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Luminaire Photometry for Temperature-Sensitive Light Sources

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Abstract—A method for the photometry of luminaires using temperature-sensitive light sources is described and evaluated. This procedure is specifically designed for use with luminaires that employ T5 and T5HO fluorescent lamps. Results of the new method are provided.

1 INTRODUCTION

Luminaire photometry has been performed traditionally using a standard procedure (CIE 1973; IESNA 2000) in a specified laboratory environment where both bare lamps and luminaire are measured and calibrated at 25°C ambient temperature. This procedure (Wash 1958; Levin 1982) (hereafter refered to as the Traditional Method) has worked well for relative photometry with conventional light sources such as Incandescent, HID and even T8/T12 fluorescent lamps. While this Traditional Method (Frank 1954; Lewin 1989; IESNA 1998) is fundamentally a sound method for these conventional light sources, it is not well suited for the photometry of newly developed light sources such as T5/T5HO fluorescent lamps (Ashdown 1999). In these instances the lamps are temperature sensitive and their light outputs are optimized at a nonstandardized temperature rather than a laboratory ambient temperature of 25°C. As a result, this Traditional Method will generate significant misgivings for the photometry of T5/T5HO-lamps luminaires (Zhang 2002). Therefore, it is desirable to refine the concept of standard photometry and broaden the photometric applications so a new procedure can be universally applicable to the photometry of all types of light sources.

The purpose of this paper is to introduce a New Concept in which the relative photometry of a luminaire is conducted in a standard laboratory environment of 25°C, while the photometric measurements and calibrations are referenced at the Lamps Operating Temperature Inside the Luminaire (LOTIL) and its photometry is relatively determined based on the lamps' rated lumens at the Lamps Optimum Design Temperature (LODT). As a result, this new testing procedure accurately and consistently reports the luminaire photometry of the temperature-sensitive light source in terms of both Luminaire Total Lumens (Total-

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$Lumens_{luminaire}$) and Luminaire Efficiency ($EFF_{luminaire}$). Its results are fully compatible with the photometry of the traditional light sources using the standard relative photometry.

2 THE DEVELOPMENT OF NEW CONCEPT PHOTOMETRY

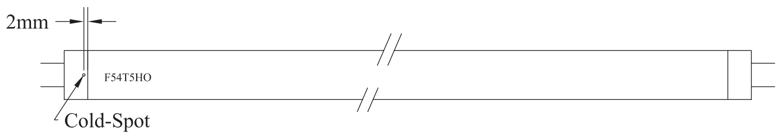
New Concept photometry consists of measurements and calibrations for determining: 1) Luminaire Optical Efficiency ($EFF_{luminaire\text{-}optical}$), 2) Lamps Thermal Effect Factor ($F_{lamps\text{-}thermal\text{-}effect}$), 3) Luminaire Total Lumens ($Total\text{-}Lumens_{luminaire}$) and 4) Luminaire Efficiency ($EFF_{luminaire}$).

First, the Luminaire Optical Efficiency ($EFF_{luminaire\text{-}optical}$) is determined by the ratio of the raw lumens of luminaire ($Raw\text{-}Lumens_{lamps\text{-}in\text{-}luminaire@LOTIL}$) to the raw lumens of bare lamps ($Raw\text{-}Lumens_{lamps@LOTIL}$). These are measured at the Lamps Operating Temperature Inside the Luminaire (LOTIL) in which the raw lumens are the collection of the relative readings of the lamps or that of the luminaire obtained from a goniophotometer. The term Lamps Operating Temperature Inside the Luminaire (LOTIL), as used in this paper, should refer to the temperature of the air in direct contact with the lamps under consideration. If the lamps are used without any mechanical enclosure in case of bare lamps, the average room temperature of 25°C usually will be the LOTIL. However, the light sources (lamps) are seldom used as the bare lamps. For example, when fluorescent lamps are installed in any sort of fixture housing that limits free air circulation between the lamps and the ambient environment, the LOTIL referred to in this paper is not the room ambient temperature, but the temperature of the air in contact with the lamps. This temperature is defined as the Lamp Operating Temperature Inside the Luminaire (LOTIL). Due to the fact that the lamps generally are operated at a higher temperature inside the luminaire than the ambient temperature of 25°C, a luminaire optical efficiency derived from the raw lumens of both bare lamps and luminaire (lamps-in-luminaire) must be referenced at the temperature of Lamp Operating Temperature Inside the Luminaire (LOTIL). It should be noted that the determination of optical efficiency is independent of the thermal characteristics of the lamps. $EFF_{luminaire\text{-}optical}$ represents an optical assessment of the luminaire system without any thermal influence. The mathematical equation of luminaire optical efficiency is defined as a ratio of raw lumens of the luminaire (lamps-in-luminaire) to raw lumens of the bare lamps at LOTIL.

$$EFF_{luminaire\text{-}optical} = \frac{Raw\text{-}Lumens_{lamps\text{-}in\text{-}luminaire@LOTIL}}{Raw\text{-}Lumens_{lamps@LOTIL}} \quad (1)$$

Exclusively considering the optical performance of the luminaire, this equation of $EFF_{luminaire\text{-}optical}$ completely eliminates the influence of lamp's light output that due to the variations of the actual lamp operating temperatures. To explore this methodology, several studies (Verderber 1987; Zhang 2002; 2004) have been conducted to evaluate the optical efficiency of luminaire at the temperature that the lamps are operating within the luminaire.

Fig. 1. The Typical Location of the Cold-Spot of T5/T5HO-lamp.



Yet, the determination of Lamps Operating Temperature Inside the Luminaire (LOTIL) is a challenging task due to the fact that the selection of the logical location in measuring LOTIL is vague. Instead, reliable temperature data can be obtained by measuring the Cold-Spot Temperature of the Lamps (CSTL) with a thermal couple attached on the cold spot of the lamps; and then converting this measurement to the temperature of LOTIL. The cold spot of a T5/T5HO fluorescent lamp, for example, is located on the metallic end cap of the lamp (brand side) within 2 mm from the glass as shown in Fig. 1. According to lamp manufacturers' literature and confirmed by our experiments, there is a systematic 10°C difference between the CSTL and LOTIL for T5/T5HO lamps. Therefore, a CSTL measurement of 45°C (113°F) can be directly translated to LOTIL of 35°C (95°F) for determining the lamp operating temperature of T5/T5HO lamps inside the luminaire.

Second, to determine the Lamps Thermal Effect Factor ($F_{lamps\text{-}thermal\text{-}effect}$), this is derived by a ratio of lamps' rated lumens ($\text{Rated-Lumens}_{lamps@LOTIL}$) at LOTIL to lamps' rated lumens ($\text{Rated-Lumens}_{lamps@LODT}$) at Lamps Optimum Design Temperature (LODT). $F_{lamps\text{-}thermal\text{-}effect}$ is a measure of light output sensitivity of a luminaire system affected by the changing temperature of the lamps operating inside the luminaire. For example, since fluorescent lamps are temperature sensitive, they produce different light output at different operating temperatures. Specifically, light output decreases if the lamps are operating away from the optimal design temperature. The thermal effect of the lamps in a luminaire system ($F_{lamps\text{-}thermal\text{-}effect}$) represents a percentage change in lumens output due to the changing of temperatures from its optimum. Its mathematical equation is expressed as:

$$F_{lamps\text{-}thermal\text{-}effect} = \frac{\textit{Rated-Lumens}_{lamps@LOTIL}}{\textit{Rated-Lumens}_{lamps@LODT}} \qquad (2)$$

It should be noted that LODT is determined at a temperature in which the lamps are optimized to provide the maximum lumen output. Once the LOTIL and LODT are established, the rated lumens of temperature-sensitive lamps at those specific temperatures can be acquired from the literature of lamp's manufacturers. The typical light-output/thermal characteristics of HID, CFL, T8/T12 and T5/T5HO lamps are illustrated in Fig. 2.

