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PERFORMANCE OF NEW HYBRID SOLAR LIGHTING LUMINAIRE DESIGN

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ABSTRACT
We report on the performance of a new hybrid luminaire designed to blend light from a fiber optic solar source with electric fluorescent lamps. The luminaire design studied involves a commercially-available fluorescent luminaire that had been modified to include optical elements for efficiently dispersing two fiber optic solar light sources. Quantitative measurements of the hybrid luminaire's optical efficiency and spatial intensity distribution/deviations are discussed. The effects of static differences and dynamic fluctuations in spatial intensity distribution are qualitatively discussed and potential design improvements examined.

INTRODUCTION
Oak Ridge National Laboratory is developing an energy-efficient Hybrid Solar Lighting System which uses large-core plastic optical fiber to permit direct utilization of visible solar light for internal lighting[1,2], see Fig. 1. A major step toward the realization of fiber optic solar lighting for internal lighting purposes is the development of a hybrid luminaire to seamlessly balance electric and fiber optic illuminants. Fluctuations in the intensity of collected solar light, due to changing cloud coverage or solar collector movement, requires rapid compensation by electric lamps to maintain a constant room illumination. If the spatial intensity distribution of a hybrid luminaire's electric lamps does not closely match the spatial intensity distribution of the luminaire's fiber optic illuminants, then the shift between artificial and solar lighting will be noticeable, and potentially distracting, to the occupant. In addition, because this technology is primarily aimed at reducing energy usage, any potential hybrid luminaire designs must maintain high optical efficiencies.

To develop an optically efficient hybrid luminaire that exhibits a static spatial intensity distribution, regardless of which lighting source dominates, various light dispersing techniques have been developed and studied[3]. Among these techniques, one dispersion device and corresponding luminaire are providing encouraging results. The construction details of this luminaire and a quantitative measurement of its optical performance are reported in this paper.

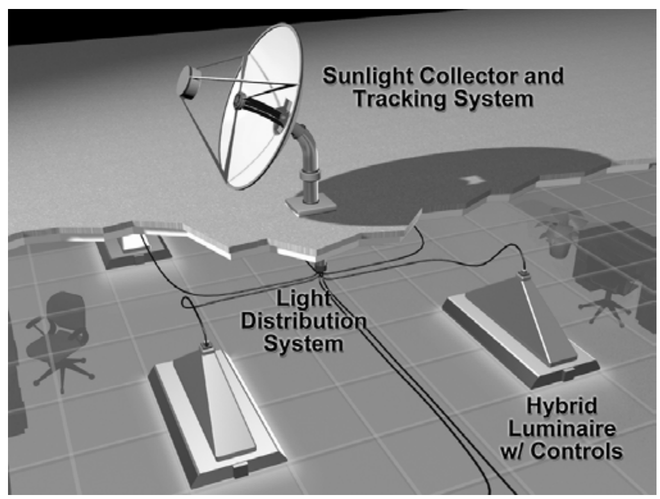

Fig. 1 - Hybrid Solar Lighting System

SELECTION AND MODELING OF COMMERICIAL LUMINAIRE
A wide variety of commercially-available luminaires exist which can be adapted for use as hybrid luminaires. However, to limit design efforts, a single Lithonia four-tube T8 fluorescent luminaire was selected for retrofitting. The Lithonia General Purpose T8 Luminaire was chosen because of its high electrical and optical efficiency, relative low cost, and easily integrated design. The GT8 luminaires also utilize an acrylic diffuser that assists in masking/merging two internal light sources. To aid in the design, construction, and testing of a hybrid luminaire, a high-detail optical model of the luminaire

was first constructed using ZEMAX ray-tracing software. This model allowed the luminaire to be simulated under various configurations. The modeled luminaire was simulated within a six-foot cube, to provide intensity distribution data at various positions and working distances. An example of one such simulation is shown in Fig. 2.

