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Original Publication

McCluney, Ross, "Color-rendering of Daylight from Water-filled Light Pipes",
Reprinted from *Solar Energy Materials* 21 (1990) 191-206.

Publication Number

FSEC-PF-423-90

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Color-rendering of Daylight from Water-filled Light Pipes

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Abstract

Water-filled light pipes can be used to transport concentrated beam solar radiation from a solar collection system to a utilization system, altering the spectral distribution of the radiation in a beneficial way in the process. One use for such a system would be for the daylighting of the core interior spaces of buildings, spaces that are far removed from outside walls or the roof and are therefore not amenable to conventional daylighting with sidelights or toplights. The filtering action of the water can be used to remove unwanted infrared and ultraviolet radiation while affecting the visible portion of the radiation only slightly. There are limits, however, to the distance such light can be propagated in water without undesirable color shifts. Comparing with warm white fluorescent light this distance appears to be about 6 to 8 meters. Comparing it to daylight, the distance extends to about 10 to 12 meters. The distance for a significant drop in the color-rendering index is approximately 10 meters. Filters can be added to the light pipe to partially compensate for unwnated color shifts and to extend the maximum distance for transfer, but substantial transmission losses are thereby incurred. Due to these limits, it is suggested that the most likely use of such light pipes would be in a hybrid water/air system, where the water-filled portion of the light pipes would be of limited length and would be used primarily for infrared heat removal. It is possible that separate color-correcting filters can be replaced by appropriately selected dyes added to the water. Another possible use for a version of the water-filled light pipe is for spectral shaping and heat removal in concentrating PV solar energy conversion systems.

Introduction

The daylighting of the interior spaces of buildings provides many benefits [1], including energy savings [2], visual connections with the outdoors (and the psychological benefits deriving therefrom), and good quality, healthy illumination to promote worker productivity [3]. For these benefits to be realized, however, the design of the building must be carefully executed [4] and the problems that can result from improperly placed and shaded fenestration apertures must be dealt with in all stages of the design process [5].

Traditional approaches to daylighting design deal mainly with the perimeter spaces of buildings, leaving the core areas wholly to electric lighting. Several proposals have been made, however, for collecting daylight outside a building and directing or piping it to the interior or core spaces far removed from the perimeter areas [6].

Water-filled light pipes have been proposed for transporting solar direct-beam illumination from concentrating collectors to the cores of habitable spaces [7]. However, water has a nonuniform transmittance over the visible portion of the spectrum. Thus, its use as a transport medium will impart a color to the light emerging from the end of the light pipe, as well as an attenuation of the flux passing through the pipe. Countering this is the advantage that by stripping the incident solar radiation of its infrared component, water-filled light pipes can deliver light of high luminous efficacy (ratio of light flux in Lumens to total radiant flux in Watts) to the illuminated space. The heat load on the space cooling system is therby reduced, conserving energy and contributing to enhanced human comfort. The heat removed can even be used for other purposes inside the building, notably for pre-heating domestic hot water.

The purposes of this paper are to describe these effects, provide estimates of the maximum distances solar radiation can be so piped without imparting unacceptable color, and discuss the limits of the use of possible color-correcting filters inserted into the emerging beam.

Problems of attenuation at water-to-air and water-to-solid interfaces, of particulate scattering effects, and the effects of impurities in the water are not addressed. The intent is to determine fundamental limits to the usefulness of the concept, using optimistic but not unreasonable assumptions, not to explore its overall technical feasibility.

Definitions

Let c_λ be the extinction coefficient in reciprocal meters of clean water at wavelength λ in nanometers. Ignoring multiple scattering effects, if the incident irradiance spectrum is $E_\lambda(0)$ in W m^{-2} nm^{-1} then, to a first approximation, the spectrum emerging after propagation through a distance x in meters will be given by

$$E_\lambda(x) = E_\lambda(0)\ e^{-c_\lambda x} \tag{1}$$

From this expression we can describe the following relevant quantities.

Emerging total irradiance:

$$E_e(x) = \int_{300}^{3000} E_\lambda(x)\ d\lambda \tag{2}$$

Emerging total illuminance:

$$E_v(x) = 683\int_{380}^{760} E_\lambda(x)\ V_\lambda\ d\lambda \tag{3}$$

where V_λ is the C. I. E. standard photopic luminous efficiency function [8].