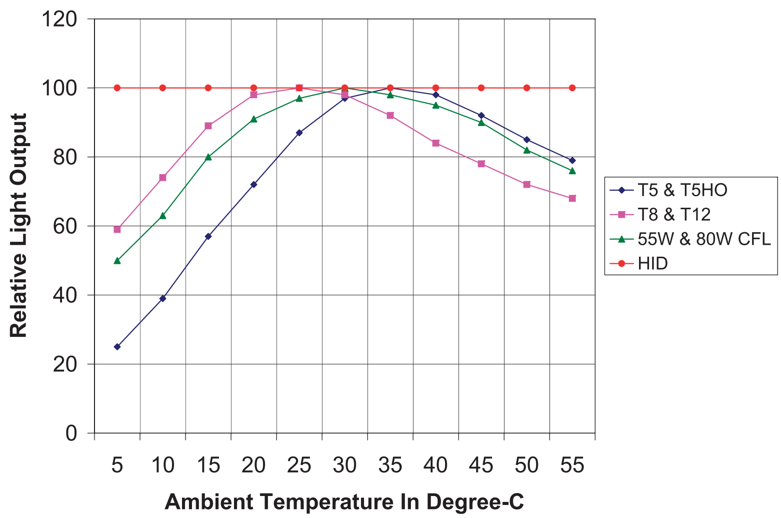


Fig. 2. Light-Output/Thermal Characteristics of HID, CFL, T8/T12 and T5/T5HO Lamps.

As a result, the ratio of lamps' rated lumens at two temperatures of LOTIL and LODT is defined as the lamps' thermal effect factor of a luminaire system ($F_{lamps\text{-}thermal\text{-}effect}$), and its numerical value is normally less than one. For an ideal luminaire design, the lamps' light output is thermally optimized and Lamps Operating Temperature Inside the Luminaire (LOTIL) is equivalent with Lamps Optimum Design Temperature (LODT), therefore, $F_{lamps\text{-}thermal\text{-}effect}=1.0$. In the case of nontemperature-sensitive light source, its thermal effect factor also is equal to one.

Third, calculate the Luminaire Total Lumens ($\text{Total-Lumens}_{luminaire}$). To determine the $\text{Total-Lumens}_{luminaire}$ in the calibration process of the relative photometry, the photometric measurements obtained at the LOTIL must to be calibrated by the lamps' rated lumens at the same temperature of LOTIL. Its mathematical equation is expressed as a product of $EFF_{luminaire\text{-}optical}$ and $\text{Rated-Lumens}_{lamps@LOTIL}$:

$$\begin{aligned} \textit{Total-Lumens}_{luminaire} &= EFF_{luminaire\text{-}optical} \times \textit{Rated-Lumens}_{lamps@LOTIL} \\ &= \textit{Raw-Lumens}_{lamps\text{-}in\text{-}luminaire@LOTIL} \times \frac{\textit{Rated-Lumens}_{lamps@LOTIL}}{\textit{Raw-Lumens}_{lamps@LOTIL}} \end{aligned} \quad (3A)$$

Finally, the Luminaire Efficiency ($EFF_{luminaire}$) is calculated by the product of two components - Luminaire Optical Efficiency and Lamps Thermal Effect Factor. It is mathematically expressed as a ratio of the Luminaire Total Lumens referenced at a standard laboratory temperature of 25°C to the lamps' rated lumens specified at Lamps Optimal Design Temperature (LODT).

$$\textit{Total-Lumens}_{luminaire} = \textit{Raw-Lumens}_{lamps\text{-}in\text{-}luminaire@LOTIL} \times \frac{\textit{Rated-Lumens}_{lamps@25°C}}{\textit{Raw-Lumens}_{lamps@25°C}} \quad (3B)$$

As a reference however, the Traditional Method calculates the Luminaire Total Lumens and Luminaire Efficiency by using the following two equations:

$$EFF_{luminaire} = EFF_{luminaire\text{-}optical} \times F_{lamps\text{-}thermal\text{-}effect} = \frac{\textit{Total-Lumens}_{luminaire}}{\textit{Rated-Lumens}_{lamps@LODT}} \quad (4A)$$

$$EFF_{luminaire} = \frac{\textit{Total-Lumens}_{luminaire}}{\textit{Rated-Lumens}_{lamps@25°C}} \quad (4B)$$

Compared to the photometric measurement and calibration process of the Traditional Method that references to a single temperature of 25°C, the New Concept utilizes the lamps' rated lumens specified at the Lamps Operating Temperature Inside the Luminaire (LOTIL) to calibrate the raw lumens measurements of both bare lamps and the luminaire, which in turn determines the Luminaire Total Lumens. The Luminaire Efficiency ($EFF_{luminaire}$) is defined as a ratio of the lumens emitted by a luminaire measured at the laboratory ambient temperature of 25°C to the lamps' rated lumens referenced at LODT. By incorporating both luminaire's optical performance and lamps' thermal effect factor, the equations of the New Concept refine the standard photometric procedure and extend the photometry capabilities to support every application of temperature-sensitive light sources such as T5/T5HO-lamp luminaires. The New Concept also is fully compatible with the Traditional Method for the photometry of nontemperature-sensitive light sources as well as for the photometry of the T8/T12-lamp luminaires, whose light outputs are specified at an optimal design temperature of 25°C.

3 A SIX-STEP PHOTOMETRY PROCEDURE

To introduce the New Concept, a Six-Step photometry procedure is developed to determine the four components of the luminaire photometry: Luminaire Optical Efficiency ($EFF_{luminaire\text{-}optical}$), Lamps Thermal Effect Factor ($F_{lamps\text{-}thermal\text{-}effect}$), Luminaire Total Lumens ($Total\text{-}Lumens_{luminaire}$) and Luminaire Efficiency ($EFF_{luminaire}$). It is assumed that all the laboratory conditions including laboratory ambient temperature of 25°C and the proper practices are followed based on the IESNA and CIE testing standards.

Step One: perform a traditional relative photometry and obtain $Raw\text{-}Lumens_{lamps\text{-}in\text{-}luminaire@LOTIL}$ and $Raw\text{-}Lumens_{lamps@25°C}$ at the standard laboratory ambient temperature of 25°C.

Step Two: acquire the LOTIL or CSTL. The Cold-Spot Temperature of the Lamp (CSTL) is measured by a thermal couple attached on the cold spot of the lamp(s) and the Lamp Operating Temperature Inside of the Luminaire (LOTIL) is then derived from the CSTL. The measurement of LOTIL or CSTL should be done with the lamps fully stabilized (a minimum of two hours) inside the luminaire.

