ADAPTIVE FULL-SPECTRUM SOLAR ENERGY SYSTEMS
Cross-Cutting R&D on adaptive full-spectrum solar energy systems for more efficient and affordable
use of solar energy in buildings and hybrid photobioreactors

Semi-Annual Technical Progress Report
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ABTRACT

This RD&D project is a three year team effort to develop a hybrid solar lighting (HSL) system that transports daylight from a paraboloidal dish concentrator to a luminaire via a bundle of small core or a large core polymer fiber optics. The luminaire can be a device to distribute sunlight into a space for the production of algae or it can be a device that is a combination of daylighting and electric lighting for space/task lighting. In this project, the sunlight is collected using a one-meter paraboloidal concentrator dish with two-axis tracking. For the second generation (alpha) system, the secondary mirror is an ellipsoidal mirror that directs the visible light into a bundle of small-core fibers. The IR spectrum is filtered out to minimize unnecessary heating at the fiber entrance region.

This report describes the following investigations of various aspects of the system. Taken as a whole, they confirm significant progress towards the technical feasibility and commercial viability of this technology.

- TRNSYS Modeling of a Hybrid Lighting System: Building Energy Loads and Chromaticity Analysis
- High Lumens Screening Test Setup for Optical Fibers
- Photo-Induced Heating in Plastic Optical Fiber Bundles
- Low-Cost Primary Mirror Development
- Potential Applications for Hybrid Solar Lighting
- Photobioreactor Population Experiments and Productivity Measurements
- Development of a Microalgal CO₂-Biofixation Photobioreactor

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PREFACE

This report is a joint effort between Oak Ridge National Laboratory and the University of Nevada, Reno, and as such it satisfies the reporting requirements for the University and ORNL as the M&O for this project. The reporting period is from February 1st, 2004 through July 31st, 2004.

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EXECUTIVE SUMMARY

This RD&D project is a three year team effort to develop a hybrid solar lighting (HSL) system that transports daylight from a paraboloidal dish concentrator to a luminaire via a bundle of small core or large core polymer fiber optics. The luminaire can be a device to distribute sunlight into a space for the production of algae or it can be a device that is a combination of daylighting and electric lighting for space/task lighting. In this project, the sunlight is collected using a one-meter paraboloidal concentrator dish with two-axis tracking.

During the first budget period (August 2001 – April 2003) a bench mark prototype system was developed and evaluated to determine technical feasibility of using full-spectrum solar energy systems to enhance the overall sunlight utilization in buildings and biomass production rates of photobioreactors.

During the second budget period (May 2003 – April 2004), emphasis was placed on determining those aspects of the solar lighting system that characterize performance efficiency, reliability, durability and ultimately minimum cost potential. The major accomplishment was the second generation (alpha) system for which the secondary mirror is an ellipsoidal mirror that directs the visible light into a bundle of small-core fibers.

During this reporting period, the research team made advancements in the design of the Alpha system and small-fiber bundle, updated and added components to the TRNSYS Full-Spectrum Solar Energy System model, made changes and advancements in the high-lumen test system and fiber durability tests, and made developments in the photobioreactor and its species. Potential applications for this type of solar lighting system are discussed. Major accomplishments for this period include:

TRNSYS and SMARTS2 were used to model the performance of an office building equipped with a hybrid lighting system in Tucson and Seattle. For each location, the annual energy savings and the chromaticity of the indoor light were found based on the efficacy and spectrum of the incident beam normal radiation and that of the conventional bulb paired with the system. These results and the flexibility of the TRNSYS code will assist commercial developers of this technology.

The quality of the Fresnel lens was insufficient to consistently supply 8,000 lumens to the fiber for the high lumens testing. It was replaced with a Fortech paraboloidal mirror and the receiver was reconfigured to be able to test three 12 mm fibers at the same time.

Past failures associated with a small-diameter fiber optic bundle appear to have been caused by the introduction of unwanted contaminants and epoxy into the fiber optic bundle face. Using an epoxy-free compression mount and aggressively cleaning the optical fiber face appears to result in significant reductions in fiber heating. Testing is still continuing to evaluate the long-term performance of this bundle.

A market survey is underway to identify where the HSL device is likely to have maximum reception in the market initially. Consideration is based on where the most benefits are achieved in terms of cost, energy, aesthetics, etc. Niche market opportunities are being identified.

Progress has been made in evaluating bio materials for use in the bioreactor for carbon sequestration. Thermophilic SC2 shows good growth at elevated temperatures (50°C) and at the elevated CO₂ (5% v/v supplemented). The species also had high light adaptability, growing successfully at high light intensity (246.1 $\mu\text{mol m}^{-2} \text{s}^{-1}$) and low light intensity (36.9 $\mu\text{mol m}^{-2} \text{s}^{-1}$);

PROJECT DESCRIPTION

This project is part of the FY 2000 Energy Efficiency Science Initiative that emphasized Cross-Cutting R&D in Solicitation No.: DE-PS36-00GO10500. It is a three year research project that addresses key scientific hurdles associated with adaptive, full-spectrum solar energy systems and associated applications in commercial buildings and new hybrid solar photobioreactors. The goal of this project is to demonstrate that full-spectrum solar energy systems can more than double the affordability of solar energy in commercial buildings and hybrid solar photobioreactors used in CO₂ mitigation and compete favorably with existing alternatives.

This project is a multi-team effort to develop a solar lighting system that transports solar light from a paraboloidal dish concentrator to a luminaire via a bundle of small core or large core polymer fiber optics. The luminaire can be a device to distribute sunlight into a space for the production of algae or it can be a device that is a combination of daylighting and electric lighting for space/task lighting. In this project, the sunlight is collected using a one-meter paraboloidal concentrator dish with two-axis tracking. For the second generation (alpha) system, the secondary mirror is an ellipsoidal mirror that directs the visible light into a bundle of small-core fibers. The IR spectrum is filtered out to minimize unnecessary heating at the fiber entrance region.

SCOPE OF WORK

Phase I. Assess Technical Feasibility

Determine technical feasibility of using full-spectrum solar energy systems to enhance the overall sunlight utilization in buildings and biomass production rates of photobioreactors. This was accomplished during Budget Period 1 by developing a benchmark prototype system that could evaluate the collection, distribution and utilization of concentrated solar light.

Phase II. Assess Commercial Viability

Determine the commercial viability of using full-spectrum solar energy systems to enhance the overall sunlight utilization in buildings and biomass production rates of photobioreactors. This was the emphasis for Budget Period 2. R&D was directed at characterizing performance efficiency, reliability, durability and ultimately minimum cost potential. The goal was the design and construction of a second generation or an alpha system that shows significant improvement in the performance cost ratio.

Phase III. Assess System Affordability

Demonstrate the HSL technology in a building application and a photobioreactor application. The emphasis for Budget Period 3 is the development of a third generation beta system or pre-commercial prototype system that potentially can meet the performance and cost targets.

PROGRESS TOWARDS PROJECT OBJECTIVES

The emphasis during this reporting period has been on the following items:

1. TRNSYS Modeling of a Hybrid Lighting System: Building Energy Loads and Chromaticity Analysis
2. High Lumens Screening Test Setup for Optical Fiber Used in Hybrid Solar Lighting System

3. Photo-Induced Heating in Plastic Optical Fiber Bundles
4. Low-Cost Primary Mirror Development
5. Niche Market Applications for Hybrid Solar Lighting
6. Photobioreactor Population Experiments and Productivity Measurements
7. Development of a Microalgal CO₂-Biofixation Photobioreactor

A summary of each investigation is given below.

1. TRNSYS Modeling of a Hybrid Lighting System: Building Energy Loads and Chromaticity Analysis

1.1 Abstract

The TRNSYS [1] program provides algorithms to calculate the beam and diffuse radiation on any surface as a function of time, based on horizontal radiation measurements. However, no methods are currently provided in TRNSYS to determine the spectral distribution of solar radiation. This section describes the inclusion of a spectral model in TRNSYS. The model uses Gueymard's SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) [2] algorithm to calculate the spectral power density of sunlight as a function of solar position, atmospheric turbidity, moisture content, and other atmospheric parameters. The inclusion of the spectral model was necessary to perform building illumination and energy load analyses on a 2500 m² office building equipped with a hybrid lighting system (HLS). The HLS uses two-axis tracking collectors to collect beam normal radiation that is later divided into visible and infrared components. The visible radiation is piped to luminaires inside the building using optical fibers, while the infrared radiation is focused on thermal photovoltaic arrays and used to generate electricity. The TRNSYS model was used to calculate annual building energy loads (lighting, cooling, and heating) and illumination chromaticity values (correlated color temperature and color rendering index) for office buildings in Tucson, AZ and Seattle, WA. These locations were selected to exemplify best and worst case results, respectively. Annual energy savings and chromaticity values for office buildings located in these cities are presented.

1.2 Luminous Efficiency and Efficacy

The amount of illumination provided by a light source is a function of its spectral power density (SPD). Figure 1.1 shows SPDs of four light sources: beam normal solar radiation on a clear spring day around noon in Seattle (representative of air mass 1.5), a warm white energy efficient fluorescent bulb, a full spectrum fluorescent bulb, and an incandescent bulb (in this case, halogen) from 380-780 nm, the average visual sensitivity range of the human eye.