Spectral transmittance:

$$T_\lambda(x) = \frac{E_\lambda(x)}{E_\lambda(0)} = e^{-c_\lambda x} \qquad (4)$$

Luminous efficacy:

$$\varepsilon_x = \frac{E_v(x)}{E_e(x)} \quad [Lm/W] \qquad (5)$$

Energy transmittance:

$$T_e = \frac{E_e(x)}{E_e(0)} \qquad (6)$$

Visible or luminous transmittance:

$$T_v = \frac{E_v(x)}{E_v(0)} \qquad (7)$$

Effect of Absorption by Water on the Color of Light

Measurements of c_λ have been tabulated and plotted by Jerlov [9] and Morel [10]. From these sources, representative values for c_λ have been obtained in ten-nanometer intervals from 260 to 750 nanometers and in 50 nm intervals from 750 to 2400 nm. The resulting extinction coefficient spectrum is plotted in Fig. 1.

A Simpson's Rule procedure for integrating over these two different spectral regions was used to calculate the energy and luminous transmittances of light pipes of several lengths. The results are given in Table I. Luminous efficacies of the emerging beams are also included. The corresponding spectral transmittances are shown in Fig. 2.

Plotting the logarithm of the luminous transmittance versus light pipe length in meters yields a line whose slope from 2 to 20 meters is nearly constant at approximately 0.07 m^{-1}. This is shown in Fig. 3. This value can be taken as a very approximate value for the luminous extinction coefficient c_v in the expression

Table II. **Water-Filled Light Pipe Transmittances and Luminous Efficacy**

Distance in meters	**Radiant Trans-mittance**	**Luminous Trans-mittance**	**Luminous Efficacy Lumens/W**
0.001	.9254	.9999	130
0.01	.8235	.9990	145
0.1	.6465	.9898	184
1.0	.4461	.9064	244
4.0	.2993	.7031	281
10.0	.1907	.4712	296
16.0	.1372	.3366	294
64.0	.0168	.0351	250

$$E_v(x) = E_v(0)\; e^{-c_v x} \tag{8}$$

Evaluation of Eq. 8 for the distances used in Table I shows that this representation can not be used for exacting calculations requiring good accuracy.

Plots of incident and transmitted solar irradiance spectra are shown in Fig. 4 for pipe lengths of 1, 2, 4, 8, and 16 meters. It can be seen from this figure that the red portion of the visible spectrum is strongly attenuated for lengths greater than a few meters.

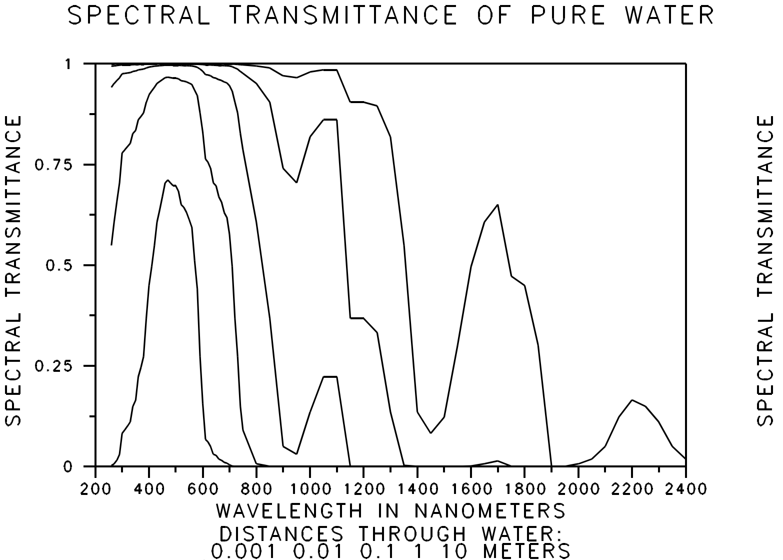

Figure 1. Spectral transmittances of various lengths of water.

