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Light Loss Factors in Roadway Lighting

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Introduction

The decision of the American Illumination Engineering Society (IES) to promote luminance or visibility methods of design for roadway lighting means that the technology in this field of lighting is progressing towards a more economical usage of electric energy. Lighting standards are being re-shaped to be closer to the real visibility needs of night driving.

However, there is still an area which has not yet been treated with the same degree of diligence and accuracy as implied by the change to luminance methods; namely, light losses or maintenance factors of light output. Current practice on this continent of calculating light loss factors is incompatible with the degree of sophistication in calculating luminances or visibility parameters.

This report is a first step in catching up with the problem of light loss factors.

Light Loss Factors in the Systems Design Program

The American National Standard practice for roadway lighting (1) contains a chapter on "illumination depreciation", and appendix chapters on "selection of luminaires" and "light loss factors". A typical total factor is quoted to be "0.64", indicating that the lowest lamp output (measured in lumens) is only 64 percent of the initial output. The two major contributions to the light losses are described as "lamp lumen depreciation" (LLD) and "luminaire dirt depreciation" (LDD), with typical values of LLD = 0.8 and LDD = 0.8.

Another common practice is the use of an average value of LLD instead of a minimum value. The reasoning behind this is that the lowest value of LLD occurs during a small fraction of the lifetime of the lamp, and only for part of the lamps because of mortality and spot relamping. The designer usually assumes group relamping at least at time intervals which correspond to the 50 percentile on the mortality curve. However, current practice is sometimes different and could be described as "indefinite spot relamping". These are reasons why some mercury vapor luminaire installations have ultimately slipped below an acceptable illumination level after a bright and impressive start. This occurs not only on roads and highways, but also on city streets.

Proper cost economics and the need to save energy require a different approach. The recent changes in design technology, from illuminance methods to methods of luminance or visisbility index do not make a great deal of sense when light losses or maintenance factors are left in a state of haziness and approximation.

A systems design program which is based on luminance methods of design must take into account maintenance strategies of luminaire cleaning, relamping, and replacement.

This paper presents the theoretical modelling of the light loss factors and its practical application as far as data for light losses has been available. The systems design program for fixed highway lighting, which has been recently introduced into the Standards of the Ontario Ministry of Transportation and Communications, contains this feature. It uses reasonable loss factor functions based on available literature and manufacturers' data.

The light losses in an installation are also influenced by burn-outs and spot relamping. However, such rehabilitations occur locally and at random. After some time road sections or clusters of luminaires may be found without too many relamped spots.

In other words, whereas light loss factors are taken into account in predicting the performance of a new or change-over installation, burn-out and spot relamping, modelled along mortality curves, are considered only for calculating maintenance costs.

It should also be noted that calculated performance predictions for maintenance strategies of "indefinite spot relamping" are hardly feasible. It is recommended that this practice be discontinued. Comparative costs of such practices can still be calculated.

History of Light Losses

As soon as a new installation is built, light losses start to accumulate, such as:

(a) Lamp lumen depreciation (LLD)

(b) Luminaire dirt depreciation (LDD)

(c) Lamp burn-outs

(d) Voltage to luminaire changes

(e) Ballast factor

(f) Luminaire component depreciation (LCD)

(g) Changes in physical surroundings

(h) Luminaire ambient temperature

Items (c), (d), (e), (g) and (h) are not subject to predictive analysis or are taken into account in other ways. Some of these losses do not apply, some can be eliminated by washing (b), by re-lamping (a) and (c), and some are permanent (f). Lamp burn-outs (c) have been discussed. There remains (a), (b), and (f), all of which are losses which increase with time.

Figure 1 shows a typical histogram of light losses, for a cleaning period T_C being half as long as the re-lamping period T_L, or $T_C = 1/2 \ T_L$. Other possibilities would be $T_C=T_L$ or $T_C=1/3 \ T_L$. Light losses from lamp lumen depreciation are recovered after each period $T_L = 2 \ T_C$. Permanent losses, LCD, are not recovered. The lowest point of output for a life span of $T_2 = 3.5 \ T_L$ is a $3 \ T_L$, the last re-lamping period before the end. At the end of the assumed life span $T_2 = 3.5 \ T_L$ (not a very reasonable assumption) there is a salvage value for the lamps.

