system, the mirror may need to be at least 18” in diameter. The mirror is discussed in greater detail in Chapter 9.

**Heat collector**

The heat beam can be collected with at least 50% optical efficiency with conventional solar collector technologies. Nonimaging optical collectors can do much better and can provide high temperature heat which would be utilized more efficiently in a building's mechanical systems than lower temperature heat, such as that recovered by ducting return air over fluorescent tubes. This thesis makes a number of suggestions regarding the type of mechanical system interface, but the efficiency at which the mechanical system would reconstitute usable work from the recovered heat is beyond its scope. The heat collector is discussed in greater detail in Chapter 10.

**Light collector**

The light beam is funnelled into light propagation tubes (PLG) or onto the ends of special fiber optic bundles. Maximum concentration is necessary to minimize transporter aperture area, so where full concentration is not realized by the source reflector the light collector may provide it additionally. Managing the energy density of light in the focussed zone at the fiber entrance is the most technologically difficult part of the system, with the potential for very high light losses, leading to absorption and the consequent thermal breakdown of the materials.

The method for coupling the light into the transporter must be very carefully derived, especially when launching into fiber bundles. The fiber bundle's interstitial voids and non-core cross-sectional surface can account for up to 30% of the bundle's cross-sectional area. This means that up 30% of the illumination directed upon the end face of a fiber optic bundle could be lost and absorbed, even if anti-reflection coated. Direct launching into a fiber bundle could decrease system efficiency by 30%, enough to compromise the system’s competitive edge over conventional
building illumination. The light collector section, Chapter 11, introduces concentrating and nonconcentrating methods for the elimination of the interstitial voids.

**Transporter**

The transport medium may be either or a combination of PLG and fiber, as will be discussed in chapter 13, System. Certain fiber optics present great potential for the low loss transport of illumination in buildings. Departing from precedent, this thesis explores the use of scientific grade fibers for the transport of light, rather than the polystyrene or polymethylmethacrylic that are used in the vast majority of decorative and technical fiber optic illumination devices. Scientific grade fibers are so expensive that cross-sectional area must be absolutely minimized if system is ever to be economically feasible, and hence implementable on a wide scale. However, reducing the fiber cross-sectional area makes getting light efficiently into the fiber that much more of a challenge, and that much more dependent on lamp characteristics.

The ultimate power handling capacity of the selected fiber optic (1.2 GW/cm²) is high enough that other constraints, such as high luminance at the lighting fixture, or thermal zones due to squeezing of the fiber at the fiber's mounts, will limit the amount of illumination carried by each (or each batch of fibers) for a given ideal source.

**Lighting fixture design**

Centralized illumination could vastly simplify lighting fixture construction. Fixtures would, categorically, no longer need structural reinforcement to support ballasts, since ballasting is centralized and therefore remote to proximity of illumination. Fixture construction would be further simplified by eliminating the requirement for heat dissipation hardware or thermal-safety switching. Fixtures can be a simple diffuser or lens, either collimating, sprinkling, or pouring light into the space, as long as adequate provisions are made for shielding the eye from the high luminance at the fiber ends.

Safety is improved because electricity is not required at fixture location for lamp operation. Illumination entering a room from a fiber or PLG transporter emerges at a predetermined beamspread. It is no longer the purpose of the lighting fixture to orient light emanating from a lamp, so the lighting fixture will not introduce any significant reduction in efficiency. Since all lumens appearing at a room interface enter a room, fixture efficiencies approach 100% and aesthetics and distribution characteristics become the only parameters relevant to fixture selection. Fixtures could readily be interchanged for mood or function by simply swapping lenses or reflectors to vary the directional distribution of the emitted beam.
Architectural lighting design

Given the flexibility of the medium, centralization could extend the bounds in which aesthetics are expressed. While a major motivation in the development of this alternative method for building illumination is reducing energy consumption in buildings, a very strong case could be made by architectural lighting designers who feel their design objectives are compromised by availability of limited product types, or by low cost fixture substitutions taking the place of specified fixtures in actual construction practice. If desired, the end-use result could be virtually indistinguishable from a conventional installation. There can be extended control over luminances in the space, but eventually with increasing fiber end luminance, the fiber ends must be affixed to diffusers or secured to illuminate indirectly.

Shuttering

A characteristic of the centralized approach is that while source light can be dimmed, shuttering of individual luminaires cannot be accomplished without loss of efficiency. The light emerging from the end of a fiber can be blocked (the light being absorbed and converted to heat), but the light entering the individual fixtures cannot be selectively unproduced. At this point in time, it appears that shuttering can exist only on a per module basis.

Supplementing with central sunbeam

Full scale development of solar lighting and heating systems has been compromised by high purchase and maintenance costs, and low probability of payback. Non-imaging stationary tracking presents a sophisticated alternative to active solar collection. Electric light and heat collection and decoupling hardware could be installed atop a building and configured to incorporate solar light and heat into the common distribution network. In this way, direct sunlight, which at peak times is 100 times as intense as that required indoors could provide as much as 50 FC to between 50 and 100 m² for each square meter of solar collector area. If economic feasibility for a central electric source can be established, costs for sunlight supplementation would be for the collection and concentration hardware only. Sunlight supplanted energy cost savings would no longer have to outweigh the added initial costs of a distribution network.

Summary

The feasibility of the proposed system rests upon absolutely minimizing energy losses in each stage of the optical process because every loss of light means lower energy efficiency, less economic initiative due to lengthened payback period, and localized heat buildup that could lead very rapidly to thermal failure in the system.
By making a series of steps toward improving the optical efficiency in fiber optic systems, fiber optic illuminators could enter the marketplace as an energy concept as opposed to a novelty concept. The use of non-imaging reflection optics reduces the ultimate number of "bounces" that the propagating light undergoes, and reduces the number of surfaces the propagating waves must travel through. Very recent advances in the optical thin films that would be applied to all of the reflecting surfaces should reduce to a near perfect minimum light lost at the interfaces of optical components.

The following chapters take a closer look at the components that would comprise such a system.
CHAPTER 7

SOURCE

Introduction

The visible (VIS) portion of the electromagnetic spectrum lies between 380 and 770 nm (Figure 7.1). The ultraviolet (UV) and infrared (IR) spectrums extend above and below the visible. UV is held responsible for rapid degradation of materials, but is easily filtered out. Sunlight is comprised of 5% UV, 45% VIS, and 50% IR. The incandescent lamp is a thermal source like the sun. Its radiative spectrum is therefore continuous (blackbody) in nature, corresponding to its absolute temperature by Equation (4-1). The incandescent lamp closely approximates this solar spectrum but burns at a lower absolute temperature, thereby not producing much at the blue end of the VIS spectrum and relatively more in the IR. Flourescent lamps do not demonstrate the same continuity. They are very discrete in spectral output and are not thermal sources. Their color temperature is correlated to the color temperature of an equivalent blackbody source.

Figure 7.1. The UV, VIS, and IR regions of the electromagnetic spectrum. Spectral curves are shown for sunlight, fluorescent lamps, incandescent lamps, and the spectral efficiency curve of the human eye.

Lumens and Watts are dimensionally equivalent and related to each other through the Spectral Efficiency curve of the eye. A single watt of power, uniformly distributed between 380 and 770 nm, yields 187 lm/watt. Thus, the highest attainable efficacy of a uniformly distributed continuous
spectrum source is about 187 lm/watt [Murdoch, 1985, p.79]. But a watt uniformly distributed between, say, 430 and 680 nm yields a greater luminous efficacy of 314 lm/watt, with only a marginal if not imperceptible change in neutrality of color, since the sensitivity of the eye is so low at the outer sections of the luminous spectrum:

\[
\phi = 683 \sum_{\lambda=430}^{680} \frac{1}{25} V(\lambda) \Delta \lambda \\
\phi = 683 V(\lambda)_{av}
\] (7-1)

where \(V(\lambda)\) values are attained from the spectral efficiency curve [Murdoch, 1985, p.77] and one watt of radiant energy is distributed throughout 25 10-nm bands, assigning \(\frac{1}{25}\) watt to each band.

\[
V(\lambda)_{av} = 10.686 / 25 = 0.46 \\
\phi = 683 \times 0.46 = 314 \text{ lm/watt}
\]

If the output spectrum more closely correlates to the eye's sensitivity curve, the luminous efficacy value would go up from here, approaching a theoretical maximum of well into the 400 or 500 lm/w ranges for continuous spectrum emission encompassing the majority of the visible spectrum. Sources have efficacies far below these theoretical values because of the heat and UV they produce, and because their spectral characteristics in the visible range do not correlate well with the eye's spectral sensitivity curve. By decoupling heat from the illumination system in such a manner that it is utilizeable in other building functions, and using a source whose spectral emission in the visible range is close to what the eye sees, luminous efficacy values taken for a source decoupled of its heat can approach the theoretical maximum.

If the most economical reutilization for the recovered heat in a particular application called for absorption by photovoltaics for use in generating electric light, the mechanical system's portion of the radiant source would contribute light. In fluorescent lamps each UV photon, generated by the arc sustained between the ends of the tube, is converted into a visible photon at the walls of the tube. But UV has more energy per photon than a visible photon, so in that conversion is a fundamental loss of efficiency on the order of one-half. The energy of a photon is related to its frequency by [Hecht, 1990]

\[
E = h v = \frac{h}{\lambda}
\] (7-2)
where \( h \) is Plank's constant, \( v \) is the frequency of the photon, and \( \lambda \) is its wavelength. A 300 nm UV photon has twice the frequency and therefore has twice the energy of a 600 nm visible photon. It is conceivable that eventual fluorescent lamps will convert each UV photon into two visible photons, thereby dramatically improving the efficacy of fluorescent lamps\(^{11}\). Along this same line of reasoning, it is conceivable that the UV generated by a radiant central source could be coupled into the fiber optic distribution network and converted to visible illumination at the emission end of the fiber.

**Wattage, color, efficacy, brightness**

The source is the component of the system that generates the light that will be used for the illumination in a building. Efficacy, not efficiency, will be compared in the evaluation of sources. Efficiency is considered the domain of the optical components. All optical aspects of the system are discussed in subsequent chapters.

Initially, 1 million watt lamps were investigated with the intention that their 100,000,000 lumens of output would be focused down to the size of a pea and routed through high energy density capacity fibers. This was quickly found to be in violation of the second law of thermodynamics. Luminance (or brightness) is a measure of the intensity of the source's emission, the amount of radiant energy leaving each \( \text{mm}^2 \) of the lamp's surface area. Systems cannot work without lamps of adequate luminance, regardless of the lumen output, which will determine the maximum amount of light carried by an individual fiber of given cross-sectional area.

While the luminance of the source is the enabling or disabling factor, luminous efficacy is the most important economic consideration. The more lumens per watt that are generated by the source, the more lumens per watt are delivered to the room. Color is the important visual consideration and should ideally be close in color temperature and constituency to that of sunlight. The longevity of the source is less important than these factors. Service life is more likely to be a question of lumen dirt depreciation, in lamps with more than moderate longevity, than operational lifetime. This is because heat-induced convection currents accelerate lumen depreciation from dirt and dust buildup on bulb jacket, and lamps are generally inexpensive over their lifetime in relation to their operational expense. Other factors for concern are stability of color with aging and during dimming, maintenance methods to ensure safety, and effect of the ballast on the power line. Still less critical features could include resistance to shock, availability of efficient electronic ballasts for efficient and quiet operation, consistency of quality of manufacture.

Quality and quantity of light is the result of the internal physics governing the lamp's operation. In depth investigations into lamp physics is taken to be outside the scope of this thesis.

\(^{11}\) Lawrence Berkeley Laboratory, University of California, Applied Science Division, Windows and Lighting Program, FY 1988 Annual Report.
Two broad families of lamps will be considered: arc discharge and microwave sulfur. An underlying assumption is that the source's output is highly radiative (demonstrating low conduction and convection losses). Linear sources, such as standard fluorescents, were found to have much too low brightness and too low a percentage of radiative output to be of use.

The light bulb market can be described as having two basic product groups: point sources and linear sources. Point sources are predominantly high intensity discharge (HID) or incandescents. Point sources offer better optical control, and with one notable exception (discussed subsequently) are thermal sources (Plankian Blackbody radiators). They also more closely emulate processes in the sun (the light is produced by the source, whereas in fluorescents the arc produces only UV), frequently resulting in continuous spectrum light similar in content to sunlight. Since it is critical to deliver the most light for the least amount of input electricity there is little point at looking at sources with lower efficacy, without very specific utilization of a larger percentage of heat. But sources with the highest efficacy (low pressure sodium and the like) are lacking in other attributes that will likely make their general usage for centralized applications in building interiors untenable, most significantly color. Most sources that were evaluated for feasibility in initial studies showed efficacies to be too low to make centralized illumination competitive with conventional methods. This shortcoming was aggravated by a total lack of availability of highly efficient, stringently collimated lighting products. Generally, the available products were either highly efficient or highly collimated, but never both. The reasons for this dichotomy will become clear in the following chapters, which start to address the optical problems associated with the successful management of the source's radiative output. This section attempts to identify those features of an ideal source that might be attainable by cross-referencing features of available sources.

Efficacy of 100 lumens/watt is desirable (prior to heat decoupling). A central system with a highly radiative source at this level of efficacy would compete very favorably with conventional fluorescents in a comparably efficient system. In comfortable environments where larger cutoff angles are required for glare control, an efficient central system might deliver as much as five times the light per watt because of the efficiency losses frequently encountered with high grade conventional lighting fixtures, Figure 1.1.

A centralized system's efficiency is highly sensitive to the cross-sectional shape and size of the arc in its source. The arc of an ideal source is confined to a point, allowing precise optical control of its emitted radiation. As the arc becomes larger, a point can be approximated by increasing the source's reflector size. However, this compounds the difficulty of accurately managing the source's radiative output in subsequent stages of collection, concentration, redistribution, etc. If the source reflector gets bigger, so will the selective mirror, light collector, heat collector, and IR and VIS source refocussing regions. For example, launching light from an
enlarged source into fiber bundles would require larger diameter fibers or more fibers in a bundle to account for the larger focal area of the reconcentrated light. This directly offsets some of the system's tenability because fiber diameters need to remain as small as possible to maintain their cost effectiveness. An enlarged arc does not affect efficiency of launching into PLG, insofar as maximum acceptance angle isn't exceeded.

A source that is spherical and radiating radially outward from the center would also be suitable for optical control. But actual source arcs are an agglomeration of point sources spread out in space, radiating radially outward from each point.

**HMI, Vortek, and Fusion Sources**

Three sources are examined here for their suitability. Each exhibits some, if not most, features within reach of the ideal. At the lower end of the conceivable power scale, the most favorable lamp color and efficacy characteristics were exhibited by an HID lamp, the Osram HMI Metallogen, which is taken here as typical of other manufacturer lines. The HMI is established in the lighting market for simulating natural sunlight for film and television applications (Figure 7.2). As expected in these applications, the HMI source does an outstanding job at rendering across the full the spectrum of color. Complexions appear healthy, navy blue is rendered as blue not black. As suggested by the Color Rendering Index values >95 for all HMI sources 125 watts to 24000 watts, the visible spectrum is rendered almost as completely as if one were outside in bright sunlight. This is shown in the product's chromaticity diagram (Figure 7.3), which shows the initial color output of the source in relation to a Planckian blackbody radiator.

![Spectral power distribution of a 575 W GS OSRAM METALLOGEN HMI lamp and the spectral distribution of daylight at 5500K (White curve)](image)

*Figure 7.2. Comparative spectral characteristics of HMI and daylight showing close correlation of HMI source to daylight at 5500K.*
The HMI is considered a compact source. Average luminance values for the HMI series approach 400 cd/mm². The arc dimensions for a 6 kw lamp are 2cm x 5mm. Approximating its luminous surface area as 100mm², and emitting in all directions $\phi=4\pi$ sr, its etendue $\phi a$ is $400\pi$ mm²-steradian. A fused silica fiber has at most an $NA=0.5$, subtending a solid angle $\pi/3$. In this best case scenario, the source's etendue divided by the fiber's solid angle subtense will indicate the amount of fiber cross-sectional area required if reconcentration of light reaches the thermodynamic limit posed by the luminance of the source. In this instance, the minimum required fiber cross-sectional area is

$$400\pi \text{ mm}^2/\text{steradian} = \frac{\pi^2 \pi/3 \text{ mm}^2}{1200} \text{ steradian} = \pi r^2 \text{ mm}^2.$$ 

This corresponds to a fiber bundle diameter of 38mm.

A 1mm diameter fused silica fiber has cross-sectional area of 0.78 mm². So at least $1200/0.78 = 1540$ fibers are required to collect and transport a 6 kw HMI sources light. This amounts to about 4 watts/fiber which is about 300 lumens/fiber or roughly the equivalent in directional light output to a 15 watt halogen incandescent reflector lamp. One can see that the source brightness and fiber diameter limit the amount of energy that is carried by each fiber. This is well below the fiber's light carrying capacity.
The HMI is popular in applications for solar simulation in testing engineering products for resistance to radiation, energy research and aerospace technology, and for irradiation of organisms in biological and medical applications. Efficacy for HMI sources is >90 lm/w for sources >575 watts in size (Figure 7.4). At 48,875 initial lumens, the output of the 575 watt HMI equals that of more than 16 4' fluorescent tubes. Higher wattage HMI's, like the 24,000 watt version generating 2,160,000 initial lumens, produces light equivalent in lumen output to 720 4' fluorescent bulbs.

<table>
<thead>
<tr>
<th>Lamp type (reference)</th>
<th>HMI 200 W</th>
<th>HMI 575 W</th>
<th>HMI 1200 W</th>
<th>HMI 2500 W</th>
<th>HMI 4000 W</th>
<th>HMI 6000 W</th>
<th>HMI 12,000 W</th>
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<td>198-</td>
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<td>Sfa 21-12</td>
<td>K25s</td>
<td>K25s</td>
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</tbody>
</table>

Figure 7.4. Cut sheet of a variety of HMI product sizes.

Another source, Fusion System's microwave sulfur source, is not yet in production. Prototype versions exhibit exceptional attributes such as dimmability, color, compactness, longevity, high wattage, and efficacy approaching 100 lm/w (inclusive of ballast and magnetron losses). The brightness, at 300 cd/mm², is slightly less than the HMI. Prototype versions are being installed in the Forestall lobby at the DoE headquarters in Washington, D.C., and may actually be coupled to some form of fiber optics or light pipe in this instance. Even at this early stage of its development it is demonstrating continuous spectral characteristics which liken it to a solar simulator, as shown in Figure 7.5. Chromaticity isn't as close to a Planckian radiator as the HMI source, Figure 7.6, and its CRI value is 86.
Figure 7.5. Spectral characteristics of Fusion's source and sunlight.

Figure 7.6. Chromaticity diagram for Fusion's microwave sources. Location of 3400 watt lamp is $X=0.31$, $Y=0.37$, for a CRI value of 86.

Fusion's source efficacies range from about 120 to 140 lumens/microwavewatt. For example, the 3400 watt source produces 410,000 lumens. The ballast (magnetron) losses are high, and for conversion of electricity into microwaves for driving the source the losses are about 41% [MacLennan, 1992], Figure 7.7. This may improve as the technology advances. It is worth noting that only 25% of the input energy is delivered as light. The rest is heat.
**Figure 7.7.** Energy Balance for 3400 watt microwave lamp system. Conducted heat to the bulb wall (20%) includes 3% of IR radiated from the hot bulb. Magnetron and ballast losses are about 41%. 25% percent of the input energy is delivered as light (figure proportions are inaccurate). [McClennan, 1992]

**Figure 7.8.** Fusion Systems compact electrodeless microwave sources (not yet in production).

Fusion's 3400 watt lamp produces its light within a sphere of 29mm in diameter (intensity profiles show a large percentage of the luminous output is actually contained within 2/3 diameter).
This rotating, mechanically cooled lamp has luminous brightness of approximately 300 cd/mm². Its UV generation is low, so UV contribution to source brightness will probably be minimal, even if 2 lumens are stimulated at the room interface for every 1 lumen equivalent of UV generated at the source.

Fusion is also examining the feasibility of a passively cooled version of the lamp, that would operate at lower microwave energy densities. This lamp would exhibit reduced brightness levels, and would require larger fiber diameters to carry a given quantity of light. The technology in its passive form could be suitable for driving larger diameter fibers or hollow light guides.