Colorimetry of Water-Filtered Light Pipes

In order to measure this effect quantitatively, the 1931 CIE spectral tristimulous functions $P_x(\lambda)$, $P_y(\lambda)$, and $P_z(\lambda)$ were used to calculate the chromaticity coordinates x and y of spectral irradiances emerging from various lengths of water pipes [11]. The relevant equations are:

$$X = \int_{370}^{744} P_x(\lambda)\; E_\lambda(x)\; d\lambda \tag{9}$$

$$Y = \int_{370}^{744} P_y(\lambda)\; E_\lambda(x)\; d\lambda \tag{10}$$

$$Z = \int_{370}^{744} P_z(\lambda)\; E_\lambda(x)\; d\lambda \tag{11}$$

$$x = \frac{X}{X+Y+Z} \tag{12}$$

$$y = \frac{Y}{X+Y+Z} \tag{13}$$

$$z = \frac{Z}{X+Y+Z} \tag{14}$$

The tristimulous functions are plotted in Fig. 5.

$$x + y + z = 1 \tag{15}$$

Taking the value of 1 for $E_\lambda(x)$ at wavelength λ' and zero for all other wavelengths, calculating the chromaticity coordinates x', y' for this "spectrum," and plotting the results for wavelengths λ' from 380 to 750 nm yields the monochromatic limit curve shown on the chromaticity diagrams to follow.

The chromaticity coordinates can be calculated for radiation emerging from blackbodies at various temperatures in degrees Kelvin. The color coordinates of light sources can be compared to these. One can thereby identify what is called the correlated color temperature of spectra emerging from light pipes in terms of the most closely associated blackbody temperature, according to a defined procedure [12].

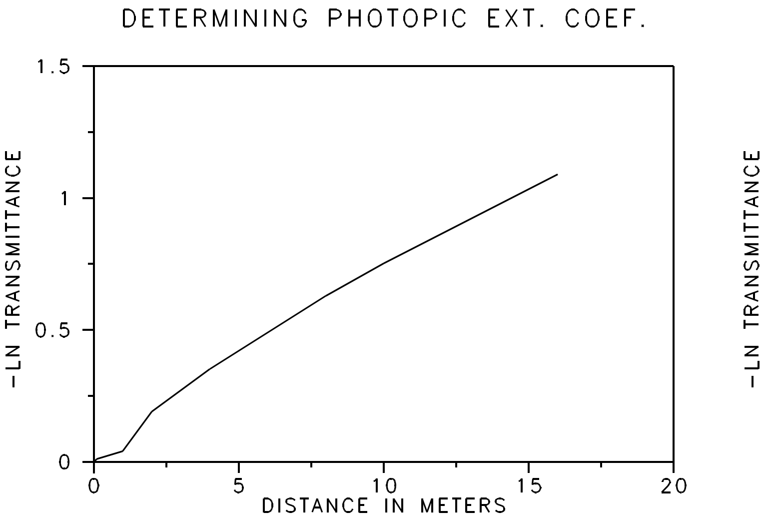

Figure 2. Plot of the negative logarithm of the photopic transmittance of a length of water versus distance. The slope of this curve is the effective photopic extinction coefficient.

According to these procedures, the chromaticity coordinates and correlated color temperatures of spectra emerging from 0, 1, 2, 4, 10, and 40 meter water pipes are given in Table II.

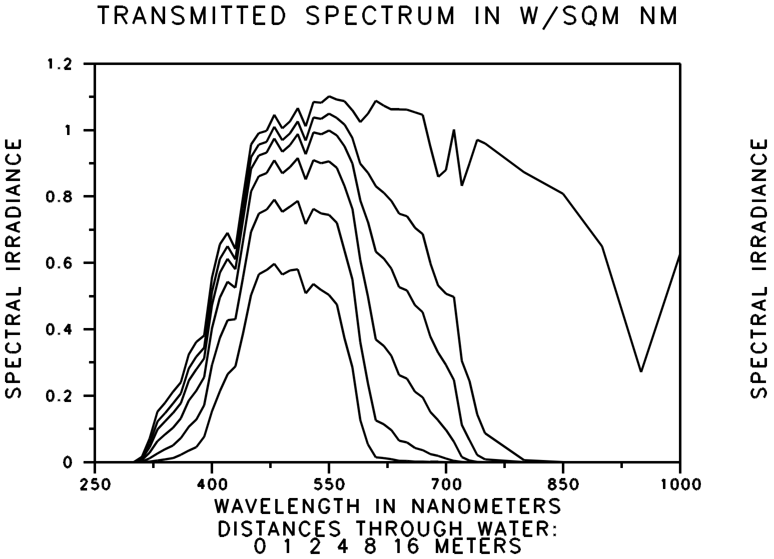

Figure 3. Transmitted irradiance spectrums for various distances through pure water.