Step Three: measure or derive the raw lumens of the bare lamp(s) at LOTIL ($Raw\text{-}Lumens_{lamps@LOTIL}$) and then calculate the Luminaire Optical Efficiency ($EFF_{luminaire\text{-}optical}$) by using equation (1).

The preferred method to obtain $Raw\text{-}Lumens_{lamps@LOTIL}$ is to directly measure the raw lumens of the bare lamp(s) at LOTIL/CSTL, where the fluorescent lamp(s) are burned and stabilized inside the luminaire at the orientation in which the lamp(s) are to be installed. After a sufficient period of stabilization (a minimum of two hours), the lamp(s) quickly are transferred without the tilt and mounted to the photometer for a bare lamp(s) reading. Testing has shown that if this transfer procedure is done within 15 seconds, an accurate bare lamp(s) reading can be obtained as if the lamp(s) are operating at the same temperature as when they are operating inside the luminaire housing. The bare lamp(s) reading remains stable for approximately two minutes before its light output starts drifting to the value at 25°C laboratory ambient temperature. This reading is the bare lamp(s) reference value that used to calculate the raw lumens of bare lamp(s) at LOTIL/CSTL ($Raw\text{-}Lumens_{lamps@LOTIL}$). It should be noted that although this method is direct and simple, it may be suitable only for luminaire applications of two lamps or less, and also for a luminaire constructed in such a way that the lamp(s) can be removed rapidly.

An alternative way to determine $Raw\text{-}Lumens_{lamps@LOTIL}$ is to calibrate $Raw\text{-}Lumens_{lamps@25°C}$ obtained in *Step One* by applying a Lamps Correction Factor ($F_{lamps\text{-}correction}$). The $F_{lamps\text{-}correction}$ is defined as a ratio of $Relative\text{-}Reading_{lamps@LOTIL}$ to $Relative\text{-}Reading_{lamps@25°C}$, and it can be obtained by the measurements of relative light outputs of the lamp(s) at both temperatures of 25°C and LOTIL in a thermal chamber or in a temperature-controlled integrating sphere. As intended, the $F_{lamps\text{-}correction}$ modifies the lumens output measurement of the bare lamp(s) at the temperature of 25°C with a correction factor at LOTIL. The procedure of obtaining $F_{lamps\text{-}correction}$ is detailed in Appendix A of this document. By applying $F_{lamps\text{-}correction}$ to the measured value of $Raw\text{-}Lumens_{lamps@25°C}$ at the laboratory ambient temperature of 25°C, $Raw\text{-}Lumens_{lamps@LOTIL}$ at LOTIL is obtained. As a result, the luminaire optical efficiency ($EFF_{luminaire\text{-}optical}$) can be accomplished by modifying the equation (1):

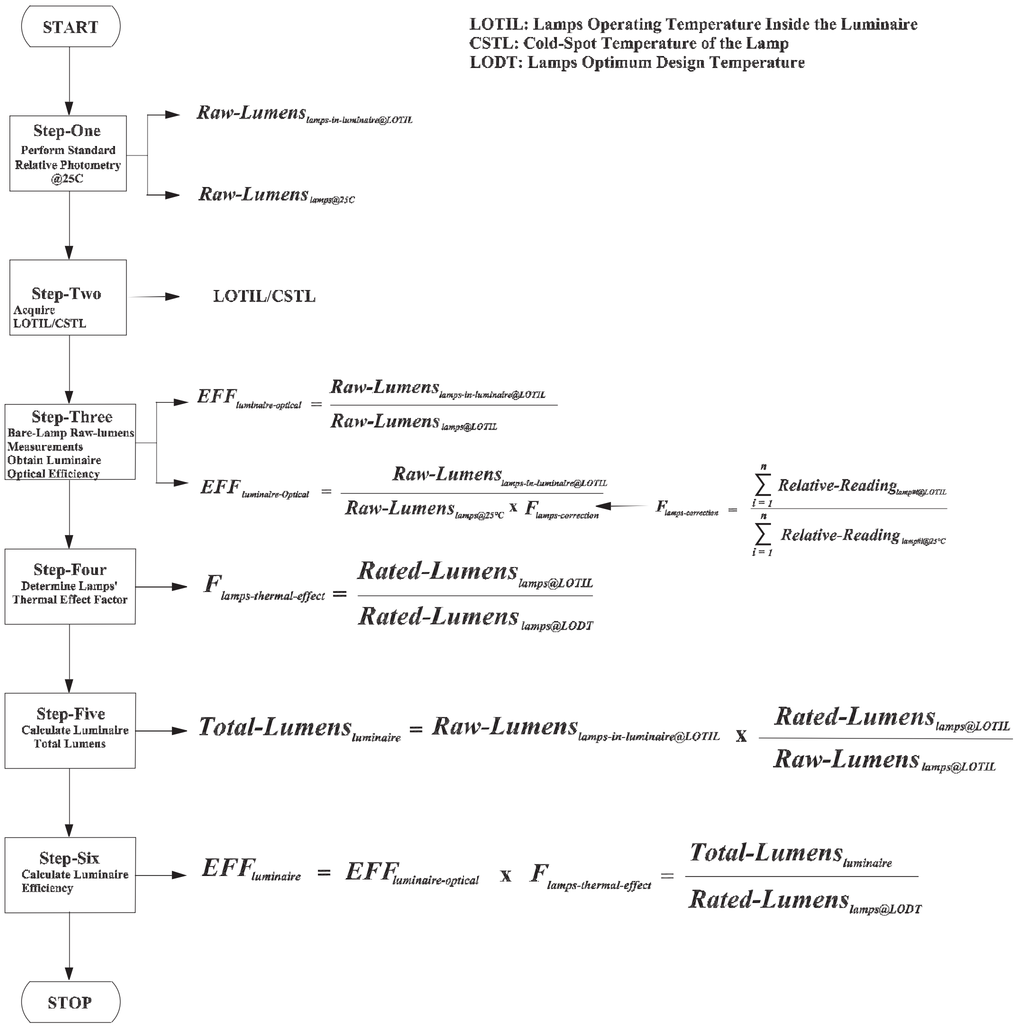
$$EFF_{luminaire\text{-}Optical} = \frac{Raw\text{-}Lumens_{lamps\text{-}in\text{-}luminaire@LOTIL}}{Raw\text{-}Lumens_{lamps@25°C} \times F_{lamps\text{-}correction}} \qquad (5)$$

Step Four: resolve the Lamps' Thermal Effect Factor ($F_{lamps\text{-}thermal\text{-}effect}$) by using equation (2), a ratio of Rated-Lumens$_{lamps@LOTIL}$ to Rated-Lumens$_{lamps@LODT}$. Calculation of $F_{lamps\text{-}thermal\text{-}effect}$ requires the knowledge of LOTIL and LODT, which are determined in *Step Two*, and the results of $F_{lamps\text{-}thermal\text{-}effect}$ are obtained by referencing the published data from the lamp manufacturers as shown in Fig. 2. For example, the lamps' thermal factors of 0.96 (4800/5000) and 1.0 (5000/5000) are derived for a T5/T5HO luminaire with lamp(s) operating at the temperatures in the luminaire (LOTIL) of 30°C and 35°C respectively.