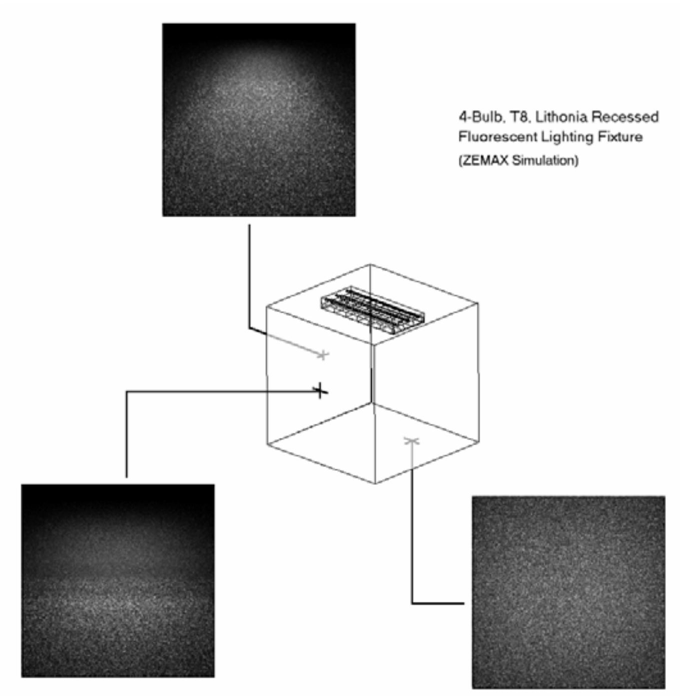

Fig. 2 - Spatial Intensity Distribution of Selected Commercial Fixture

From these simulations, it was verified that the natural conic intensity distribution of an optical fiber was highly incompatible with the intensity distribution of a fluorescent 4-tube luminaire designed for large-area lighting. It was determined that the conversion of the natural fiber optic light distribution into a into a long, uniform, cylindrical source distribution would permit the most effective blending of fiber optic lighting with fluorescent lamps.

HYBRID LUMINAIRE USING 3M SIDE-EMITTING ROD

Past attempts to develop an efficient means of converting the conic distribution of fiber optic lighting into a cylindrical distribution had resulted in less than desirable results. A partially scattering acrylic diffuser, shown in Fig. 3, had provided less than 40% efficiency and had resulted in a non-uniform intensity distribution. A search for alternative techniques revealed a new product developed by 3M. The 3M Side-Emitting Rod (Part #: LF-180-EX-D-1M), shown in Fig. 4, was similar in design to past attempts, but utilized precision machined grooves to more accurately control scattering along the length of the rod.

Fig. 3 - Early Attempt to Construct a Cylindrical Diffusing Rod

Preliminary investigations revealed that the one-meter long, side-emitting rod appeared suitable for use in a hybrid luminaire but would require additional measurements to determine the final effectiveness and efficiency of the device.

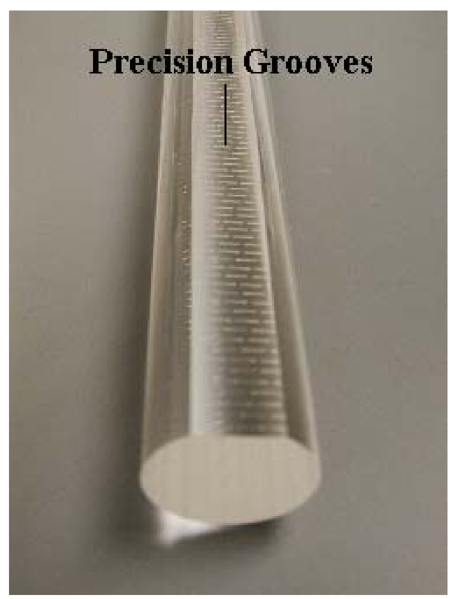

Fig. 4 - 3M Side-Emitting Rod Design

To further improve the efficiency of the side-emitting rod, a flat mirror was attached to one end of the rod. The mirror served to reflect and diverge any co-axial light that was not scattered on an initial pass through the rod. The rod was mounted within a custom-machined acrylic holder that allowed a large-core optical fiber to mate with one end of the rod. The assembly of the optical fiber, acrylic holders, and side-emitting rod are shown in Fig. 5 for one side of the rod.