Time, symbolized as T, can be expressed in terms of burning hours or years. It is suggested that burning hours be converted into years. A typical conversion would be based on 1 year = 4 000 hours.

In order to avoid excessive burn-outs, the relamping period T_L should always be shorter than the life span of the lamp. Cleaning of the luminaire could be carried out at the same time ($T_C = T_L$) or at shorter intervals. With regard to Figure 1 the lowest time below the shaded areas (representing losses) constitutes the total loss factor which is a fraction of unity. This factor fluctuates up and down depending on the periods of cleaning and relamping which must be chosen as part of the design parameters and must be communicated to those who carry out the maintenance tasks. Because of the permanent losses (LCD) the lowest luminaire output occurs at or near the end of the life span.

There is also an effect on the light distribution of the luminaire dirt and component depreciation. Dirt will probably collect unevenly on the refractor and deflector. The deflector corrosion may be randomized over the deflector surface. Both must lead to a reduction in overall output and to a change in light distribution, which cannot be predicted. Thus an installation may deteriorate not only in the level but also in the distribution of illumination.

The question may well be asked, why is a more sophisticated light loss factor required when the increase in accuracy is limited in this way? The answer is, that it is necessary to discriminate the light sources with regard to their maintenance losses and burn-out rates even when such discrimination cannot be very accurate.

Luminaire Dirt and Component Depreciation

The depreciation of luminaire output from dirt or compound deterioration is a function of the time, T. For modern, gasket sealed luminaires quantifying data for this kind of light losses can be found in References (1), IES Standard practice for roadway lighting, (2), C.F. Scholz' article on luminaire dirt depreciation, (3), H.A. Van Dusen's paper on maintenance and adjustment factors. These references were published in 1977, 1975 and 1971 respectively, and Reference (3) contains the most comprehensive data.

With regard to gasketed luminaires, the depreciation factors for eight years exposure time quoted in Reference (3) are well within the broad banded curves of the IES Standard (Reference (1), Figure B-1), however, in the "clean" and "moderate" categories, the IES values are lower for shorter exposure times, such as 3 or 4 years. The corresponding values in Reference (3) follow mostly straight lines as shown in Figure 2, whereas the IES Standard curves are definitely curved.

On the other hand, the research results reported by Scholz in Reference (2) on gasketed luminaires confirms the loss factors and straight line shape presented by Van Dusen in Reference (3), at least for the "clean" category, listed in Table 1.

In his article Scholz has demonstrated that dirt accumulation alone leads to a depreciation factor of $(0.9869)^T$, valid for Cleveland, Ohio. From this the term permanent or compound depreciation must be subtracted, which, according to Van Dusen, is 0.005 T, where T is the exposure time in years. This leads to a function which is plotted in Figure 2 as a dashed line. This line is close to the straight line of Category 2 (except for small values of T). This category is described by Van Dusen as "heavy traffic, light industrial", which indeed should prevail in Cleveland.

All this has established sufficient confidence in the luminaire dirt depreciation factors presented by Van Dusen for tightly sealed luminaires in the ambient categories 1 to 4. Straight line equations for the corresponding loss factors are shown in Figure 2, as they have been incorporated into the MTC systems design program.

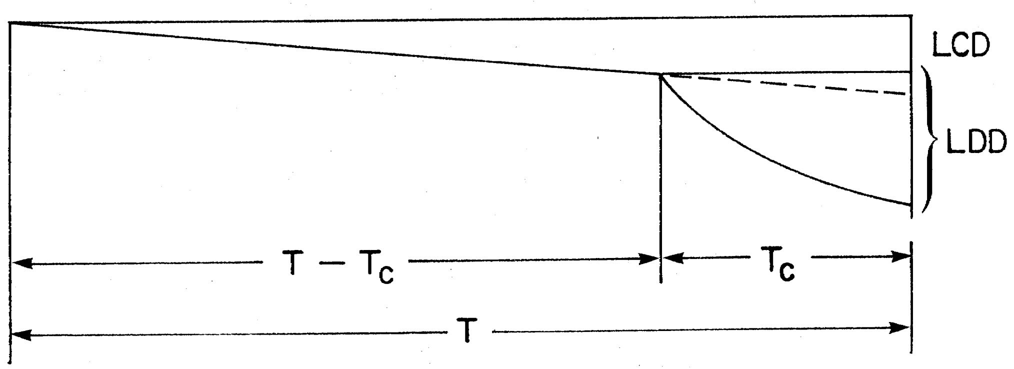
Equations or tabulated values for the ambient categories "dirty" and "very dirty" (8 and 16 in Figure 2) can be established similarly, based on the plotted points in Figure 2 or the IES Standard broad banded curves (Reference (1), Figure 3-1), wherever such categories have to be included in a computer systems design program.