Although the efficacies of fluorescent, HID, and microwave sources are equivalent, their respective efficiencies when placed inside optical components can be of an order of magnitude apart. This is largely result of two factors: the comparative size of the light emitting source, and the constituent convective and conductive nature of fluorescents. Efficiency in lighting is a radiative phenomenon. The compactness of a small arc and its highly radiative output facilitate decoupling of energy optically, which could lead to techniques for management, processing and reconstitution of non-visible energy after the light has been generated: improving conventional lighting efficiency. Convective and conductive losses have such low reconstitution potential that the output of a fluorescent lamp becomes the end point of energy processing in a conventional lighting system and therefore is not under consideration here.

Other sources, with still higher wattages, are produced by Vortek Industries in Vancouver, B.C., Canada. These are currently the highest wattage sources in the world. There a very limited market for them, usually using the heat in the beam instead of the light. The intense light from Vortek's lamps is a formidable source of heat. Targets placed at a hand's breadth from the 300 kw lamp can reach 3000°C. These are HID sources using an argon discharge. A flowing water jacket is wrapped around the arc capsule for cooling. Temperature in the cooling fluid is related to the volume of fluid flowing past the source, and is variable. Cooling water temperatures can be adjusted to surpass 100°C. All other heat is confined to the radiative output of the beam. The efficacy of their 1MWatt source is a little low, at 45 lumens/watt. The efficiency is high due to the large field beam desired by their clients (ironically, the largest of which is using the heat in the beam to burn in semiconductors), and could be higher if requirements for uniformity of irradiance across the beam were relaxed. Higher efficacy/efficiency versions could be introduced with little additional development work if a market warrants their production. Restrictive beam divergence requirements would lower attainable efficiency.
Arc size and shape, longevity, and lumen maintenance

The HMI sources have a relatively small arc, but their longevity at 750 hours is inconvenient for continuous use. The HQI, an emerging source with characteristics very close to the HMI, has an extended longevity to 10,000 hours. Because of its lower general efficacy it is not competitive with HMI, except at the 1000 watt range where all characteristics are superior to HMI. Short life is not a great compromise to the proposed system because centralization of location will accommodate ready replacement and scheduled maintenance, just as short life doesn't compromise HMI use in the lucrative film and television industry where longevity is much less significant than color rendition. Replacement bulb cost is an inconsequential portion of the total lighting fixture/ballast cost and lumen dirt depreciation isn't of principle concern where the lamp is being replaced continually.

The Fusion source is slightly larger than a comparable HMI, but the arc shape is spherical and the plasma does not wander so it may accommodate optical coupling and smaller optical components. Fusion's source has been tested to 10,000 hours with no evident failure mode. Test results on an 8400 hour bulb show no sign of vitrification. The outside of the bulb showed effects of abrasion which is likely due to the forced air environment in which it was subjected to unfiltered cooling air. A cleaner environment or use of filtered air cooling should improve maintenance, Figure 7.9. Fusion's source longevity is many times that of an HMI source. However, where longevity is great increased emphasis must be placed on luminaire cleaning regimens to sustain output, assuming lumen maintenance (natural aging reduction in lumen output) is of not too great a consequence.

Figure 7.9. Spectra of Fusion source at zero and 8400 hours.
Radiative output

A central source must demonstrate a large, if not almost complete, percentage of radiative output. Conduction and convection losses are not recoverable with regenerative potential and require further energy to remove from the building envelope. Conceptually, a central module will be taking a radiation source and re-focussing it as two sources: a heat source (presumed IR, but possibly including UV) and a visible light source (also possibly including UV). The success of centralization of illumination in buildings hinges upon the successful management of this radiative output and the minimization of convective and conductive heat losses, which are attributable to the thermal conductivity of the leads, absorption of radiation by ionized gas, etc. Convective losses ducted to ceiling plenums constitute marginal heat pre-emption and do not in any meaningful way constitute heat recovery.

Energy Distribution of Metallogen (HMI) lamps

Like the sun, the lamps considered here are highly radiative. The UV content of the emitted radiation can be considerable, as can be seen in the output profile of the HMI lamp, Figure 7.10. Some of this may be recoverable and reutilizeable, depending on which splitting mirror the central system assumes. The HMI, which is encapsulated within a fused quartz capsule, would be positioned in the central module out of proximity to the area being illuminated. This UV component (which is stopped by almost any medium) would be almost entirely absorbed by the quartz capsule and should not pose any additional physical hazard. Any UV leaving the source could be absorbed at the splitter, which is a glass or Pyrex substrate. Labor personnel would have to be specialized in centralized luminaire treatment just as electricians are currently trained to exercise care inside cherry pickers when cleaning high voltage luminaires in building ceilings, or street lamps. If the source is
to be changed while other sources are operating in its vicinity, eye protection would be used as a safeguard in the brightroom.

Fusion's source is highly radiative in the visible region, but since it is not a thermal source there is less IR emission and virtually no UV. Instead, there are large convective and conductive losses. The microwave energy is absorbed by an argon-sulphur plasma that emits radiation 50% in the visible, 1-3% in the UV, and 20% in the IR. The rest of the energy put into exciting the discharge is lost as convection and conduction (25%). So while its brightness is high relative to standard HID lamps, its potential for contributing to heat recovery and reutilization is not as favorable, and it is unlikely to drive anything but larger diameter fibers to appreciable energy throughput levels.

**Dimming**

Considerable dimming capability adds to the list of favorable attributes of the HMI, and is indicative of what is technologically attainable in the general sense. HMI can be dimmed to 30% luminous output with nominal color shift. As seen in Figure 7.11, dimming of HMI sources from 100% of rated output to 30% of rated output results in a color temperature increase from 5550°K to 5900°K. This would be experienced as a shift toward blue, with heightened perceived volume of blue colors and a lessening of red. These dimming characteristics are typical of the Vortek and Fusion sources. The Fusion source can be dimmed to about 10%, the Vortek source can be dimmed to 1%.

![Figure 7.11. Dimming of HMI sources from 100% of rated output to 30% of rated output sees a color temperature increase 5550K to 5900K.](image)
**Color shift**

A color shift is expected over the lifetime of the HMI and is characteristic of metal halide lamps in general, although there has been noted improvement in consistency and quality in recent years. Color temperature falls 0.5 to 1° K per hour burned so it is apparent that a centralized system using an HID source will have a rendering capacity that varies over time, at least until this color shift problem is rectified in HID source technology.

Fusion's source demonstrates no color shift over time (chromaticity diagram with threshold curves showing lamp's color shift over time is not available).

**Lamp lumen depreciation**

A shortcoming of HMI and HID sources in general is their lumen depreciation over time, referred to as the Lamp Lumen Depreciation factor, or LLD. While the efficacy does not change significantly, the HMI's lumen depreciation factor of 0.7 indicates that the source might have to be replaced before it actually expires, for reasons other than color shift. If the output drops significantly, then adequate illumination might not be attained. To compensate for this degradation, system dimming could be adjusted for the diminishing output by setting the dimmer to 80% full initially, and tapering up to 100% near the end of the bulb's projected life. Furthermore, the color shift toward blue that results from dimming would compensate for the color shift toward red that results from aging. Toward the end of bulb life, dimming for maintained output would be reduced from 80 to 100%, and would consequently introduce less blue. Calculations for maintained illumination levels would be taken at the 80% of potential initial value.

Fusion's source does not present any appreciable lumen depreciation.

**Summary**

Lamps are getting smaller, color is getting better, source wattages are growing, and efficacies are improving as the technology of light sources matures. Market driven improvements in source technology are already converging with the needs of incipient central illumination. Carried a step further, what is needed is a very bright, compact central source with excellent color and high efficacy, whose output is almost entirely radiative.

Ideally, we'd want a source with the brightness of xenon and all other attributes (luminous efficacy in particular) of HMI or Fusion Systems. The HMI, Fusions System, and short arc xenon lamps exhibit average luminance levels of 400, 300, and 1000 cd/mm², respectively. These are enough to drive 1-mm-diameter fibers to 300, 200, and 750 lumens. These values are fall short of the 2000-3000 lumen/mm²-fiber that would be required to make central lighting competitive with conventional lighting in the basic case, as will be explored in a subsequent chapter (the use of larger diameter fibers negates economic incentive at the large scale). Questions remain as to
whether the ideal source doesn't exist because of some fundamental physical principle, or because of a technological limit resulting from the lack of an economically warranted specific need. Once the market potential of centralized illumination, and the ready feasibility of other system components, is demonstrated source manufacturers may be motivated to increase the brightness of their sources while maintaining efficacy. This may place structural demands on the source's capsule, may require higher internal bulb pressures, might reduce lifetime of early versions since the fused silica quartz capsule becomes brittle from prolonged exposure to intense levels of UV.

Xenon arc sources have the highest brightness, but their luminous efficacy is too low to make central illumination generally feasible. Central illumination is specifying a source with light control capabilities that larger-scale light-projection specialists desire but haven't had the market clout to motivate the development of: a source that surpasses the luminance of the sun. Additionally, light source manufacturers are being asked, in essence, to produce a bulb that would replace 30 or 300 or 3000 of the ones they already produce. Considering that it would likely cost disproportionately less than the bulbs it replaces, it is also understandable that light bulb makers might be less than responsive to such a request.

This thesis proposes that source brightness and efficacy problems might also be addressed with the potential of converting a source's UV into visible by using a phosphor plate at the emission end of the fiber. In this way, the UV can contribute to the luminous efficacy of the source, and the brightness would be supplemented by the amount of UV to VIS conversion. Currently, the maximum amount of light that can be carried by a fiber is limited by the luminous brightness of the source (lumens/mm² or candela/mm²) not the lumen output of the source. As we shall see, this underplays some fiber's capacity for carrying large quantities of UV as well as visible light. In other words, one could define luminous brightness as a combination of UV brightness and VIS brightness, not VIS brightness alone as stipulated by the IES.

Taken to the extreme, is the realization that a central light system could be driven by a source that exists entirely in the UV. If the physical foundation exists for a highly efficacious source in the UV then the lighting in a building could be generated by invisible light. Keeping in mind that each UV photon has twice the energy of a VIS photon, theoretically the UV efficacy and brightness can triple the luminous efficacy and brightness of the source.

The rest of this thesis assumes the existence of an ideal source: a source whose brightness is so high that the amount of energy carried down the fiber lengths is limited by energy loss concerns, not energy production ones. The brightness of the lamp is what is seen at the emission end of the fiber. Under such an assumption, the thesis will establish the viability of all other system components. In the interim that an ideal source doesn't exist, currently manufactured sources may be substituted with expected compromised results.
SOURCE REFLECTOR

The source reflector is the element that directs the radiant energy generated by the source away from the source and toward the transport medium. Efficiency is a predominant concern, as is preservation of optical extent (a thermodynamic quantity that maximizes the ratio of source's luminance to the level of illuminance at the transporter's entrance). Conventional reflectors that direct light from a source into a spotlight rarely exhibit greater than 50% efficiency, and usually much less.

Precision forming, highly reflective films, and deep source reflectors are not economical in general interior illumination. Plenum height restrictions contribute to this lack of economy by requiring shallow fixtures in order to maximize the number of floors for a given building height. More to the point is that higher order energy savings measures in conventional fixtures do not afford payback because of the nominal energy that each fixture is managing. The expense of these energy saving measures can dwarf the costs saved by increased efficiency. However, the use of one central source means that the cost for improving efficiency through precision can be spread over the number of fixtures that the source reflector is accommodating. Efficiency improvements have much greater consequences when high energy densities are managed by individual reflectors. This chapter lays out some of the theory that concerns us in determining what form the source reflector will take. Source reflector shape may actually vary from application to application depending on such factors as source brightness, internal lamp characteristics, and number of room fixtures being driven.

An electric light source emits radiation in all directions. The radiative output of all reflector lamps has two superimposed beams: direct and reflected, as shown in Figures 8.1-3. Light that is redirected by the source reflector is called the reflected beam. Directionality of the reflected beam is accomplished with parabolic, elliptical, or compound reflector shapes.
Chapter 8  Source reflector

Figure 8.1. Light sources emit in all directions.

Figure 8.2. Reflected beam is collimated.

Figure 8.3. Control of direct beamspread is determined by depth of reflector in relation to lamp size and placement.
In applications where beam control is desirable, such as solar simulation, downlighting, spotlighting, etc, a large component of the direct light is commonly siphoned off leaving only the beam of reflected light and a small percentage of the direct light for use as illumination (carrying with it its portion of radiant heat)(Figure 8.4). The light that is siphoned off is usually concealed within the fixture by obstructing barndoors or absorptive baffles, with absorption manifest as a thermal rise. The more directionally demanding the reflector, the lower the fixture's efficiency and the higher its temperature.

![Diagram of a reflector with excess beamspread siphoned off.]

*Figure 8.4. Excess beamspread is frequently siphoned off leaving only the reflected component and a small percentage of the direct component emerging from fixture.*

It is evident that the deeper the baffle, the greater the degree of collimation. It is less apparent that a solid angle of 30° (π/3 sr) covers 2/3 less of the lamp's surface area than a 45° solid angle (π sr). So, baffles subtend significantly more of the lamp's emitting surface area than the solid angle of emitted light.

Elliptical reflectors are also commonly used in theatrical and architectural applications. Architecturally, they are particularly useful when it is desired to minimize the size of the exit aperture, resulting in a less cluttered ceiling plane (Figure 8.5). In theatre, ellipsoidals are used to intentionally strip off the direct light resulting in a beam of reflected light that has nearly uniform luminance across it.

In contrast to a parabolic reflector which has one focal point and parallel reflected rays, the elliptical reflector has two focal points with reflected light originating at one and converging at the other. In buildings, the fixture is recessed such that the ceiling aperture is
placed at one focal point allowing reflected light from the fixture above the ceiling to converge until it reaches the small exit aperture and diverge as it passes through it into the space. In either application type, the direct radiation is trapped completely in the fixture, thus lowering fixture efficiency, increasing heat, and necessitating thermal hardware for heat dissipation.

*Figure 8.5. An ellipsoidal with ceiling plane or barndoor shutters.*
The second most common method of siphoning off direct light to limit beamspread is the shielded filament (Figure 8.6). Shielding traps the direct light inside the fixture, where interreflections cause it to 1) leak out at uncontrolled angles, 2) be reabsorbed and converted to heat, 3) pass back through the source to be reflected. In some versions of the shielded filament lamp, the tip of the reflector is transparent to let light trapped between the filament shield and the tip of the reflector to escape from the fixture, avoiding heat buildup (Figure 8.7).

Figure 8.6. Filament shield obstructs direct component. Only reflected component emerges.

Figure 8.7. Light that would be trapped between the filament shield and the tip of the reflector escapes out of rear of the fixture, avoiding heat buildup.
Alternatively, a spherical filament shield can redirect the direct beam into the reflected beam, although this can destabilize the lamp's operation (Figure 8.8). The radial center of shield's curvature is concentric with the source's center. This approximation holds that the source itself is a point; which is not accurate. Emitted light rays that are not concentric with the radial center of the source emerge from the reflector with slight angular divergence. Better optical control is attained when the reflector is large relative to the size of the lamp (i.e. the arc within the lamp). The filament shield, too, would perform better optically if it were large enough and far enough away to approximate the source as a point.

![Diagram](image-url)  
*Figure 8.8. Spherical Filament shield can convert the source's direct component into indirect radiation, thereby increasing the reflector system's efficiency.*
The spherical filament shield can increase the efficiency of the optical system by allowing more of the lamp's constituent radiation to be coupled into the distribution system. The direct and indirect beams become one superimposed indirect beam, however the filament shield interferes with that component of the combined beam close to the source. Moving the filament shield away from the source doesn't negatively affect the optical behavior of the device (Figure 8.9). The source's direct light is reflected back through the lamp and onto the parabolic reflector where it is collimated. There is still a direct component that escapes because a large port is bored out of the center of the filament shield to let the beam diameter pass through. The larger the radius of the filament shield, the more efficient and more collimated the beam will be, and the less the lost direct spill light component will be.

Figure 8.9. A spherical filament shield geometry. There is progressively less and less direct light lost as the filament shield moves outward from the source, as long as its center of curvature is concentric with the source's center.
The spherical filament shield pairs conveniently with the ellipsoidal (Figure 8.10). There is no interference, and theoretically a great percentage of the source's radiation can satisfy the transport media's launching requirements.

Figure 8.10. A spherical filament shield is more conveniently applied to the ellipse than to the parabola. The source is placed at focal point $F_1$. Fibers are shown at focal point $F_2$. 
Similarly, this design could lead to an exceptionally efficient lensed ellipsoidal for theatrical applications, with a spherical filament shield used in lieu of obstructionistic barndoor louvers (Figure 8.11).

Figure 8.11. A lensed ellipsoidal with spherical filament

Imaging optics, of which spheres, parabolas, and ellipses are a part, image the source. That is, a spherical source becomes a spherical image. Within an ellipsoid, as shown in Figure 8.10, the spherical source at focal point 1 (F1) results in a spherical image at F2, the point of fiber entry. Light subjected to optical aberrations can fall outside of the image.

As of this writing nonimaging optics is still a largely theoretical, physically unproven domain. A nonimaging optical solution will manifest higher efficiencies than an imaging optic for a number of reasons, 1) the rays emitted from outside the source’s radial center will not be subjected to multiple interreflections as they can be in imaging optical systems, 2) aberrations are contained within the target zone, especially over short focal lengths where imaging optics have the greatest aberrations. Here, nonimaging optics are used in a capacity reverse to their original solar collection intention with the source located at the absorber position in the optic (Figure 8.12).
Chapter 8 Source reflector

Figure 8.12. Depth of nonimaging source reflector collimates direct component of radiation to within collector acceptance angle. 1" diameter source is located at optic's absorber position. Nonimaging shape reduces number of inter-reflections over an imaging parabolic.

For higher source wattages where surface breakdown in the reflective tip is of concern, one might assume a hemispherical imaging optic at the tip, as posed by Roland Winston (Figure 8.13). The reflector tip is increased in size and displaced back in space in order to reduce the energy density incumbent upon the reflector surface. He considered the source as an opaque transmitter, and therefore, recommended offsetting the lamp laterally from its center position such that the reimaged source would lie beside the actual one, not superimposed on top of it. Offsetting the source in this fashion would in effect double the size of the apparent source, and result in a doubling of the minimum cross-sectional area of the transporter. In actuality, sources demonstrate varying degrees of opacity. So, Winston's assertion is conservative. Some sources lend themselves well to reentrant light. Others do not. In the interest of attaining a maximum luminance of the source, precise reimaging of the source on top of itself is shown. The component of light reflected by this section of the reflector is sent back through the source opposite in direction to which it was emitted. A practical version has yet to built and attainable efficiencies are speculative.
Summary

Compound reentrant reflector systems can be inherently concentrating. Where convergence is not germane, concentration is accomplished by the light collector. The methods are disclosed in a later chapter. Even basic shielded filament lamps are uneconomical for common lighting applications, although increasingly called for in high contrast retail lighting or task lighting submarkets, where energy efficiency is not the design driver. Compound reflectors would also be uneconomical at low energy prices as their energy savings doesn't offset the expense of more intricate devices. This type of device is only warranted where significant energy savings can be realized, which is necessarily an application in which the reflector is handling an order of magnitude more light energy than conventional norms.

It is expected that nonimaging optics will achieve concentrations closer to the theoretical limits than imaging optical systems. At the theoretical limit, source brightness is transferred to the focal point. Imaging optical systems transfer images. The quality of output depends upon the degree to which aberrations are resolved. Image forming systems work best when the focal length of the projection lens is large relative to the lens diameter. In concentrating optical systems the focal lengths are necessarily short. It is difficult to
preserve image integrity under these circumstances. The imaging solutions presented in this chapter may be subjected to aberrations that would undermine the concentration. Nonimaging optical systems successfully map optical zones onto other optical zones. Image incoherency is not of consequence. So while nonimaging optics are high aberration, they are so in the extreme, and can transfer energy at the expense of image information. There may be multiple solutions to transferring a lamp's energy to a specified focal region, even combining elements of the above solutions.

This chapter assumes a source reflector which has only one exit port. Theoretical efficiencies are high. In practice the necessity of keeping the source reflector small introduces energy losses, especially near the optic tip where the reflector substrate is in close proximity to the emitting surface. Furthermore, the reflectivity of the film internal to the source reflector will experience accelerated degradation due to aging and UV if unnecessarily high radiation densities are incumbent upon it. Future chapters examine the possibility of bidirectional or multidirectional source reflectors that would reduce the energy density upon the tip region of the source reflector (for a given source) by partitioning the source's radiative output. Multiport source reflectors would also improve efficiency by reducing the amount of redirection of light. However, a one port solution is necessary where brightness of the source is low because multiport reflectors will reduce the attainable luminance by that number of ports, after concentration.
CHAPTER 9

MIRROR

This chapter explores the attributes of an ideal mirror. Specifically, it will look at what is desirable for a basic case application of central light and will examine to what extent these attributes are attainable with current technology. Two particular options for the mirror are explored. One is a readily available commercial product called Thermoshield. Although it will be seen to fall short of contributing to efficient energy management, under certain circumstances it can still demonstrate proof of concept. The other option is a more specialized type of mirror to be found in high power laser applications, where researchers require small mirrors with selective filtering properties and other specific angular or energy density requirements. Because of the case specific requirements of laser experiments there is little inventory of stock products. Instead, all mirrors are built to specification. Current manufacturing methods are not geared up to accommodate anything larger than 2" square. In addition to spectral properties, thermal and structural properties are examined in this chapter to determine if available technology is capable of supporting the energy densities required by the basic case.