Light is visually evaluated radiant power. To determine the amount of luminous power in lumens (lm) provided by a light source, the amount of radiative power at each wavelength is multiplied by the photopic luminous efficiency curve, $V(\lambda)$, which is plotted in Figure 1.2 on the right vertical axis. The luminous efficiency curve converts radiant power watts (W) to luminous light watts (lW). The total number of light watts for a given SPD are then integrated and multiplied by 683 lumens/lW to yield the luminous power in lumens. Further details of this procedure are provided by [4].

Figure 1.1 Examples of light source spectra in visible wavelengths: Beam normal radiation (AM 1.5), halogen, warm white energy efficient fluorescent, and full spectrum fluorescent.

The ratio of the luminous power (lm) in a given amount of radiant power (W) is called the luminous efficacy. Light sources with high efficacy deliver more light for a given amount of radiant power and tend to have SPDs with power concentrated in the visible spectrum. Most of the power of halogen bulbs and other incandescents is found in the infrared and typical efficacies for these bulbs are 15-25 lm/W. Fluorescent bulbs have more radiant power in the visible range. Typical luminous efficacy values for full spectrum fluorescent bulbs are 55 lm/W, and energy efficient fluorescent bulbs can approach 100 lm/W.

About half of the power in natural sunlight is in the visible range with the other half in the infrared. Large luminous efficacies (approx. 100 lm/W) result because a significant fraction of the power peaks close to the maximum sensitivity of the eye at 555 nm [$V(555 \text{ nm})=1$].

In the HLS, the cold mirror filters the infrared from the visible radiation in the incident beam normal radiation. Visible light directed into the optical fibers has very little power in the infrared; the beam normal radiation delivered to the luminaires has an efficacy of about 200 lm/W.

When performing building energy analyses, the average lighting efficacy of light sources within a building is an important parameter. Higher efficacy lamps cause smaller cooling loads because less energy enters the building with the desired amount of illumination. The Results section will further quantify this effect.

1.3 The Color Temperature of a Light Source

Though the luminous efficiency curve in Figure 1.1 indicates the relative sensitivity of the eye to power in different wavelengths, the color that will be perceived by a typical human observer from a given SPD cannot be calculated from this information. The color matching functions shown in Figure 1.2 are needed for this calculation.

Figure 1.2 The x, y, z color matching functions [5]

The color matching functions are derived from experiments in which human observers used a colorimeter to match a given light source color by adjusting the power of light in only three wavelengths: red (700 nm), green (546.1 nm), and blue (435.8 nm). The X, Y, Z color system is derived from these measurements and uses the x, y, z color matching functions to calculate the tristimulus values, X, Y, and Z that completely describe a color stimulus. The tristimulus values are calculated according to [5] in the following manner:

$$X = \int_{\lambda} P(\lambda) \bar{x}(\lambda) d\lambda \quad (1)$$

$$Y = \int_{\lambda} P(\lambda) \bar{y}(\lambda) d\lambda \quad (2)$$

$$Z = \int_{\lambda} P(\lambda) \bar{z}(\lambda) d\lambda \quad (3)$$

where $P(\lambda)$ is the light source power at wavelength, λ .

From these tristimulus values, chromaticity coordinates x and y are calculated using

$$x = X / (X + Y + Z) \quad (4)$$

$$y = Y / (X + Y + Z) \quad (5)$$

The chromaticity coordinates x and y, derived from an incident SPD and the color matching functions, predict the perceived color of the light source using the x,y chromaticity diagram shown in Figure 1.3. To use this diagram, locate the position where the x chromaticity coordinate on the horizontal axis intersects with the y chromaticity coordinate on the vertical axis. The intersection point is the perceived color of the light source. The x, y chromaticity coordinates of the four light source spectra of Figure 1.1 are indicated on this figure.

All four light sources appear white, though the warm white fluorescent gives a yellower, "warmer" light while the beam normal radiation gives a more blue, "cooler" light. The dark line on Figure 1.3 is created by

calculating the chromaticity coordinates of blackbody SPDs at different temperatures. These spectra are created using Planck's equation for blackbody radiation at a specified wavelength as a function wavelength and temperature (K).

Figure 1.3 1931 CIE x,y chromaticity diagram

The "warmth" or "coolness" of light sources is quantified by the temperature of a blackbody that yields the same color light. For instance, a blackbody at 3000 K produces the same color of light as the warm white fluorescent, though their chromaticity coordinates differ. The warm white fluorescent is said to have a correlated color temperature (CCT) of 3000 K. The CCT of the halogen bulb is 4100 K. Compared to the warm white fluorescent, more of the power of the full spectrum fluorescent occurs at shorter wavelengths, yielding a "cooler" CCT of 5000 K. Beam normal radiation in Seattle (AM 1.5) is 5200 K. The method by which x,y coordinates are transformed into a CCT is detailed by [5]. In general, it involves isothermperature lines that intersect the Planckian locus and interpolation of chromaticity coordinates between these lines to give a CCT value.

1.4 The Color Rendering of a Light Source

The CCT defines the perceived color of a light source. It does not indicate how well the light source will render the color of objects it illuminates. For that, another colorimetric index is needed, the color rendering index (CRI).

The CRI of a light source is a measure of the color shift of objects illuminated by that light source in comparison to the same objects illuminated by a reference illuminant of comparable color temperature. A CRI of 100 means that the light source in question renders the color of eight color samples in the same manner as the reference

illuminant. The CRI has been defined so that the color differences seen between a 3000 K fluorescent bulb and a 3000 K blackbody spectrum yield a CRI of 50.

The eight color samples used in the calculation of the CRI are defined by their spectral reflectances at given wavelengths. Samples are selected to yield a range of colors in the visible spectrum, e.g. sample one appears light greyish red under sunlight while sample six appears light blue. These reflectance curves can be found at [6].

The more closely the SPD of the light source matches the SPD of the reference illuminant, the better the CRI of the light source. Figure 1.4 shows the warm white fluorescent and halogen SPDs with their corresponding reference illuminants and their corresponding CRI values. The CRIs of the full spectrum fluorescent and the beam normal radiation are 90 and 100, respectively.

Figure 1.4 Calculation of the CRI for the halogen and warm white fluorescent spectra.

The calculation of the CRI is somewhat involved and the reader is referred to [4], [5], and [6] for detailed explanations. In brief, the chromaticity coordinates of the light reflected by each sample ($i = 1$ through 8) are calculated using modified forms of equations 1 through 5 and a resulting color difference, ΔE_i , is calculated for each of the color samples lit by the light source and the reference illuminant. ΔE_i is used to calculate a color rendering index for each sample, R_i , defined by

$$R_i = 100 - 4.6\Delta E_i \quad (6)$$

and the CRI is the average of the eight color rendering indices:

$$CRI = \frac{1}{8} \sum_{i=1}^8 R_i \quad (7)$$

1.5 The Atmospheric Model, SMARTS2

The SPD of the light source is required to calculate luminous power, luminous efficacy, and the CCT and CRI of light sources. While TRNSYS uses TMY2 data that include the magnitude of beam normal radiation every hour of the year for many geographic locations, TMY2 data do not include the SPD of the beam normal radiation for that hour. Proper modeling of the hybrid lighting system requires an incident SPD on the collector each hour of the year. SMARTS2 was linked to TRNSYS to provide this SPD from 280-2500 nm at 5 nm intervals.

SMARTS2 calculates the clear sky beam normal SPD incident on a tracking surface given approximately ten parameters including elevation, precipitable water, aerosol optical depth, time of day, day of the year, location, and concentration of atmospheric pollutants. TMY2 data contain hourly precipitable water and aerosol thickness data. TRNSYS passes time of day, day of the year, location, and TMY2 data to SMARTS2 to find the clear sky SPD of the beam normal radiation for that hour. This SPD is integrated and scaled to match the beam radiation recorded in the TMY2 data file.

1.6 The TRNSYS HLS Model

The TRNSYS HLS model consists of interconnected component models that include a weather file, radiation processors, a hybrid lighting model, a building model, building schedules, utility rate schedules, and output components. Simulation results include annual energy and monetary savings gained from the hybrid lighting system as well as colorimetric indices, the CCT and the CRI.

The TMY2 weather file is used with SMARTS2 to generate the SPD of incident radiation on the collector for each hour of the year. This SPD is attenuated by the spectral and wideband transmittances of the collecting and cold mirrors, the fiber entrance region, the fiber itself, and the luminaires.

The spectral transmittance of the mirrors and fiber are shown in Figure 1.5. The luminous and radiant power provided to the workspace is calculated from the SPD that remains after passing through these components.

Figure 1.5 Spectral transmittance of one meter length of optical fiber and spectral reflectance of the mirrors [3]

Within TRNSYS, the light output from the hybrid lighting system model is sent to the building model. The building is modeled using the Type 56 multi-zone building model. Type 56 is a FORTRAN subroutine which is designed to provide detailed thermal models of buildings. The model consists of two windowless 2500 m² zones. One zone uses one of the three bulbs detailed in Figure 1.1 exclusively while the other zone pairs this bulb with light delivered by the HLS. Identical schedules in the two zones simulate the heating, cooling, and ventilation of a typical mixed-use environment. Additional gains in the model account for the people, computers, and lights in the building. Cooling in the building is supplied using a chiller with a constant COP of 3 and heating loads are met using an 80 % efficient natural gas furnace. Using local utility rate schedules, energy costs are calculated for the two zones of the building model with the difference representing the energy savings due to the hybrid lighting system.