The luminaire dirt depreciation factors as shown in Figure 2 include luminaire component depreciation which is permanent and is assumed to be half a percent per year or 0.005 T, starting at the beginning of the installation. Thus, washing of the luminaires rehabilitates only with regard to actual dirt, not the permanent deterioration of the luminaire components. With regard to Figure 1, the lowest light output occurs after an exposure time T which is a multiple of the cleaning or washing period T_C. Since permanent depreciation is included in the loss during this period T_C, the value of T_C must be subtracted from T in order to obtain the component depreciation prior to the last period of T_C only. For example, for the point of lowest output, in the "clean" category, the loss factors are:

Luminaire component depreciation, LCD = $1 - 0.005\ (T-T_C)$

Luminaire dirt depreciation, LDD = $0.96 - 0.013\ T_C$

Note that actual dirt losses accrue only during the period T_C after the last cleaning. The following loss histogram illustrates this relationship:



The dashed line indicates the portion of LCD which is already included in LDD.

Lamp Lumen Depreciation

The losses of luminaire output from lamp or bulb deterioration are also a function of time, T. The main variable is the time of burning. There is some influence from the number of cycles of ignition and extinction, which is usually assumed to occur once in 24 hours. Usually, burning hours are converted to years, assuming an average burning time of 4000 hours per year. In this way the available data on lamp lumen depreciation can be fitted into the system illustrated in Figure 1, shown as item 2. Losses from lamp deterioration are recovered after each relamping period, T_L.

Data for lamp lumen depreciation are provided by lamp manufacturers. It should be noted, however, that these data assume a standard ballast and supply voltage which may indicate additional losses mentioned earlier. It is not feasible to predict these, but it is advisable to check with the lamp manufacturer if the design conditions in terms of ballast and voltage are different. With these and other qualifications in mind (such as temperature and other environmental factors), a systematic search for and evaluation of lamp lumen depreciation data has resulted in the following list, presented in Table 2. With regard to this table, the following notation has been used:

f = lamp lumen depreciation factor (LLD)

t = burning time of lamp, in hours (or years)

T_e = burning time of lamp at the end of its life span, more specifically at 50 percent mortality, in hours or years.

$\tau = t/T_e$ = independent variable of LLD function, to present them in normalized fashion.

For low pressure sodium lamps (LSP) the lamp lumen output does not decrease, but rather increases slightly. Therefore a factor f = 1.0 = constant is assumed. The deterioration of this lamp does not show in terms of a loss in output but in terms of an increase in power supply drawn by the lamp. Its life span (T_e) is 18,000 h (4.5 years), according to Philips' data. The consolidated data presented in Table 2 is subject to changes and modifications as new information becomes available.

The equations presented in Table 2 have been derived from manufacturers' data (4), following closely approximately fitted curves. Examples of the underlying simplified curve fitting are presented in Figure 3, 4, 5 and 6.

Examples of Light Loss Computation

Calculation of total light losses in accordance with the proposed prediction model described in the preceeding paragraphs is best carried out within a computer systems program of lighting design, such as described in Reference (5) for roadway lighting. The following example, however, is calculated manually, to illustrate the models of computation.

Example 1/ Clean environment: Nearby smoke or dust generating activity, moderate to heavy traffic, ambient particulate level less than 300 micrograms per cubic metre, refer to Table 1 and Figure 2.