The mirror is a selective filter for decoupling the light and heat from the source's radiation beam. A flat mirror is suggested for initial studies. It will create two beams from the one principle beam incident on it. Mirrors with complex geometries can also be used or integrated into the curvature of optical surfaces. Their general behavior is in principle easy to understand but the potential complexity of their surfaces and lack of precedence in manufacture raise questions about how efficiently these complex mirrors could separate and direct radiation by frequency, especially over wide angular variations. One complex curvature, called for now the Clamshell, is introduced conceptually in a later chapter. Its optimization, as well as other such complex mirror filters, is left to future research.

There is wide precedence in selective wavelength filtering [deWinter, 1990, p.974], however, at the time of this writing there are no off-the-shelf filters available that are large enough to split the radiation beam from a central source reflector driven by a lamp of 1, 2, or even 3" in diameter (the mirror would need to be at least 12", and conceivably much larger, as shown Figure 9.1). This is due to a current manufacturing limitation in chamber size, since the predominant use of such filters is in laser applications that require very small filters.
A smaller mirror can be used for the re-entrant imaging reflector system. It is placed just prior to the focus. In order to accommodate physical placement of the mirror, it is necessary to either increase the optical path length by lengthening the distance between focal points, or decrease the radius of curvature of the spherical filament.
Figure 9.2. The distance between focal points is increased slightly to allow for insertion of selective mirror.

For systems that do not reutilize heat, dichroic mirrors can be used on reflective surfaces. They do not exhibit high efficiency, but can be useful for smaller light conveyance systems such as those using plastic fiber. A redundant heat mirror is placed at the focus to ferret out remaining IR that would damage fiber core material. This is not a system of comprehensive radiation management, but heat still needs to be dealt with in order to achieve stable operation (Figure 9.3).
Figure 9.3. The ellipsoidal arrangement can be dichroically coated for smaller systems without the incentive for heat reutilization.

It is important to prioritize the minimization of lighting losses before the minimization of radiant heat losses since luminous efficiency determines the energy competitiveness of a centralized system. A bandreject filter with sharp cutoff around the frequencies 430nm to 680nm would be ideal for decoupling of heat and light (Figure 9.4). In this instance, most of the UV and IR would pass through the mirror to be collected by the heat recovery system for subsequent conversion into heat and usable energy. In the event that a bandreject filter can't attain high enough spectral efficiency, or that the UV is to be transported with the VIS and reconstituted as light by using a phosphor plate at the other end, a light pass (hot mirror) or heat pass (cold mirror) filter might be more suitable. A heat pass filter could reflect VIS and/or UV, and transmit heat while absorbing and re-emitting a small percentage of it as convective heat for ducting out of the system through secondary active ventilation means. A light pass filter could transmit light and some UV, and reflect IR. However, passing light instead of heat through the filter (and substrate) means that higher light losses will result from absorption than if a cold mirror were used to reflect the light. Consequently, cold mirror is the preferred splitter. Due to the very low spectral efficiency of the
human eye at the lowest and highest ends of the visual spectrum, imprecise cutoff will not impair perceived color renditioning.

Figure 8.2. Beam Spill desired band reject characteristics.

Figure 9.4. Beamsplitter's desired band reject characteristics.

This chapter examines a source beam divergence of 10° on either side of the optic axis when determining the spacial arrangement of the optical components. At 10° divergence, the beam is easily manageable. However, losses in the source reflector might be higher than desirable at long focal lengths. A 45° mirror should be able to accommodate angular incidence from 0° up to 20° on either side of the optic axis if the extent of source divergence in the worst case is to be considered. Beyond 20° divergence the size of the mirror becomes untenable. The sensitivity of the mirror to angular divergence of incoming light therefore needs to be examined. Values for reflectance and transmittance for 45° incidence with 20° divergence are shown in figure 9.7, and will be discussed shortly.

Can a mirror be designed to accommodate 10,000 watts or 100,000 watts or higher? Can a mirror tolerate the maximum expected beam divergence of ±20° at a 45° incidence? Are there cost effective options for bandpass, low pass, and high pass filters? What characteristics are compromised at excessive angles of incidence?

Flat Mirror

Thermoshield

"Thermoshield" is a widely used and relatively cheap heat rejecting filter. Its used to keep ice cream and makeup from melting under the intense heat of TV lights. If it is aligned perpendicularly to the optic axis it rejects heat by sending it back into the source: a questionable practice since this increases filament temperature thereby decreasing lamp life in lamps not specifically designed for
this purpose (engineered into GE IR lamps as an energy saving device). While effective for its intended usage, its efficiency is far from what would be required for general use in a centralized application. As shown Figure 9.5, visible transmissivity averages 90%. In the near IR reflectivity is about 40%. Far IR reflectivity approaches 90%.

Thermoshield is good for demonstrating the basic underlying principle of heat and light decoupling, but its thin film surface is susceptible to dust and dirt (and fingerprints) so its performance decreases appreciably over time. Its flexibility also reduces control of divergence of the heat and light beams, since it sags in the center and doesn’t remain absolutely flat. Adhering it to a transparent substrate would improve its workability and durability but would introduce other losses such as additional fresnel reflections off of each face of substrate and absorption in substrate. The efficiency of Thermoshield would improve if an antireflection coating were adhered to its obverse side.

Figure 9.5. Heat shield curve. Reflectivity vs. wavelength.
Stacked dielectric film

As shown in Figure 9.6, a band-reject mirror can be manufactured to within respectable approximation of the desired spectral characteristics. However, only one optical coatings manufacturer, Optical Coating Lab Inc (OCLI), was agreeable to producing a mirror of the required size. It is estimated that the production of an initial mirror would cost about $5000 and would include the costs of fitting a chamber to the required substrate size, designing the film and substrate for adequate power density capacity, thermal stresses, and spectral characteristics at $45^\circ \pm 20^\circ$. Repetitive members would cost between $100 - $500 each. Each mirror is coated on one side with a stacked dielectric thin film and would be installed (as would the rest of the central module's optical components) in a sealed module that would minimize dirt intrusion.

The maximum extended-duration radiation intensity that such a film can withstand is 70 kw/cm$^2$ [OCLI, tech support]. Spectral characteristics shift with angle of incidence, as shown in Figure 9.7. At $25^\circ$ incidence, 100% reflectivity is attained from 425 to 800, bringing some UV into the light beam for a mirror optimized to the visible at $45^\circ$ inclination. At $65^\circ$, the nominal quantity of light energy that is passed to the heat collection optic will be absorbed and converted to heat. The mirror should be inclined at less than $45^\circ$ if the divergence angle is more than $20^\circ$. Band pass filters with sharper UV and IR cut-offs would be more expensive and perhaps not economical.

![Figure 9.6 Overall average reflection for cold mirror at 45° incidence. UV control is marginal. 10% of IR is reflected with visible.](image-url)
Efficiencies would improve with second side coating. A reverse side antireflection coating would reduce the shown reflected IR from 10 to 6%. The film on substrate maintains an 800°C thermal breakdown [OCLI, Mark Demery].

The logical high temperature substrate is Pyrex. It is a glass derivative possessing a high coefficient of thermal expansion. It is used because it is less inclined to fracture under the stresses of thermal strains.

**Summary**

Thermoshield is inexpensive but its performance is marginal if not unacceptable. Its use in such an application would be limited to very low power densities, and probably without heat recovery since the near-IR is largely passed with the VIS. The technology exists for the fabrication of a mirror with the desired spectral, energy density, and angular variation characteristics. The requirements of a mirror for an efficient demonstration of the concept of centralized illumination are attainable with existing thin film technology, with one notable exception: an unprecedentedly large
mirror is required. A bandreject filter is the default: relegating UV to IR. However, the mirror would become simpler if the UV is piped with the light instead of being absorbed with the IR: needing only one transition frequency instead of two. It is preferable to use a cold mirror as opposed to a warm mirror when maximizing the luminous efficacy of the system.

Should the UV be treated as light or heat? That is, will the UV lend more efficacy improvement to the system when it is converted to heat or light? No conclusion is being drawn at this time because it is beyond the scope of this thesis to determine how effectively the UV could be converted to visible light by a phosphor plate at the room interface. One can refer to research being conducted at LBL that is directed at improving the efficacy of fluorescent lamps through the stimulation of two visible photons per UV photon [LBL Windows and Daylighting Group, Annual Report, 1992]. In any event, the mirror can be tailored to suit. If the end use requirements support the UV and VIS being piped together, the most efficient scenario would be accomplished by a cold mirror with a transition frequency at about 680 nm. It should also be recounted from Chapter 7, Source, that the luminous efficacy of the light component would be increased if the mirror's transition frequencies trimmed off the outer portions of the visible spectrum and sent them to IR. In this way the system's visible spectrum would be more closely correlated to the spectral sensitivity curve of the human eye. Due to the eye's relative insensitivity in the outer regions of the visible range, a considerable increase in luminous efficacy could result from a rather inconsequential compromise of perceived color quality.

Also, although a couple of other options will be suggested, a flat mirror is assumed throughout the thesis in order to proceed toward development of an easily buildable demonstration version of the system. Complex mirror forms suitable to either optical arrangement are not readily available and would require added development cost and time. At this point in time, the most sensible optical configuration is the one that is easiest to build. An optical designer could opt for sophisticated configurations when more aspects of the system have been proven in practice.

**Mirrored lens**

A mirrored lens is suggested as a possible direction for future research. Beam decoupling would be accomplished by using a concave mirror as a converging or collimating lens. A film with appropriate spectral characteristics would be applied to the lens surface to reflect VIS and/or UV. The focal point of such a lens would coincide with the source's center, with the reflected beam converging at infinity or at some distance convenient for launching light into transport system.
As the substrate assumes the shape of a lens, one could optically focus the energy passing through the substrate as well as the energy being reflected by it. In this way, the decoupling mirror could conceivably offer partial or total concentration of light and heat. An aspheric lens could be designed to maximize the energy concentration levels in order to minimize the diameter of the light transport medium and to maximize the temperature at the heat focus.

One other suggested alternative to the flat mirror is the "clamshell" configuration, as divulged in a later chapter. This is a series of complex optical surfaces including the mirror, light collector, heat collector, and source reflector, integrated into a single unit.
Chapter 10

HEAT COLLECTOR

Stationary nonimaging collection devices are designed to capture radiation from a moving source. A reflective film is applied to the opaque collector substrate after it is cast into a nonimaging optical collector shape. The heat collector designed for this proposal is a direct transfer of technology from the solar industry: a nonimaging optic with a cylindrical absorber surface to pass a heat transfer fluid. The collector will see energy stripped of light. The collector itself should not differ technologically from preceding non-imaging optical solar collectors, except that the solar acceptance angle can be reduced such that it accepts the angle subtended by the electric source beam in lieu of a wide solar range. Conveniently, this will accomplish higher temperatures of the recovered heat for a given flux density.

![Diagram of heat collector](image)

Figure 10.1. Source energy absorbed at a nonimaging solar optic’s heat concentration focus.

Heat collectors can assume any continuous absorber configuration. Line focus troughs are assumed in this chapter for simplicity. Point focus collectors would have higher concentration and temperature levels, as explained in Chapter 4, but the amount of energy recovered may not justify the more complicated manufacture, production, and analysis of the 3D optic.
From equation (4-8), an optic with a 12" entrance aperture, a, and an incoming divergent beam $\phi_{\text{max}} = 20^\circ$, needs an exit aperture surface area of at least 4.1", or of diameter 1.3", to collect all of the incoming radiation after concentration. The depth of the collector can be found from equation (4-9).

Spacial restrictions may necessitate a truncation of the optic. Dimensions of the truncated optic are determined by location of incidence of the extreme ray leaving the source reflector, proximity of the mirror and necessary clearances for the redirected illumination beam (Figure 10.2, 10.3). Increasing source beam divergence results in greater heat collector truncation, larger heat collector, and larger mirror.
Figure 10.2. Approximate relative depth to diameter relationships for source and heat collector for 10° source divergence.

Figure 10.3. Relaxation of angular divergence of source to ± 20° results in other optical components increasing in size. Untruncated heat collector envelope would wrap around source. Reflector surface away from heat focus isn't within source beam's extent and can be truncated to the point of extreme ray incidence. Construction lines shown.
Placing the reflecting surface in a vacuum eliminates degradation of the surface's reflectance, and thus higher quality reflector materials that are more susceptible to damage can be used without failure (frontal surface silver or aluminum $r = 0.91-0.96$, instead of anodized aluminum typical of reflector designs $r = 0.81-0.85$)[deWinter, 1990, p.346]. This will compromise the secondary heat recovery system in that forced air convection will not be able to take place inside the evacuated assembly. Forced air can still be circulated along the outside of the device. Care will have to be taken to minimize the fresnel reflection losses introduced by whatever surface is being used to close the envelope.

Tracking line focus troughs have shown excellent performance up to $\geq 300^\circ C$ [de Winter, 1990]. Point focus concentrators are the only means to achieve high temperature $\geq 400^\circ C$ for sunlight. Since the angle subtended by the electric source ($20^\circ$ half-angle, $\phi$) is much greater than the angle subtended by a stationary solar source ($0.267^\circ$ half-angle, $\phi$), the recovered temperatures in the electric application will be somewhat lower because the extent of the heat collection optic isn't filled (see Equations (4-1, 4-4)). These temperatures are still significantly higher than for typical stationary collecting troughs that do not incorporate non-imaging optics. Methods for overlapping heat collectors, or partitioning heat collection angles to subtend portions of the source's beam could be future routes of inquiry for preserving the high temperature reconstitution potential of heat collection (discussed in more detail in Chapter 11). Methods presented in that chapter suggest approaches for optimizing the heat recovery for specific source extent ranges and mechanical system interfaces.

The temperature of the recovered heat is a direct consequence of the concentration ratio of the heat collection optic, the degree to which its extent is filled, and the temperature of the emitting source. The output temperature of the collection optic's heat transfer fluid may be designed to interface with the available mechanical equipment by varying optical or fluid flow parameters to produce a suitable fluid temperature for a particular application. But the majority of the work derived from the heat recovery system will likely come from the solar source because of the comparative amounts of energy involved. A 10,000 m$^2$ 3-storey building could collect 500 w/m$^2$ of IR during peak hours, or about 1,666,500 watts with rooftop collection alone (3,333 m$^2$ x 500 w/m$^2$). To light the space electrically with conventional means would require at least 9.0 watts/m$^2$ (1.0 watts/ft$^2$). With central means, the 9.0 watts/m$^2$ would generate 4.5 watts/m$^2$ (0.5 w/ft$^2$) of interior space IR for about 45,000 watts, or about 1/37 the solar contribution at peak times. Integrating over the course of the day might increase the potential electrical heat contribution to about 1/10 that of the solar contribution for this particular building configuration. In general, this comparison is highly dependent on the aspect ratio of the building and on the particular climate (number of sunny days, latitude) in that area. Low aspect ratio buildings would see a greater percentage of solar heat, whereas high aspect ratio buildings in cities would be able to collect
relatively less from the rooftop and would see a more competitive percentage of heat recovered from electric light.

**Summary**

Solar collector area is allocated to just offset electric lighting capacity in peak sunlight conditions (60,000 - 120,000 lumens/m²) and would correspond to roughly 1 m² of collector area per 50 - 100 m² of floor area [Duguay, 1983], depending on the optical efficiency of the collection and distribution system. Examples, such as the 10,000 m² given above, would run the risk of delivering too much light if more than 100 to 200 m² of collector were used. This places the collection of solar heat and solar light at odds, because 3000 m² of potential rooftop collection area could not entirely be used for light collection in this low aspect ratio example. An ideal situation for rooftop light collection would be an urban high rise with an aspect ratio of 50 to 100. But likely transmission losses due to the long length of transport in high rises counteracts the ideal scenario, so an aspect ratio of about 30 might be closer to the ideal for light collection (all collected light is used for interior illumination). In short, the solar heat collection potential is restricted by the solar light collection potential.

How can one make use of the simultaneous maximum contribution potential of both? A solution depends as much on architectural factors as technological ones, and will likely be case specific. Also, this thesis does not quantitatively address any technique for the usage of solar energy entering the building's envelope through peripheral fenestration, which could dramatically increase the contribution of solar lighting and solar heating for a given building shape, especially high aspect ratio buildings. A transparent solar collector that could be a paradigm for windows that admit light (outside image might be blurred), yet capture, collect and concentrate the sun's IR is introduced in Chapter 14. This future work looks toward a complete reversal of the stereotype building that uses energy to encapsulate itself from the energy incumbent upon its envelope. Instead, it suggests that exterior building surfaces integrate or become heat collecting non-imaging shapes, and that buildings become pseudofunctioning energy-absorbing and energy-processing organisms. These steps would redefine the notion of energy-architecture. The concept of plane glass window is largely negated as an energy entrance aperture. The transparent solar collector could be adopted in part, or in whole, along the exterior of a building. Even opaque or structural portions of the building envelope could incorporate material assuming nonimaging optical troughs or cones for the absorption and assimilation of solar energy for conversion into heat power (see Chapter 14).

This thesis concentrates on central systems that assume only core generated and received energy (via rooftop). It is interesting to note that the current state of the art in solar energy controlling techniques addresses peripheral fenestration only. The most widely implemented strategy for solar light and heat energy control is the shaded or partially reflective window. Its
basic mission is keeping solar heat out of the building envelope. Among the most prized research at RPI Lighting Research Center, in Troy, New York, is an electrochromic shading device that denies the existance of solar heat and solar light when its intrusion into the space gets too high. Solar heat may enter in the morning hours only to be shuttered away in afternoon hours when, ironically, the sunlight and solar heat are at their highest potential and their energy would overwhelm the comfort of the interior environment. In no way does any current perimeter fenestration system constructively use both. A course for future research might be to devise a selectively inefficient central system that collects solar light at some percentage less than theoretically possible, and in proportion to the building's specific utilization potential. Or, perhaps alternatively, utilizing the full rooftop collection potential and siphoning off surplus light with the IR for conversion into heat power. In this scenario, at least, maximum available solar heat can be harnessed.

The principal rationale for adopting a solar collection strategy has to do with lighting efficacy, where solar supplementation could conceivably supplant a building's entire electric light production in periods of peak sunlight. Smaller central applications would be evaluated on a case specific basis to decide whether or not it would be economical to optically recover and concentrate the IR, to leave it unconcentrated for local hot water usage, or to simply duct it out of the building envelope. The solar light system is likely to be supplemental to the electric light system because of the sun's peak lived duration. The electric heat system would likely be subordinate to the solar heat system in building applications because of the large potential collection area for solar heat. Since central light is a building level system it could influence the building formally. Consequently, attaining a balanced, thriving system is as much incumbent upon the architect as the technologist.

Optimizing a building's central system also throws the mechanical engineer head first into the preliminary design process. The solar and electric heat system will be used to either partially or wholly drive the mechanical system of the building (excluding ventilation, since it is not anticipated that the use of photovoltaics to produce electricity from collected IR will provide the most economical scenario for reutilization of IR). This is in notable contrast to the conventional A/C system that requires additional electricity to run a compressor to remove heat generated by light and other things, negating the the lighting system's potential energy contribution. Central IR reutilization could also offset the use of gas, coal, oil used for hot water and room heat.