The simulation uses a heating set point of 20°C with a night setback of 17° C. Cooling is active at 26°C and above. Relative humidity within the building is allowed to float between 30 and 60%. Illumination levels within the building are set to 500 Lux which is the IESNA recommended lighting level for general office work [7]. Occupancy schedules model a typical 8 am to 5 pm work week. Infiltration and ventilation rates are based on information provided in ASHRAE 62–2001. Rate schedules from utilities near the various locations are used to determine the time variant prices of natural gas and electricity.

Eight HLS 1.7 m² modules are used to collect the beam normal radiation. During clear sky conditions, this collecting area provides about half of the lumens needed to illuminate the workspace.

1.7 Simulation Results and Discussion

The annual electrical load of the office building is the sum of the annual lighting and cooling loads. Figure 1.6 shows the percentage reduction in the total electrical load, the annual energy savings per 1.7 m² module, and the effect of the TPV as functions of location and lighting efficacy.

The HLS system performs much better in Tucson than Seattle. One reason is that eight modules in Tucson provide a larger percentage of the required illumination during the year than eight modules in Seattle. Figure 1.7 shows the number of hours in the year that the HLS is providing 0 to 100% of the required illumination in Tucson and Seattle.

As the number of modules increases, lighting fractions would increase until the HLS is providing 100% of the required illumination for some hours of the year. At this point adding collector area becomes counter-productive as more energy enters the building than required, increasing the cooling load and doing nothing to reduce the lighting load. For this reason annual energy savings per module begins to decrease at a certain number of 1.7 m² modules. Previous studies [8] have shown that for the 2500 m² building of this analysis, this saturation level corresponds to 15 modules in Tucson and 18 modules in Seattle.

Figure 1.6 HLS reduction in electrical load and annual energy savings per 1.7 m² module in Tucson and Seattle

Figure 1.7 Number of hours that HLS with eight 1.7 m² modules is providing specified percentage of required illumination to 2500 m² building in Tucson and Seattle.

Figure 1.8 presents chromaticity results for two days in Tucson. In this simulation, the building was equipped with warm white fluorescent bulbs that, if working without the HLS, provide a CCT of 3000 K and a CRI of 53.

Figure 1.8 CCT and CRI delivered by HLS in Tucson

March 6 was a cloudy day, with some hours yielding little beam radiation. For these hours the CCT and CRI match that of the fluorescent lighting. March 7 was a clear day. The spectrum of light delivered by the HLS combines with the spectrum of the fluorescent lighting to increase the CCT and CRI of the indoor light.

Figure 1.9 details the number of hours the indoor light is at the specified CCT for the given location and bulb source. Figure 1.10 presents CRI results similarly. In general, the HLS maintains or increases the CCT and CRI of the indoor light provided by conventional bulbs. As the number of modules is increased and the bulbs are progressively dimmed, the CCT and CRI will approach that of the HLS delivered light.

Figure 1.9 The number of hours at the specified color temperature for all simulations. (WWF - warm white fluorescent, FSF - full spectrum fluorescent)

Figure 1.10 The number of hours at the specified color temperature for all simulations.

1.8 Conclusion

TRNSYS and SMARTS2 were used to model the performance of an office building equipped with a hybrid lighting system in Tucson and Seattle. For each location, the annual energy savings and the chromaticity of the indoor light were found based on the efficacy and spectrum of the incident beam normal radiation and that of the conventional bulb paired with the system. These results and the flexibility of the TRNSYS code will assist commercial developers of this technology.

A more detailed report on this work can be found in Appendix A, Frank Burkholder's Master's Thesis, University of Wisconsin.

1.9 References

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2. High Lumens Screening Test Setup for Optical Fiber Used in Hybrid Solar Lighting System

2.1 Abstract

A research team led by Oak Ridge National Laboratory has designed a Hybrid Solar Lighting System for transporting daylight to building interiors via optical fibers [3]. Light carrying capacity, flexibility, and cost are important design factors for choosing an appropriate fiber, and these factors have pointed to the use of large-core plastic fibers. For the hybrid approach to be practical, the fibers must perform well for approximately 20 years, thus long-term transmission data are needed.

This section describes the design and analysis of two experimental apparatuses. One of these two has been chosen to evaluate the long-term optical performance of three different brands of large core fiber as a screening test for the Hybrid Lighting System. The test setup must supply a specified amount of lumens, protect the fiber from heat, and allow for periodic degradation measurements to be taken easily. This is a comparison and screening test only.

2.2 Introduction

The experiment objective is to compare the transmission and attenuation of three different types of optical fibers when exposed to concentrated sunlight for a period of several months. The data will be used to recommend a fiber for use in the Hybrid Solar Lighting System. The Hybrid Solar Lighting System calls for each fiber to carry approximately 8,000 lumens, therefore the selected testing apparatus must be capable of supplying a minimum of 8,000 lumens to each fiber. Each fiber must be adequately protected from infrared (IR) wavelengths to remain below its respective maximum rated operating temperature. The selected fiber brands to be tested are: 3M, Poly Optic and Lumenyte.

A test plan is developed that meets the project requirements. The design of the two test systems is shown as well as the performance results for one of the configurations. Test preparation steps required regardless of the apparatus are also discussed, such as investigation of the quartz and the polishing method exercised on the optical fibers.

2.3 Experimental Method

Test Plan

A 10 meter length of fiber will be placed in the testing apparatus and exposed to concentrated sunlight for a prescribed test period. Test data will include fiber temperature at various distances from the entrance surface, overall lumen output and spectral transmission in the 250nm to 900nm range. At the end of the test the cutback method will be used and again both overall lumen output and spectral transmission will be measured at each length. In order to generate a useful transmission graph, it is recommended that transmission be measured at 2nm to 5nm wavelength intervals [2]. The transmission data will be taken for each length of fiber and written to an Excel sheet for post processing.

The 10 meter length was chosen because that is the length used in the Hybrid Solar Lighting System and because it should be a long enough segment to offer an opportunity to monitor color shift. One of the benefits of daylighting is that white light is supplied instead of the lower color temperatures supplied by most artificial lights; thus, color shift needs to be monitored to ensure that a possible benefit is not being lost. The cutback method will be used at the end of each test because it has been adopted as the standard approach for measuring attenuation in optical fibers [2].

Instrumentation

Transmission at various wavelengths is measured using a spectroradiometer by StellarNet Inc. Overall lumen output is measured using a four inch integrating sphere and a hand-held spectrometer by Labsphere, as illustrated in Figure 2.1. The photopic curve is the commonly accepted definition of the wavelengths the average human eye responds to. The lumen is a measurement of wavelengths in the visible region, weighted by the photopic curve, so a good way to measure overall transmission is the number of lumens at various distances down an optical fiber [2].

Figure 2.1 Spectrometer and integrating sphere

A Cogent high intensity discharge light with voltage regulator will be the light source used for testing after the fiber has been removed from the testing apparatus. This source will be allowed 10 minutes warm up time to stabilize.

Test Apparatus #1

The first of the two test apparatuses is shown in Figure 2.2 and includes a 35 inch diameter Fresnel lens, a supporting truss, a hot mirror, an IR cutoff filter, and a quartz rod to protect the fiber from heat. The entire system mounts to a solar tracking device.

Theoretical Performance

The theoretical plausibility of this test setup was verified using a simple TracePro model and Microsoft Excel. TracePro is an optical modeling program that allows the user to draw three dimensional objects and then apply optical properties. The TracePro model includes an ASTM standard solar source for air mass 1.5, a hot mirror, an infrared (IR) filter, a quartz rod and the initial surface of the optical fiber. TracePro traced the rays and then created a flux report. The number of watts striking the entrance surface of the fiber in the visible region were summed up in Excel, and then that number was multiplied by 200 lumens/watt which is the standard number for filtered sunlight. By this method, the theoretical number of lumens available is substantially more than the 8,000 lumen minimum, as displayed in Table 2.1.

Figure 2.2 Fresnel Testing Apparatus

Table 2.1 Theoretical lumens with Fresnel Lens

Surface	Incident Watts	Lumens
Fresnel	546.80	109,360.66
Hot Mirror	212.72	42,544.69
IR Filter	176.70	35,340.05
Quartz Rod	122.98	24,595.22
Fiber Entrance	118.06	23,611.41

Actual Performance

The Fresnel testing apparatus was set up with a piece of quartz (no fiber attached) and several lumen readings were taken on different clear days. These readings indicated that the Fresnel system was only able to consistently supply approximately 6,000 lumens to the exit surface of the quartz, which would be the entrance of the fiber. The major difference in the theoretical and actual results is believed to come from imperfections in the Fresnel lens. This is a relatively cheap, low quality piece of plastic and the large diameter and harsh outdoor environment leaves much room for defects in the lens, scratches, dirt etc. There is also a small amount of blockage (shown in Figure 2.2) caused by the assembly holding the lens that was not accounted for in the model.