Step Five: determine the Luminaire Total Lumens (Total-Lumens$_{luminaire}$) by using equation (3A), in which the raw lumens measurement of the luminaire (Raw-Lumens$_{lamps\text{-}in\text{-}luminaire@LOTIL}$) is calibrated by a ratio of Rated-Lumens$_{lamps@LOTIL}$ to Raw-Lumens$_{lamps@LOTIL}$ specified at Lamps' Operating Temperature Inside Luminaire (LOTIL).

Step Six: finally, calculate the Luminaire Efficiency by using equation (4A). The product of two factors, Luminaire Optical Efficiency and Lamp Thermal Effect Factor or a ratio of the Luminaire Total Lumens at a standard laboratory temperature of 25°C to the Lamps' Rated Lumens at LODT, results the Luminaire Efficiency (EFF$_{luminaire}$).

Following is a schematic chart of the Six-Step procedure, which demonstrates the measurement variables and calibration equations for each step.



4 PHOTOMETRIC COMPARISONS USING THE NEW CONCEPT VS. THE TRADITIONAL METHOD

To evaluate the proposed procedure, the photometric predictions performed with the New Concept and the Traditional Method for both T5HO-lamps and T8-lamps luminaires are presented herein.

Three imaginary fixtures with a fixed optical efficiency of 90 percent were used for the photometric predictions of the luminaires. The Lamp Operating Temperature Inside Luminaire (LOTIL) was controlled at three corresponding temperatures such as 25°C, 30°C and 35°C. In addition to these three luminaire thermal designs, three T5HO test lamps and three T8 test lamps with the different light-output/thermal characteristics were selected to examine the photometry of the luminaires. Figures 3 and 4 illustrate the light-output/thermal characteristics of three T5HO test lamps and three T8 test lamps operating at different ambient temperatures (LOTIL). The corresponding data in Fig. 3 represents the light-output/thermal characteristics of three T5HO test lamps (T5HO-A, T5HO-B, and T5HO-C), in which only the test lamp (T5HO-B) matches the manufacturer's specifications.

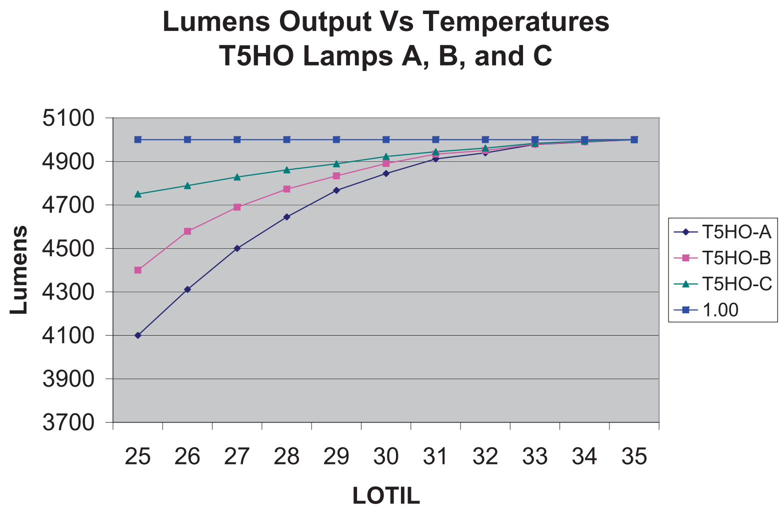


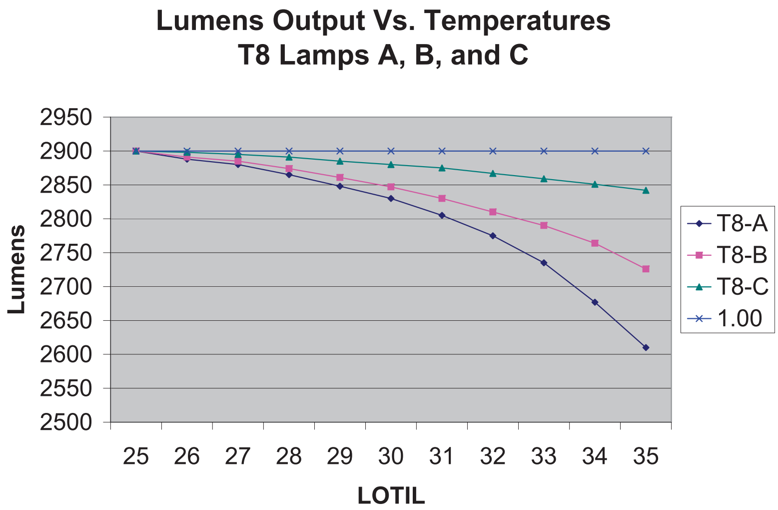
Fig. 3. Lumen Output vs Temperature of T5HO Lamps A B and C.

As the data shows, individual T5HO lamps generate considerable lumen output variations even at the same ambient temperature. At a temperature of 25°C, for example, three test lamps generate the different lumen outputs of 4100 lm, 4400 lm, and 4750 lm with the maximum lumen output discrepancy of 15 percent between the individual test lamps of T5HO-A and T5HO-C.

Individual T8 lamps, however, typically create a small difference in the lumen outputs at the temperature of 25°C since the lamps' lumen outputs are optimized at 25°C. Illustrated in Fig. 4, three T8 test lamps have shown various light-output/thermal characteristics at the temperatures from 25°C to 35°C. Likewise, the test lamp of T8-B is assumed to be a standard lamp that meets the lamp manufacturer's specifications.

With a total of six test lamps (T5HO-A, T5HO-B, and T5HO-C) and (T8-A, T8-B, and T8-C), and three luminaire thermal designs (LOTILs=25°C, 30°C and 35°C), 18 combinations were employed to predict the photometric performances of the luminaires. All luminaire photometry were evaluated in terms of Luminaire Total Lumens and Luminaire Efficiency by using both the New Concept and the

Fig. 4. Lumen Output vs Temperature of T8 Lamps A B and C.



Traditional Method. The results are illustrated in Tables 1 to 4 , while the detail explanations of data in the individual cells for Table 1 and 3 are shown in Appendix B.

TABLE 1.
Photometry Comparisons of T5HO-lamp Luminaires LOTIL = 25°C, 30°C and 35°C; (T5HO-A, T5HO-B, and T5HO-C)