The mechanical system should be derived to most wholly utilize the energy made available by centralization. Absorption chilling is a logical approach to harnessing the available energy, but it is also possible to derive favorable scenarios for keeping the IR as radiative. In buildings where radiative heat is desirable, it is conceivable that the IR collected from the electric and solar sources could be routed through its own patchbay of fiber optics into the rooms, thereby providing directional radiative heat. Regardless of which strategy for heat reutilization is adopted, one fundamental tenet emerges: use radiant energy as energy, not electricity.
CHAPTER 11

LIGHT COLLECTOR

The light collector is the component of the system that moves the light from the central module into the transport medium, providing concentration when necessary. Because of the large aperture area of a PLG transporter, it doesn't need a light collector. The source reflector serves in that capacity: limiting the source beam's extent to within that of the film's acceptance angle and the tube's aperture area (refer to Chapter 8, Source Reflector, for a palpable design). A source reflector that limits divergence more than required effectively reduces the aspect ratio dependence of the PLG transporter, allowing for more efficient throughput. The optical challenge in the utilization of PLG for building illumination resides in the emission of light. If a PLG network is designed for emission, then its transportation capability is hampered, and vice versa. And how would a main transport trunk, to be subdivided into individual room emitters, support an angle of divergence that fills its extent (Chapter 5)? At the scale of the building, a lighting system composed entirely of PLG would be roughly equal to or surpass the building's mechanical system in consumption of space. With such an appetite for space, it is necessary to involve fiber optics in the light piping scenario. If so, then it is necessary to develop a method for efficiently launching light into them.

Fused silica fibers are very small, but each fiber can carry enough light energy to power a room lighting fixture. A bundle of one hundred 800 um core fibers would barely reach 1/2" cross-section. This is why the luminous intensity of the source is so essential to feasibility. To get 1000 lumens through a 1 mm diameter fiber means, roughly, that the source needs to emit lumens at the order of 1000 cd/mm^2. It appears as though this is assuming an ideal optical system that reconstitutes the source's intensity at the point of fiber entry, the thermodynamic maximum. In actuality these figures may assume that concentration of about 1/2 thermodynamic maximum is reached, as will be explained shortly.

Properties of fiber optics are discussed in detail in chapter 5. However, some basic properties must be recounted here. A fiber internally reflects light at the interface between its core and cladding material. It does so with great accuracy and precision: 99.9% of light is reflected with each bounce. This is true for all angles within the fiber's acceptance range, usually less than 27°, as expressed by its numerical aperture which is simply the sine function of that angle permitting the range of acceptance angles 0-90° to be expressed conveniently on a scale from 0 to 1. Another property, the core packing fraction, is the
amount of cross-sectional space occupied by the fiber core material in a bundle of fibers. Core packing fraction losses consist of two parts: 1) interstitial void loss which is the cross-sectional space left over by a packing a cylinders, and 2) core/cladding ratio loss which is the percentage of cross-sectional area taken by the cladding and the percentage of light consequently lost being not coupled to the core.

Getting light into the fiber is the technologically most difficult aspect of the proposed system. There is no precedent, and efficiency is the key concern. If efficiency in coupling isn't attained, centralization is not competitive with conventional illumination and prone to breakdown due to localized zones of high thermal stress. The light collector, then, must concentrate the source beam to near its theoretical maximum (to minimize fiber aperture and expense) and launch into the individual fibers without interstitial void loss and without exceeding the numerical aperture of the fiber.

The following sections investigate the use of a nonimaging stationary solar collector as the basis for a light collection and concentration optic. The basic principles for the light collector will then logically follow the theory presented for the heat collector, only now the radiation is not incumbent upon an absorber tube inside the concentrator's envelope. Instead, light must leave the optic in such a fashion as to be coupled into fiber optics. Multiple microcollectors are introduced as a means for partitioning the source's light into individual fibers for transport. The microcollectors may provide additional concentration, but more importantly they will be merged in a fashion similar to vaults in a ceiling to eliminate the interstitial void losses. Filling the hollow microcollectors with fused silica can more than double their attainable concentration. Collecting UV emitted from the source and optically processing it with the light could further increase the luminance and lumen output of the room emitter. Inclusive of UV and concentration within a solid medium, the short term attainable lumen transport through a 1000 um core fused silica fiber using the highest-luminance high efficacy HID source (400 cd/mm²) may hover around 1000 lumens: enough to replace a 75 watt halogen spot. Lumen output from the same fiber but using a xenon source (2600 cd/mm²) may be as high as 6000 lumens, or more: enough to replace two 34 watt fluorescent tubes. These values are still below the theoretical threshold of a fiber's energy carrying capacity.

**Fiber Optic Illuminators**

Precedence in the launching of light into fiber optics lies largely in the domain of fiber optic illuminators for medical imaging (endoscopy), fiber optic products for photographic effects, and neon-like sidelaylighting products for decorative architectural use. Light is launched into the fibers with lenses, parabolic, or elliptical optical reflectors (Figures 11.1,
In these instances, some of the light emanating from a source is focused to within a small focal area that is filled by the end of the fiber. Reflected rays are focused, direct rays do not converge. The concentration system can not exceed the fiber's numerical aperture requirements. An image of the source appears at the focus and, consequently, across the fiber's end face. As with conventional lighting fixtures, fiber optic illuminators burn hot because the heat generated by the source is dissipated, not managed. Absorption of the lamp's direct light component, as well as the dichroic treatment of the IR, passes heat to the outside of the housing via conduction and convection.

Figure 11.1. A parabolic reflector and converging lens are frequently used to launch illumination into fiber optics. Here the reflected beam is launched but the direct beam is largely lost. Reflected light converges at the lens's focal point, which resides at or just beyond the fiber optic's end face. Maximum concentration of the imaging optical system is 1/4 the maximum concentration of the nonimaging optic concentrator.
Toward a System of Comprehensive Radiation Management

The simplest method for launching light from a source into a bundle of fibers would be to array them around the source (Figure 11.3). If the fiber's NA is filled, then extent of the source is preserved (with the exception of interstitial void losses). This conceptually simple system does not involve an optical system, and in reality, the radiative heat emitted by the source would cause the fiber's collective surface to assume a temperature that would be intolerable for stable operation. So, theoretically this would work for a heatless source.

Figure 11.2. An elliptical reflector is subjected to the same losses and is constrained by the same limits of imaging optical concentration. The fiber's end is placed at the ellipse's second focal region.

Figure. 11.3. Fibers arrayed a source such that each fiber subtends a portion of the exitance.
Individual fibers are positioned a distance from the source such that the radiation is within the fiber's field of view. For the purposes of this preliminary investigation the source diameter is assumed 3.8 cm (1.5") (comfortably larger than Fusion Systems' 3400 watt source), and the fiber's numerical aperture is taken at 0.45 ($\phi_{\text{crit}} = \sin^{-1} 0.45 = 27^\circ$). The maximum acceptance angle of the fiber is 27° and the minimum distance that the fiber end can be placed from the exit aperture is determined by:

$$
\tan 27^\circ = 0.5 = \frac{a/2}{d} = 1.9 / d
$$

$$
d = \frac{3.8 \text{ cm } (1.5")}{}
$$

![Diagram](image)

*Figure 11.4. The minimum distance that a fiber can be placed from the source is a function of the numerical aperture of the fiber and the diameter of the source. A fiber placed too close, $d_1$, will not couple all incident light. A fiber placed ideally, $d_2$, will fill its numerical aperture. A fiber placed far, $d_3$, will couple all light but will be larger in diameter than is necessary to preserve extent.*

The use of an optical system 1) allows for reconstitution of the source's brightness at a location farther from the harsh physical environment close to the source, 2) permits the light to be collected through an aperture. For lighting purposes, the optical system involves a source reflector for substantially redirecting the source's output from a spherical distribution to a conical one, and a concentration/collection device for reconstituting the energy density of the source prior to transport. This simplification neglects practical thermal considerations. As was shown in Chapter 8, the source reflector can assume concentration duties.

In this thesis, reflectors are used in lieu of converging lenses so that light rays encounter one optical surface instead of two with each bounce. Light can be launched from a large source into one larger fiber. The most direct optical method would be to fill the exit aperture of the collector/concentrator with one fiber (Figure 11.5). While there are no core
packing fraction losses associated with launching into a single fiber, the expense of fibers with large diameters can be disproportionately higher than smaller diameter fibers. Since energy efficiency is not of principle concern for most conventional fiber optic applications, manufacturers opt for bundling smaller fibers together to fill a focal region of the concentrating optic. Bundled fibers can also be bent more easily, and routed in different directions. Some unfortunate and very basic problems ensue.

As with the nonimaging optic heat collector, radiation concentrated by the light collector is emitted adirectionally. The more sharply restricted the beam divergence of the incoming light, the higher the level of achievable concentration for a given flux. In order to contain the output of the light concentrator to within the acceptance angle of the fiber, the concentration ratio will have to be reduced. This makes the fiber larger in diameter and economically less advantageous.

Utilizing a nonimaging collector for its maximum concentration potential would send light far outside of the fiber's maximum acceptance angle (Figure 11.5). Fiber optics will accept light up to 27° on either side of its optic axis, or more. So while there would be higher concentration and smaller fiber diameter, there would be large losses in addition to the packing fraction losses.

When bundles are used instead of individual fibers there may be a savings in material cost but sizeable losses in optical, and hence energy, efficiency. The same angular acceptance restrictions persist, only now worsened by core packing fraction losses.
Although nonimaging optic concentrators achieve maximum concentration when the output subtends $2\pi$ steradian, emitting to somewhat less than the full hemisphere can provide an additional degree of flexibility in designing the optical system to concentrate and launch light into individual fibers. Nonimaging optical concentrators that emit at $\pi/2$ are really a subclass of the family of optics that subscribes to Equation (4-8). In order to emit at less than $\pi/2$, the reflector is biparabolic along much of its length and conal near the tip (Figure 11.6). The Edge Ray principle permits determination of such a collector shape that will concentrate to near the theoretical maximum in consideration of the angular constraints of the emitted light.

As explained in Chapter 4, ideal concentration is governed by

$$C = \left(\frac{n\sin\varphi}{n'\sin\varphi'}\right)^2.$$

(4-8)
Core packing fraction losses impact the feasibility of the proposed system by compromising efficiency and by limiting the source's magnitude to within tolerable thermal limits posed by radiation trapped and absorbed within the fiber's interstitial voids. The next section will explore the use of microcollectors to reduce core packing losses to near zero.

**Microcollectors**

Fiber optics can be coupled directly to the exit aperture of a collector whose emerging beam is contained to within the fiber's numerical aperture. A microcollector of, say, 2.2 mm entrance diameter and 800μm exit diameter would fit directly onto the end of an 800μm core fiber. The beam exiting the microcollector would need divergence, $\phi'$, constrained to within $27^\circ$ for direct coupling, stipulating an entrance beam, $\phi$, of 9.4° and a distance of 11.3 cm {4.5"}.

$$\tan 9.4^\circ = (a/2) / d$$

$.17 = 1.9 \text{ cm/d} \{ 0.75"/d \}$

$$d = 11.18 \text{ cm} \{ 4.5" \}$$
In this case, the microcollector provides concentration of 7.75, from equation (4-8). This moves the fiber away from the source yet permits filling of the fiber's NA and hence preservation of extent. However, the thermodynamic limit of source brightness is apparently exceeded by filling the microcollector cavities with fused silica, which would increase the attained concentration by the index of refraction squared ($n^2 = 1.5^2 = 2.25$). In the medium of fused silica, the luminance can surpass that of the source in air. The concomitant use of the source's emitted UV for stimulation of VIS phosphors at the room emitter would allow the luminance at the room emitter to rise still further.

Concentrating microcollectors are of use only when the incoming beam is more collimated than the fiber's acceptance angle.

**Partitioning of light using nonimaging optical reflectors**

When microcollectors are packed, they have the same interstitial void losses as fibers, amounting to at least 9% of its cross-sectional surface area (Equation 12-7)(Figure 11.8).
If the microcollector's envelopes are overlapped, as illustrated by the left two cones in the cross section on the next page (Figure 11.9), the packing fraction problem can be circumvented. Decreasing collector length, however, increases the optic's acceptance angle and lowers its maximum concentration.
Figure 11.9. Overlapping of microcollector envelopes eliminates core packing fraction losses but truncates the optic, thereby reducing its concentration ratio.

Microcollectors can be repeatedly merged in this fashion,
resulting in a honeycomb-like grid. The centers of the microcollectors form equilateral triangles

with each microcollector becoming a paraboloid extruded within a hexagon (Figure 11.10).
As can be seen in the figure, the microcollector is the shallowest at the place of greatest truncation. Spires emerge at the diagonal cross-sections, much like the spires that result at the overlapping joints of cathedral vaults. Angular and length values can be found from [Winston, 1985, p.92]:

Figure 11.10. Merged microcollector is a paraboloid extruded within a hexagon.
\[ L_t = \frac{a'(1 + \sin \phi) \cos(\phi_t \phi)}{\sin^{2} \frac{1}{2}(\phi_t)} \]  

(11-1)

where \( L, \phi, a \) are the length, acceptance angle, and entrance aperture diameter of the untruncated optic, respectively, and \( L_t, \phi_t, a_t \) are the length, angle subtended, and entrance aperture diameter of the truncated optic (Figure 11.11).

**Figure 11.12.** Dimensions for a truncated optic are determined from equation (11-1), where \( L, \phi, a \) are the length, acceptance angle, and entrance aperture diameter of the untruncated optic, respectively, and \( L_t, \phi_t, a_t \) are the length, angle subtended, and entrance aperture diameter of the truncated optic.

**Partitioning light using imaging optics**

Where optical concentration is being accomplished completely by the source reflector, an imaging microcollector may be suitable for launching light into a fiber optic bundle without interstitial void losses. A large fiber rod of square cross-section is placed at the focal zone. Each side of the square equals the focal zone in diameter. The corners receive no light. Light propagates down the square fiber by total internal reflection. The output of the end of the square fiber feeds a squared multiple of square fibers, enough to fill out a grid (Figure 11.12). These square fibers terminate into circular fibers. The diagonal of each square fiber equals the diameter of each circular fiber. By observing these geometrical ratios, the fiber's numerical aperture is not exceeded and no light is lost.
Each 0.4" square feeds a 0.57" fiber. The total cross-sectional area increases from $\pi \text{ in}^2$ to $25(0.57^2 \pi/4) = 6.21 \text{ in}^2$. Interstitial void losses are avoided, however, cross-sectional area nearly doubles. Elimination of interstitial voids occurs at the expense of an increase in total cross-sectional area (and a relative decrease in brightness). If the square rod is composed of fused silica, then the possible doubling of luminous concentration is reversed by the increase of extent. Fiber sizes shown are large for illustrative purposes. The grid may be comprised of any squared number of fibers, or multiple number of squared subsets.

Suppose 250,000 lumens are focussed upon a 2" diameter spot (area $= \pi 2^2/4 = \pi$)(luminance $= 2500/\pi = 80,000 \text{ lm/in}^2$). Then, 10,000 lumens emerge from each of the 25 square fibers after passing through the square rod. Those 10,000 lumens are delivered by a 0.56" diameter fiber (area $=0.25 \text{ in}^2$)(luminance $= 40,000 \text{ lm/in}^2$), representing a decrease of 50% in brightness commensurate to the increase in cross-sectional surface area.

**Hemispherical mapping of microcollector grid**

The microcollector dimensions are, so far, determined for collimated (slightly divergent) radiation emitted by a directional source placed at an effectively infinite distance.
away (the sun). This scenario changes for an adirectional source (2\pi steradian) placed a short distance away. By orienting each microcollector such that the source lies within its field of view, the microcollector grid is wrapped around the adirectional source. If placed far enough away that the source approximates a point, the angular divergence of the entering beam is reduced increasing the allowable concentration prior to the fiber optic's angular cutoff.

The microcollector grid is mapped onto a hemisphere, or other hollow volume, with the light source at its radial center (Figure 11.13). Each microcollector is positioned at a distance from the source such that all illumination falls within the individual collector's acceptance cone at an angle not to exceed the fiber's numerical aperture after microcollector concentration. If the source is flat or oval, the microcollectors at or near the optic center experience the widest initial beam (\(\alpha\)) and, consequently, can concentrate very little before exceeding the fiber's NA. This brings down the microcollector's entrance aperture size. Off-axis microcollectors encounter a less divergent beam (\(\beta\)) due to the apparent decrease in exit aperture diameter when viewed off-angle.

![Figure 11.13. Microcollector grid wrapped around an adirectional source emitting 2\pi sr. A fiber is affixed to the exit aperture of each microcollector.](image-url)
A microcollector grid could be a solid planar or hemispherical matrix of microcollectors that are truncated and fused together to form a solid coupler. The individual fibers would be plugged in. The microcollectors can eliminate core packing fraction losses, and can facilitate the launching of light by effectively enlargening the fiber’s diameter (at the expense of incoming beam divergence). By increasing the distance between the source and the collecting optic, a heat decoupling mirror can be inserted and thermal conditions can be stabilized. The microcollector grid can provide additional concentration, although at no point in air exceeding the source’s luminance. Filling the microcollectors with fused silica would surpass the maximum attainable luminance in air by a factor of 2.25 according to Equation (4-8), with the index of refraction of fused silica being 1.5. With the use of microcollectors the luminance of light launched into the fiber (and emitted from the other end after transport) can exceed the luminance of the source.

**Lensed microcollector**

Shown below (Figure 11.14) is a deep concentrator for use with the imaging optical method for eliminating interstitial void losses. With an entrance diameter of 25 cm and an exit diameter of 8 cm, the collector would accommodate a square rod of 8 cm per side which would support 100 12 mm (1/2") fibers, or on the order of 6400 1 mm fused silica fibers. Its concentration ratio (equation 4-8) is 7.5 for a 5° entrance beam divergence (10° total conal acceptance) and emission angle of 27°.

![Figure 11.14. Light collector with a 22 cm entrance aperture and a 8 cm exit aperture with 5° acceptance angle and 27° emission angle. Concentration is 7.5 and supports 100 12mm (1/2") fibers.](image)

\[
\begin{align*}
\alpha_1 &= 22 \text{ cm} \\
\alpha_2 &= 8 \text{ cm} \\
\phi_2 &= 27^\circ \\
\phi_1 &= 9.4^\circ \\
C &= \left(\frac{\alpha_1}{\alpha_2}\right)^2 \\
    &= \left(\frac{\sin\phi_1}{\sin\phi_2}\right)^2 \\
    &= 7.5 \\
\end{align*}
\]
The depth at 163 cm \( \{65"\} \) is excessive. However, introducing a refractive element can reduce the length by bringing the focal length in from infinity (Figure 11.15).

Additionally, "by removing some of the entrance aperture a considerable reduction in length can be achieved with very little reduction in concentration" [Winston, 1985, p.92].

Lenses should be very low dispersion. Fresnel lenses would not be suitable since the divergent light from the source would hit the inside of the scored fresnel grooves. Fresnel lenses require strict collimation to be energy efficient. Tighter collimation would increase the concentration ratio further.

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\[ \text{Figure 11.15. Converging lens at entrance aperture reduces optical length. Dotted lines converge at lens focus.} \]

\[ \text{Figure 11.16. Truncating collector reduces length at the expense of a slight decrease in entrance aperture diameter and concentration ratio.} \]

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In order to attain the desired concentration ratios in this example a source beam divergence of 5° is required. The depth of a standard source reflector to accommodate this tight a beam would be impractically long. A compound parabolic reflector with a spherically shielded filament would be an efficient way to get collimation within 5°. Collimation permits the insertion of a heat mirror without increasing the optical path length or extent.

**Summary**

This chapter presents a concept of partitioning light for efficient coupling of illumination into individual fiber optics for distribution of light throughout a building. The use of tracking solar collection optics in a stationary application makes fullest use of nonimaging optics for radiation collection and concentration without the heliotracking normally required by point focus methods for maximum concentration of sunlight and solar heat. Nonimaging optics provides higher concentrations than imaging optics in heliotracking applications or in instances dealing with divergent light, yet both approaches are applicable.

The light collector must accommodate the extent of the radiation beam leaving the source (divergence and aperture). If a cluster of light collectors is underfilled, the individual collectors may be oriented toward the aperture of the source reflector so that their acceptance angle is reduced. The rays approaching the collector optic at its maximum acceptance angle are focused along the circumferential rim of the exit aperture, \( P_0 \).

The hollow or solid microcollectors at the fiber ends can be overlapped, improving optical efficiency by eliminating core packing fraction losses, which in turn permits the utilization of sources of greater radiant power and intensity. Filling the microcollectors with fused silica results in concentrations at the microcollector/fiber connection surpassing the luminance of the source. Consequently, this concentration is transported along the fiber length and emitted at the visible end of the fiber.