Test Apparatus #2

The second test apparatus, shown in Figure 2.3, utilizes a parabolic mirror rather than a Fresnel lens. Instead of testing one fiber per system, four fibers are placed in a bundle. A cold mirror, IR cutoff filter and quartz rod are

still used to control the temperature at the fiber entrance, but one rectangular piece of quartz is used rather than individual cylindrical pieces. This quartz rod doubles as a non-imaging device to help ensure that all the fibers are illuminated evenly.

Figure 2.3 Test Apparatus #2

A model of test apparatus #2 was created in TracePro and the theoretical results, shown in Table 2.2, are very encouraging. This system is still in the construction stage and performance data is not yet available. However, unlike the Fresnel test setup, it is expected that the model of the second apparatus will better represent the experimental setup due to higher quality optical components, especially the primary and secondary mirrors.

Table 2.2 Theoretical lumens for Parabolic Mirror

Surface	Incident Watts	Lumens
Primary Mirror	846.77	169,353.68
Secondary Mirror	820.62	164,123.02
IR Filter	550.24	110,048.61
Quartz Exit	524.33	104,866.58
Fiber #1 Entrance	50.89	10,178.00
Fiber #2 Entrance	50.47	10,094.00
Fiber # 3 Entrance	50.12	10,024.00
Fiber # 4 Entrance	50.76	10,152.00

2.4 Experiment Components and Test Preparation

Change in Temperature from Entrance Surface to Exit Surface of Quartz Rod

Heat is an obvious problem when using plastic fibers to transport solar light. To combat this problem, a hot mirror and IR filter are used to cut out the near IR, and a quartz rod is used to help cut out the longer IR wavelengths. The length of the quartz rod used in the final testing will depend on the actual available energy from the chosen testing apparatus. However, a small experiment was performed to gain an understanding of the temperature difference between the entrance and exit surfaces of quartz rods of different lengths. Figure 2.4 summarizes the results of this experiment normalized by the entrance temperature. A higher normalized

temperature value corresponds to a greater temperature drop along the length of the quartz. As shown, the trend is that the difference between the entrance and exit temperatures is greater with longer quartz.

Figure 2.4 Normalized temperature difference between entrance and exit surface of quartz rod

Lumen loss in fused quartz rod

Since the length of the quartz rod is inversely proportional to the temperature at the entrance of the fiber, it is important to know the effect the quartz has on light transmission. An experiment was performed to measure the lumens lost in various lengths of the fused quartz rod. The rods were connected to a Cogent light source as shown in Figure 2.5.

Figure 2.5 Cogent light/ quartz setup

Two trials were performed and the results are shown below in Table 2.3. As shown in Table 2.3, there is so little visible light lost through the quartz that it is difficult to even accurately measure. Variations in measurements could be due to the quartz being placed at slightly different distances from the light source or at slightly different depths into the integrating sphere.

Table 2.3 Lumen loss through fused quartz rod

Quartz Test Using Cogent Light Source 12-8-03		
Quartz Length (cm)	Trial 1 Lumens	Trial 2 Lumens
4	80	80.3
6	81.8	80.3
8	80.5	79.9
10	80.9	80.3
12	80.3	80.3

Fresnel Reflection and Bonding

Fresnel reflection occurs at the surface of the fiber. Some light that strikes the surface of the fiber is reflected even when the incidence angel is within the numerical aperture of the fiber. This is caused by a change in the index of refraction as light travels from air to the fiber. When two fibers or a piece of fused quartz and fiber are joined together, they are sometimes separated by a small air gap, causing Fresnel reflection to occur twice in each junction [1]. The formula below (taken from [1]) calculates the fraction of incident light that is reflected, where n_1 is the refractive index of the fiber core and n_0 is the refractive index of the separating medium (air).

$$R = \left(\frac{n_1 - n_0}{n_1 + n_0} \right)^2 \quad (1)$$

Using a fiber core refractive index of $n_1 = 1.498$ and assuming air to have a refractive index of $n_0 = 1.0$, the Fresnel reflection between air and the fiber is about 4%. The refractive index of the quartz is similar to that of the fiber, so the junction causes a loss of roughly 8%.

To help reduce the losses caused by this junction, the quartz and fiber were fused together. A device was constructed that holds the fiber and quartz in alignment and then presses them together (see Figure 2.6). The device was then placed in the Fresnel testing apparatus and the available heat fused the two together. A small experiment was performed to test the bond between the quartz rod and the fiber. The holding device was set up and the quartz and fiber were pressed together but not bonded. The quartz was then connected to the cogent light source and the lumen output was measured to be 2780 lumens. The quartz and fiber were then placed in the Fresnel testing setup and given enough time to bond. After bonding the reading was 2900 lumens, an increase of about 4%.

Fiber Polisher

All fibers used in the testing are polished using the same equipment and sequence. The fiber polisher, shown in Figure 2.7, consists of a threaded tube just large enough in diameter for the fiber to fit though. The fiber is clamped in place at the bottom where a plastic collar protects the fiber from being damaged while clamped. Fine threads on the tube allow for small vertical adjustment of the fiber. The polisher has variable disc speed and eccentricity.

Figure 2.6 Holding device for fusing quartz rod and plastic fiber.

Figure 2.7 Fiber polisher

The polishing sequence begins with cutting the fiber using a PVC cutter. Then a coarse sandpaper is used to create a square end on the fiber. This step is followed by a finer sandpaper and then by a sequence of 3M polishing pads, which have 30, 15, 9, 3 micron finishes. They are used in that order and everything is kept irrigated by a pressurized water tank. This procedure consistently produces a high-quality polish on the fibers.

2.5 Conclusions

The Fresnel lens test setup supplies enough concentrated light for much of the necessary preliminary testing, but does not consistently supply 8,000 lumens to the fiber. As 8,000 lumens was one of the experiment requirements, this setup will not be used for the actual testing. Instead, the parabolic mirror and fiber bundle approach will be used. This method also saves space and money since all three fiber types can be tested at once using the same mirror.

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3. Photo-Induced Heating in Plastic Optical Fiber Bundles

3.1 Introduction

Past evaluations of the Hybrid Solar Lighting technology have identified potentially significant reductions in system cost though the use of a single, large-diameter (1.5”) bundled fiber as the method for collecting concentrated sunlight. Unfortunately, implementation of this approach has been impeded due to overheating in the fiber bundle. Prior to this reported investigation, it was unclear as to what the possible failure mechanisms were and to what extent each was contributing to fiber overheating. The quantitative investigation of this problem was difficult due to the large number of possible heat contributors combined with the difficulties associated with trying to control the many variables encountered with on-sun testing (i.e. ambient temperature, cloud coverage, solar intensity, etc.). Therefore, a method was developed for simulating, within a laboratory environment, the photo-induced heating occurring in an on-sun optical fiber bundle. This method allows the effects of singular variables to be isolated and quantified at a much reduced lumen flux density. The performance of the optical fiber bundle can then be extrapolated for on-sun conditions.

3.2 Experimental Setup

The experimental setup consisted of a high-intensity fiber optic artificial light source (Cogent) connected to a ½” diameter split-bundle optical fiber, and an infrared thermographic camera (FLIR). The artificial light source coupled approximately 2100 lumens of visible light into the split-bundle optical fiber. The output of this split-bundle fiber was then aimed at a target (typically a 1.5” fiber optic bundle) to induce optical heating. The optical heating produced was measured with a thermographic camera located approximately 6” from the target’s illuminated surface. Figure 3.1 shows an optical fiber bundle being tested as viewed from the thermographic camera (note the artificial light being aimed at the bundle via two smaller fibers to the left and right).

Figure 3.1 Thermographic Camera’s View of Optical Fiber Bundle

Using this setup, it was possible to produce a controlled method for photo-induced heating of an optical fiber bundle. Various optical fiber bundles were prepared to test and quantify possible heat contributors. Based on previous investigations, the list of possible contributors to bundle heating were identified as:

1. Fiber Core (optical absorption)
2. Fiber Cladding (optical absorption)
3. Collet Material (optical absorption)
4. Bundle Air Voids (optical absorption)

5. Epoxy (optical absorption)
6. Bundle Contaminants (optical absorption)
7. Fiber and epoxy outgassing
8. Uneven flux distribution at the fiber face
9. Surface losses/effects between integrating rod and bundle

Unfortunately, due to time constraints, it was only possible to evaluate variables 1-6. To test each variable, a fiber optic bundle was constructed that attempted to isolate the variable of interest. The 2-D temperature profile of the bundle was then measured for one minute before being illuminated with the artificial source. While illuminated, the bundle's 2-D temperature profile was measured for an additional five minutes. After five minutes, the illumination was turned off and the cooling bundle's profile recording for another four minutes (for a total measurement time of ten minutes).

3.3 Photo-Induced Heating in Fiber Core Material

The fiber optic bundles used had approximately 126 individual, 3mm diameter, optical fibers. The fibers were constructed from a PMMA core with a Teflon cladding. PMMA is a common plastic with good optical clarity. Nonetheless, it still is known to absorb visible light and had to be considered as a factor in heating the optical bundle. To isolate this variable, a solid PMMA rod was acquired with the same optical characteristics as the individual fiber core's. The heating in the PMMA rod was measured as a result of photo-induced heating using the optical setup described previously. The heating over a ten minute measurement period is shown in Figure 3.2:

Figure 3.2 Heating in Fiber Optic Core

Given the S/N ratio and the temperature stability of the camera/experiment, no detectable temperature rise was measured in the solid PMMA rod. These results are in agreement with other experiments found in the literature

associated with optical damage in PMMA optics. Given these results, optical absorption in the fiber core was determined to not be a significant contributor to overheating in the fiber bundle.