Four alternative light sources: (1 year = 4,000 h)

1) 700 W Clear Mercury (MV),	24 000 h life
2) 400 W HPS,	24 000 h life
3) 180 W LPS,	16 000 h life
4) 330 W HPS on MV Ballast,	16 000 h life

Relamping: for 1) and 2) T_L = 5 years
for 3) and 4) T_L = 3 years
Washing: for 1) and 2) T_C = 5 years
for 3) and 4) T_C = 3 years

Total life of installation: T_n = 15 years.

Lamp Component Depreciation

$LCD = 1 - 0.005\ (T_n - T_c)$

for 1) and 2) $LCD = 1 - 0.005 \times 10 = 0.95$

for 3) and 4) $LCD = 1 - 0.005 \times 12 = 0.94$

Note that this is not the total lamp component depreciation, but only the depreciation up to the last cleaning and relamping cycle, $(T_n - T_c)$. The total LCD loss would be expressed by the factor: $1 - 0.005 \times 15 = 0.925$.

This factor cannot be used because the permanent depreciation is included in the equation for luminaire dirt depreciation for the last period T_c.

Luminaire Dirt Depreciation

$LDD = 0.96 - 0.01\ T_c$ (refer to Figure 2)

for 1) and 2) $LDD = 0.96 - 0.013 \times 5 = 0.895$

for 3) and 4) $LDD = 0.96 - 0.013 \times 3 = 0.921$

Lamp Lumen Depreciation
(refer to Table 2)

for 1) and 2) $= t/T_e = 5/6 = 0.8333$

for 3) and 4) $= t/T_e = 3/4 = 0.750$

for 1) $f = 0.96 - 0.25 \times 0.8333 = 0.752$

for 2) $f = 1 - 0.10 \times 0.8333 - 0.20 \times 0.8333^2 = 0.752$

for 3) $f = 1.0$

for 4) $f = 1 - 0.53 \times 0.75 + 0.26 \times 0.75 = 0.749$

Total Loss Factor

for 1) $0.95 \times 0.895 \times 0.752 - 0.639$

for 2) $0.95 \times 0.895 \times 0.750 = 0.638$

for 3) $0.94 \times 0.921 \times 1.000 = 0.866$

for 4) $0.94 \times 0.921 \times 0.749 = 0.648$

The example calculations have resulted in typical values which have been assumed traditionally in a relatively clean environment for sealed luminaires (0.64), except for low pressure sodium. The following second example is going to illustrate larger looses.

Example 2/ Moderately (clean or dirty) environment: Moderate smoke or dust generating activities nearby. The ambient particulate level is no more than 600 micrograms per cubic metre.

Two alternative light sources:
1) 250 W Mercury Vapor (color corrected) vertical burning
2) 100 W HPS
Relamping: T_L = 5 years or 20 000 h
Cleaning (washing) T_c = 2.5 years = 1/2 T_l
Total life span: T_n = 15 years

Lamp Component Depreciation
LCD = 1 - 0.005 (15 - 2.5) = 1 - 0.005 x 12.5 = 0.9375

Luminaire Dirt Depreciation, (refer to Figure 2)
LDD = 0.93 - 0.022 x 2.5 = 0.8750

Lamp Lumen Depreciation, (refer to Table 2)
= t/T_e = 5/6 = 0.8333 for 250 W M.V.
= t/T_e = 5/5 = 1.000 for 100 W HPS
for 1) (MV) f = 0.98 - 0.40 x 0.8333 = 0.6467
for 2) (HPS) f = 1.0 - 0.18 - 0.08 = 0.8400

Total Loss Factor
for 1) 0.9375 x 0.8750 x 0.6467 = 0.530
for 2) 0.9375 x 0.8750 x 0.7400 = 0.607

This second example is more typical of city street lighting, and more light losses must be expected in such cases, in spite of more frequent luminaire cleaning.

Finally, the same example without intermediate cleaning ($T_C = T_L = 5$ years):

LCD = 1 - 0.005 (15 - 5) = 0.95

LDD = 0.93 - 0.022 x 5 = 0.82

LLD as before

Total Loss Factor without intermediate cleaning:

for 1) 0.95 x 0.82 x 0.6467 = 0.504

for 2) 0.95 x 0.82 x 0.7400 = 0.576

Total losses can be as much as 50%.