The optical system presented in this chapter anticipates fiber optics as the transport medium. Coupling of light into Prism optical Light Guide is a much simpler matter since its diameter is many times greater than any fiber optic. Maximum concentration is not critical for coupling into PLG transporters, unless light will be subsequently branched into multiple fiber optic transporters. The source's extent is not preserved in PLG applications if the hollow guide is underfilled. In the following chapter, Module Configuration, the system elements so far introduced in this and in previous chapters will be combined in different ways to constitute entire building illumination systems.
CHAPTER 12

Module configuration

How can the components presented in the previous chapters lead to coherent system for the comprehensive management of radiation from a central source? Tolerable beamspreads and attainable efficiencies of the individual components have been discussed and possibilities exist for a wide variety of configurations. On the simplest level the optical system takes a given source of particular extent, processes it, and delivers it to the room's lighting fixtures for use as illumination. The optical system doesn't differentiate between high brightness or lower brightness lamps, it just delivers light commensurate to the source's brightness over the number of fibers the lumen output of the lamp can support. The source reflector must orient the light away from the lamp with maximum efficiency, and is most efficient when it is particular to the specific size and shape of the arc in the lamp. A reflector that preserves extent necessarily lets reflected light out with one bounce. Since the source reflector replaces a multitude of conventional source reflectors, there is some latitude economically for designing it for maximum attainable efficiency.

The nonimaging light collector negates the image of the source's arc, concentrating it into an amorphous zone of average brightness. However, in the nonimaging optical scenario, the farther that the light collector is from the exit aperture of the source reflector, the less filled its numerical aperture is and the less energy density it is receiving. All light rays incident upon the collector can be handled by it, however, its extent is underfilled. As we shall see, arraying additional sources laterally can serve to couple more light energy into the system by compensating for the unfilled extent of the collection optic. There will be an increase in brightness and lumen throughput, but a decrease in efficiency as there will now be rays outside of the collectors acceptance angle. This can be ameliorated somewhat through stricter collimation of the source beam, by use of a re-entrant parabolic reflector with a large hemispherical filament cap. The exit port in the large hemisphere will have to be the size of the parabola's diameter in order to allow the reflected beam to pass through. Unlike the ellipsoidal version of this reflector type, there will be loss in the direct component of light. The only loss-free way to preserve the extent of the source throughout the entire system is to connect the collector entrance aperture with exit aperture of the source reflector. This compounds the difficulty of decoupling radiative heat from the system for reutilization because there is no room for the mirror.

The luminous efficacy of the source is different from the luminous efficacy of the system. While the variety of relevant source efficacies range from 10 to 100 lumens/watt,
the system efficacy approaches the maximum theoretical limit for continuous spectrum light regardless of the type of source. The luminous efficacy of the system becomes more a matter of 1) a close correlation between the lamp's spectral output in the visible range with that of the spectral efficiency curve of the human eye, and 2) the width of the spectrum transported.

The diagrammatic system design involves one source, one source reflector, one light collector and one heat collection trough. As explained in this chapter, each of these optical components may be an assemblage of smaller elements, with each element managing a portion of its respective radiant energy beam. Sources too may be clustered, their beams focused toward the point of fiber coupling. Observing certain limits, this would increase effective source brightness, permitting fibers to be driven to an adequate luminance level with lamps of current brightnesses. This chapter discusses longitudinal source arrays, transverse source arrays, clustered source arrays (also called lamp banks); longitudinal, transverse, and clustered light collectors; point focus, transverse, longitudinal, and clustered heat collectors. Anticipating the existence of extremely high brightness, high efficacy, high lumen output lamps, this chapter introduces the concept of source partitioning, which is an inherently efficient method for limiting the divergence of source beams. It however, does require that 2, 4, or 6 beams emerge from the source, which means that the reconstituted brightness at the fiber coupler would be proportionately less than single port source reflectors would provide. Lastly, this chapter also introduces a
modularized unit called the clamshell that performs all of the optical processes within a single light bulb entity.

**Longitudinal source array**

If a linear heat collection trough is used, a multitude of sources could be aligned longitudinally, along the length of the heat collection trough. The illumination would be coupled into fibers, or simply coupled directly into PLG tubes (as shown, Figure 12.2). The light will flow right in, as long as the beam's divergence and diameter is within the PLG's acceptance angle and aperture. A nonimaging optical source reflector preserves the extent of the source, with divergence angle determined by reflector aspect ratio. The beam's diameter is a function of its the distance from the source and its divergence angle. The source reflector could also be of the re-entrant parabolic type. If each source beam is 5kw, then 2.5 kw of IR reaches the collector from each source and temperature is determined by the heat collector's concentration ratio.

![Figure 12.2. Alignment Of Sources Along Collection Optic's Longitudinal Axis.](image)
**Transverse and clustered source arrays**

Similarly, sources could also be arrayed transverse to the heat collection trough, although this is difficult because the heat collector is optically constrained in the transverse direction. One can consider this under certain circumstances where multiple lamps are warranted. The potential advantage of this is that the effective source brightness at the point of fiber entry could be the additive brightness of the individual sources.

![Diagram](image)

*Figure 12.3. Transverse alignment increases the divergence of the source beam.*

Tranverse alignment of sources increases the divergence of the source beam from $\alpha$ to $\beta$. This either reduces the heat collection optic's concentration ratio by requiring a broadening of its acceptance angle (Figure 12.3), or all light won't be coupled because it is exceeding the solar angle for which the collector was designed. Furthermore, the larger transverse area consumed by the sources causes interference with the light reflected from the selective mirror (Figure 12.4).

Sources transverse to the heat collector's optic axis will see a reduced apparent aperture, $\cos \beta$, and will consequently require an increased depth or narrower aperture to maintain a tighter beam (Figure 12.5). The cumulative divergence of sources would need to fall largely or entirely within the acceptance zone of the heat collection optic. Similarly, sources placed farther from the heat collector see a reduced aperture, Figure 12.6.

Transverse alignment of sources may be acceptable if clustered together, near the heat collector's optic axis. In this case, a marginal compromise in heat collection efficiency due
the increased source beam’s divergence might permit much larger system source capacity, without exceeding given spacial constraints (insertion of mirror, etc...).

Figure 12.4. Interference resulting from transverse alignment

Figure 12.5. Tighter beam required for sources transverse to the optic axis.

Figure 12.6. Tighter beam required for sources moved away from the collection optic to overcome problems associated with transverse alignment.
Angular splay of transverse sources is beyond acceptance angle of heat collector, or collection optic's acceptance angle is too wide to attain adequate concentration level.

Acceptable angular splay. Stacking of sources in the transverse direction marginally widens heat collector acceptance angle and compromises heat collector efficiency.

Bidirectional alignment. Transverse and longitudinal cluster. Line focused.

Figure 12.7. Alignment of sources along collection optic's transverse axis. A) transverse with unacceptable angular splay, B) transverse with acceptable angular splay, C) bidirectional
Inclining longitudinally arrayed source beams toward the heat (or light) collection focus would increase heat energy density by the total multiple number of sources in that cluster, Figure 12.7.

**Transverse heat collectors**

As beam divergence of the source or lamp bank increases it becomes more difficult to decouple heat for collection, and to fill the extent of the collection device. This difficulty is explicit in the transverse direction for multiple sources. The collectors warrant a convergent beam, the source provides a divergent beam. Transverse alignment necessitates a compromise.

For a given input beam, the transverse alignment of multiple heat collectors permits a decrease in collector depth for a specified concentration and temperature output (Figure 12.8). The increase of system extent is less than with the single deep reflector, because the extent of the individual smaller collector is better filled by orienting the individual reflectors toward the source center. The amount of energy is the same in either scenario, as is absorber surface area (each partitioned heat collectors has an absorber with proportioned less surface area). Extent is better preserved with transverse alignment, so higher collection temperatures can result.

Figure 12.8. Transverse alignment of sources and heat collectors. Overall beam divergence may be too high to place light decoupling mirror.
Point focus heat collector

The components of a central system are all point focus optics because the transport media are circular in cross-section, and the source’s emission is spherical in nature. The likely exception is the heat collection trough. Linear heat collectors simplify geometric considerations in the heat recovery system, and mechanical systems exist for accommodating heat flow through a linear absorber tube. Reutilization temperatures will be lower than with a point focus optic, but the heat is more readily integrated. In large system applications, or a smaller system with a large heat output, heat collection schemes may be devised that utilize efficient point source heat collector/concentrators. Akin to a solar furnace, a point focus heat collector would square the recovered concentration ratio over a comparable linear focus collector, leading to a much higher temperature and the consequent more efficient reutilization of recovered heat. Point focus heat collectors are likely to be more expensive than linear heat collection optics because they must be built to withstand high concentrations of heat.

![Diagram](image)

*Figure 12.9. Linear trough could be replaced by a point focus trough.*

The depth of a clustered component is less than the large optic that it would replace. If longitudinally arrayed, transversely arrayed, or clustered, point focus heat collectors have the same intersticial void losses as bundled fibers. However, all point focus optics can be treated in the same manner as the microcollectors at the fiber coupler: truncating and merging them to eliminate intersticial void losses.

Overlapping envelopes

A source cluster may oriented toward a single or clustered heat collector. Overall source divergence is assumed to be within the collector's acceptance angle (the heat collection and light collection angles are necessarily the same).
All clustered or arrayed 3D elements have voids. Those that are emitting radiation do not lose energy in the voids. Those that receive uniform energy do. For example, if source reflector elements are clustered, and truncated and merged in the same method as the microcollectors in the fiber optic coupler, source beam divergence would increase. There is no foreseeable benefit to doing this. However, if the component assemblies that receive radiation are merged in this fashion then the void losses can be circumvented.

**Light collector cluster with overlapping envelopes**

Inclining longitudinally arrayed source beams toward one focus at the entrance of the light coupler would result in a cluster of source beams converging in that zone. The luminance at the exit aperture of the light collection optic (the entrance aperture of the fiber) would surpass the luminance of an individual source by the number of sources in that cluster.

![Figure 12.10. Source beam divergence is strictly controlled for single light collector.](image)

The farther that the collector is from the source, the larger will be its required aperture and depth for a given beam divergence. Maximum optical performance, therefore, requires a light beam that is low in divergence and compact in diameter. But such constrained source divergence will be difficult to attain without source reflector losses. A cluster of light collectors would better fill the extent of a wider than desirable beamspread coming from the source. The greater the source's divergence and beam diameter, the greater the number of...
individual light collector elements that will have to clustered: forming an assemblage of light collectors as discussed in Chapter 11.

Merging the light collectors into a fiber optic coupler can avoid interstitial void losses which, just like the core fraction of fibers, constitutes an energy loss of at least 9% in the interstitial voids and a commensurate buildup of heat due to the losses in that area. The optic axes of the individual light collectors are oriented to converge at the source focus. The collectors partition the beam field (Figures 12.11, 12.12).

*Figure 12.11. Cluster of light collector/concentrator cones for large lamp bank applications - truncated and oriented 5°. Spires result in 3-D due to overlapping envelopes.*
The light collectors merged in this fashion will experience a small compromise in concentration because the aperture area of the individual elements is reduced slightly (from circular to hexagonal, as illustrated by the merging of microcollectors in Chapter 11) so that the energy each element manages is lessened. The merging technique is not applicable to the source cluster. The components may be configured as in Figure 12.13. This is a feasible arrangement when individual sources cannot provide enough brightness to drive individual fibers to the necessary room emitter lumen levels. The brightness contribution of multiple sources is conveyed to each fiber. A lamp’s total lumen output is matched to the number of fibers.

*Figure 12.12. Longitudinal array of sources and light collector clusters.*
The next section prescribes an alternative to clustering of sources. The approach anticipates the existence of sources with brightness of at least 3000 - 6000 cd/mm². With such brightness it is possible to significantly reduce the practical energy losses experienced in the source reflector or reflectors. This following section presents a technique for the treatment of these exceptionally bright sources that leads to a version of the central system which would attain maximum efficiency.

**Source partitioning**

A central system could be driven with a bank of fairly high brightness, high lumen output sources. The brighter that the sources are, the fewer that will be required in the cluster to deliver the desired 3000 lumens to individual single-fiber lighting fixtures. A single source with brightness of 3000 cd/mm² could run an entire system if its lumen output were high enough. With an even higher brightness source, on the order of 12,000 to 18,000 cd/mm² one can partition the source beam to deliver 3000 lumens to each fixture, dividing the brightness by the number of ports, Figure 12.14. This would eliminate the energy lost in the tip of the reflector, which could in turn allow for a reduction in the length and depth of the source reflector for a required divergence without surpassing the rated energy density tolerance of the source reflector material. If the source's UV is to be transported for phosphor stimulation at the lighting fixture, or if a fused silica fiber optic...
coupling device is used, then the lower threshold for the adequate brightness of a source being partitioned for delivering 3000 lumens to the room interface could be cut by as much as 2/3.

Figure 12.14. Partitioned source with light collector cluster.

The source's radiant output is partitioned into six identical zones. The source reflector is a hexidirectional cone, each cone subtending approximately $2/3 \pi$ steradians. Each reflector portion is actually a collector/concentrator with a concentration ratio of 20 used opposite to its intended capacity, thereby expanding and collimating its portion of the source's radiation to within desired angular parameters.

From equation (4-8), an expansion ratio of 6 results in a $25^\circ$ divergence from a $90^\circ$ source beam. The ratio of aperture areas also equal 6.

$$C = \left(\frac{a}{a'}\right)^2 = \frac{\sin^2 90}{\sin^2 25} = 5.59 \approx 6$$

Consequently, if an entrance aperture of 2" is large enough to receive its full subtended portion of the source's radiation, the reflector has an exit aperture of about 4.75" (Figure 12.15).
Light collectors are clustered and merged to receive the partitioned light. For example, each light collector couples to a single large diameter fiber and subtends 5° of the source beam. Each single fiber terminates into a square fiber near the room interface that feeds 225 single fibers (or any other squared multiple or subset, see Chapter 11). Placing the square coupler nearer the source would unnecessarily increase the system's extent, and a larger cross-sectional area of fiber would be required to carry the light. Using the square coupler eliminates interstitial voids, but lowers energy density being transported and increases system extent. In order to minimize fiber cross-section, and hence required fiber material, this extent increasing device should be placed nearer to the end of the light transporter. A cluster of 20 light collectors subtends a solid angle of about 20°. At 20 light collectors per cluster this amounts to 4500 fibers per branch, or 27,000 fibers per central assembly (Figure 12.17).
Working backwards from the end-use requirements one can establish the approximate magnitude of the required source. An output of 2500 lumens from the end of a fiber would provide roughly the luminous equivalent of a 32 watt fluorescent lamp housed inside of a highly efficient reflector, or a 150 watt incandescent halogen. Conventional point source fixtures are placed every 25 ft$^2$, or so. With the same spacing, and one fiber running to each fixture, the 27,000 fixtures illuminate an area of 675,000 ft$^2$, or 27 floors at 25,000 ft$^2$/floor. These 27,000 fibers carrying 2500 lumens each require a source magnitude of 67,500,000 lumens. This corresponds to 0.675 MW source for an HID lamp at 100 lumens/watt.

Fixtures emitting 2500 lumens are placed every 25 ft$^2$ of floor space, illuminating to 100 FC at CU = 1 for direct illumination or 50 FC at CU = 0.5 for indirect illumination. 675,000 watts/675,000 ft$^2$ corresponds to 1.0 watt/ft$^2$ of lighting related electricity, prior to factors for heat pre-emption, heat recovery and mechanical system reutilization of electric light heat, sunlight integration, solar heat recovery and mechanical system reutilization of solar heat. The 1.0 watt/ft$^2$ is a maximum value for energy consumption using conventional terminology. It does, however, assume a perfect system. Energy payback scenarios inclusive of energy losses are discussed in Chapter 13, System.

The required luminance of the source can also be determined by working backwards from the lighting fixture. The 2500 lumens emerging from an 1000 um core fiber
correspond to a luminance of 2000 lumens / mm$^2$. The use of fused silica microcollectors in the coupling stage roughly halves the required luminance of the partitioned source, which is about 1000 lumens / mm$^2$. A source that is partitioned 6 ways would require 6 times this luminance, or 6,000 lumens / mm$^2$. The potential UV contribution for increasing apparent source brightness could reduce this from 10% (the naturally occurring UV portion in an HID source) to as much as 67% (a source emitting half of its radiant energy as 1000 lumens / mm$^2$ and the rest in the UV could stimulate the phosphor emission to total as much as 3,000 lumens / mm$^2$. The tenability of this assertion is left to future research). The use of banked sources with converging beams could also reduce this required source brightness level.
Figure 12.17. Cross-section through four of six branches of a central assembly for 675,000 square foot building. Source is at center and is partitioned into six orthogonal beams by source reflector. Each beam is split by a spectral mirror. The heat beam is directed onto a solar concentration optic for refocusing. The light beam is passed through the mirror into a cluster of light collectors which further partition the light for launching into individual fibers. Configuration could be changed to pass heat and reflect light. Low concentration heat optic shown.

The depth of the nonimaging source reflector determines the divergence of the partitioned radiation beam. The more constrained the divergence at this stage the better that the extent is preserved when the mirror is positioned, but the higher the energy losses due to optical imperfections, interreflections, absorption, etc. A compact source facilitates better optical management through the entire system.

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Desired light flow levels in the fibers can be achieved by varying the source's radiative output and intensity. Dimming is centralized, not localized. Localized dimming connotes some type of energy loss, either through reflective or absorptive shuttering. Uniformity of amount of light coupled into each fiber is in the domain of the fiber coupler, and remains an area of concern.

**Clamshell**

This section introduces a modularized version of the entire optical system: a single light bulb with two outputs, one light and one heat. The clamshell is two superimposed optical systems, enabled by spectral mirror technology. It assumes a nonimaging reflector shape which preserves the extent of the lamp. The light is sent out in a beam, the angular divergence of which is determined by the depth and concentration ratio of the reflector. The tip of the light reflector is reflective VIS and transparent IR. The IR passes through the tip and is coupled into the heat collection optic. The heat collection optic may be an ellipsoidal, or two CPC's faced end to end. A heat reflector/light transmitter (AR coated visible/ high reflectivity coated IR) is placed in the light beam, completely enclosing the source.

The heat system is a closed system, with light siphoned off and directed out by the light reflector by nonimaging optical means. The radiative heat energy is retained and decoupled for subsequent use. The heat focus may be linear or point in nature.
The clamshell is a method for decoupling and reconstituting heat while preserving the extent of the source. The source reflector is a nonimaging optic. The VIS reflecting IR transmitting tip is either an involute of the source, spherical, or other surface shape. The heat recovery system is either ellipsoidal or has two CPC's faced end to end. The source tip of the heat optic is reflective IR transmissive VIS.

The light emerging from the nonimaging source reflector has extent equal to that of the source. Therefore the source's brightness is also conveyed there. Fibers placed at the aperture will receive the brightness of the source. There will however, be intersticial void losses. Using the square coupler technique will eliminate those energy losses but will increase the extent of the optical system by the ratio of total cross-sectional area before and
after insertion of the coupler. The energy density of the source in IR is transferred to the heat focus (optical extent is preserved in both systems).

![Diagram of fibers, nonimaging light reflector with spherical tip, and ellipsoidal heat recovery system.](image)

*Figure 12.19. Extent preserving optical method with fibers.*

**Conclusion**

The form of the central module depends on the brightness and lumen output of the source, the transport method and the number of lighting fixtures, the amount of generated heat, and the mechanical system's interface. This chapter presented options that could be utilized by an ideal source, or a multitude of less than ideal sources. The emitting surface area of each source must equal, more or less, the total cross-sectional surface area of the fibers if the fibers are to approach the brightness of the lamp. This is true regardless of whether the system is large or small, and has one source or many. Systems with clustered optical components can afford to be less rigorous in preserving extent. They can attain adequate brightness levels through superposition of individual source beams. This way they can approach filling the extent of the receiving optic.

This chapter presents general techniques for arranging the optical elements. They can be applied in a case specific manner. The current lack of suitable sources reduces the options significantly. Were adequate source brightnesses available, the system would use one source (1000 to 1,000,000 watts) to couple into as many fibers as the lamp's lumen output can justify. If brightness is low then a multitude of sources could be banked together until the requisite brightness is attained at the fiber coupler. The fiber coupler may have microcollectors filled with fused silica to increase concentration of light carried along the length of the fiber. The system should be engineered such that each 1 mm fiber carries between 3000 to 6000 lumens, possibly partitioning into fibers of still smaller diameter to transport and deliver 1000 lumens to specified locations.

The higher the energy density of the system the more cost effective that it is. At luminance levels higher than 2000 cd/mm², the fiber end becomes dangerously bright, and too much point source light would be emitted for standard low bay installations. Banking
sources will have higher losses because they exceed the extent of the optical system. The angle of divergence determines the physical spacing of components. Optical components spread over greater distances will demonstrate better thermal behavior because the components are larger and the energy densities incumbent upon the optical surfaces would be less. Close component arrangements would experience greater thermal stresses because of the high energy densities of even slight energy losses. The module could be small or huge: a simple integrated light bulb or an entire optical light room ("bright room").