3.4 Photo-Induced Heating in Fiber Cladding Material

Approximately four percent of the area of the fiber optic bundle face is made of the cladding material Teflon. To test the optical absorption of the Teflon, twenty 3mm diameter by 50 mm long fibers were configured side-by-side into a 60 mm x 50 mm “sheet” of optical fiber. In this configuration, light shined onto the sheet would illuminate a solid surface of cladding material. The heating in the fiber cladding was measured as a result of photo-induced heating using the optical setup described previously. The heating over a 10-minute measurement period is shown in Figure 3.3:

Figure 3.3 Heating in Fiber Optic Cladding

In a five minute period, the “sheet” of cladding increased in temperature by roughly 3° C, indicating strong absorption by the optical cladding. However, because an actual bundle face does not approximate a sheet of cladding, but rather an area that consists of 96% core and only 4% cladding, the heating due to cladding in an actual fiber bundle would be closer to 0.12° C. Given this reasoning, the optical absorption in the fiber cladding was determined to not be a significant contributor to overheating in the fiber bundle.

3.5 Photo-Induced Heating in Fiber Collet Material

The fiber optic bundles used in the HSL system are typically mounted within a fiber optic collet or mount. Past collets have been made from either aluminum or transparent PMMA. Previous experimental experience appeared to indicate that a reduced fiber bundle temperature was associated with the use of a PMMA collet. However, experiments performed using the setup described previously, with a fiber optic bundle mounted in a PMMA collet and an aluminum collet, failed to result in any measurable differences between the two

assemblies. It was preliminarily concluded that the heating of the optical fiber bundle was not dependent on the choice of collet material. It was noted, however, that optical factors in the laboratory setup (such as the illumination spot size) did not accurately match those that would be encountered during on-sun testing. Therefore, future studies are recommended before the bundle's collet material can be eliminated as a contributor to overheating in the optical fiber bundle.

3.6 Photo-Induced Heating in Fiber Air Voids

Gaps are visibly noticeable in commercially available, fused, fiber optic bundles of large diameter. These gaps, or voids, are often merely air-filled. The manufacturer of the commercial fiber currently being used, speculated that these air-filled voids are being optically heated by the incoming solar radiation. To test this theory, a commercial bundle with visible voids was tested and measured. The 2-D temperature profile of the heating is shown in Figure 3.4:

Figure 3.4 Temperature Measurement Showing Five Fiber Bundle Voids (Dark Spots Near Fiber Center)

The five dark spots near the center of the fiber optic bundle area associated with the visible voids. Although it is difficult to measure the actual temperature of the air in the voids, the surrounding temperature of the voids provides an average value for the void temperature. As can be seen in Figure 3.4, there was no noticeable temperature rise surrounding the voids. Therefore, it was concluded that the optical absorption in the fiber air voids was not a significant contributor to overheating in the fiber bundle.

3.7 Photo-Induced Heating in Fiber Epoxy

The fiber optic bundles used in the HSL system are often mounted within a fiber optic collet using an optical adhesive. These adhesives are fairly transmissive throughout the visible spectrum. However, optical absorption in the optical epoxy has long been suspected as a source of heating in the mounted bundles. To isolate the effect of epoxy absorption, 126 3mm diameter fiber were epoxied together using an optical adhesive typically used for mounting. The fibers were not fused together as they typically are in a commercial bundle. This was done to ensure that the only heat contributor would be due to the epoxy (since core and cladding material had been identified as non-contributors). The heating in the epoxied bundle is shown in Figure 3.5.

Figure 3.5 Heating in Epoxied Optical Fiber Bundle

In a five minute period, the “sheet” of cladding increased in temperature by roughly 3.5° C, indicating strong absorption by the epoxy. Consequently, the optical absorption in the mounting epoxy was determined to be a likely and significant contributor to overheating in the fiber bundle. Based on these results, it was decided that future bundle assemblies be fixed using compression-mount techniques.

3.8 Photo-Induced Heating Due to Contaminants

The gaps or voids discussed previously are often not filled with air. More often than not they are filled with contaminants. These contaminants are most likely impacted polishing material which has been compressed into the voids during final polishing. In addition, there also appears to be contaminants within the fused fiber itself. It appears that during the operation of fusing the fiber’s end face, debris located on the fiber cladding can become fused within the fiber face. This debris, along with contaminants impacted into void spaces, acts a heating centers within the fiber. To test this theory, a commercial fiber with observable contaminants and fused debris was illuminated using the setup described previously. A 2-D temperature profile of the bundle face after being illuminated for only a short period of time is shown in Figure 3.6.

Figure 3.6 Heating Caused By Contaminants

The “hot-spots” in Figure 3.6 corresponded precisely to the areas of visible contamination. In a five minute period, the average bundle temperature increased in temperature by roughly 3.5° C. Consequently, the contamination was determined to be a likely and significant contributor to bundle overheating. Unfortunately, the contamination proved difficult to remove. It was finally determined that wet polishing of the optic bundle followed by 2-hours of ultrasonic cleaning resulted in a bundle with significantly less contamination. The effects of these processes on bundle temperature are shown in Figure 3.7:

Figure 3.7 Reduction in Bundle Heating with Reduced Contaminants

From Figure 3.7, it is apparent that the heating of the optical fiber bundle can be reduced significantly using the cleaning procedure developed.

3.9 Conclusions

Past failures associated with a large-diameter fiber optic bundle appear to have been caused by the introduction of unwanted contaminants and epoxy into the fiber optic bundle face. Using an epoxy-free compression mount and aggressively cleaning the optical fiber face appears to result in significant reductions in fiber heating. These techniques were applied to a commercial bundle that was then tested on-sun for a two week period. The fiber bundle survived for the full two-weeks of testing with no observable damage to the optical fiber face, an achievement that had previously been unobtainable. Given past experience with optical fiber failures, it appears likely that this fiber bundle would have survived for a considerable amount of time. Testing is still continuing to evaluate the long-term performance of this bundle.

4. Low Cost Primary Mirror Development

A new supplier has been located for the primary mirror. Bennett Mirror Technologies, from New Zealand, has been tasked with providing a primary mirror that meets the current stringent specifications of the benchmark glass mirrors. The mirrors they are supplying for testing are 3mm, 4.5mm, and 6mm thick acrylic parabolic dishes. The mirror is a back-surface mirror, so the reflective surface will be protected by a layer of acrylic. This should prove to be a very durable mirror that can withstand years of service in outdoor environments. The manufacturer has claimed that some of its mirrors have been used in outdoor conditions for at least ten years with no noticeable degradation.

Mirrors are being sent to ORNL, UNR, USU and SAIC for testing. Different mounting techniques are being investigated, as the mirror will not hold a parabola unless well supported, due to how thin it is. Finite Element Analyses are being performed on different mounting structures to determine the most suitable design to support the paraboloid geometry and to prevent damage during high winds. Figures 4.1 and 4.2 show the grid used in the FEA analysis and an example deformation figure. More detailed results will be available in future reports.

Figure 4.1 FEA Grid

Figure 4.2 Deformation of mirror with spring preloads

5. Potential Applications for Hybrid Solar Lighting

5.1 Background

The Hybrid Solar Lighting (HSL) device collects sunlight using roof-mounted solar concentrators and delivers the light deep into buildings through optical fibers. Light is delivered using a hybrid luminaire that combines both the collected sunlight and conventional electric lights. The electric lights dim in proportion to the amount of sunlight available and can potentially reduce electric lighting energy consumption during the daytime. One of the areas that needs development is the identification of applications where the HSL device will show a maximum energy savings potential. This document analyzes a number of applications where the HSL device can be used, based on parameters such as required levels of illuminance, recommended correlated color temperature (CCT) and color rendering index (CRI) of the source, typically used sources, total lumens used, and the energy consumption of the source used.

5.2 Potential Applications

The HSL is a unique device that provides sunlight directly into building interiors and has the potential for energy savings during the daytime by reducing the use of electric lights. Depending on the size of the optical fibers used (different diameters from large core to small core), the average amount of light available for illumination use at the end of each fiber can vary from a 100 lumens to more than 1000 lumens when there is full availability of sun. Hence, it can be used in applications that employ sources ranging from a 10W 'A' lamp to a 32W fluorescent lamp. Previous reports [1] indicate that the quality of the light after it passes through the mirrors and the optical fiber does not significantly change the full spectrum of sunlight, and has a high CRI (~100) and a CCT of about 5000 K. The length up to which the fiber can provide useful illumination will also be a point of consideration when choosing the application. Currently, the HSL device can deliver up to 50,000 lumens at 10 m away from the concentrator during a sunny day, with a loss of about 50% at that length [1]. The actual amount of light emitted from the fiber end at any time depends on the luminous flux collected by the solar concentrator. Thus, the illuminance fluctuates according to the change in sun availability. There are some niche applications where the unique qualities of the HSL device will be a good match. These are discussed below.