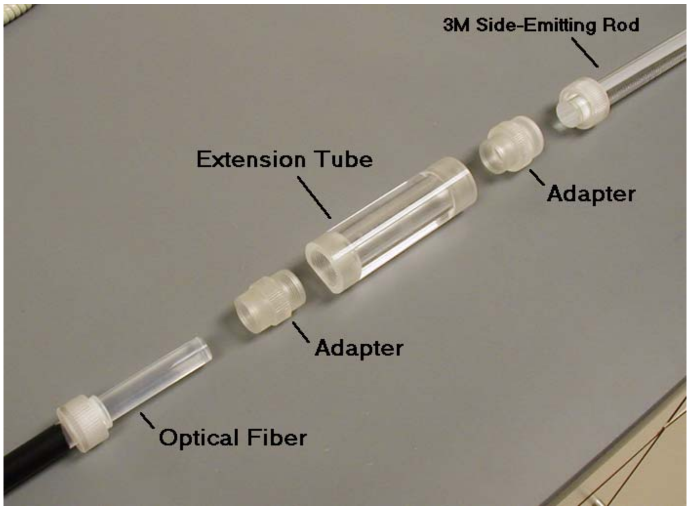

Fig. 5 - Side-Emitting Rod and Holders

Two assembled rods were mounted within a 4-tube fluorescent fixture, as shown in Fig. 6. The two side-emitting rods were located on each side of the ballast cover, directly between the two corresponding fluorescent tubes.

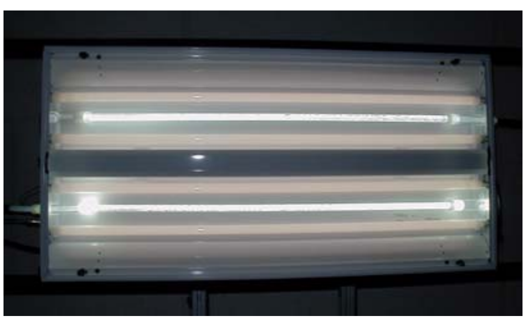

Fig. 6 - Hybrid Luminaire with Side-Emitting Rods (Diffuser Removed)

The hybrid luminaire was mounted, and its performance tested, within ORNL's Illumination Cell (see Fig. 7). ORNL's Illumination Cell is a six-foot cube equipped with mounts in the ceiling for attaching a fluorescent luminaire. A re-locatable, spectrally neutral, white wall within the cube allows the intensity distribution at various positions to be observed. A Prometric CCD colorimetry system allows the intensity and color distribution, incident on the white wall, to be precisely mapped.

Fig. 7 - ORNL Illumination Cell

The finished hybrid luminaire was mounted within the Illumination Cell and its optical performance measured (see Fig. 8).

Fig. 8 - Mounted Hybrid Luminaire with Fiber Optic and Fluorescent Sources On

RESULTS

The spatial intensity distribution on each of the five walls of the Illumination Cell was measured for the hybrid luminaire. Because we were concerned with effectively blending two different lighting sources, the distribution measurements of the luminaire were performed twice; once with all fluorescent lighting on and fiber optic lighting off, and once with fiber optic lighting on and fluorescent lighting off. The measurements produced ten intensity distribution maps, which were cropped and normalized so that they could be easily compared.

Under ideal conditions, the intensity distribution of the fluorescent lighting and the fiber optic lighting would be identical. In such a situation, any rapid change from one source to the other would be non-perceivable to the occupant. Actual measurements of the hybrid luminaire, however, revealed significant differences in intensity distribution between the fluorescent and fiber optic sources. For a nearby side-wall, the hybrid lighting fixture exhibited two "hot spots" near the center and top corner of the wall (see Fig. 9). A maximum percent difference of 12% was measured for a patch of wall roughly one square foot in area.

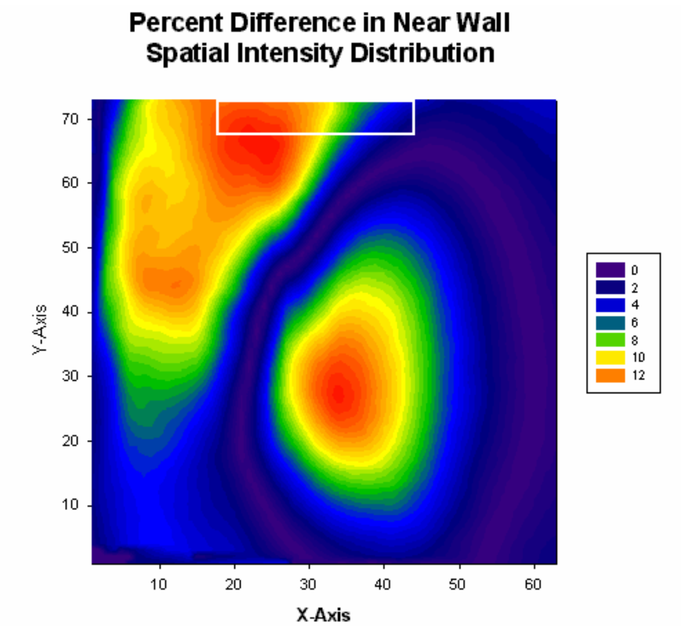

Fig. 9 - Differences in Spatial Intensity Distributions for Near Side Wall (White Box Indicates Orientation of Luminaire)

The largest difference, however, was measured at the floor of the Illumination Cell, directly beneath the hybrid luminaire. The percent differences in intensity between the fiber optic and fluorescent sources are shown graphically in Fig. 10. A significant portion of the floor area, roughly six square feet, has an intensity difference of greater than 20%. The highest measured percent difference was 27% and occurred slightly off-center of the luminaire's mounted position.