Presently, xenon is the brightest source. It is the only one with high enough brightness to drive a 1 mm fiber to 3000 lumens. Its efficacy is low but its large throw of heat offers a tradeoff of sorts. In a retail application for example, a central xenon system could compete handily with incandescent halogens by providing the same lighting quality (color and contrast) with the added benefit of a thermal power source at the order of 2.5 watts/ft$^2$ (if the heat reutilization can be justified to the point of payback for the additional hardware). Future systems with single high brightness high efficacy high output lamps could drive the illumination for entire building systems with the optical configurations presented in this chapter. Until then sources may have to be clustered, their beams focused toward the fiber coupler. To this end, the chapter introduces longitudinal source arrays, transverse source arrays, clustered source arrays (also called lamp banks); longitudinal, transverse, and clustered light collectors; longitudinal, transverse, point focus, and clustered heat collectors. This thesis anticipates the development of sources with brightness adequate to support source partitioning for improved source reflector efficiency. Also introduced is a modularized, extent-preserving, version of the central module that encapsulates all the optical processes in a single contained unit: the clamshell. The clamshell deviates from the planar mirror approach to decoupling source heat.

By using a source with highly radiative output its energy can be managed optically. Light and heat are optically directed at points or lines (refocused but not reimaged). Generally, the heat collectors are troughs (line focus) whereas light collectors are compound parabolic with overlapping envelopes. As the source moves closer to the collection optic, the angle subtended by the collection optic increases. Conversely, the closer that the source is to the heat collector the greater the acceptance angle that the heat collector must be designed for, and the lower that the attainable heat concentration ratio becomes. Furthermore, the greater the extent of the partitioned source beam, the more optical hardware that will be required for recompressing and further partitioning the light.

There will be certain practicable limits in the amount of source collimation that is achievable. Light collectors will be truncated in the merging process. Optic centers of the light collectors will be oriented to the source focus. Light collectors will be arrayed to
accept the divergence of the source beam. Clearly, the closer the light collectors are to the source the less overall aperture they will consume and less that extent will increase.

The capacity of the system to provide illumination to large spaces can be increased by increasing the radiant power of the source. In a smaller system, lamps may be placed along longitudinal axis, transverse axis, or both as long as beamspreads remain largely inside of the collection optic's acceptance angles.

The next chapter examines the economics of a central system.
CHAPTER 13

SYSTEMS

This chapter examines the economic feasibility of two central systems and compares them with conventional systems. Economic feasibility hinges upon 1) system efficiency, and 2) preservation of optical extent. For these analyses, the preservation of optical extent is assumed.

The first system, SysteM1, is a small system, capable of being developed and implemented with currently available technology. The second system, SysteM2, revisits the example introduced in the previous chapter, the high-rise with a partitioned source, examining it in more detail. SysteM2 is more comprehensive and future oriented.

Cost for SysteM1 is estimated for prototype systems through mass manufactured units. Cost for SysteM2 is more speculative, but is established through similar reasoning. Lighting fixture emission characteristics are discussed and generic examples of lighting fixture types are provided.

Early, prototypical systems will be much more expensive than manufactured ones. This is because under normal circumstances component cost comes down as the quantity of produced components goes up. The optics are expensive initially because they are not mass manufactured, and must be built to specification as is generally done in specialty markets.

The techniques for producing them are manually intensive and vary from application to application. This will be the case until there is a standard repertoire of components that can be assembled to cater to most of the demand for centralized lighting products. The cost estimates of future systems do not reflect amortized research and development expenses. The microcollector coupler prototype, for example, will be expensive because the device is small, optically accurate, and physically precise. But once one is made, many could be stamped from the same mold.

None of the optical components is inherently expensive. None of the material substrates or films is rare. The ballast costs about 30 cents per electrical watt of transformed power. The source reflector, while deep, specially coated, and of different shape than a conventional reflector is still essentially the same device. It is a precise higher-grade version that requires more material because of its depth. Once an optimal shape is derived for mass production, it should be significantly less expensive to produce than the multitude of high-quality conventional spun reflectors it is replacing.

Conventional lighting costs from $2.50 to $6.50 per square foot of interior space [John Penney Co, Electrical Contractors, 1991]. Systems with better beam control and
lower perceived luminance levels are at the high end of this spectrum. Those installations with exposed bulbs that appear bright to the casual observer are generally less expensive. Half the cost is installation and electrical distribution from a local panel. The other half is fixture cost.

An expression for the average work-plane illuminance contributed by a lamp [Murdoch, 1985] is

\[ E = \frac{\text{Lumens} \times (CU)(LLF)}{A} \quad (13.1) \]

where Lumens refers to the initial lumens emitted by the lamp, coefficient of utilization (CU) is a combined measure of fixture efficiency and the efficiencies of room surfaces for redirecting light to the work-plane, area (A) is of the floor plan, and light loss factors (LLF) are included to account for a maintained light level over time.

For comparing a central lighting system with a conventional lighting system of identical light distribution characteristics (superpositioned within the same room for experimental comparison), CU as it relates to wall surface reflectance falls out of the equation. The CU factor, for purposes of comparison, then relates only to the fixture's distribution. The comparison is nonspecific. That is, room dimensions are not needed. Since the light emitted by the fiber is directional, the simplest method for comparing energy efficiency is orienting it downward. As \( CU = 1 \), the walls are not used, the ceiling is not used. If the fixture efficiency and light loss factors are then known, one can determine the number of lamps required to provide 100 FC to the work-plane by re-arranging variables. If the fibers are oriented other than downward (upward for indirect lighting) the efficiency of the system is unchanged, but the efficiency of the system's ability to get light to the work plane does change, and changes in a way that is specific to the size of the room, its surfaces. By orienting everything down we can see how well the systems (essentially in space) perform with regard to one another's energy efficiency.

**SysteM1**

At the smaller end of the conceivable application scale is a module for illuminating 500 SF of interior space. A standard grid ceiling plan requires somewhat less than 1 linear foot of fiber per square foot of floor space to distribute light evenly throughout the space, as is approximated in the reflected ceiling plan of Figure 13.1. If the lamp module is placed centrally at the ceiling plane, the longest fiber run is about 12 feet.
Figure 13.1. Reflected ceiling plan of a 500 SF office grid. In this most basic layout, less than 1 linear foot of fiber is required for each square foot of floor space.

From equation 13-1, 50,000 total lumens are needed, with 2000 emerging from each of the 25 the lighting fixtures \([100 \text{ FC} = 50,000 \text{ Lumens} / 500 \text{ SF}]\), to deliver 100 FC to the work surface if \(\text{CU} = 1\), \(\text{LLF} = 1\). Fixture efficiency in the conventional formula
corresponds now to system efficiency. If this is a more realistic 75%, then 67,000 lumens are needed from the lamp to include efficiency of the fixture (source reflector).

The use of fused silica fiber is predicated on the low loss transport of high energy density over lengths that support the central replacement of hundreds or thousands of individual lamps. An installation of 500 SF has runs of only 1' - 12' in length. Because of these short runs, the use of high attenuation fibers in lieu of low attenuation fibers would not compromise system efficiency significantly. For carrying a given quantity of light (2000 lumens in this example) the cross-sectional area will be much greater than fused silica, because plastic cannot support the energy density that fused silica can. However, at the time of this writing, a 1 mm diameter fused silica fiber has roughly the same cost as a 12 mm plastic fiber.

High attenuation plastic fibers are suitable for such a small application. They cannot sustain any UV, and they will be driven to nearly their capacity. By narrowing the spectrum of transported light, as suggested in chapter 6, the energy density will be optimized on a per wattage basis with the human eye's sensitivity. In order to deliver 2000 lumens it should do so at 250 lm/watt (please refer to chapter 6 for substantiation).

![Figure 13.2. Schematic cross-section of system](image)

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If used for the elimination of interstitial voids, the square coupler can increase the source's extent to the degree that the fiber's capacity is not exceeded. While a fused silica distribution system can support well beyond the energy density of the source, an extent preserving optical system would concentrate too much of the lamp's energy on the plastic fiber's end. A fiber with a 12mm diameter has 1.0 cm\(^2\) cross-sectional area, so it may need to carry at least 8 watts/cm\(^2\) of radiant energy if it to deliver 2000 lumens. Plastic fibers may be overpowered at 10w/cm\(^2\) if transported spectra coincide with absorption bands in the fiber material.

To this end, a 700 watt Philips MSD lamp is sought for initial studies using a re-entrant imaging system (Figure 13.2) with no heat reuse (passive heat preemption). The arc is not as compact as would be desired for longer range transport, but in this instance it is being selected because it is all regards similar to HMI, just smaller. Its 70,000 lumens should deliver 100 FC to the work-plane, assuming a 75% efficient system. Some scattering losses may result from re-entrant light subjected to fresnel reflection by the bulb capsule. However, if the capsule is small the scattered reflections will lie largely within the source's extent and will therefore not constitute losses.

Each square fiber is 9mm in diameter in order to butt to and completely fill each 12mm diameter circular fiber. The total cross-section of the bundled square fibers is 45mm. The focal zone of the concentrating optic must efficiently launch its light into this zone. The 7mm arc within a re-entrant reflector (so its emission is 2\(\pi\) sr) can be easily projected into the 45mm focal zone with an acceptance angle of \(\pi/3\) sr.

\[
\begin{align*}
\text{source extent} & = 2\pi \text{ sr} \left(7^2\pi/4\right) \text{ mm}^2 \\
& = 241.8 \text{ sr mm}^2 \\
\text{focal zone} & = \pi/3 \text{ A} \\
& => A = 230.9 \text{ mm}^2 \\
& => d = 8.6 \text{ mm} \leq 45 \text{ mm}
\end{align*}
\]

An extent preserving optical system requires 8.6 mm diameter focal zone to project the entirety of its lamp's output. This is smaller than the actual fiber diameter, but the fiber diameter cannot be reduced or the fiber's energy density capacity will be exceeded.

At the time of this writing, the lamp driving the proposed system is twice the lamp wattage of the largest commercially available fiber optic lighting device. With efficiency also twice that of any available fiber optic lighting product, it will deliver at least four times the light of the device type it supersedes.

While technologically expedient, plastic fiber technology can barely support a
central system of even this small size. Economic feasibility hinges upon maximizing energy density, yet not exceeding capacity. Plastic fiber systems illuminating larger spaces will experience more significant losses en route. There is no room for growth unless larger diameter fiber is used, or better clarity for longer lengths become available. The light from the 1200 watt HMI lamp, for example, could not be uniformly distributed within a larger space with any respectable efficiency.

The light emission character of the central system is comparable to conventional point sources such as tungsten-halogen and compact fluorescent. Tungsten-halogen is bright, very directional, downward oriented illumination. Compact fluorescents are duller lamps and cannot be optically directed with as much precision, so reflectors also serve as baffles to moderate the glare effects of laterally emitted light. Still, compact fluorescents offer softer light, with less contrast than tungsten-halogen.

Without heat pre-emption and reuse, the system efficacy becomes the luminous efficacy of lamp, with central and conventional sources having similar values. Larger, more comprehensive systems can compete with fluorescents in energy performance even though their light is more like tungsten-halogen in character. For smaller systems such as SysteM\textsuperscript{1}, tungsten-halogen is an appropriate comparison because the lighting character is nearly identical and a central system could replace a tungsten-halogen installation with very little apparent visual difference.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure13-3.png}
\caption{Reflected ceiling plan of a 500 SF office grid. An alternate plan would offer nonuniform, more individualized, footcandle distribution.}
\end{figure}

The central system has inherent lighting design flexibility, and there are unlimited
alternatives to the square grid downlight arrangement. In figure 13.3, for example, a 16 fixture square grid could be uplighted with the remaining 9 fixtures being used as wall washers. The reflected light would engage other room surfaces and decrease CU (less would fall on worksurface, more on walls), although the uplighted sections result in more uniform distribution reaching the workplane. Average fiber runs increase, as would average en-route losses.

Similarly, multiple systems can be interlaced, illuminating larger spaces by utilizing one lower wattage module for wall sconces or accent lighting, and a higher wattage module for downlighting. Using lamps of different color temperatures to drive the combined systems would articulate the layering.

**SysteM1 Initial Cost and Operating Cost Projections**

Prototype costs are fairly reasonable, but lamp, ballast, fiber costs will still need to come down to compete with conventional systems. Following are projected cost estimates for early prototypes through mass manufactured units. The lamp used may vary over the course of development. The MSD700 will be used initially because of its availability. It costs about $700 when purchased individually.

<table>
<thead>
<tr>
<th></th>
<th>p'type</th>
<th>β-sites</th>
<th>early products</th>
<th>mass products</th>
</tr>
</thead>
<tbody>
<tr>
<td>lamp</td>
<td>700</td>
<td>500</td>
<td>200</td>
<td>100</td>
</tr>
</tbody>
</table>

The cost is assumed to be $500 for each of the 5 lamps to be purchased for the beta-sites, which may be Fusion System's Sulfur lamp or another suitable compact arc HID. The projected costs are $200 for eventual substitutes purchased in quantity. The projected cost is $100 for mass produced lamps within pre-focused modules (This does not include an amortization of tooling costs).

<table>
<thead>
<tr>
<th>reflector module and housing</th>
<th>1000</th>
<th>200</th>
<th>200</th>
<th>100</th>
</tr>
</thead>
</table>

The prototype reflector will cost $1000; multiple reflectors for the beta-sites are projected to cost $200 each, since the tooling will be paid for during prototype fabrication. Early commercial systems will use the same tooling. Mass produced units are estimated to
Magnetic ballasting will cost $500 initially, and should come down to $250 with competitive estimates, and down to below $100 if they are to be manufactured in Mexico or overseas. Electronic ballasting appears to be too expensive to be economical at the time of this writing, since the none of the lamps considered here are in enough demand by those requiring the attributes that electronic ballasts provide. Manufacturers of ballasts generally require the purchase of 100,000 or so units prior to the development of a prototype ballast.

Fiber cost is about $5 per lineal foot for 12mm. In quantity of 8 x 20,000' purchases per year it is $4.40. There may be competitive price reduction to $2 per linear foot within a couple of years. Adding the amounts in each column, we arrive at system costs for the prototype, beta-sites, early commercial systems, and mass manufactured modules.

The prototype and beta-site installations will cost $3200 and $1950 respectively. Early manufactured systems should cost about $1300 in consideration of the discussed component cost reductions. Eventual mass manufactured systems are estimated to cost $700 initially, without consideration of installation labor, profit margin, and life-cycle advantages. Also shown are estimated cost in $/SF and $/per point.

Approximate payack periods can be determined by considering the operational expenses of a 700 watt system operating 3000 hours per year (12 hours/day 5 days/week) at $0.10/kwhr. Typical of an urban area, this would require $210 in electricity per year. Differing scenarios are shown below.
Incandescent energy consumption can easily exceed 5w/ft\(^2\), and this is why installations that are predominantly incandescent have become rare for large floor plans in commercial building interiors. For maintenance reasons, the short life of incandescent lamps further inhibits their use. Incandescent use is of premium quality and expense, and may be cost effectively applied as a supplement to ambient fluorescent systems. Exclusive incandescent use is seen in high-end retail installations. Compared with a similar tungsten-halogen MR-16 or PAR lamp installation at 5w/ft\(^2\):

<table>
<thead>
<tr>
<th>$/kwhr</th>
<th>yearly operation</th>
<th>$/yr for a 700 w syst</th>
<th>$/yr for MR-16's</th>
<th>diff $/yr * 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>2000</td>
<td>70</td>
<td>250</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>105</td>
<td>375</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>140</td>
<td>500</td>
<td>720</td>
</tr>
<tr>
<td>0.1</td>
<td>2000</td>
<td>140</td>
<td>500</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>210</td>
<td>750</td>
<td>1080</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>280</td>
<td>1000</td>
<td>1440</td>
</tr>
<tr>
<td>0.15</td>
<td>2000</td>
<td>210</td>
<td>750</td>
<td>1080</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>315</td>
<td>1125</td>
<td>1620</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>420</td>
<td>1500</td>
<td>2160</td>
</tr>
</tbody>
</table>
In the italicized scenario, there is a $1080 operating cost advantage over two years. This advantage will be more if the establishment has weekend lighting or if it is in a major metropolitan area (New York, Los Angeles) where peak electricity costs are higher. This does not consider maintenance advantages (no lamp burnout factor, central instead of local cleaning, 5000 - 15000 hour life instead of 1000 - 2000), or other light loss factor advantages (LDD, LLD) which would be reflected in a more comprehensive evaluation that included life cycle costs. A comparative evaluation of the lighting system's beneficial impact upon HVAC operation and size, as well as installation costs would improve the payback period further. Where energy costs are lower the payback period is extended.

If the system efficiency objectives are met then the payback period is 2 years if initial costs are $1080 apart. So, for a $1300 MR-16 installation ($2.60/ft2 or $52/point), the fiber product can cost $2380 and still be competitive.

The cost of the square coupler and luminaire assemblies are assumed to be negligible.

**SysteM2**

What about bigger systems? Systems that are larger than 500 SF require light to get farther than 12' away from the source. With plastic fiber, light cannot get much farther than 12' from the source because of the fiber's attenuation, unless the light is projected from the emission end (with its associated divergence) to some diffusive/reflective surface, in which case it is a projection system rather than a distribution system. High attenuation total internal reflection TIR does not accommodate a larger distributed light system. A low loss mechanism for light transport has to be used.

In certain instances hollow light guide may used to extend propagation length, such as a vertical transporter to couple into multiple fibers. Attenuation in PLG as a function of length can be much less than plastic fiber, if larger diameters (aspect ratio dependence) are acceptable. However, hollow light guide is not preserving of the lamp's optical extent if it is underfilled, and efficient usage would require clustering sources. Coupling into fibers after propagation along an underfilled length of hollow guide transport would not reconstitute the source's brightness, and would therefore require more, if not significantly more, fiber aperture area than if the lamp's light were launched directly into fibers.

Lowest attenuation media are comprised of purer, more expensive compounds. They carry energy farther, and their clarity permits a higher density of energy to be transported. An extent preserving optical methodology could, therefore, drive the transport fiber to within the energy density of the source, thereby, minimizing the overall aperture.
area of the transporter.

In bigger systems, the overall quantity of fiber per unit of light energy transported goes up as average run lengths do. Since larger systems may require more than 1LF/ft² of fiber, any growth in system size requires a decrease in fiber diameter in order to remain economically competitive. One can see that use of plastic fiber has the opposite effect. Plastic fibers need to become larger if light is to be transported farther. That is, if the beginning of the fiber is within an appreciable level of its energy density threshold, larger diameter fiber is required to accommodate a greater lumen input such that the required level of emission is reached.

The existence of vertical runs in a system would increase the required fiber amount disproportionately. The use of PLG for the vertical run to each floor can reverse this. The length of vertical transport would determine width of pipe (aspect ratio dependence), which would in turn inform lamp diameter. A lamp of adequate lumen output and of small extent (calculated for minimization of fiber cross-section) might underdrive the vertical hollow guide segment, forcing an uneconomical increase of extent and fiber size. Either the PLG diameter must decrease or the extent of vertical runs can be filled with multiple sources, larger sources, or supplemental sunlight.

Short lengths of solid core media could connect vertical and horizontal PLG tubes, so that extent doesn't increase around corners as was illustrated in a previous chapter. Since they would be of large diameter and short length, they could be made from PMMA without inducing much attenuation. There would be interface losses, which can be minimized through the use of optical coatings. This technique could support a hybrid transport/distribution system that utilizes PLG in vertical and horizontal runs to transport light to a multiple of fiber distribution subsystems. Interface losses would become significant if a multitude of such solid core bends were used serially. The relative lengths of fiber for distribution and PLG for transport would be specific to each application. Since PLG is a hollow guide it is much less expensive than a solid guide of comparable cross-sectional area.

**System² Initial Cost and Operating Cost Comparison**

The major cost component of a central system is the fiber. The published price of 3M 1 mm core fused silica fiber is $1.50/ft and at least one linear foot of fiber is required per square foot of illuminated interior space, for larger applications. Lighting fixture costs are reduced since they are vastly simplified over conventional norms. Large scale, high energy density conveyance requires fused silica. Plastic fibers cannot get the light far
enough from the source to distribute it over more than 500 SF.