This data is plotted on the chromaticity diagram of Fig. 6. For comparison purposes, the coordinates of several commercially available sources of electric illumination are also shown. Using the warm white fluorescent lamp as an indicator of the maximum distance from the white point that is permissible, we see that the corresponding maximum water pipe length would be around 30 meters.

Warm white is perhaps not the best source with which to compare our filtered daylight. Looking at the IES Lighting Handbook 1981 Reference Volume [13], we see that fluorescent sources can have color temperatures ranging from 5800 to 6500 K. Fig. 5-17 of that handbook, giving the color coordinates of daylight (about 6100K and x=.31, y=.33) and several fluorescent lamps, we see that color temperatures over 7000 should not be too objectionable. This would limit maximum pipe lengths for use with fluorescent lamps to about 4 meters. Beyond about 6-8 meters, it is anticipated that the blue/cyan tint of the emerging daylight will start to become quite noticeable when compared with fluorescent light.

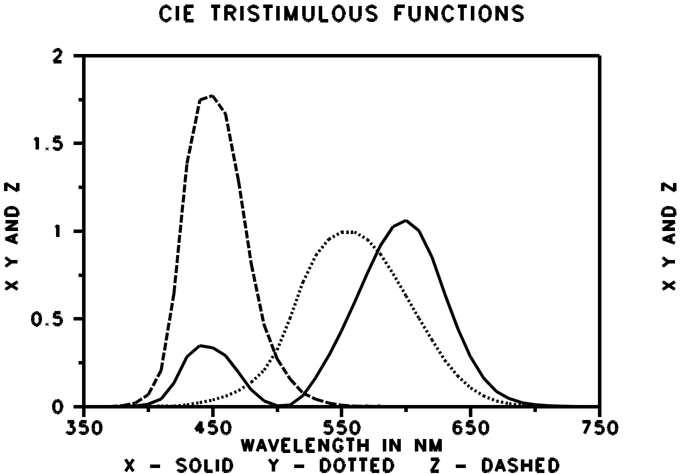

Figure 4. Spectral tristimulous functions used in the CIE 1931 system of color specification.

Using this criterion, water-filled light-pipes can just barely be long enough to be useful for illuminating the core spaces of multistory buildings.

Table II. Chromaticity Coordinates and Correlated Color Temperature

Distance in meters	x	y	Correlated Color Temperature	
			ReciprocalMegaKelvin	Degrees Kelvin
0	.3456	.3574	198	5051
1	.3263	.3583	175	5714
2	.3093	.3588	154	6494
4	.2815	.3585	129	7752
10	.2324	.3529	91	10,990
40	.1700	.3157	30	33,300

This is a little discouraging but can be misleading. Natural daylight has long been accepted as having high color rendering properties. Perhaps it would be better to compare our water-filtered sunlight to some reference daylight spectra. Judd, MacAdam, and Wyszecki [14] subjected 622 daylight spectral irradiance distributions measured by Budde, Henderson, Hodgkiss, Condit, and Grum to eigenvector analysis. They found that the resulting chromaticity coordinates cluster close to the following equation:

$$y \approx -3.0x^2 + 2.87x - 0.275 \qquad (16)$$

To see how our water-pipe emerging light compares with this daylight color coordinate line, let us plot both on the same graph. The result is shown in Fig. 7. Wyszecki and Stiles [11] state that the correlated color temperature of north clear blue sky light can exceed 40,000 K. According to these authors, overcast sky ranges up to 7000 K, as does diffuse-only horizontal illuminance on a clear day. We can see that the water-filtered coordinates depart substantially from the daylight ones when the distance exceeds about 10 to 15 meters. The departure from the daylight curve, however, is not as great as the departure from the white point, labelled W in Fig. 7. Thus, it appears that pipe lengths as great as 10 to 12 meters might be aceptable. A more recent study of the color temperature of light from the sky was completed by Inagaki, Oki, and Nakamura. They found color temperatures ranging from around 5000 K near the sun on a partly cloudy or hazy day to over 11,000 K for clear blue sky light about 90° from the sun [15].