Conclusions and Recommendations

Design methods for roadway lighting should include a rational and more accurate estimate of total light losses from dirt, and from lamp and luminaire deterioration.

This requires setting a maintenance strategy in the design stage, determining the anticipated life span (T_n) of the installation, and deciding on cleaning and relamping periods, (T_C) and (T_L).

Using available current data, light loss factors as a function of time (T) can be established for luminaire component, luminaire dirt, and lamp lumen depreciation (LCD, LDD, LLD). Such functions are subject to modification with innovative changes in lamp and luminaire design and with environmental conditions. These factors determine light losses at particular time periods, according to Figure 1. Near the end of the life span there is a point of minimum output of lamp lumen which corresponds to the maintained minimum level of illumination, and the design maintenance or light loss factor must be calculated for this point.

It is recommended that this method or calculation should be introduced into roadway lighting design standards.

References

(1) American National Standard Practice for Roadway Lighting, IES TRANSACTION, Journal of IES, October 1977.

(2) Scholz, C.F., "Reducing Theory to Practice-Luminaire Dirt Depreciation Maintenance", Journal of IES, April 1975.

(3) Van Dusen, H.A. "Maintenance and Adjustment Factors in Street Lighting Design Calculations".

(4) From various lamp manufacturers, data on lamp lumen depreciation.

(5) Jung, F.W., Blamey, C., "Computer Systems Program for Roadway Lighting", TRB Record #628, National Academy of Sciences, Transportation Research Board, Washington, D.C., 1977.

Table 1/ Ambient Categories

Select the appropriate curve in accordance with the type of ambient as described by the following examples:	No. in accordance with Ref. 37 (Van Dusen)
VERY CLEAN - No nearby smoke or dust generating activities and a low ambient contaminant level. Light traffic. Generally limited to residential or rural areas. The ambient particulate level is no more than 150 micrograms per cubic metre.	.....(1)
CLEAN - No nearby smoke or dust generating activities. Moderate to heavy traffic. The ambient particulate level is no more than 300 micrograms per cubic metre.	.....(2)
MODERATE - Moderate smoke or dust generating activities nearby. The ambient particulate level is no more than 600 micrograms per cubic metre.	.....(4)
DIRTY - Smoke or dust plumes generated by nearby activities may occasionally envelop the luminaires.	.....(8)
VERY DIRTY - As above but the luminaires are commonly enveloped by smoke or dust plumes.	.....(16)

Table 2/ Lamp Lumen Depreciation Factor (LLD) = f

Type of Lamp	Modelling Equation for (LLD) = f	Life Span	Date of Information	Manufacturer
Color Corrected Mercury Vapor horizontal burning position *400 W, *250 W, 175 W	$f = 0.96 - 0.50\,\tau$ * upper boundary: $= 0.96 - 0.45\tau$ lower boundary: $= 0.96 - 0.60\tau$	24 000 h 24 000 h	November 1973	CGE
Color Corrected Mercury Vapor vertical burning position *400 W, *250 W, 175 W	$f = 0.98 - 0.40\,\tau$ * upper boundary: $f = 1.00 - 0.30\tau$ lower boundary: $f = 0.97 - 0.50\tau$	24 000 h 24 000 h	November 1973	CGE Sylvania CGE
Clear Mercury Vapor	$f = 0.96 - 0.25\tau$ upper boundary: $f = 0.99 - 0.18\tau$ lower boundary: $f = 0.95 - 0.35\tau$	24 000 h	- -	Philips Sylvania
High Pressure Sodium Vapor 70 W, 100 W	$(f = 1 - 0.10\,\tau - 0.15\,\tau^3)$ $f = 1 - 0.18\,\tau - 0.08\,\tau^3$	20 000 h 20 000 h	January 1978 February 1978	Philips CGE
High Pressure Sodium Vapor 150 W, 200 W, 250 W, 400 W, 1000 W	$f = 1 - 0.10\tau - 0.20\,\tau^2$ $(f = 1 - 0.27\,\tau^2)$	24 000 h 24 000 h	February 1978 January 1978	CGE Sylvania Philips
High Pressure Sodium Vapor on Mercury V. Ballast 1) 330 W 2) 360 W	1) $f = 1 - 0.53\tau + 0.26\,\tau^2$ 2) $f = 1 - 0.12\tau - 0.08\,\tau^2$	16 000 h 16 000 h	January 1978 February 1978	Philips Sylvania