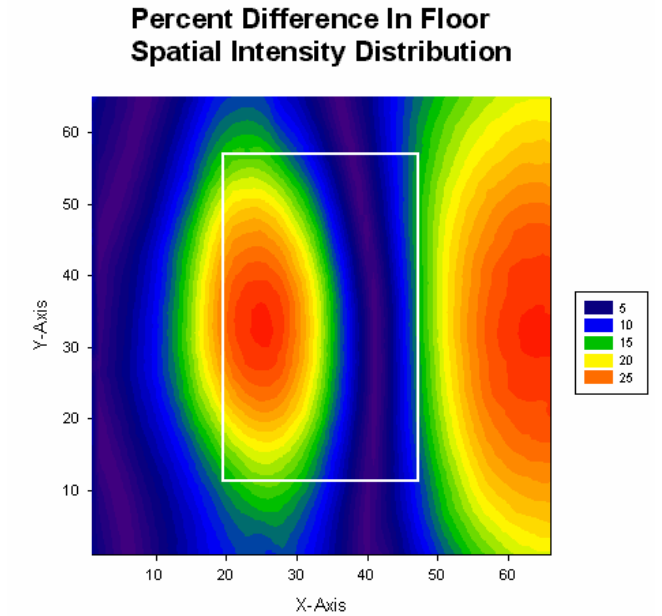

Fig. 10 - Differences in Floor Spatial Intensity Distribution (White Box Indicates Orientation of Luminaire)

The non-symmetric nature of the distribution was somewhat unexpected and may be the results of differences in total flux between the two 3M side-emitting rods. Potentially, the non-symmetry could also be due to slight variations in the mounting of the side-emitting rods. Because the current mounting did not rigidly position the side-emitting rods within the luminaire, there was some opportunity for positional variation.

The final efficiency of the 3M side-emitting rods, within the fluorescent lighting fixture, was determined by integrating all of the mapped intensity distributions for the fiber optic source and dividing by the known output of the optical fibers. The measured efficiency was approximately 58.4%. For the Hybrid Solar Lighting System to be economically feasible, it has been estimated that a hybrid luminaire design is needed which is 85% efficient. Obviously, the current luminaire efficiency is significantly lower than desired. However, it is suspected that a significant portion of the fiber optic light (≈20%) was lost due to coupling losses. Since this experiment was conducted, an improved method for coupling large core optical fibers has been developed with coupling losses as low as 3%. Given these improvements, the efficiency of the 3M side-emitting rod, within the hybrid luminaire, could potentially approach 75%. Such an increase, if confirmed, would make this technique a viable candidate for use with the Hybrid Solar Lighting System.

CONCLUSIONS

The hybrid luminaire presented in this paper still requires a significant amount of additional testing, modeling, and re-design before its physical implementation can realize its full potential. It is hoped that the incorporation of improved coupling connections and rigid mounts will significantly improve the efficiency of the hybrid luminaire to greater than 75%, while also increasing its effectiveness at blending fluorescent and fiber optic sources. In addition, there is still much research which needs to be conducted to determine the effects of small-area intensity fluctuations. With the current Hybrid Solar Lighting System, and hybrid luminaire, a small-area intensity fluctuation of 27% would be experienced over a four to five second period. Whether or not this slow fluctuation would be distracting to an occupant still remains to be determined and is expected to be the focus of future research.

ACKNOWLEDGMENTS

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REFERENCES

1. J. D. Muhs, "Hybrid Solar Lighting Doubles the Efficiency and Affordability of Solar Energy in Commercial Buildings", CADDET Energy Efficiency Newsletter December 2000, p. 6.
2. J. D. Muhs, "Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems", *Solar 2000, July 16-21, 2000,* American Solar Energy Society.
3. D. D. Earl, J. D. Muhs, "Preliminary Results on Luminaire Designs for Hybrid Solar Lighting Systems", *Solar 2001, April 21-25, 2001,* American Solar Energy Society.