In the previous chapter a single source system for a high-rise was partitioned to attain maximum source efficiency. The 27,000 fixtures were required for the illumination of 675,000 sq ft of illumination (point source are placed every 25 ft\(^2\)). Each fiber was carrying 2500 lumens and 67,500,000 total lumens were delivered. At 1 linear foot of fiber/ft\(^2\) of office space, 675,000 ft\(^2\) of fiber is required. At $1.50 / ft this amounts to $1,000,000 fiber cost. The ballast and all lighting related electrical wiring is estimated to cost $300,000. Total module costs including manufacture and installation is approximated to be $150,000, or about $1,450,000 ($2.15/ft\(^2\)) total initial cost. Costs for PLG transport segment and solid core turns are assumed negligible. This is roughly equivalent to a low end office building, and about half to one-third the initial cost of a lighting system with comparable quality in a high end office building. Energy consumption is about 1.0 watt/ft\(^2\). This is prior to factors for HVAC reduction due to heat pre-emption, heat recovery and mechanical system reutilization of electric light heat, sunlight integration, solar heat recovery and mechanical system reutilization of solar heat.
Figure 13.4. Diagrammatic central assembly for 675,000 square foot building described in Chapter 12. Initial cost estimates at $2.15 sq ft. are less than one-half the cost estimates for an equivalent conventional system.
The first system, Figure 13.4, is diagrammatic. There is an increase in optical path length. Where the mirror is inserted into the system, radiant energy diverges. This means that the collection optic will be underfilled unless supplemental source light is coupled into the system at this juncture. The only time optical path length isn't increased for a beam that is not being totally internally reflected is when the beam is perfectly collimated. This may be accomplished with a re-entrant reflector type that is parabolic-spherical. Alternatively, Figure 13.5 shows an extent preserving optical system. The heat system is an enclosed system, yet all IR energy is not reconstituted at the IR focus because the superposition of four or six IR zones does not accommodate the physical placement of any optical components within the zone of coincidence. Efficiency of heat recovery is sacrificed for efficiency of light coupling. Since the radiant heat from multiple zones are coincident, the IR focus can attain higher temperature than the individual sources. The temperature may be higher, however the amount of heat will be lower than the total of the four sources by the 
amount of heat lost (recouped perhaps convectively).

Regardless of whether the system is extent preserving or not, multiple fibers are arrayed at the light focus. The interstitial voids are to be eliminated with the circle to square to circle transformation method, or additional concentration can be achieved (within thermodynamic limits) by merging nonimaging optical microcollectors to match the numerical aperture of the optical system with that of the reflection system.

**Efficiency Comparison**

This section compares a full size centralized system and a conventional system, more closely examining factors affecting efficiency. Every installation is different in both the central system and conventional systems. For example, the amount of and method of mechanical cooling is climate and building type dependent. Light loss factors attributable to dirt and dust accumulation depend on climate, building usage, cleaning regimens, and lamp type. Light loss factors vary considerably even within the category of commercial buildings so it is difficult to make a complete or precise comparison, except to perhaps bound the problem. Central systems are not as susceptible as conventional systems are to the maintenance factors that degrade performance. Because of the elimination of convective currents at the fiber's emission end, and the programmed replacement of the central source before expiration, the lumen maintenance and depreciation factors will be better than conventional lighting. Maintained values are close to initial values.

In this brief analysis, conventional illumination is represented by the compact fluorescent, which is by all standards the state of the art in energy efficiency and longevity. At the time of this writing, many federal and state government programs underwrite the retrofitting of compact fluorescents in residential, commercial, and industrial applications. While it is unlikely that a large building would be lighted exclusively with compact fluorescents (for reasons of initial cost), they are closer in directional characteristics to a central system than linear fluorescents. Compact fluorescent installations are at the higher end of the cost spectrum because more point sources are needed for uniform coverage than linear sources, and more labor is required for the installation of more fixtures. To make the comparisons fundamental, compact fluorescents are compared with the central systems for efficiency and luminous distribution, while linear fluorescents are compared with the central system in the evaluation of cost. The labor involved with installation of one of multiple fiber ends is approximated at 1/2 to 1/4 that of a conventional fixture (connections completed at factory, no electrical work at luminaires).
**Cases**

Six cases compare a central system's overall efficacy in delivering the same number of lumens to the room as a conventional system, building upon reutilization of lighting heat and incorporation of solar energies that are enabled via the central electric system's collection and distribution systems.

Where there is no A/C penalty from heat produced by the lighting system, in a cool climate perhaps where excess building heat is ducted out with a fan, a central system that preempts heat from entering the space but does not collect and reutilize the heat in any way is most difficult to justify economically. This will be referred to as case 1. Case 2 considers this in the context of a more advantageous system in which there is a seasonal or year round A/C penalty (by #15 explained shortly), such as the majority of commercial office buildings that are perpetually cooling (even when they are heating). Cases 3 and 4 compare a conventional system with a central system that reutilizes this heat partially or completely by the mechanical system. Case 5 considers a comparison balanced for the introduction of peak solar light. Lastly, case 6 is a system balanced for the introduction of maximum solar heat and daylong solar light. While the individual energy loss factors change on a case by case basis and could vary widely, conservative values are chosen to reflect expected conditions.

**Assumptions of conventional system**

The following assumptions are made for a 13 watt compact fluorescent lamp.

1. **BF - Ballast Factor**
   
   1 - 3 watt ballast loss for magnetic or electronic ballasts driving a 13 watt compact fluorescent; consult Valmont, Magnetek or others.

2. **EFC - Efficacy**
   
   50 - 80 lumen /watt efficacy value for compact fluorescent lamps; consult GE, Osram / Sylvania, or others.

3. **Removal of heat**
   
   The ASHRAE guidelines stipulate a 0.4 heat removal factor, that is 0.4 watt is required to remove 1 watt of heat. Actual factor is climate dependent and may be much lower if not all heat is to be removed, especially in cooler climates where a fan removes the heat instead of an air conditioner.

4. **LDD - Lumen Dirt Depreciation**

   The IES reference handbook suggests a 0.8 LDD lumen dirt depreciation factor for a cat IV fixture.
in a clean environment with a 24 month cleaning interval. Convective currents stimulated by heat
deposit dust and dirt on lamp and fixture surfaces. Factors of 0.9 or above are unusual and require
frequent cleansing.

5. LLD - Lamp Lumen Depreciation

Lamp Lumen Depreciation factor is a result of natural lamp aging. It affects some lamps more
than others, but all lamps are affected to some degree. Most notably affected are incandescents (not
halogen) and metal halide whose LLD factors can approach 0.6. A 0.8 value for compact
fluorescent lamps is taken from GE, or Osram / Sylvania catalog.

6. EFF - Efficiency

The IES Ready Reference Handbook provides efficiency factors for most lamp fixture types. For
recessed downlights, efficiency values decrease as visual comfort increases. Consequently, fixtures
with good efficiency generally result in a low utilization of light (indirect lighting) or glare
conditions (low beam control). The value used is for a recessed high efficiency fixture for a large
point source.

Assumptions of Centralized System

Energy use ratios are shown at the top of each page. Light/energy losses en route are shown conceptually as per unit quantities.
The central source is shown in per unit value, and is not necessarily a single port source reflector. The following assumptions are applied.

7. LDD - Lumen Dirt Depreciation

Centralized cleaning, 6 month intervals, hermetically sealed cabinet allow for the absolute
minimization of LDD lumen dirt depreciation. Convection currents at the room emitter are nearly
eliminated due to the pre-emption of heat.

8. LLD - Lamp Lumen Depreciation

The lamp lumen depreciation LLD is likely to be higher than the LDD, especially for high
brightness HID technologies. The effects of low LLD can be lessened through the programmed
replacement of the lamp before expiration. LLD can also be partially offset by increasing the line
voltage toward the end of lamp life. This will affect the color of the light. Lamp cost is a
negligible portion of the entire system cost so the lamp is treated as disposable and can be replaced
frequently without affecting economics. Fusion Systems reports a 0.95 LLD. That value is taken here.
9. REFLECTOR EFFICIENCY

0.95 efficiency of directing illumination from lamp onto microcollector array, or first TIR interface. Maximum attainable reflectivity in visible region. Anti-reflection coating is applied to any surfaces that energy passes through, such as a refractive microcollector.

9A. COUPLER EFFICIENCY

0.90 efficiency in elimination of intersticial voids, uniformizing beam, and launching of light into fibers. May include losses in microcollectors due to imperfections, kaleidoscoping square coupler, etc... Fiber ends are AR coated. Microcollectors have the highest attainable VIS reflectivity.

10. FIBER ATTENUATION

3M 1mm fused silica core, TECS clad, 10db att @ 475nm 50 meter run

11. LOSS AT EMITTER LENS

Lens affixed to end of fiber to reduce luminance. Gould Inc. graded index miniature lenses, antireflection coated 0.5% loss (0.25% at each end surface) or reflector NiOptics, Evanston, Ill.

12. LDD(2) - Lumen Dirt Depreciation at room emitter

0.98 factor for dirt accumulation on lens end. Reduced due to elimination of convection currents associated with localized heat, assumes clean environment.

13. Value for reconstitution of heat energy.

Assumes that all IR is decoupled but that only 70% of IR is converted to heat. Sunmaster non-imaging solar collection hot water energy transfer efficiency, 1975.

14. BF - Ballast Factor

Ballast losses are assumed at 7% of required lamp power.

15. HEAT REMOVAL

removal of heat generated by ballast and absorption of light lost en route. ASHRAE factor 0.4.

16. HEAT RECOVERY

This does not make a statement as to how efficiently recovered heat will be utilized, which is a function of temperature of the recovered energy and mechanical system performance.

17. BEAM SPLITTER

18” x 18” selective filter on glass substrate. 98%+ efficiency available
CASE 1

no A/C penalty
clean interior environment
recessed fixtures
no heat reuse
80% light system efficiency
ENERGY USAGE COMPARISON

2 : 1

centralized source of 675,000w @ 100 lm/w scaled down for one of 27,000 individual luminaires

25 w (2500 lm) centralized source

HEAT

LIGHT FIBER

CONVENTIONAL

3 watt ballast loss (#1)

4 - 13 watt compact fluorescent @ 80 lm/w =4160 lm (#2)

LIGHTING FACTORS

TOTAL LUMENS
= 4160 lumens
xLDD(.8)(#4)
= 3330 lumens
xLLD (.8)(#5)
= 2665 lumens
xEFF (.75)(#6)
= 2000 lumens

LIGHTING ENERGY

52 w (lamp power) + 3 w (ballast losses) = 55 w for 2000 net lumens

55W

SINGLE SOURCE

2036 (transported)

LIGHTING FACTORS

TOTAL LUMENS
= 2500 lumens
xLDD(1.0)(#7)
= 2500 lumens
xLLD (.95)(#8)
= 2375 lumens
xOPTICAL EFF(.95)(#9)
=2256 lumens
xCOUPLING EFF (.95)(#9A)
=2143 lumens
xFIBER ATTEN. (.95) (#10)
=2036 lumens
xEFF (.995)(#11)
xLDD(.985)(#12)
=1995 lumens

LIGHTING ENERGY

25 w lamp power per unit + 0.52 w ballast losses (#14) = 25.5 w for 2000 net lumens

25.5W
CASE 2

- A/C penalty
- clean interior environment
- recessed fixtures
- no heat reuse
- 80% light system efficiency
ENERGY USAGE COMPARISON

3 : 1

centralized source of 675,000 @ 100 lm/w
scaled down for one of 27,000 individual luminaires
25 w (2500 lm)
centralized source

25 w (2500 lm)
compact (2)(#2)
2036 (transported)

25 w lamp power per unit
+ 0.52 w ballast losses (#14)
= 25.5 w for 2000 net lumens

76W

25.5W
CASE 3

A/C penalty

- clean interior environment
- recessed fixtures
- 70% heat reuse
- 80% light system efficiency
ENERGY USAGE COMPARISON

4 : 1

centralized source of 675,000w @ 100 lm/w
scaled down for one of 27,000 individual luminaires
25 w (2500 lm)
centralized source

12.5w IR beam
12.0 w
2400 lm

2400

LIGHT FIBER

HEAT
12w (@70%) = 8.4w
POWER to HVAC (#13)

HEAT REMOVAL
20.8 watts for removal of 52 watts heat (#3)

LIGHTING FACTORS
TOTAL LUMENS
= 4160 lumens
xLDD(.8)(#4)
= 3330 lumens
xLLD (.8)(#5)
= 2665 lumens
xEFF (.75)(#6)
=2000 lumens

2000 lumens

LIGHTING ENERGY
52 w (lamp power)
+ 3 w (ballast losses)
+ 20.8 w (AC penalty)
= 75.8 w for 2000 net lumens

76W

CONVENTIONAL

nonimaging optical reflector or lens

SINGLE SOURCE

2036 (transported)

LIGHTING FACTORS
TOTAL LUMENS
= 2500 lumens
xLDD(1.0)(#7)
= 2500 lumens
xLLD (.95)(#8)
= 2375 lumens
xOPTICAL EFF(.95)(#9)
=2256 lumens
xCOUPLING EFF (.95)(#9A)
=2143 lumens
xFIBER ATTEN. (.95) (#10)
=2036 lumens
xEFF (.99,5)(#11)
xLDD(98.5)(#12)
=1995 lumens

2000 lumens

LIGHTING ENERGY
25 w lamp power per unit
+ 0.52 w ballast losses (#14)
+ 1.6 w removal of heat (#15)
= 27.1 w for 2000 net lumens
- 8.4 w reused HVAC power
= 18.7 w for 500 net lumens

18.7W
CASE 4

A/C penalty
clean interior environment
recessed fixtures
100% heat reuse
80% light system efficiency
ENERGY USAGE COMPARISON

5.2 : 1

centralized source of 675,000w @ 100 lm/w
scaled down for one of 27,000 individual luminaires

25 w (2500 lm)
centralized source

HEAT
12.5 w (@100%) = 12.5w
POWER to HVAC (#13)

conventional source of 675,000w @ 100 lm/w
scaled down for one of 27,000 individual luminaires

25 w (2500 lm)
centralized source

HEAT REMOVAL
20.8 watts for removal of 52 watts heat (#3)

LIGHTING FACTORS
TOTAL LUMENS
= 4160 lumens
xLDD(.8)(#4)
= 3330 lumens
xLLD (.8)(#5)
= 2665 lumens
xEFF (.75)(#6)
=2000 lumens

LIGHTING ENERGY
52 w (lamp power)
+ 3 w (ballast losses)
+ 20.8 w (AC penalty)
= 78.8 w for 2000 net lumens

2000 lumens

SINGLE SOURCE

nonimaging optical reflector or lens

2036 (transported)

LIGHTING FACTORS
TOTAL LUMENS
= 2500 lumens
xLDD(1.0)(#7)
= 2500 lumens
xLLD (.95)(#8)
= 2375 lumens
xOPTICAL EFF(.95)(#9)
=2256 lumens
xCOUPLING EFF (.95)(#9)
=2143 lumens
xFIBER ATTEN. (.95) (#11)
=2036 lumens
xEFF (.99.5)(#11)
xLDD(98.5)(#12)
=1995 lumens

LIGHTING ENERGY
25 w lamp power per unit
+ 0.52 w ballast losses (#14)
+ 1.6 w removal of heat (#15)
= 27.1 w for 2000 net lumens
- 12.5 w reused HVAC power
= 14.6 w for 500 net lumens

2000 lumens

76 W

14.6 W

p. 210
CASE 5

partial peak-sun integration (enough sunlight to supplant 1/2 of electrical light)
A/C penalty
clean interior environment
recessed fixtures
70% heat reuse
80% light system efficiency

This case assumes 1250 solar lumens are integrated for each fixture, reducing electrically provided lumens from 2500 to 1250. With luminous efficacy of sunlight taken as 125 lumens/watt [Littlefair, 1990], this amounts to 10 w of radiant energy: one-half (5w) of which is light and one-half (5w) of which is IR. This corresponds to a solar collector surface area of 1/50th m² per fixture (neglecting losses), or 540 m² to provide this much light to each of the 27,000 fixtures in this example.
ENERGY USAGE COMPARISON

11.7 : 1

INTEGRATED SOURCE

centralized source of 675,000w @ 100 lm/w
scaled down for one of 27,000 individual
luminaires

12.5 w (1250 lm)
centralized source

Sun heat + Electric light heat
5 w + 6.25 w = 11.25 w
11.25 w (@70%) = 7.9 w POWER to
HVAC (#13)

CONVENTIONAL

3 watt ballast loss (#1)

HEAT REMOVAL
20.8 watts for
removal of 52
watts heat (#3)

4 - 13 watt compact
flourescent @ 80 lm/w
=4160 lm (#2)

LIGHTING FACTORS
TOTAL LUMENS
= 4160 lumens
xLDD(.8)(#4)
= 3330 lumens
xLLD (.8)(#5)
= 2665 lumens
xEFF (.75)(#6)
= 2000 lumens

LIGHTING ENERGY
52 w (lamp power)
+ 3 w (ballast losses)
+ 20.8 w (AC penalty)
= 75.8 w for 2000 net lumens

76W

SINGLE SOURCE

4160 lm (#2)

nonimaging optical
reflector or lens

LIGHTING FACTORS
TOTAL LUMENS
= 2500 lumens
xLDD(1.0)(#7)
= 2500 lumens
xLLD (.95)(#8)
= 2375 lumens
xOPTICAL EFF(.95)(#9)
= 2256 lumens
xCOUPLING EFF (.95)(#9A)
= 2143 lumens
xFIBER ATTN. (.95) (#10)
= 2036 lumens
xEFF (.995)(#11)
xLDD(.985)(#12)
= 1995 lumens

LIGHTING ENERGY
12.5 w lamp power per unit
+ 0.26 w ballast losses (#14)
+ 1.6 w removal of heat (#15)
= 14.4 w for 2000 net lumens
-7.9 w HVAC power
= 6.5 w for 2000 lumens

6.5W
CASE 6

total sun integration (peak solar hours)
A/C penalty
clean interior environment
recessed fixtures
70% heat reuse
80% light system efficiency

This case illustrates enough sunlight integration to completely offset electrical lighting during peak solar conditions. Solar collector surface area would have to be doubled over that of case 5, to 1/25 m² per fixture or 1080 m² for the total building installation. The building exists in a generative capacity, with collected solar heat stored as thermal energy or fed back to the grid.
ENERGY USAGE COMPARISON

76 : -3.9 generative

INTEGRATED SOURCE

centralized source of 675,000w @ 100 lm/w
scaled down for one of 27,000 individual
luminaires
0w (0 lm)
centralized source

SUN
2500

10.0 w
2400 lm

IR beam
10.0 w

2400

LIGHT FIBER

10.0 w (@70%) = 7 w POWER to
HVAC (#13)

CONVENTIONAL

3 watt ballast loss (#1)

HEAT REMOVAL
20.8 watts for
removal of 52
watts heat (#3)

ceiling

4 - 13 watt compact
fluorescent @ 80 lm/w
=4160 lm (#2)

TOTAL LUMENS
= 4160 lumens
xLDD(.8)(#4)
= 3330 lumens
xLLD (.8)(#5)
= 2665 lumens
xEFF (.75)(#6)
=2000 lumens

LIGHTING FACTORS

LIGHTING ENERGY
52 w (lamp power)
+ 3 w (ballast losses)
+ 20.8 w (AC penalty)
= 75.8 w for 2000 net lumens

76W

SINGLE SOURCE

nonimaging optical
reflector or lens

2036 (transported)

TOTAL LUMENS
= 2500 lumens
xLDD(1.0)(#7)
= 2500 lumens
xLLD (.95)(#8)
= 2375 lumens
xOPTICAL EFF(.95)(#9)
=2256 lumens
xCOUPLING EFF (.95)(#9A)
=2143 lumens
xFIBER ATTEN. (.95) (#10)
=2036 lumens
xEFF (.995)(#11)
xLDD(.985)(#12)
=1995 lumens

LIGHTING FACTORS

LIGHTING ENERGY
0 w lamp power per unit
+ 0 w ballast losses (#14)
+ 4 w removal of absorbed light (#15)
= 6 w for 2000 net lumens
- 7.9 w HVAC power
= - 3.9 w for 2000 lumens

-3.9W generative
These system level comparisons measure lighting efficiency in delivering 2000 lumens to a room. In Case 1, luminous efficiency and system efficiency are essentially the same. When A/C penalty is included in case 2, the efficiency ratio increases to 3:1. Case 3, introduces some reuse of the lighting related heat and the energy comparison jumps to 4:1. Case 4 presents the instance of an improved optical system for heat recovery, which is possible given the radiative nature of the recollection process, 5.2:1. Case 5, 11.7:1, demonstrates partial sunlight and solar heat integration. Immediately, there are tremendous excesses of heat power available. Case 6, a generative case, is balanced such that sunlight can drive the lighting system during peak hours. A 1080 m² rooftop solar collector array is required. A seventh case, not included, would overpower the light fixtures with solar light in order to take full advantage of the solar heat. In this instance, inefficiencies would have to be introduced such that some of the sunlight is siphoned off and absorbed by the heat system prior to being transported so that too much light isn't brought into the room.