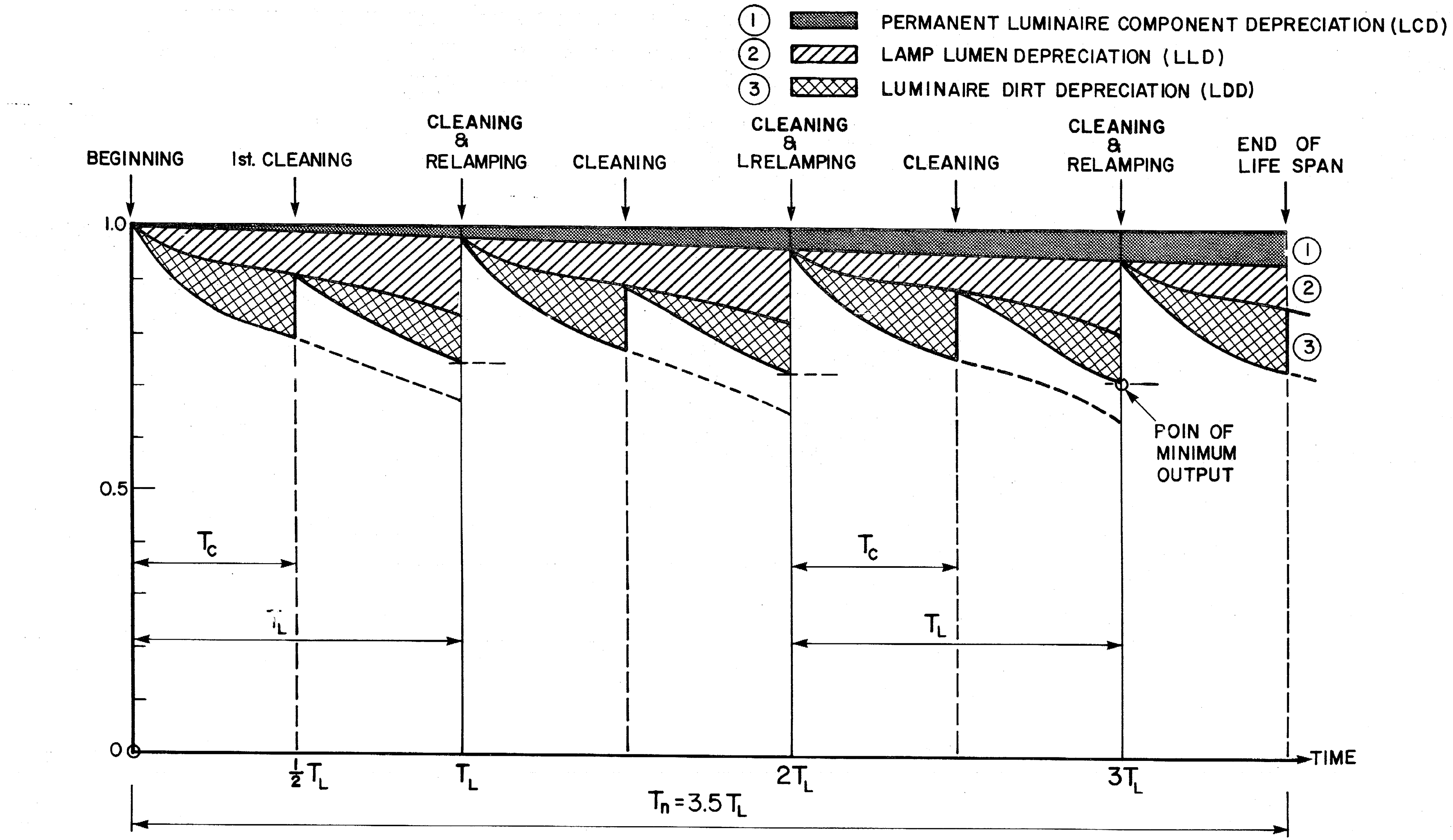


Figure 1, Light Losses of Luminaires with Time