LOTIL = @25°C	T5HO-A		T5HO-B		T5HO-C	
$EFF_{luminaire\text{-}optical}$ = 90%, $F_{lamps\text{-}thermal\text{-}effect}$ = 0.88	New-Concept	Trad-Method	New-Concept	Trad-Method	New-Concept	Trad-Method
Luminaire Raw-Lumens @LOTIL	3321.0	3321.0	3564.0	3564.0	3847.5	3847.5
Lamp Raw-Lumens @LOTIL or @25°C	3690.0	3690.0	3960.0	3960.0	4275.0	4275.0
Lamp Rated-Lumens @LOTIL	4400.0		4400.0		4400.0	
Lamp Rated-Lumens @LODT or @25°C	5000.0	4400.0	5000.0	4400.0	5000.0	4400.0
Luminaire Efficiency	***79.20%***	***90.00%***	***79.20%***	***90.00%***	***79.20%***	***90.00%***
Luminaire Total Lumens	***3960.0***	***3960.0***	***3960.0***	***3960.0***	***3960.0***	***3960.0***
LOTIL = @30°C	T5HO-A		T5HO-B		T5HO-C	
$EFF_{luminaire\text{-}optical}$ = 90%, $F_{lamps\text{-}thermal\text{-}effect}$ = 0.978	New-Concept	Trad-Method	New-Concept	Trad-Method	New-Concept	Trad-Method
Luminaire Raw-Lumens @LOTIL	3924.0	3924.0	3960.9	3960.9	3987.0	3987.0
Lamp Raw-Lumens @LOTIL or @25°C	4360.0	3690.0	4401.0	3960.0	4430.0	4275.0
Lamp Rated-Lumens @LOTIL	4890.0		4890.0		4890.0	
Lamp Rated-Lumens @LODT or @25°C	5000.0	4400.0	5000.0	4400.0	5000.0	4400.0
Luminaire Efficiency	***88.02%***	***106.34%***	***88.02%***	***100.02%***	***88.02%***	***93.26%***
Luminaire Total Lumens	4401.0	4679.0	4401.0	4401.0	4401.0	4103.6
LOTIL = @35°C	T5HO-A		T5HO-B		T5HO-C	
$EFF_{luminaire\text{-}optical}$ = 90%, $F_{lamps\text{-}thermal\text{-}effect}$ = 1.0	New-Concept	Trad-Method	New-Concept	Trad-Method	New-Concept	Trad-Method
Luminaire Raw-Lumens @LOTIL	4050.0	4050.0	4050.0	4050.0	4050.0	4050.0
Lamp Raw-Lumens @LOTIL or @25°C	4500.0	3690.0	4500.0	3960.0	4500.0	4275.0
Lamp Rated-Lumens @LOTIL	5000.0		5000.0		5000.0	
Lamp Rated-Lumens @LODT or @25°C	5000.0	4400.0	5000.0	4400.0	5000.0	4400.0
Luminaire Efficiency	***90.00%***	***109.76%***	***90.00%***	***102.27%***	***90.00%***	***94.74%***
Luminaire Total Lumens	***4500.0***	***4829.3***	***4500.0***	***4500.0***	***4500.0***	***4168.4***

Studying the predicted results of T5HO-lamp luminaires in Table 1, the New Concept provides accurate and consistent photometry, which reports the identical result for the same luminaire design regardless of the differences in light-output/thermal characteristics from the different test lamps (the photometry of T5HO-A, T5HO-B, and T5HO-C horizontally across the Table 1). Indicating from the photometry, the thermal management is the key to optimize the photometric performance of the luminaire. By controlling the Lamps Operating Temperature Inside the Luminaire of three T5HO-lamp luminaires (LOTILs=25°C, 30°C and 35°C), the photometric results reveal the superior luminaire performance while the LOTILs come close to the optimum of T5HO-lamp (LOTIL=35°C). By carefully integrating the measurement results of the luminaire's optical efficiency and the lamps' thermal effects, the New Concept precisely predicts the Total Lumens and Efficiency of the luminaires in all three thermal designs.

The traditional Method, however, either underestimates or over reports the Total Lumens of T5HO-lamp luminaires by more than 7 percent, and overstates the Luminaire Efficiency by as much as 20 percent. Directly associated with the variations in the light-output/thermal characteristics of the test lamps, the Traditional Method generates significantly different photometric results when the different test lamps are used for the photometry of the same luminaire. With the exception of when a test lamp happens to have the identical characteristic as the lamp manufacturer's specifications, the numerical value of Luminaire Total Lumens appears to have the same result as predicted as the New Concept. However, the Traditional Method always overestimates the Efficiency of T5HO-lamp luminaires, often by a significant magnitude. Table 2 summarizes the photometric errors of three T5HO-lamp luminaires when three different test lamps were utilized in the relative photometry of the Traditional Method.

TABLE 2.
Percentage Photometric Errors of T5HO-Lamp Luminaires by Using Traditional Method LOTIL = 25°C, 30°C and 35°C; (T5HO-A, T5HO-B, and T5HO-C)

Three T5HO Test-Lamp Samples		T5HO-A	T5HO-B	T5HO-C
T5HO-lamp Luminaire	Efficiency	13.64%	13.64%	13.64%
LOTIL = 25°C	Total-Lumens	0.00%	0.00%	0.00%
T5HO-lamp Luminaire	Efficiency	*20.82%*	*13.64%*	*5.96%*
LOTIL = 30°C	Total-Lumens	*6.32%*	*0.00%*	*−6.76%*
T5HO-lamp Luminaire	Efficiency	*21.95%*	*13.64%*	*5.26%*
LOTIL = 35°C	Total-Lumens	*7.32%*	*0.00%*	*−7.37%*

T5HO-Lamp Luminaire with Optical Efficiency of 90%

Illustrated below are the detailed photometric calibration processes of a T5HO-luminaire design (LOTIL=35°C) using a specific test lamp (T5HO-C) in which the lumen values are outlined in the ovals.

The outcomes presented in Fig. 5 reveal that the Traditional Method under-reports the Luminaire Total Lumens and overvalues the Luminaire Efficiency because the photometric measurements and calibrations are incorrectly referenced at a laboratory ambient temperature of 25°C rather than the lamp's operating temperature of 35°C. A -7.37 percent undervalue of Luminaire Total Lumens is instigated due to a combined result of a -12 percent of rated lumens and a -5 percent of raw lumens for T5HO lamps. Consequently, a + 5.26 percent overvalue of Luminaire Efficiency is produced due to the smaller rated lumens of 4400 lm used in the denominator of the Luminaire Efficiency calculation. As a result, the errors are introduced in the photometric process of the Traditional Method.

Unlike T5HO lamps with maximum lumens output specified at a temperature of 35°C, T8/T12 lamps are designed to maximize the lumen outputs at a temperature of 25°C. Therefore, by selecting the test lamps that meet lamp manufacturer's specifications and methodically following the standard CIE and IESNA testing procedures, the photometric result of using the Traditional Method for T8/T12 is compatible with the New Concept. This is because T8/T12