Niche applications

The variation in the available light can be an advantage if the HSL is used in applications where the illuminance requirement changes with the brightness of the adjacent exterior spaces. Tunnel entrances and building entrances are typical examples where the eye needs to adapt to the interior light level when coming from a bright exterior. This adaptation is necessary during the daytime but not at night. In this case, there is a need for higher light levels with increases in sunlight.

Adaptation

When we enter a movie theater in the daytime, it is difficult to steadily walk around to look for empty seats. Once our eyes adapt to the dark light level, however, we can clearly see the surroundings and may find many seats to be empty.

Human eyes handle visual information over a wide range of luminances, approximately 12 log units [2]. However, to deal with such a wide range, the visual system has to adjust its sensitivity to the ambient luminance levels. As time passes in the dark, the sensitivity of the human eye increases. The time needed for adaptation usually depends on the size of the change in luminance. For changes in luminance of approximately 2 to 3 log units, adaptation is complete in less than a second. For larger luminance changes, it may take human eyes a few minutes to adapt to the luminance level.

When the visual system is not completely adapted to the ambient brightness, its capabilities are limited. When we enter a darker interior space from a brighter exterior space, we often have difficulties seeing objects and the interior appears dark and gloomy. Therefore, any entrances (e.g., tunnel entrances and building entrance lobbies) are potential applications of for the HSL.

Tunnel Entrance Lighting

To provide appropriate visibility at a tunnel entrance, it is very important to account for the adaptation process. There are two effects that should be avoided when designing tunnel entrance lighting—the black hole effect and the blackout effect [3].

The black hole effect is caused by a perceived difference in the external and internal luminances. If the difference in luminance is too large for drivers to have sufficient confidence that the path in the tunnel is clear, the driver tends to reduce speed. The blackout effect is also caused by the luminance contrast between the adaptation level before and after entering a tunnel. Drivers entering a tunnel at a relatively high speed require sufficient time for adaptation. If the illuminance is very high on a fine day and the tunnel entrance is poorly illuminated, drivers may also reduce their speed. Such sudden reduction in speed caused by the black hole effect and the blackout effect induce traffic jams and may result in collisions.

Hence, the lighting at the entrance has to be bright enough to allow the eye to quickly adapt from the exterior brightness during the day. Tunnel entrances typically have more luminaires than the interior of the tunnel. These extra luminaires are switched on during the day and need to be turned off during the night. When this switching is not done properly, the extra illumination leads to a loss of energy and causes glare at the entrance at night because of the increased light levels. By using the HSL device as a supplemental system, the lighting at the entrance will automatically adjust for exterior brightness.

Figure 5.1a Entrance to a tunnel in daytime

Figure 5.1b Tunnel entrance at night

Implementing the HSL system will have a number of challenges, and such a system will have to strictly follow the lighting codes for tunnels. Not all tunnel entrances may accommodate the proper positioning of the HSL concentrator to get the sun all through the day. There is also a limitation on how deep into the tunnel the lighting system can provide useful light.

Similarly, entrances to buildings also require illumination adjustments to allow for adaptation from exterior brightness. Here again, the HSL device will be an appropriate source, but eye adaptation is not as critical in building entrances as it is for tunnel entrances.

Storefront lighting and veiling reflections

The contrast of a visual task depends on the glossiness of the task surface and on the geometric relationships between the light sources, the task, and the eyes. If the visual task produces a mirror angle between the eye and the luminaire or another bright object, contrast is reduced. This effect is called a veiling reflection [2]. Veiling reflections from luminaires cause discomfort glare on computer VDT screens.

Figure 5.2 Storefront with a veiling reflection of the bright outdoors

The same problem is experienced in a storefront with glass windows that face a large outdoor space, such as a courtyard. A bright daytime exterior may cause people to not be able to see the products displayed behind the glass window unless the illuminance levels of the display increase in proportion to the brightness outside. In cases where there are no displays behind the glass windows, the light levels inside the store are also an indicator of whether the store is open or not. Here again, higher light levels in the interiors are required during a bright day to attract people into stores. By using the HSL device as a supplemental lighting system, the need for varying light levels can be accommodated without increasing lighting energy consumption.

Cost would be a limiting factor in using the system for a storefront display application, but if we can show significant improvement in sales and energy savings, this could be a feasible application.

Other Applications

Most other applications require constant levels of illuminance. Using the HSL for such applications would require proper controls that adjust the electric light to compensate for the variation in sunlight. While this is a barrier, significant energy savings due to a reduction in the use of electric lighting could overcome this barrier. In these applications, the HSL cannot replace the existing lighting systems, but it can supplement the existing systems and reduce their usage. Some of these applications are discussed below.

Museum Lighting

The primary visual task in a museum is for the public to view the displayed natural artifacts and examples of human achievement [2]. There are four types of museum displays: flat displays on vertical surfaces (e.g., paintings on walls), display cases (e.g., rare artifacts), three-dimensional objects (e.g., sculptures), and realistic environments. Each of these has unique challenges.

One of the critical issues in museum lighting is the deterioration of the object on display due to the radiated heat from traditional light sources such as halogens and PAR lamps. With the use of the HSL device, the radiated heat can be reduced because the HSL device uses an IR filter at the concentrator and produces little radiated

heat, if any. The color properties of sunlight (full spectrum and high CRI) are very appropriate in museum applications and can ensure good color discrimination when viewing a work of art [4].

Figure 5.3 Museum lighting with traditional halogen luminaires

Recommended Illuminance levels Horizontal Vertical	50-500 lux 50-500 lux
Correlated Color Temperature (CCT)	2800-6500 K
Color Rendering Index (CRI)	>90
Typically used source	MR, PAR, halogen lamps
Lumens per fixture	100-2000
Typical energy use per fixture	20-100 W

To use the HSL device as a light source would require matching the light distribution from the fibers with the light distribution of the original lighting system. To maintain constant illuminance at the task, the controls should be designed to change the illumination levels of the electric light in accordance with the variations in the available sunlight.

The positioning of the HSL concentrator and the available length of fiber for useful illumination will be limiting factors in the device's application in museums.

Retail Lighting

There are three goals to be achieved with retail lighting: attract the customer, allow the customers to evaluate the merchandise, and facilitate the completion of the sale [5]. The primary visual task of retail display lighting is to attract the customer passing by the display. Display lighting is typically brighter than ambient lighting.

Display lighting in most retail stores is switched on during store hours, even during the daytime, and typically uses halogen MR, PAR and other incandescent light sources. The HSL is a good supplemental lighting system for display lighting, not only to reduce energy consumption during the daytime, but also to improve the life of the existing sources, which will lead to reduced maintenance costs. The color rendering properties of the system also make it an appropriate source. The retail lighting application has the highest potential for energy savings because the existing sources for this application (incandescents and halogens) have low efficacy, and there are a large number of retail establishments that are open during the day. Also, most retail stores are only one or two stories high and hence the required length of the optical fiber is minimized.

As with all other applications, matching the light distribution to the current lighting systems and the control system to maintain light levels will be the first barriers that need to be overcome.

Figure 5.4 Lighting in a typical retail outlet during the daytime

Recommended Illuminance levels Horizontal Vertical	1000-10,000 lux 300-500 lux
Correlated Color Temperature (CCT)	2800-6500 K
Color Rendering Index (CRI)	>90
Typically used source	MR, PAR, halogen lamps
Lumens per fixture	500 - 1000
Typical energy use per fixture	20W - 100W

General Office Lighting

The primary goal of office lighting is to facilitate efficient task performance by the people working in the lighted environment. It is also important to create a stimulating working environment; office lighting contributes to the environment that affects the mood and productivity of office workers [2].

Many types of visual tasks are performed in an office space, and each of these requires a set of unique lighting conditions. Generally, office lighting should provide a glare-free environment and enough ambient illumination on horizontal and vertical surfaces. Task lamps can provide the additional illumination needed for more critical visual tasks. Energy-efficient lighting is very important to office lighting. Good lighting design paired with energy-efficient lighting systems will cut down on the overall energy consumption of the office. Currently, most office lighting systems use linear fluorescent sources.

The HSL system can be used as a supplemental system to provide general ambient illumination in offices. Designed with good lighting controls, the HSL has the potential to reduce energy consumption in office lighting.

Because of the sheer number of office buildings and their lighting energy requirements, this application has the potential to save a lot of energy in the long run.

But most office buildings are multi-storied structures. The HSL device loses 50% of the captured light at 10 m [1]. Hence, it can be used only for the uppermost floor of an office building. Unlike the case of retail lighting, the energy savings of this application will be relatively less because the currently used linear fluorescent sources are much more efficient than incandescent and halogen sources. To actually get the full energy benefits of the system, dimming ballasts would need to be used with the existing fluorescent lighting systems, which could be an added expense if they are not already being used.

Figure 5.5 Typical office lighting for open plan offices

Recommended Illuminance levels Horizontal Vertical	300-500 lux 50 lux
Correlated Color Temperature (CCT)	3000-5000 K
Color Rendering Index (CRI)	>80
Typically used source	Linear fluorescent
Lumens per fixture	2000 - 6000
Typical energy use per fixture	32-94 W

Restaurants (daytime)

The primary visual task in a restaurant dining area is to create a mood for the customer's dining experience while at the same time allowing them to see the food they are eating, the menu they are ordering from, and the faces of their dining companions. There are three types of dining spaces: intimate, leisure, and quick service [2]. The lighting mood in these spaces can range from subtle and soothing to bright and vibrant, which creates a unique set of design challenges for each type of space.