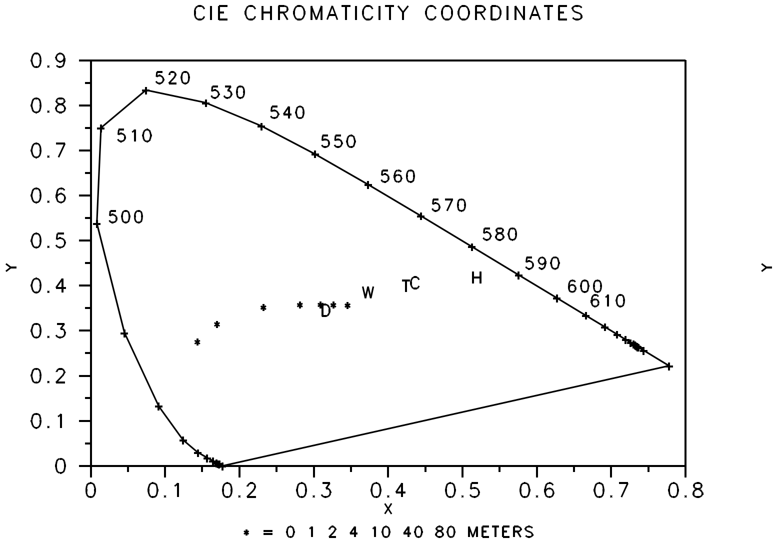

Figure 5. CIE chromaticity diagram showing the colors of daylight, the colors of light emerging from various lengths of water, and the colors of four electric discharge lamps.

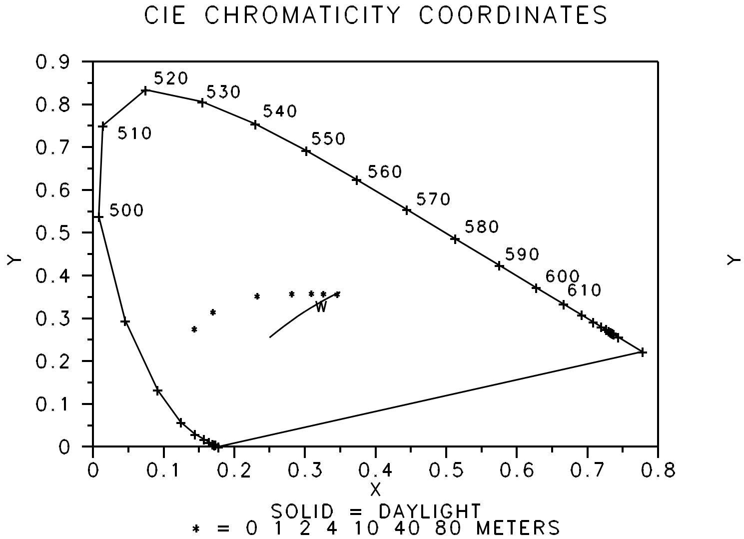

Figure 6. CIE chromaticity diagram showing the white point (W), the colors of daylight (solid line), and the colors of light emerging from various lengths of pure water (*).

From the literature on evaluating the color of light sources we find that there are two ways of assessing this color. One is personal preference. The other refers to the color rendering properties of the illuminant. The personal preference approach has not been quantified and is so subjective that it is not a suitable basis for selecting illuminants analytically. Ultimately, however, any proposed system of illumination should be evaluated visually by several different observers before final decisions are made to use it.

Color Rendering Index

We will evaluate the color of light emerging from water-filled light pipes using the *1964 CIE Method of Measuring and Specifying Color Rendering Properties of Light Sources* [16]. This method is based on the definition and use of a Color Rendering Index (CRI). The CRI is a measure of the shift in object color that occurs when the object is illuminated by the test source, in comparison to a reference light source, whose CRI is defined to be 100.

To determine what the reference light source is for a given test source, we must find out what the correlated color temperature of the test source is. Once this is known, the reference light source is a Planckian black body having the same temperature, when this temperature is below 5000K. Above 5000K the reference source is daylight having the same correlated color ter

Kelley [17] and Wyszecki [18] provide a portion of the CIE 1931 (x,y) chromaticity diagram with lines of constant correlated color temperature (isotemperature lines) drawn on it, over the range from 0 to 660 micro reciprical degrees (mireds). Correlated color temperature T_c is related to mireds by: $T_c = 10^6$/mired. The diagram is also published in the IES Lighting Handbook [13] and temperatures are given in reciprocal megakelvins, a unit that has replaced the microreciprocal degree. This graph can be used to determine T_c for any light source of known chromaticity coordinates that fall in the range of the plot. This is the method used here to determine correlated color temperatures.