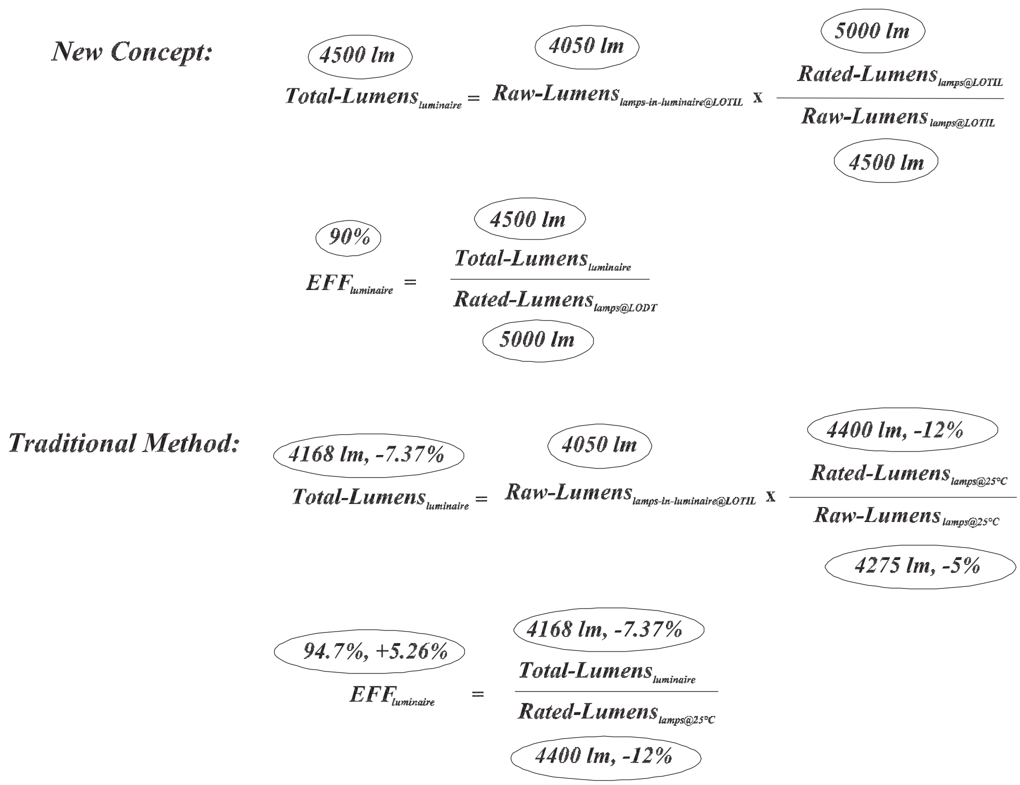


Fig. 5. The Detailed Photometric Calibration Processes of a T5HO-lamp Luminaire Using the New Concept and the Traditional Method.

lamps are optimized, and the photometry is measured and calibrated at the same temperature of 25°C. To support this conjecture, the photometric predictions of three T8-lamp luminaires using three different test lamps are demonstrated in Tables 3 and 4.

As illustrated in the above predicted results, the New Concept and Traditional Method produce compatible photometry for the T8-lamp luminaires in most applications, and especially bear well matched results when using a test lamp (T8-B). As a matter of fact, the Traditional Method practically is a special application of the New Concept that specifically is designed for the photometry of a perfect test lamp being optimized with the maximum light output at a standard laboratory temperature of 25°C. Even with a difference in light-output/thermal characteristics among individual T8 test lamps, the photometric results generated by using the Traditional Method could be acceptable. To explain the details of this calibration process, the photometry of a typical T8-lamp luminaire (LOTIL=30°C) with a test lamp (T8-A) is illustrated in following Fig. 6.

As shown in the calibration procedure of Fig. 6, the photometric results generated from the Traditional Method are realistically reporting the photometry of T8-lamp luminaire even with the actual performance of the test lamp being mismatched with the manufacturer's specifications. With less than one percent uncertainty, the photometric results of the Traditional Method can be approximated as is conventionally accepted for the lighting applications. It is demonstrated from Tables 3 and 4, the photometry of T8-lamp applications using the Traditional Method have (on average) created the photometric uncertainties within ± 2 percent, and in the worst case scenario may approach ± 4 percent.

Also, it is observed from the photometric predictions of both T8-lamps and T5HO-lamps luminaires that the Efficiency values of T5HO-lamps luminaires

TABLE 3.
Photometry Comparisons of T8-lamp Luminaires LOTIL = 25°C, 30°C and 35°C; (T8-A, T8-B, and T8-C)

LOTIL = @25°C	T8-A		T8-B		T8-C	
$EFF_{luminaire\text{-}optical}$ = 90%, $F_{lamps\text{-}thermal\text{-}effect}$ = 1.0	New-Concept	Trad-Method	New-Concept	Trad-Method	New-Concept	Trad-Method
Luminaire Raw-Lumens @LOTIL	2349.0	2349.0	2349.0	2349.0	2349.0	2349.0
Lamp Raw-Lumens @LOTIL or @25°C	2610.0	2610.0	2610.0	2610.0	2610.0	2610.0
Lamp Rated-Lumens @LOTIL	2900.0		2900.0		2900.0	
Lamp Rated-Lumens @LODT or @25°C	2900.0	2900.0	2900.0	2900.0	2900.0	2900.0
Luminaire Efficiency	*90.00%*	*90.00%*	*90.00%*	*90.00%*	*90.00%*	*90.00%*
Luminaire Total Lumens	*2610.0*	*2610.0*	*2610.0*	*2610.0*	*2610.0*	*2610.0*
LOTIL = @30°C	T8-A		T8-B		T8-C	
$EFF_{luminaire\text{-}optical}$ = 90%, $F_{lamps\text{-}thermal\text{-}effect}$ = 0.982	New-Concept	Trad-Method	New-Concept	Trad-Method	New-Concept	Trad-Method
Luminaire Raw-Lumens @LOTIL	2292.3	2292.3	2305.8	2305.8	2332.8	2332.8
Lamp Raw-Lumens @LOTIL or @25°C	2547.0	2610.0	2562.0	2610.0	2592.0	2610.0
Lamp Rated-Lumens @LOTIL	2847.8		2847.8		2847.8	
Lamp Rated-Lumens @LODT or @25°C	2900.0	2900.0	2900.0	2900.0	2900.0	2900.0
Luminaire Efficiency	*88.38%*	*87.83%*	*88.38%*	*88.34%*	*88.38%*	*89.38%*
Luminaire Total Lumens	*2563.0*	*2547.0*	*2563.0*	*2562.0*	*2563.0*	*2592.0*
LOTIL = @35°C	T8-A		T8-B		T8-C	
$EFF_{luminaire\text{-}optical}$ = 90%, $F_{lamps\text{-}thermal\text{-}effect}$ = 0.94	New-Concept	Trad-Method	New-Concept	Trad-Method	New-Concept	Trad-Method
Luminaire Raw-Lumens @LOTIL	2114.1	2114.1	2207.7	2207.7	2302.2	2302.2
Lamp Raw-Lumens @LOTIL or @25°C	2349.0	2610.0	2453.0	2610.0	2558.0	2610.0
Lamp Rated-Lumens @LOTIL	2726.0		2726.0		2726.0	
Lamp Rated-Lumens @LODT or @25°C	2900.0	2900.0	2900.0	2900.0	2900.0	2900.0
Luminaire Efficiency	*84.60%*	*81.00%*	*84.60%*	*84.59%*	*84.60%*	*88.21%*
Luminaire Total Lumens	*2453.4*	*2349.0*	*2453.4*	*2453.0*	*2453.4*	*2558.0*

TABLE 4.
Percentage Photometric Errors of T8-Lamp Luminaires by Using Traditional Method LOTIL = 25°C, 30°C and 35°C; (T8-A, T8-B, and T8-C)

Three T8 Test-Lamp Samples		T8-A	T8-B	T8-C
T8-lamp Luminaire LOTIL = 25°C	Efficiency	*0.00%*	*0.00%*	*0.00%*
	Total-Lumens	*0.00%*	*0.00%*	*0.00%*
T8-lamp Luminaire LOTIL = 30°C	Efficiency	*−0.63%*	*0.00%*	*1.13%*
	Total-Lumens	*−0.63%*	*0.00%*	*1.13%*
T8-lamp Luminaire LOTIL = 35°C	Efficiency	−4.26%	*0.00%*	4.26%
	Total-Lumens	−4.26%	*0.00%*	4.26%

T8-Lamp Luminaire with Optical Efficiency of 90%

using the Traditional Method always are higher than that of T8-lamps luminaires, and sometimes greater than 100 percent (an invalid and unachievable result per the law of physics). Even when both T5HO lamps and T8 lamps are used in a same fixture with the identical optical design, the photometric predictions as illustrated reveal significant misconceptions with the luminaire Efficiency of 109.8 percent for the T5HO-lamp luminaire and 90 percent for the T8-lamp luminaire. This near 20 percentage-point difference generated between the applications of both T5HO lamps and T8 lamps of the same fixture is clearly a misrepresentation, and it is certainly an unfair efficiencie's advantage for the application of T5HO-lamps luminaires.