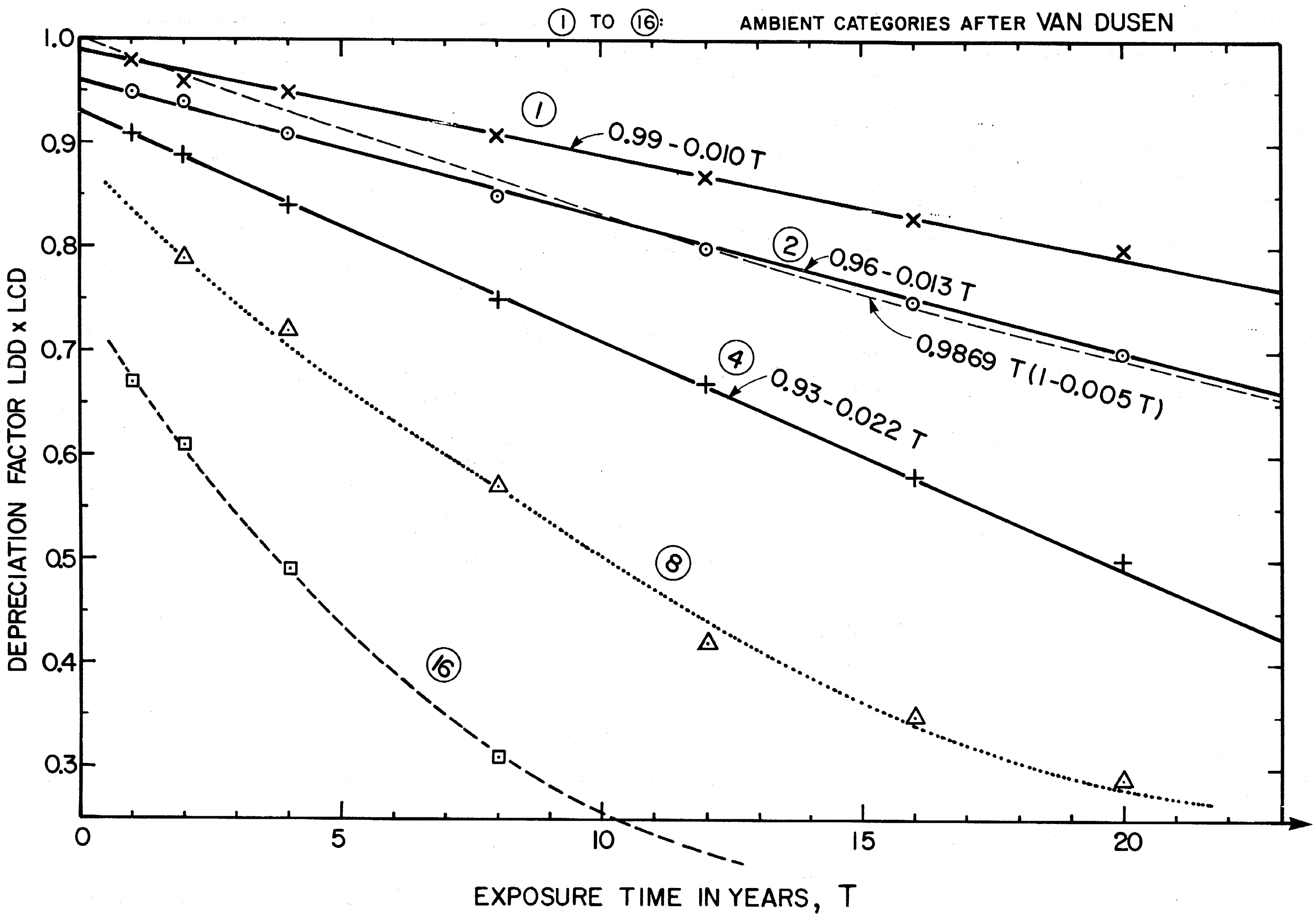


Figure 2, Luminaire Dirt and Component Depreciation (Sealed Gaskets)