To calculate the CRI we must transform the 1931 CIE coordinates (x,y) into the coordinates (u,v) of the *CIE 1964 Uniform Colour Space*:

$$u = \frac{4x}{-2x + 12y + 3} \qquad (17) \qquad\qquad v = \frac{6y}{-2x + 12y + 3} \qquad (18)$$

We also need the parameters c and d, defined as

$$c = \frac{1}{v}(4 - u - 10v) \qquad d = \frac{1}{v}(1.708v + 0.404 - 1.481u) \qquad (19)$$

These, and additional parameters, are calculated for both the test and the reference illuminant, as well as for the product β_λ

reference color samples. This data is then used to calculate the degree of colorimetric shift of the light reflected from eight reference objects exposed to the test illuminant, compared with their color when exposed to the reference illuminant. The CRI is the mean of the differences R_i

ΔK_i

reference color sample.

A computer program was written to perform these calculations, following the procedure described by Nickerson and Jerome [19]. The reference illuminant spectral distribution was calculated from the black body radiation law:

$$M_\lambda = \frac{c_1}{\lambda^5 \left(\frac{e^{c_2}}{\lambda T} - 1\right)} \qquad [\frac{W}{m^{-3}}] \tag{20}$$

where

$$c_1 = 3.741 \times 10^{-16} \qquad [W\,m^2]$$

and

$$c_2 = 1.439 \times 10^{-2} \qquad [m\,K]$$

The results are shown in Table III, along with the color temperature and color rendering index from the IES Lighting Handbook [13] for several electric light sources for comparison. The CRI values are plotted versus distance of travel in water in Fig. 8.

Table III. Color Rendering Indices

SOURCE	CORRELATED COLOR TEMP	CRI
Warm white fluor.	3020	52
Warm white deluxe	2940	73
Cool white fluor.	4250	62
Cool white deluxe	4050	89
Daylight fluor.	6250	74
Metal halide lamp	3720	60
High pressure Xenon	5920	94
High pressure sodium	2100	21
Tungsten Halogen	3190	100
Sun + water, 2 meters	6494	82
Sun + water, 4 meters	7752	70
Sun + water, 10 meters	10,989	50
Sun + water, 40 meters	33,333	37

If we take a CRI of 50 as a minimum, it appears that the maximum permitted distance is about 10 meters or 33 ft. This is a very respectable value. The quantity of light emerging is not great at such large distances, as is seen in Table I, but useful quantities could be provided.

A possible fallacy with this approach comes from the definition of color rendering index by reference to another light source, itself chosen to be a good one, at least for rendering colors. By shifting the reference point for assessing the CRI of daylight emerging from different lengths of water, we are referring back to light which itself is getting bluer and bluer—deeper blue sky light, essentially. The light pipe makes this light even bluer, and can impart a bluish tint to some o

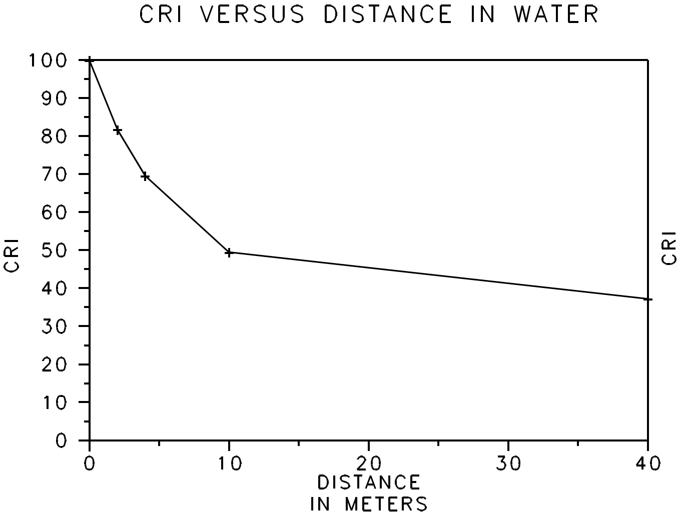

Figure 7. Color Rendering Index as a function of distance sunlight travels through pure water.