The light level requirements in a restaurant setting change throughout the day. In the daytime, spaces are usually more brightly lit than during the nighttime. Using the HSL as a supplemental lighting system for ambient lighting can reduce the amount of electric lighting needed during the day to create the brighter atmosphere. Variations in the HSL lighting could also create an ambient lighting effect giving cues about the exterior to those sitting inside the restaurant. The illumination from the HSL would not be needed during the nighttime.

Figure 5.6 Dining area of a typical restaurant

Recommended Illuminance levels Horizontal Vertical	50-100 lux 30 lux
Correlated Color Temperature (CCT)	2800-6500 K
Color Rendering Index (CRI)	>90
Typically used source	Incandescent, MR, PAR
Lumens per fixture	500 - 2000
Typical energy use per fixture	< 100W

This application will not show high energy savings, as in the case of retail lighting, but could work as specialty lighting in high-end restaurants, which could attract customers and lead to greater revenue. Using the HSL device in this application is of value only in locations where there are no windows and there is an opening to the sky.

Hallways

The primary visual task in a hallway is safe and easy navigation from one part of a building to another during normal hours and during an emergency. Usually, hallways are deeper into a building, with little or no access to windows. In most hallways, the lights need to be switched on almost all the time the building is occupied (sometimes even 24 hours). Using the HSL luminaire, significant energy savings can be achieved during the day for hallways and corridors in office and hospitality facilities. As an added advantage, during a power outage the HSL would remain “on” and continue to provide illumination.

As in the case of other applications, usable length becomes an issue in this application. Oftentimes, corridors are multiple times longer than the 10 m limit on the current HSL technology. Moreover, corridors are mostly found in multi-storied buildings, and the HSL can only serve the top floor in a building.

Figure 5.7 Typical hallway in a hotel facility

Recommended Illuminance levels Horizontal	50 lux
Correlated Color Temperature (CCT)	2800-6500 K
Color Rendering Index (CRI)	>80
Typically used source	Linear fluorescent, incandescent, compact fluorescent
Lumens per fixture	1000 - 3000
Typical energy use per fixture	30W - 75W

5.3 Conclusion

These are some of the applications where the HSL device is likely to have maximum reception in the market initially. Which application actually should be chosen for further development depends on where the most benefits are seen (cost, energy, aesthetics, etc.). Some of the applications described are niche markets, such as the tunnel lighting where the HSL serves the application well but may not have a large energy savings or cost benefit. Some applications, such as retail store lighting, may have a large energy benefit but first have to overcome a number of technical challenges. In all applications, advancements in the efficiency of the HSL over greater lengths and a reduction in price would make it more viable as a supplemental lighting technology. Nevertheless, the HSL is a clean and simple lighting technology showing good potential for vast energy savings. One or two of the above applications will be chosen as the initial target market for the HSL for further development.

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6. Photobioreactor Population Experiments and Productivity Measurements

6.1 Bioreactor Testing

After redesigning the header, it is now capable of a high degree of coverage and an excellent distribution during the high volume flow during harvesting. The secret was to find a higher acceptable populating velocity. In other words, the flow rate was increased during the time when the organisms were being attached to the membranes, which was originally thought to be limited to 0.5 gpm per linear foot of membrane. The water flow rate has since been increased to 1.5 gpm per linear foot with excellent results. The net result is a more consistent coverage flow to go along with a more consistent harvesting flow (which is nearly 15 gpm per linear foot) and a better overall organism growth. Pictures of coverage are shown below.

Figure 6.1 Left screen coverage at 1.5 gpm/ft

Figure 6.2 Right screen coverage at 1.5 gpm/ft

6.2 Productivity Measurements

A sustainability test was initiated with approximately 30 gallons of algae and 2 Omnisil membranes. The initial mass determination procedure has been completed, which allowed for the quantification of the algae growth over the course of the experiment. The daily yield of organism was determined, after harvesting each night and is shown in Figure 6.3. Also shown in Figure 6.3 is the average (daily) solar flux for Athens, Ohio, during the experiment, as measured at Scalia Laboratory, Ohio University's weather station. The results are not considered significant, as they have not been repeated. However, they are presented here because of the trend.

Figure 6.3 Preliminary Productivity Data

It should be noted that the productivity for the following day tracked the average solar flux for the previous day's growth very well (correlating to over 98%). It is hoped that these experiments can be repeated soon to confirm this. However, it seems intuitive that if the solar collector/distributor system is tuned to produce an optimal photon flux ($100\text{--}200\ \mu\text{mol m}^{-2}\text{ s}^{-1}$), that reducing the daily photon exposure would correspondingly reduce biomass productivity.

7. Development of a Microalgal CO₂-Biofixation Photobioreactor

7.1 Abstract

There is renewed interest in microalgal biofixation of carbon dioxide (CO₂) in photobioreactors hooked up to solar concentrators as a strategy to help reduce the release from electric power plants into the atmosphere of CO₂, a greenhouse gas (GHG). A number of studies on this approach were conducted during the 1990's, which identified its practical challenges. Since then, however, significant advancements have been made, particularly on the design of the solar concentrator, development of light-transmission and distribution devices, as well as in the selection of CO₂-fixing microalgae species. The objectives of this study were: (1) to determine the growth rates of *Chlorella vulgaris* and SC2, an unidentified thermophilic cyanobacterial species collected from the Yellowstone National Park, at varying levels of light and at elevated temperature and CO₂ concentration; and (2) to design a bench-top lab-scale photobioreactor for growing cyanobacteria for CO₂ fixation.

7.2 Introduction

There is renewed interest in microalgal biofixation of carbon dioxide (CO₂) in photobioreactors hooked up to solar concentrators as a strategy to help reduce the release from electric power plants into the atmosphere of CO₂, a greenhouse gas (GHG). A number of studies on this approach were conducted during the 1990's, identifying its practical challenges. Significant advancements, however, have been made on design of solar concentrator, development of light-transmission and distribution devices, and in the selection of microalgae species.

There have also been advancements in the selection of microalgae species for CO₂ mitigation. While mesophiles, which typically grow at 13-45 °C, were heavily studied during the 1990's, the recent studies have also focused on thermophiles or high-temperature-tolerant species. Thermophiles can grow at temperatures ranging from 42-75 °C. An advantage in using thermophiles for CO₂ sequestration is the significant reduction in cooling costs. A disadvantage, however, is increased loss of water due to evaporation. The recent studies also focus on byproduct-producing microalgae, which could increase the economic feasibility of the strategy by offsetting mitigation costs [1].

Changes in the political domain relating to CO₂ sequestration have also been brewing. The planning for the implementation of international policies for regulation of greenhouse gases (GHGs), such as the Kyoto protocol, is underway. Although the United States is not a signatory to the Kyoto protocol, the U.S. is implementing its own domestic climate policy notwithstanding [2]. Based on these new policies, various new concepts, such as the international GHG emission trading, have emerged. It is believed that political incentives will help achieve the feasibility of CO₂ mitigation projects.

The use of solar-powered photobioreactors for CO₂ sequestration has various advantages. These include higher productivity, smaller land area requirement, higher light utilization efficiency through use of fiberoptic light guides, higher water use efficiency, and higher harvesting efficiency. Genetically engineered cyanobacterial species might also be used without concern for disturbing the natural environment.

7.3 Objectives

The long-term goal of this study was to investigate the potential of Hybrid Solar Lighting (HSL) in photobioreactor biomass production systems, especially in CO₂ mitigation systems. The specific objectives of the current study were: (1) to determine the growth rates of *Chlorella vulgaris* and SC2, an unidentified thermophilic cyanobacterial species collected from the Yellowstone National Park, at various light levels at

elevated temperature and CO₂ concentration; and (2) to design a bench-top lab-scale photobioreactor for growing cyanobacteria for CO₂ fixation.

7.4 Materials and Methods

Strain and medium

One mesophilic species and one thermophilic species of cyanobacteria were tested. For the mesophilic species, *Chlorella vulgaris* (UTEX 259) was used, obtained from the Culture Collection of Algae at the University of Texas at Austin (UTEX). For the thermophilic species, a pure culture of an unidentified cyanobacterial strain of 1.2. S.C.(2) [referred to hereafter as SC2], originally isolated from Yellowstone National Park by Dr. Keith Cooksey of Montana State University was used (Figure 7.1). Proteose medium, a standard medium for *Chlorella vulgaris* (UTEX 259), was used to culture the latter, and BG-11 was used to culture SC2.

Figure 7.1 Flask cultures of SC2.

Culture conditions

Samples were illuminated with 40-Watt, 1.22-m (or 48-in)-length fluorescent lamps. Sixteen hours of daily photoperiod were employed. For CO₂ condition, either room ambient CO₂ or elevated CO₂ concentration was used. The average room ambient CO₂ concentration over 24 hours was within the range of 370 - 405 ppm (μmol/mol). For the elevated CO₂ condition, pre-configured 5% CO₂ was used, supplied to the batch culture in a Pyrex flask via 1/8 OD tubing system. The CO₂ concentration in ppm level was measured using an IRGA, LCA-4 (Analytical Development Company Limited, Hertfordshire, England). Percentage level of CO₂ concentration was measured using a NOVA Model 302WP (NOVA analytical systems Inc., NY).