In validating the New Concept, IESNA Testing Procedures Committee conducted a round-robin test of T5HO-lamp luminaire by using both the New Concept and the Traditional Method within five photometry laboratories between the years of 2004 and 2005 (IESNA-TPC 2005). A data summery is included in Appendix C. As the results shown by the New Concept, all five participant labs

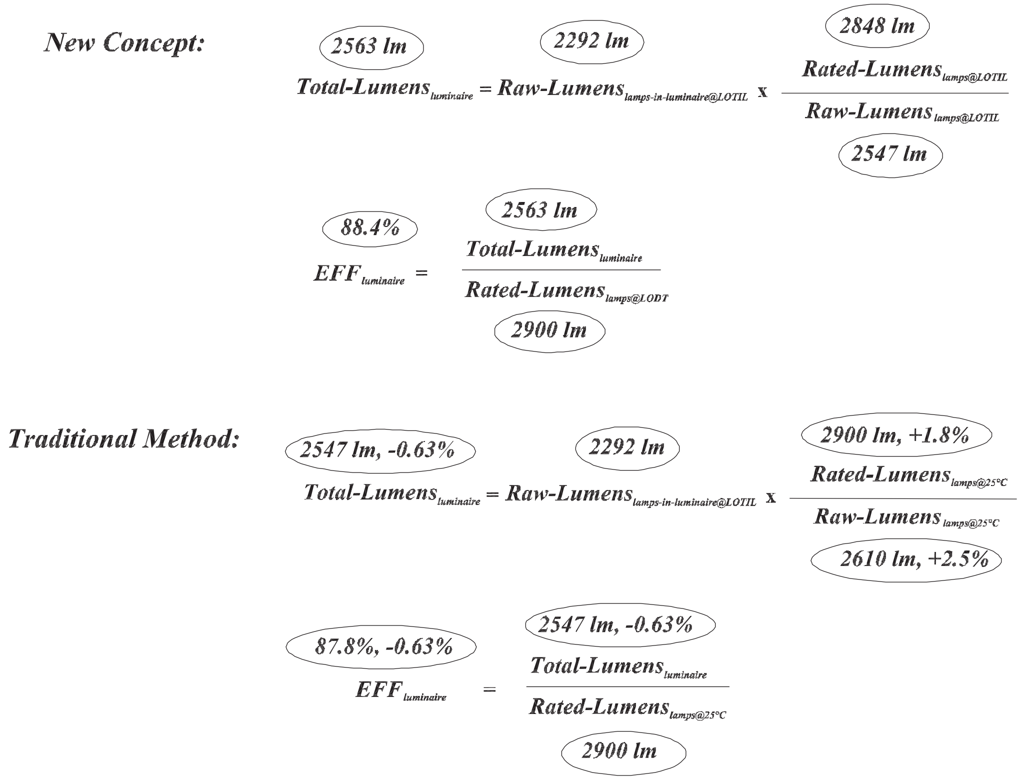


Fig. 6. The Detailed Photometric Calibration Processes of a T8-Lamp Luminaire Using the New Concept and the Traditional Method.

produced consistent photometry with photometric uncertainty within the acceptable lighting industry accuracy. Regardless of how an individual test lamp behaved and/or where the photometry was performed, the resulting Luminaire Total Lumens and Luminaire Efficiency of the New Concept were consistent and dependable. The Traditional Method, however, over-reported the Luminaire Efficiency as much as + 16.9 percent and underestimated the Luminaire Total Lumens as much as -10.3 percent as compared to the actual photometric performance of the luminaire. Additionally, by using the Traditional Method, the considerable photometric variations were introduced between five photometry laboratories even when the luminaire was designed at its optimal operating temperature and test lamp was identical.

5 CONCLUSIONS AND RECOMMENDATIONS

The photometry based on the New Concept is theoretically robust, in which photometry measurement and calibration are referenced at the Lamps Operating Temperature Inside the Luminaire (LOTIL) and the Luminaire Efficiency ($EFF_{luminaire}$) is defined as the ratio of the lumens emitted by a luminaire measured at a standard laboratory temperature (25°C) to the lamps' rated lumens referenced at Lamps Optimum Design Temperature (LODT).

The Six-Step photometry procedure is practical. Its concept can be universally applicable to the photometry of all types of light sources whether or not they are temperature sensitive, ranging from Incandescent, HID, Fluorescent, Inductive and light emitting diodes (LEDs), to future lamp technologies.

The proposed procedure is fully compatible with the photometry of the conventional light sources using the traditional photometric procedure, and it can be simplified if the test lamps are fully corresponding with the lamp manufacturer's specifications. While the New Concept is the recommended method for the photometry of temperature-sensitive light sources, the Traditional Method (Current CIE and IESNA standard photometric procedures) can continue to be used for the luminaire photometry of nontemperature-sensitive light sources. The Traditional Method also may be useful for the photometric applications of T8/T12 lamps or the lamps with their light outputs optimized at a temperature of 25°C if the selection of test lamps is properly performed. Carefully selecting the test lamps to meet the lamps' specifications will ensure the accuracy and consistency of the photometry, and therefore minimize the uncertainty of the luminaires' photometry within a conventional acceptable accuracy of ± 2 percent.

APPENDIX A: DETERMINE LAMPS CORRECTION FACTOR ($F_{LAMPS\text{-}CORRECTION}$)

The measurement procedure of using a thermal chamber to obtain $F_{lamps\text{-}correction}$ is described as following.

- Set up lamp(s) on a bare-lamp rack (similar to the rack used for the bare lamp measurement for the Traditional Method) inside a thermal chamber with the lamp(s) in the same orientation as installed in the fixture. Install photo detector and ballast at outside of thermal chamber to eliminate possible equipment errors due to the temperature influence of the thermal chamber.
- Energize bare lamp(s) and allow them to stabilize a minimum of two hours in the thermal chamber at a 25°C ambient temperature. Maintain and measure ambient temperature within thermal chamber at the same elevation as the lamp(s) and at least 6" from the end of lamp(s). Be sure to have a radiant energy shield midway between the lamp(s) and the temperature measuring device to eliminate any direct radiant energy. Upon lamps' stabilization, take a relative light output reading ($\text{Relative-Reading}_{lamps@25°C}$) perpendicular to the length of the lamp(s).
- Without extinguishing and moving the lamp(s), gradually raise the ambient temperature within the thermal chamber to the temperature level equivalent to LOTIL/CSTL where the lamp(s) operated inside of the luminaire, and allow lamp(s) to stabilize for a minimum of two additional hours. Upon stabilizing the lamps at LOTIL/CSTL, take another relative light output reading ($\text{Relative-Reading}_{lamps@LOTIL}$) perpendicular to the length of the lamp(s).