The eye is quite adaptable to color shifts and can still distinguish different colors even in the presence of these shifts. This has been amply demonstrated with modern high pressure sodium vapor lamps which impart a yellowish tint, but are still capable of providing tolerable color rendering, even though the CRI value shown in Table III is low. However, light which is considerably bluer than the bluest daylight can be expected to have some resistance to its use for ambient and/or task illumination by building occupants. Thus, we must temper the optimistic results given above with the caution that color-rendering index alone is not a sufficient measure of the acceptability of a light source.

Color-Correcting Filters

It might be possible to correct the blue appearance of water-filtered light by the use of color correcting filters, to improve the color-rendering of the light. This will inevitably result in loss of light flux, since the filter will, in essence, be stripping off some of the blue portion of the spectrum to better match the red portion. At great distances, the red is almost completely gone and no amount of filtering will be able to bring it back. This method will therefore be of limited usefulness

Looking at a Kodak filter catalog, filter series 86 (yellowish) appears to have spectral transmittance curves that would be capable of attenuating the blue end of the color spectrum much more than the red end. Four filter transmittances were selected, for filters 86, 86A, 86B, and 86C. The spectral transmittance of each of these was multiplied by the spectrum of light emerging from 10 meters of water and the chromaticity coordinates of the resulting filtered spectra were calculated. These are plotted in Fig. 9. Looking at the four curves that come together at one point on this plot, the point where they come together is the unfiltered 10 meter point. The four additionally filtered points are indicated by the numbers 1 through 4, indicating the effect of these four filters on the light emerging from the light pipe. The lines are drawn to indicate the effects of each of the four filters in moving the color of the light emerging from the light pipe upward and to the right. The white point is labeled W on this figure and daylight colors are indicated by the lower solid line.

We can see that these filters do tend to move the color of the light emerging from the pipe more toward the right and away from the blue region of the spectrum, but the resulting color is above the white point, in the direction of greenish yellow. This may be an acceptable color but it is difficult to tell without calculating the the CRI values and obtaining visual appraisals of the

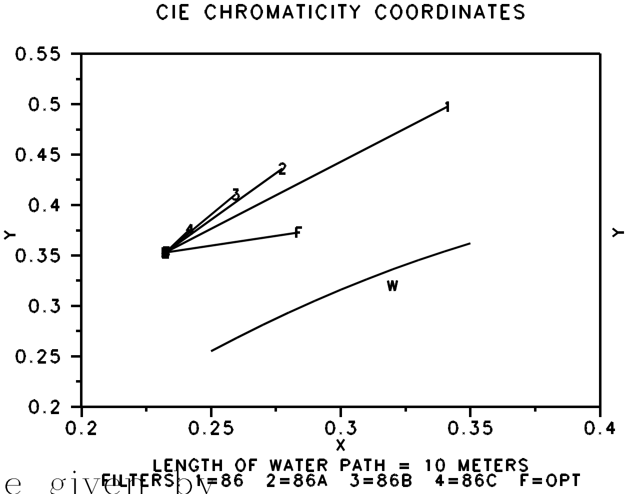

Figure 8. Light emerging from 10–meters of water and from several Kodak filters. W indicates the white point and the lower solid line is the daylight color line described in Eq. 16. F is for a theoretically optimum filter.

Let us see if a more optimum filter transmittance spectrum can be defined. There are several possible definitions of such a spectrum. One would be to invert the effect of the water, that is, to have a filter transmittance spectrum that is the complement of the water transmittance. Eq. 4 gives the spectral transmittance of the water at distance x. The color correcting filter proposed here would have its transmittance given by

$$T_{f\lambda} = 1 - e^{-c_\lambda x} \tag{23}$$

Multiplying the 10–meter transmitted spectral flux curve by this spectral transmittance and calculating the resulting chromaticity coordinates yields point F in Fig. 9. This point is closer to the daylight line and the white point than the points for the Kodak filters.