Payback period estimates are applicable only if a conventional system's initial cost is less than a comparable central system. In this event, operating expense savings are amortized against the difference in initial costs. Initial cost of central systems are projected to be less than comparable conventional systems, however, it is too far from practice to be able to deduce this accurately. If a low expense electric light system is taken as $2.50/ft², then initial cost is in the range of $1,687,500. If the central system costs more than anticipated, say $4.00/ft², then its cost is $2,700,000. The differential of $1,012,500 corresponds to 10,000,000 kwhr at $0.10/kwhr. The compact fluorescent installation is consuming on the order of 2.0 w/ft², or 1350 kw (assuming 1.6 w/ft² lighting, and 0.4 w/ft² cooling related to lighting). This is 13,500 kwhr taken over a 10 hour day. That is, it is requiring almost $1350 per day to operate. Operational expense on a yearly basis is $404,000 (6 day week). It is against this figure that one can estimate payback periods. A central system can at best reduce the electrical expense to zero during peak solar conditions. In that case, the heat power generated is assumed to just compensate for the electrical energy consumed during off-peak conditions. The initial cost factor is still a pivotal one. Where electrical energy is more expensive the relative increase of efficiency will more pronouncedly impact the payback period.

If the central system has a system efficiency of 3:1 over that of a conventional system, as in case 2, then it would be consuming an overall 0.67 w/ft². The savings of 1.33 w/ft² would amount to $262,000/yr, exclusive of maintenance advantages. Savings in electrical expenses would outweigh initial cost disadvantages of a central system in not more than 4 years. A conventional system comprised of compact fluorescents, or of other
lamps with similar directional characteristics, could easily cost much more than $2.50/ft\(^2\). Obviously, the payback period will be less where electricity expenses are higher.

A case 4 central system with efficiency of 5.2:1 would consume 0.4 \(\text{w/ft}^2\), offering $323,000/yr in electrical savings. This would reduce the payback period to within 3 years. Yet, even a case 5 system that integrates sunlight to partially offset peak noontime interior conditions with 11.7:1 efficiency advantage will not bring the payback period within the one to two year time frame that would stimulate capital interest.

Capital interest will exist where conventional systems cost more, say $5/ft\(^2\). In such a case payback periods are hard to formulate because initial cost is already less than a conventional system. The cost of energy in the US is not high enough to give an economic edge to energy saving technologies that are not less expensive initially.

**Emission**  
It is unlikely that compact fluorescent fixtures will achieve better efficiencies and improved light loss factors for recessed downlighting. The end lighting is similar for the two systems, with better optical control and distribution characteristics likely to be with the central system because of the compactness and directionality of the light emitted from the fiber in comparison to the relative dullness of the compact fluorescent. A pendant mounted fluorescent direct/indirect lighting fixture has better efficiency than a recessed one whereas a recessed, directional central fixture would be likely to exhibit greater efficiency than one modified to direct its light upward. The efficiency scenarios are representative of general point lighting, where good beam control is desired. Lesser beam control works against an inherent advantage of the central system's emitter.

Each watt of transported illumination can provide as much as 250 lumens, regardless of the type of source. As discussed in previous chapters, there are certain limits to the amount of concentration an optical system can provide. The intensity of illumination carried along the fiber length depends on a number of factors: 1) the energy density of the radiation emitted at the source (brightness), 2) whether multiple lamps are banked together and additively converging their light, 3) the use of filled microcollector, and 4) the concomitant transport of UV for phosphor stimulation at the lighting fixture.

In this chapter it is assumed that adequate energy density can be provided by the source to drive each fiber to 3000 lumens. In many applications a 3000 lumen point source is too bright to provide comfortable downlighting, so providing 1000 lumens per fiber for emulating a 75 watt halogen PAR is seen as the minimum feasible fiber output for economic feasibility and widespread marketability. Generally, the less light delivered per fiber, the less economically viable the system is in comparison to a conventional system.

The best case economically is the worst case for the room emitter. A 3000 lumen
incandescent lamp is considered too bright for many interior applications. 3000 lumens emitted from a 800 um core fiber (0.5 mm$^2$) is even brighter, at 6000 lumens/mm$^2$. This brightness must be shielded from the eye. In downlighting applications this could be accomplished with a lens. Indirect lighting would reduce the luminance significantly, but downlighting more efficiently utilizes the light since it is delivered where needed, not diffused over all wall surfaces. Alternatively, the 3000 lumens could drive a fluorescent simulator, as shown in Figure 13.7. Any of a number of commercially available lenses can be affixed to the fiber end for reducing brightness. Lenses, glare shields, diffusing plates become designer's tools for enhancing the visual comfort of the space by manipulating emission.

Since the fiber may be emitting UV, as well, a phosphor plate could convert the UV to VIS while shielding the occupant from glare. A recessed downlight is the simplest construction, needing only a lens to reduce the luminance of the emission end if the fiber. Figure 13.6 suggests two other fixture types for use as the room emitter. In both instances the fiber end is shielded. Some of the blue end of the spectrum is absorbed in the fiber so for longer fiber runs the delivered color is similar to incandescent halogen.
Figure 13.7 is a simple, low-loss optical system for diffusing fiber piped light in such a way as to simulate a fluorescent tube. A mirror is placed at each end of a transparent tube that has a refractive TIR film applied to its interior. A light carrying fiber is punched through the center of one of the mirrors. This becomes the entrance end of the device. The light then bounces along the length of the tube diffusing 2% of its energy with each bounce, provided that the light emitted from the fiber is within the acceptance angle of the film. When the light hits the mirror at the end of the tube it is sent back along the length diffusing more light with each bounce. Only a negligible percentage of light gets reflected back into the fiber.

The 3000 lumen output is the rough equivalent of a 34 watt fluorescent tube. However, a simple way to reduce the luminance at the output is to collect it into the device
outlined above. Shorter lengths would have higher surface luminances. It assumes only visible light is transported down the fiber. Phosphors coated on the inside of the tube to convert UV to light would interfere with the refractive nature of the emitting device, and the PLG material will breakdown over time when subjected to UV.

At 48" to fit into existing fixtures as a retrofit, the tube would be 1" in diameter to simulate brightness of a T-8, and 1 1/2" in diameter to simulate brightness of T-12. Luminance would vary according to surface area, so lengths greater than 48" would have decreased luminance for a given fiber output. This would grant a great deal of flexibility to interior lighting designers who might want to experiment with troffer lengths differing from conventional practice. Even within the vein of conventional ceiling grids, luminance can be suitably tailored on-site without having to resort to changing lamps, ballasts, and fixture hardware.

A high-attenuation fiber could also be used, but luminance along its length would be likely to be less uniform. Also, its absorption losses would be higher, and its brightness might be too high for visual comfort so it would have to be placed inside a diffusing volume which would lower further its efficiency when compared to the method suggested in this disclosure.
CHAPTER 14

CONCLUSION

Half of the sun's energy that reaches the earth is light and half of it is radiative heat. The sun can provide 10,000 FC and 500 w/m² of heat simultaneously at peak conditions, or 1 kw/m² of heat if all of the energy is absorbed. Solar heat causes AC loads to skyrocket in buildings with large fenestrations, working against the huge potential merit of perimeter sunlighting. Peripheral shading devices are in effect denying that solar heat is available energy. Building's are overwhelmed by radiant energy and usable light. Because the energy isn't managed, it is expeditiously rejected. Buildings are consuming energy to encapsulate themselves from the energy incumbent upon their envelopes. In an age when much of the conservation effort in this country and in the world is trying to reduce the energy consumed by buildings, the state of the art daylighting and energy research is being accoladed for reducing AC by rejecting solar heat associated with sunlight. Ironic.

With electrochromic devices being developed at RPI Lighting Research Center and other places, solar heat may enter the building interior in the morning hours only to be shuttered away in afternoon hours along with the sunlight, when solar energy is at its highest potential. In no way do perimeter fenestration systems permit the usage of light and heat, it is one or the other or neither. And the use of photovoltaics is largely uneconomical, (they don't pay for themselves with the energy they produce and do little more than burden the reputation of solar energy because they are so expensive and their feasibility is so limited), and arguably counterproductive when turning solar energy into electricity for conversion back into light. With this in mind, it is difficult to justify that the majority of solar research dollars are funnelled into photovoltaic research.

Only central solar energy via rooftop collection is considered strategically in this thesis, although the techniques presented here could be extended to the exterior wall surfaces of a building as well (Figure 14.1). The building becomes an energy sponge as opposed to an energy shield: passing through some or all the light, soaking up and concentrating the heat energy, or absorbing all energy for concentration and conversion into a high temperature thermal reservoir. This thesis does not address any other peripheral usage of sunlight and solar heat.
Figure 14.1. Transparent concentrating solar collector for use as a window or skylight (above). Heat mirror applied to nonimaging optical trough (or merged matrix of 3D optics) with transparent substrate. Depth of trough determines angular cutoff so that thin film doesn’t experience angles of incidence outside of its optimum performance range. Heat collecting and concentrating wall (below).
Even small rooftop collection strategies for sunlight can overwhelm a building’s interior with light during peak periods. This sets an upper limit to the amount of solar collection applied at the rooftop. Because the sunlight is so intense, the solar heat constituent remains underutilized. One approach to increasing the usable heat that is garnered by this collection strategy might be to use an inefficient system: siphoning off surplus light with the IR for conversion into heat power. Or at least, devising a scheme to siphon off surplus only during peak solar conditions. In this way, the building would be optimized for solar light and heat collection earlier and later in the day without being overpowered by sunlight at noon. If the siphoned energy were managed instead of rejected then the sun's full potential could be harnessed all day long. The proportion of light to heat admitted would be designed with regard to building type.

The work presented in this thesis is a solar technology masquerading as an electric one. Presented is an approach to assimilating solar techniques to reverse the demise of solar energy through incorporation of electric light. There is yet no source of artificial light that runs on anything other than electricity. So, we are dependent on the electric source for the generation of light much of the time. The electric light is at least half heat, and generally much more. In the lighting of building interiors, we are using heat sources for their light. Even energy saving fluorescent lamps are 80% heat. Lamp/fixture combinations that emit more than half of their energy as light are not suitable for interior illumination because their color strays too far from CIE standards for interior illumination. Those suitable for interior illumination sustain overall efficiencies of up to 20%. The rest is wasted energy that the consumer pays the electric utility for producing, and which is ducted out of the space by even more wasted energy.

The better the visual comfort of the space, the lower the overall efficiency of conventional illumination by virtue of the coefficient of utilization CU or fixture efficiency. Because of the heat accompanying the production of light at the fixture, convective currents are set up that circulate dust and dirt around the light bulb jacket, depositing dust and dirt that reduces output of the lamp/fixture by 20% over 24 months, even in a clean environment. Lamp output naturally decreases with age. This lops another 20% off of the lamp’s lumen output over two years. A lamp that lasts for 10 years, such as the recently heralded E-Lamp, is covered by dust and dirt by that time and the output is reduced commensurably. It is less expensive to replace a bulb than to clean one regularly. Central illumination tends to reverse a number of the shortcomings exhibited by conventional illumination methods by: centralizing cleaning, relamping, and maintenance, providing full spectrum excellent color light, eliminating thermal, structural, and electrical hardware in room lighting fixtures.
The luminous efficacy of the source is different from the luminous efficacy of the system. While the variety of relevant source efficacies range from 10 to 100 lumens/watt, the system efficacy approaches the maximum theoretical limit for continuous spectrum light of 250 to 300 lumens / watt regardless of the type of source. The concomitant use of sunlight and solar heat to offset electrical consumption can give a central electric system significant cost and operating expense advantages, without compromising the quality of the visual environment. If anything, the controlled beamspreads of light energy emerging from the transporter will allow the designer greater flexibility and precision in articulating space.

The electric system was intended to supplement the solar one: offsetting costs by sharing the expensive distribution grid. However, basic economic studies indicate that the electric system could warrant the expense of the distribution grid itself, making rooftop solar collection strategies a mere matter of affixing simple rooftop hardware only. This could revitalize the sunlighting segment of the solar industry whose systems couldn’t pay for themselves in solar’s last great wave of installations in the 1970’s.

There are two completely separate yet interdependent sets of technical problems with the central electric system: the source and the optical system. While preserving extent, the optical system preserves the electric (and solar) source’s output as radiative, permitting optical processing of the energy as a means for comprehensive radiation management. The optical system directs the energy, decouples the IR from the sources, reroutes it and processes it for its potential as a thermal power source. The light and heat energy may be processed using nonimaging optics, a type of very high aberration optic that allows for concentrations to surpass that of ordinary concentrating lenses and to approach the thermodynamic maximum (that of the luminance of the source). Nonimaging optics is being developed by Roland Winston, University of Chicago, for solar applications. The differences between the management of solar energy and electrically induced radiation are not trivial. Sunlight is in a collimated form, from a source with a very high density of energy. The electric light is emitting in all directions and it is difficult to manage and convey optically without large losses. The energy density of the electric light also falls well short of that of the sun.

The exact mechanical system interface is beyond the scope of this thesis, although cooling through absorption chilling is a likely candidate for the electrically and solarly generated IR when the heat can’t be used directly within the building envelope. The IR could also be converted to electricity via photovoltaics. Better system efficiency could be attained with the invention of a heat transfer tube that integrates photovoltaics along the absorption surface (thereby capturing the energy that radiates out of the rear of the pv device), or the radiative heat could be transported through fibers to serve heating needs.
This thesis introduces optical techniques that if properly developed can satisfy the two factors that are critical to the feasibility of centralization: the absolute minimization of the fiber transporter cross-sectional area, and the absolute minimization of energy losses which not only reduce the competitive energy efficiency advantage of centralized light but lead to localized zones of high thermal stress and failure. The work takes departure from conventional fiber optic illumination devices, letting fiber optic lighting get much bigger than the novelty applications it now satisfies.

Conventional fiber optic devices are fundamentally inefficient and restricted to low source power because the sources are not compact enough (the fiber's NA is filled yet the source's extent is greater than the fiber's), and because the energy trapped in the fiber's interstitial voids leads to thermal breakdown. Some of the heat is dissipated through the use of dichroic reflectors and active or passive cooling, but the large component of heat that is still resident in the beam is abruptly absorbed within the interstitial voids or melts the inherently absorbing (high attenuation) fiber that is being used for its backscattering effect. In no conventional devices is the IR kept radiative, and the feasibility of doing this in a central system rests on finding application for the recovered heat, which building applications would fulfill.

This thesis determined that extremely high-output (1,000,000 watts), high-efficacy (100 lm/watt) lamps with superior color renditioning quality may not be suitable for fiber optic deployment. The optical system is controlled by the source in one critical way: brightness. The maximum amount of light that can be carried by a fiber is limited by the brightness of the source (lumens/mm²) not the lumen output of the source. The higher the luminance of the source the more efficiently and economically the optical system will be able to manage the source's output. For the most efficient module configuration, this brightness should equal the luminance of the fiber end: 2400 lumens through a 1 mm² fiber requires 3000 cd/mm² emitted by the source. So although the fibers can carry the light, and although an optical concept for coupling the light into the fibers without loss is presented, there isn't a source currently made (xenon excepted) that is capable of driving the fibers to the desired level of luminous output, even though the lumen output of some are plentiful. Sources with lower brightness, yet other desirable attributes, would require many times more fiber aperture area to deliver 3000 lumens to the room interface. This would impair economic feasibility for larger systems. The lowest lighting level capacity that would open up entry markets are systems carrying 1000 lumens per fiber, emulating 75 watt halogen PAR lamps.

The brightest source is xenon, emitting at 2600 cd/mm². Although its efficacy is low, it is highly radiative. Like an incandescent, it throws a lot of heat with high utilization
potential. The attributes of xenon make it a candidate for a system that emphasizes the heat. A xenon application would provide enough heat so that even in a small application it could serve some utility. Such availability of waste heat should encourage the development of room size absorption chiller units. A building could also use two simultaneous but completely different systems. One with xenon for general ambient lighting carrying 3000 lumens per fiber, layered against one with HID carrying 1000 lumens per fiber.

Higher efficacy lamps are generally too dull to serve in a single source version of the central module, although this fact can be tempered by any or all of a number means. One such means is the inclusion of the UV generated by the source (as much as 10% of the sources output energy), with the light being transported to the habitable space. The UV would be emitted from a fiber's end in a cone like the fiber's acceptance cone: a spotlight of VIS and UV. If the luminaire's glare shield in this instance has a coating of phosphors the cone of UV radiation emitted from the fiber could be absorbed and re-empted as visible light into the room. In the system being proposed by this thesis the UV efficacy of the source can be taken into account as a contributor to the luminous efficacy. Or, in other words, the definition luminous brightness is a combination of UV brightness and VIS brightness, not VIS brightness alone as is commonly understood.

Taken to the extreme is the realization that a central light system could be driven by a source that exists entirely in the UV. If the physical foundation exists for a highly efficacious source in the UV then the lighting in a building could be generated by invisible light (like a fluorescent tube the size of a building). Keeping in mind that each UV photon has twice the energy of a VIS photon, theoretically the UV efficacy and brightness can triple the luminous efficacy and brightness of the source.

A more immediate means to increase the effective brightness of the source is to use a solid microcollector, which would concentrate light to beyond the source's luminance within that medium. Using fused silica microcollectors to match the index of refraction of the fused silica fiber core would allow an increase in luminance of 225% over the source luminance at the point of fiber entry.

Sources of lower brightness can also be clustered to increase apparent source brightness. Clustering also increases the aggregate beam divergence, although the loss in concentration potential because of this is more than offset by the multiple increase in energy density. Clustering of sources cannot be used when the extent of the optical system matches that of a single source.

Piping light gives lighting back the flexibility it had before becoming encumbered with electrical, structural and thermal dissipation hardware. It may finally reduce the amount of electricity we generate to drive electric lights, remembering that energy-saving
fluorescent lamps are 80% heat, and that the electricity used to produce that heat is generated by burning coal, oil, or atoms in some countryside power plant, whose SO₂ emission trails lead all the way into Canada's fertile wilderness.

3M's atrium (Progressive Architecture, October 1993) is arguably the first significant architectural application of light piping film. Although visually intriguing, it's opaque corners belie many underlying flaws in the understanding of the optical properties of light conveyance. Linear sources could have been used with better energy efficiency than the point sources used in that application for emulating linear sources. Pieces of the puzzle have to be put together in a certain way if piped illumination is to get beyond its decorative novelty and be applied in ways that change the face of buildings and their energy consumption. The basis of this work is an argument in support of this: light piping is a means to revolutionize our way of thinking about the nature of lighting building interiors. But lighting designers will have to adopt an optical engineer's vocabulary of light flow if light piping is to avoid being relegated as gimmickry. This is how buildings may eventually be lighted. It will be much cheaper at the scale of a building than conventional illumination methods. And the sun's energy is free.

In a way we've gone backwards since Edison's initial accomplishment. The system being proposed makes a step toward reversing this and in doing so enables the sun to play its suitable role: contributing both light and heat in a form acceptable to the building's energy equation, not summarily rejecting one or both as is the vast majority of current practice.
REFERENCES


**Company Product Literature from:**

Collimated Holes, Campbell, CA  
Evaporated Coatings (ECI), Willow Grove, PA  
Fibre Light Lmtd., Halesowen West Midlands, United Kingdom  
Fusion Systems, Rockville, MD  
GE Lighting, Nela Park, Cleveland, OH  
Himawari, La Forét Engineering Co., Lmtd. Tokyo, Japan  
Infrared Engineering Lmtd., Maldon, Essex, England  
Lumatec GMBH, Munchen, West Germany  
Lumenyte International, Costa Mesa, CA  
Melles Griot, Irvine, CA  
3M Specialty Optical Fibers Division, West Haven, CT  
3M Traffic Control Materials Division, St Paul, MN  
Optical Coatings Lab Incorporated, Santa Rosa, CA  
Osram Corporation, Montgomery, NY  
Philips Lighting Company, Somerset, NJ  
TIR Systems, Ltd., Barnaby, British Columbia

**Communication with:**

Collimated Holes, Campbell, CA  
Fusion Systems, Rockville, MD  
John Penney Co, Electric Contractors, Cambridge, MA  
Melles Griot, Irvine, CA.  
3M Specialty Optical Fibers Division, West Haven, CT  
3M Traffic Control Materials Division, St Paul, MN  
Optical Coatings Lab Incorporated, Santa Rosa, CA  
Osram Corporation, Montgomery, NY  
Pioneer Optics, Hartford, CT  
TIR Systems, Ltd., Barnaby, BC, Canada  
Vortek Industries Ltd., Vancouver, BC, Canada

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