  With these two measurements, the Lamps Correction Factor ($F_{lamps\text{-}correction}$) is determined by a ratio of the relative reading ($\text{Relative-Reading}_{lamps@LOTIL}$) of bare lamps at LOTIL to the relative reading ($\text{Relative-Reading}_{lamps@25°C}$) of bare lamps at 25°C in the thermal chamber by equation (6).

$$F_{lamps\text{-}correction} = \frac{\textit{Relative-Reading}_{lamps@LOTIL}}{\textit{Relative-Reading}_{lamps@25°C}} \tag{6}$$

Another way to determine $F_{lamps\text{-}correction}$ of the test lamp(s) is to pre-calibrate a group of lamps, and measure the relative light output characteristics of each individual lamp at the temperatures of LOTIL from 25°C to 45°C at a small interval such as 0.5°C. Then all the recorded data of an individual lamp is saved in the database for the future use of calculating the Lamps Correction Factor ($F_{lamps\text{-}correction}$) of multiple lamps. For example, a four lamps application, the Lamp Correction Factor is calculated by the ratio of the summations of individual lamp's relative readings between the temperatures at LOTIL ($R_{lamp\#@LOTIL}$) and 25°C ($R_{lamp\#@25}$) by equation.

$$F_{lamps\text{-}correction} = \frac{R_{lamp\#1@LOTIL} + R_{lamp\#2@LOTIL} + R_{lamp\#3@LOTIL} + R_{lamp\#4@LOTIL}}{R_{lamp\#1@25^\circ C} + R_{lamp\#2@25^\circ C} + R_{lamp\#3@25^\circ C} + R_{lamp\#4@25^\circ C}}$$

A general equation of determining $F_{lamps\text{-}correction}$ is expressed as equation (7), where *n* is the number of lamps and *i* is the *i*th lamp from 1 to *n*.

$$F_{lamps\text{-}correction} = \frac{\sum_{i=1}^{n} Relative\text{-}Reading_{lamp\#i@LOTIL}}{\sum_{i=1}^{n} Relative\text{-}Reading_{lamp\#i@25^\circ C}} \tag{7}$$

APPENDIX B: PHOTOMETRIC CALCULATIONS AND CALIBRATIONS

The explanations of photometric calculations and calibrations for the individual cell in Table 1 and 3, where a T5HO test lamp of T5HO-C is installed in a fixture with LOTIL=30°C.

Lamp: T5HO-C, Laboratory Ambient Temperature: 25°C		
$EFF_{luminaire\text{-}optical}$ = 90%, $F_{lamps\text{-}thermal\text{-}effect}$ = 0.978	New-Concept	Traditional-Method
Luminaire Raw-Lumens @LOTIL	Luminaire Raw-Lumens (3987 lm)	Luminaire Raw-Lumens (3987 lm)
	A Measure-Value Obtained @LOTIL = 30°C	A Measure-Value Obtained @LOTIL = 30°C
Lamp Raw-Lumens @LOTIL or @25°C	Bare Lamp Raw-Lumens (4430 lm)	Bare Lamp Raw-Lumens (4275 lm)
	A Measure-Value Obtained @LOTIL = 30°C	A Measure-Value Obtained @25°C
	$EFF_{Luminaire\text{-}Optical}$ = 3987/4430 = 90%	
Lamp Rated-Lumens @LOTIL	Bare Lamp Rated-Lumens (4890 lm) @LOTIL = 30°C	
	Rated by Lamp Manufacturer	
Lamp Rated-Lumens @LODT or @25°C	Bare Lamp Rated-Lumens (5000 lm) @LODT = 35°C	Bare Lamp Rated-Lumens (4400 lm) @25°C
	Rated by Lamp Manufacturer	Rated by Lamp Manufacturer
	$F_{lamps\text{-}thermal\text{-}effect}$ = 4890/5000 = 0.978	
Luminaire Efficiency	88.02% = 90% × 0.978 = 4401/5000	93.26% = 4103.6/4400
	A Calculation-Value Calibrated @LOTIL = 30°C	A Calculation-Value Calibrated @25°C
Luminaire Total Lumens	4401 lm = 3987/4430 × 4890 = 90% × 4890	4103.6 lm = 3987/4275 × 4400 = 93.26% × 4400
	A Calculation-Value Calibrated @LOTIL = 30°C	A Calculation-Value Calibrated @25°C

APPENDIX C: IESNA TPC T5HO-LAMP LUMINAIRE ROUND ROBIN DATA SUMMARY FOR OCTOBER 2005

LAB	TEST TYPE	LAMPS*	INPUT WATTS	LUMINAIRE EFFICIENCY	% DIFFERENCE FROM 94.15%	LUMINAIRE TOTAL LUMENS	% DIFFERENCE FROM 9417.5 lm
LAB A	Traditional-Method	SYLV.	120.4	103.1	9.41%	9076	−3.67%
LAB B	Traditional-Method	SYLV.	120.0	99.2	5.27%	8731	−7.33%
LAB C	Traditional-Method	SYLV.	121.9	98.6	4.63%	8677	−7.91%
LAB D	Traditional-Method	SYLV.	121.9	105.4	11.85%	9277	−1.54%
LAB E	Traditional-Method	SYLV.	120.9	107.7	14.30%	9480	0.62%
AVERAGE				**102.8**	**9.09%**	**9048**	**−3.96%**
LAB A	New-Concept	SYLV.	120.4	93.8	−0.47%	9380	−0.44%
LAB B	New-Concept	SYLV.	120.0	96.0	1.87%	9595	1.84%
LAB C	New-Concept	SYLV.	121.9	92.7	−1.64%	9272	−1.59%
LAB D	New-Concept	SYLV.	122.0	93.3	−1.00%	9326	−1.02%
LAB E	New-Concept	SYLV.	120.9	95.4	1.23%	9535	1.20%
AVERAGE				**94.2**		**9422**	

LAMP* The same test-lamps were used by all five labs, which were provided by SYLVANIA.

LAB	TEST TYPE	LAMPS*	INPUT WATTS	LUMINAIRE EFFICIENCY	% DIFFERENCE FROM 94.15%	LUMINAIRE TOTAL LUMENS	% DIFFERENCE FROM 9417.5 lm
LAB A	Traditional-Method	LAB-1	120.4	107.1	13.79%	9426	0.14%
LAB B	Traditional-Method	LAB-2	120.0	98.3	4.44%	8654	−8.06%
LAB C	Traditional-Method	LAB-3	121.4	95.9	1.89%	8440	−10.33%
LAB D	Traditional-Method	LAB-4	122.0	106.9	13.57%	9403	−0.11%
LAB E	Traditional-Method	LAB-5	120.9	110.1	16.97%	9690	2.94%
AVERAGE				**103.7**	**10.13%**	**9123**	**−3.08%**
LAB A	New-Concept	LAB-1	120.4	95.2	1.15%	9524	1.18%
LAB B	New-Concept	LAB-2	120.0	94.9	0.83%	9492	0.84%
LAB C	New-Concept	LAB-3	121.4	93.2	−0.98%	9318	−1.01%
LAB D	New-Concept	LAB-4	121.9	91.9	−2.36%	9193	−2.34%
LAB E	New-Concept	LAB-5	120.9	95.4	1.36%	9538	1.33%
AVERAGE				**94.1**		**9413**	

LAMP* Different test-lamps were used for the photometries of all five labs.

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