Another possibility would be to dissolve suitably chosen dyes in the water to further alter its spectral transmittance. This method was used by Laporta and Zaraga [20] to make transmitting bandpass filters for the ultraviolet portion of the spectrum and followed more genera

It seems from these results that further work in developing optimum filters could yield even greater improvement in the color–rendering properties of water–filtered sunlight. Through this method, it should be possible to extend the acceptable distance which light is permitted to travel through a water–filled pipe to, say, 10 to 15 meters. There will, however, be substantial loss of flux through the water and the color–correcting filter, with an overall transmittance to visible light below

Photovoltaic Application

Plots of the spectral responses of two photovoltaic energy conversion cells [22] are shown in Fig. 10, along with plots of the spectral transmittances of water for 1, 4, and 16 centimeter path lengths. One can see from this that the water effectively serves as a low-pass filter of the radiation incident on the cells, cutting off radiation with wavelengths greater than those in the transition region shown in the Figure. The location of the cutoff region can be adjusted by changing the path length through the water. Clearly longer path lengths are appropriate for cells with a limited range of spectral response, such as the amorphous silicon ones. Shorter path lengths appear better suited for cells with extended spectral response, including monocrystalline and polycrystalline ones.

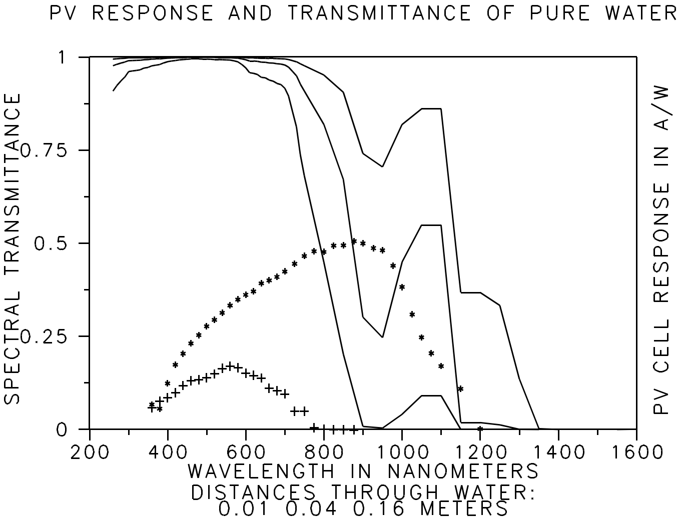

Figure 9. Comparison of spectral responses of two photovoltaic cells with the spectral transmittance of water. + Amorphous silicon * Monocrystaline silicon.

Conclusions and Recommendations

Water-filled light pipes can be used to bring cool, filtered sunlight indoors in a controlled manner. As this light travels through such pipes, spectrally selective absorption and scattering in the water removes infrared radiation and reduces the flux of red light more than other parts of the visible spectrum. The result is light of slightly blueish color which has reduced color-rendering properties. The distance which this light can be transmitted before its color becomes objectionable in comparison with warm white fluorescent light appears from this preliminary assessment to be about 6 to 8 meters. Comparing it to daylight, the distance extends to about 10 to 12 meters. The distance for a significant drop in its color-rendering index is approximately 10 meters. Color-correcting filters can be designed for use with such pipes to extend the maximum distance of light transfer but the attenuation of light resulting from these combinations greatly reduces the efficiency of the pipe.

The visible transmittance of 5 and 10 meter long pipes is about 28% and 19%, respectively. Use of color-correcting filters will drop this even further. For some applications, mainly those which can tolerate relatively low levels of illumination, or applications where cost-effectiveness is not a major consideration, these light losses might be tolerable since they can be compensated for by using larger sunlight collection systems. In other cases, the white appearance of the emerging light, its color-rendering property, and the efficiency of transmission are very important. In such cases only short lengths of water-filled pipes can be used.

It seems that the best solution in such cases would be a hybrid combination of air-filled and water-filled light pipes. The water-filled section would strip off the infrared portion of the spectrum, reducing the thermal energy content of the emerging beam, and the air-filled portion would distribute the light to the areas needing illumination. The higher refractive index of water could serve an optical purpose in the design of the concentrating collector used to focus sunlight on the pipe. The water could fill the collector (if the structural loading resulting from the weight of the water can be handled acceptably) thereby increasing the concentration ratio. The water-filled portion could be placed at the focus of the concentrator, and shaped to improve flux throughput. Other hybrid possibilities can be explored for special application areas.

The possibilities for use of water to filter the radiation impinging upon solar photovoltaic energy conversion arrays are intriguing and should be explored further. Not only can the water remove unused infrared radiation from the illuminating beam but also it can be employed as a cooling medium, lowering the operating temperatures of the array and hence increasing conversion

Acknowledgement

Portions of this work were supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy through grant DE-FG01-84CE22122.

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