Conditions for mesophilic species

Growth characteristics of *Chlorella vulgaris* (UTEX 259) at 25, 35 and 50 °C with ambient CO₂ condition were examined. Each constant-temperature treatment was achieved using a heated water bath (MW-1130A-1, Blue M, Blue island, IL, USA) (Figure 7.2). The inoculation was conducted under aseptic conditions under a laminar flow hood to avoid contamination. Fifteen ml of algae inoculum was used for each sample, and each sample had a total volume of 50 ml. The initial biomass used for inoculation was measured non-destructively via optical density.

Figure 7.2 Apparatus for the heated water-bath experiment.

The change in biomass over time was monitored using both measurements of optical density and dry weight. For optical density, absorbance at three fixed wavelengths, 438, 540 and 678 nm, were scanned using a Beckman DU640 spectrophotometer (Beckman Instruments, Inc., Fullerton, CA). Four-week long experiments were conducted. Two different light intensities, 212.2 ± 7.0 (S.E.) $\mu\text{mol m}^{-2} \text{s}^{-1}$ and 102.5 ± 1.8 (S.E.) $\mu\text{mol m}^{-2} \text{s}^{-1}$, were used, representing high and low light conditions, respectively.

Conditions for thermophilic species

Growth characteristics of the thermophilic species SC2 at elevated temperature (50 °C) and elevated CO₂ (5% v/v) were examined. The high-CO₂ air was made to pass through a filter and a humidifier filled with autoclaved nano-pure water into 250-mL Pyrex flasks wherein the cultures were grown. Incoming flow was measured using a flow meter. Three light intensities, 250 (average 246.1), 200 (average 203.0), and 100 (average 100.1) $\mu\text{mol m}^{-2} \text{s}^{-1}$ were tested. The experiment was conducted for eight days. Two samples were harvested every other day.

Harvest

Each biomass sample was oven-dried at 105 °C in accordance with standard cyanobacteria sampling [3]. Prior to the oven-drying process, the sample was either centrifuged or filtered to separate the biomass from dissolved nutrients. Samples of *Chlorella vulgaris* were centrifuged using Eppendorf 5810R (Eppendorf AG, Hamburg, Germany) and samples of SC2 were filtered with Whatman filter papers.

7.5 Results

Mesophilic species

The thermal adaptability of the *Chlorella vulgaris* strain (UTEX 259) used in this study was limited. The strain failed to survive at elevated temperature (50 °C). The strain even showed limited growth at 35 °C. *Chlorella vulgaris*, however, grew reasonably well under both high and low light conditions at 25 °C. After day seven, the dry weight began to plateau. The maximum dry weights for high and low light conditions were 0.438 g/l and 0.389 g/l, respectively (Figure 7.3). The initial inoculum concentration was 0.064 g/l for both light conditions. The resulting specific growth rates (μ) were 0.228 and 0.231 day⁻¹ for the high and low light conditions, respectively, and the doubling time (T_d) was three days for both lighting conditions. Significant difference in dry biomass did not exist between two conditions.

Figure 7.3 Maximum dry weights of *Chlorella vulgaris* (UTEX 259) under two light conditions.

Thermophilic species

SC2 grew quite well at an elevated temperature of 50°C and at elevated CO₂ (5% v/v supplemented). Figure 7.5 shows the changes in dry weights over time under three different light intensities. There were a few days of lag period, followed by the exponential growth phase. The maximum dry weights, occurring on day eight, under 250, 200 and 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ were 0.428 g/l, 0.664 g/l and 0.427 g/l, respectively. The initial inoculum concentration was 0.071 g/l for the three treatments. The specific growth rates (μ) were 0.341, 0.516 and 0.382 day⁻¹ and the doubling times (T_d) were 48.8 hr, 32.2 hr and 43.5 hr for 250, 200 and 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively. In additional experiments, it was observed that SC2 also successfully survived at the lower light intensities of 36.9 and 70.19 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

Figure 7.4 Dry weight changes over time for three light intensities in $\mu\text{mol m}^{-2} \text{s}^{-1}$.

Following figure is a composite of results with previous experiment.

Figure 7.5 Composite of growth curves for three light intensities.

Development of bench-top lab-scale bioreactor

A bench-top lab-scale photobioreactor for growing cyanobacteria for CO₂ fixation was designed and constructed (Figures 7.6 and 7.7). The size of the reactor was 29.2 cm W x 40 cm H x 61 cm L (or 11 1/2" W x 15 3/4" H x 24" L). A small pump (Beckett Corporation, Irving, Texas), with 227 L/hr (60GH) capacity, was used for delivering the nutrient solution on top of the rectangular membrane onto which the cyanobacteria would attach and grow. The nutrient solution (BG-11) would be delivered through a 1.27-cm (1/2-in ID) PVC pipe. Three rectangular membrane frames (45.72 cm W x 25.40 cm H or 18" W x 10" H) as growing substrates or supports were enclosed in a transparent airtight closure. The piping system also served as the structure to hold the screen. A Plexiglas top cover was used to allow penetration of photosynthetic radiation. Air movement within the chamber was controlled using two DC fans (FBA12G, Panasonic) and a DC power supply. The air movement was regulated by simply changing the voltage supply. Under 12 V DC operation, the average wind speed at the center was 0.7 ± 0.2 m/s. The temperature within a photobioreactor was controlled using a constant water bath (National Appliance Co., Portland, Oregon) and heat exchanger. Further improvements are currently being implemented to operate the membrane-based photobioreactor.

7.6 Discussion

Certain species of *Chlorella* had been studied for both CO₂ mitigation and for their commercial potential as a health food. The strain of *Chlorella vulgaris* (UTEX 259) used in this study, however, showed limited thermal adaptability, and presents a challenge in exposing such a strain to direct flue-gas injection from an electric power plant. Previous studies reported that some strains of *Chlorella* are thermotolerant. For example, *Chlorella pyrenoidosa* can grow at 39 °C. [4] reported that an unidentified *Chlorella* sp. (UK001), which was isolated from a spring in Oh-ita prefecture, Japan, could grow at 40 °C. [5] also reported that an unidentified *Chlorella* sp. (strain K35), isolated from a Japanese fresh-water environment, could grow at 40 °C, although there was a five-day lag before growth. This same species, however, failed to grow at 45 °C. *Chlorella vulgaris* (UTEX 259) used in this study apparently had a lower optimal temperature than those cited in the literature.

Previous studies showed high adaptability of *Chlorella* sp. to elevated CO₂ conditions. For instance, [4,6] reported that *Chlorella* sp. UK001 could grow successfully at 10% CO₂ condition. It was also reported that *Chlorella* sp. could be grown at 40% CO₂ condition [5]. Further, [7] found a strain of *Chlorella* sp. T-1 which could survive at 100% CO₂, though its maximum growth rate occurred under 10% CO₂ concentration. The light requirements for some species of *Chlorella* sp. were also studied. Typical light intensity requirements of microalgae are relatively low in comparison to those for higher plants. For example, the saturating light intensity for *Chlorella* sp. is only approximately 200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ [5].

Figure 7.6 Schematics of membrane photobioreactor.

Figure 7.7 Operation of membrane photobioreactor.

The thermophilic SC2 could grow very well at the elevated temperature of 50 °C and at elevated CO₂ (5% v/v supplemented). The species also exhibited high light adaptability, growing successfully under high light intensity (246.1 $\mu\text{mol m}^{-2} \text{s}^{-1}$) and low light intensity (36.9 $\mu\text{mol m}^{-2} \text{s}^{-1}$). This result is useful in determining the best lighting strategy to be used for a CO₂-mitigation photobioreactor.

Only limited attention has been given on the selection of materials for membrane immobilization of cyanobacteria. [8] used 74-mesh nylon bolting cloth fused to the rim of a perforated, 9-cm plastic petri dish bottom. The use of such non-absorbent support avoided dehydration and related problems resulting from the high matric potential of water in a filter-paper support. An interesting finding made by [8] was the greater CO₂ exchange rate of *Chlorella pyrenoidosa* in membrane-supported culture than in suspended/stirred and bubbled cultures. [9] used a glass microfiber filter (Whatman) for photosynthesis study of *Spirulina*. These experiments, however, were conducted for only a short time period and only small membrane sizes were used. The investigation of optimal membrane materials for thermophiles for long-term operations has yet to be done. Further improvements and strategic engineering designs are needed to realize optimal microalgal CO₂ sequestration systems.

7.7 Conclusions

1. The thermal adaptability of the strain of *Chlorella vulgaris* (UTEX 259) used in this study was limited. The strain failed to survive at the elevated temperature of 50 °C. The strain even showed limited growth at 35 °C;
2. SC2 could grow at the elevated temperature (50°C) and at the elevated CO₂ (5% v/v supplemented). The species also had high light adaptability, growing successfully at high light intensity (246.1 $\mu\text{mol m}^{-2} \text{s}^{-1}$) and low light intensity (36.9 $\mu\text{mol m}^{-2} \text{s}^{-1}$);
3. The membrane photobioreactor was designed and constructed. Further studies on membrane materials, initial biomass loading and nutrient circulation rate would be needed.

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