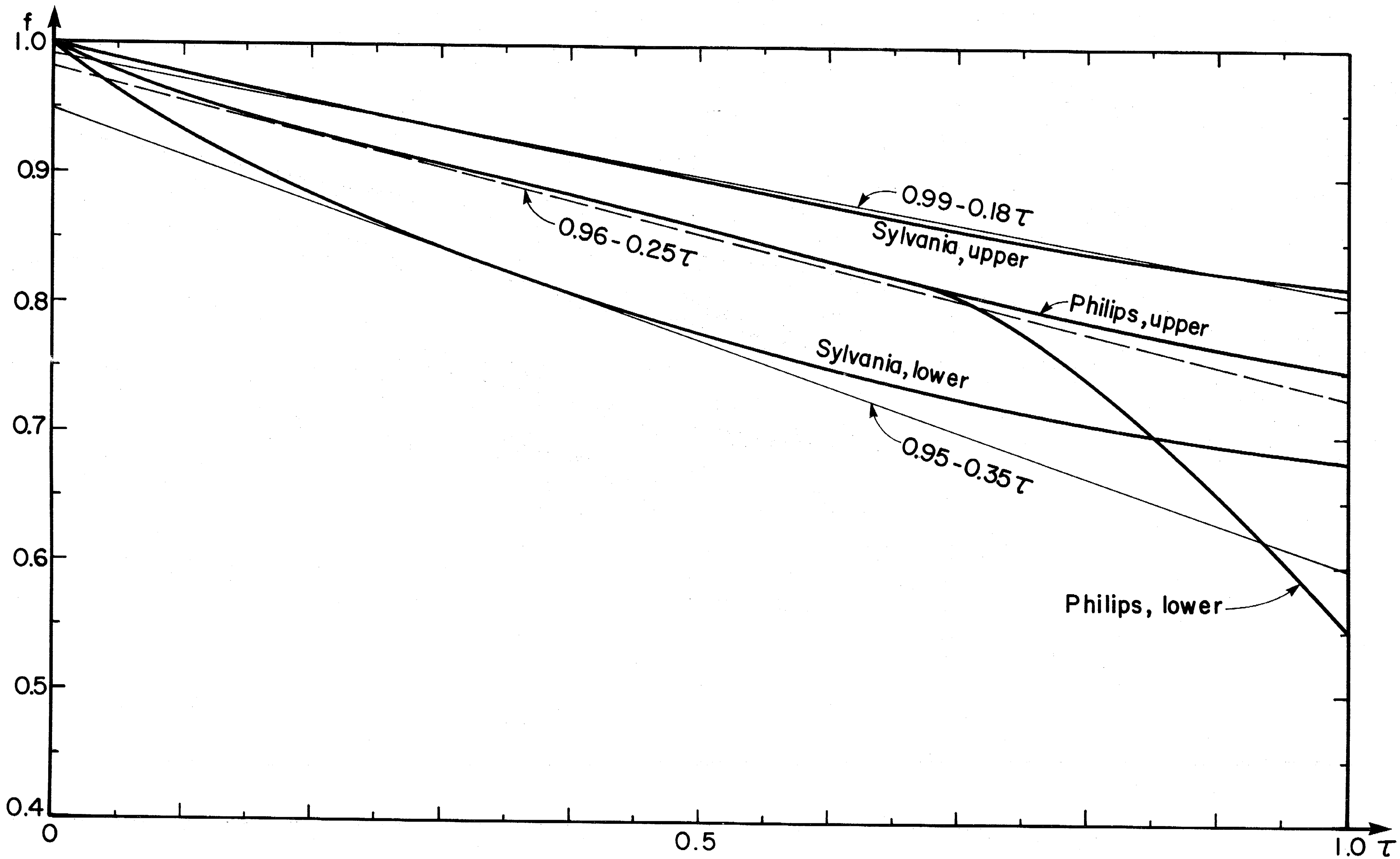


Figure 3, Normalized LLD - Functions for Clear Mercury Lamps

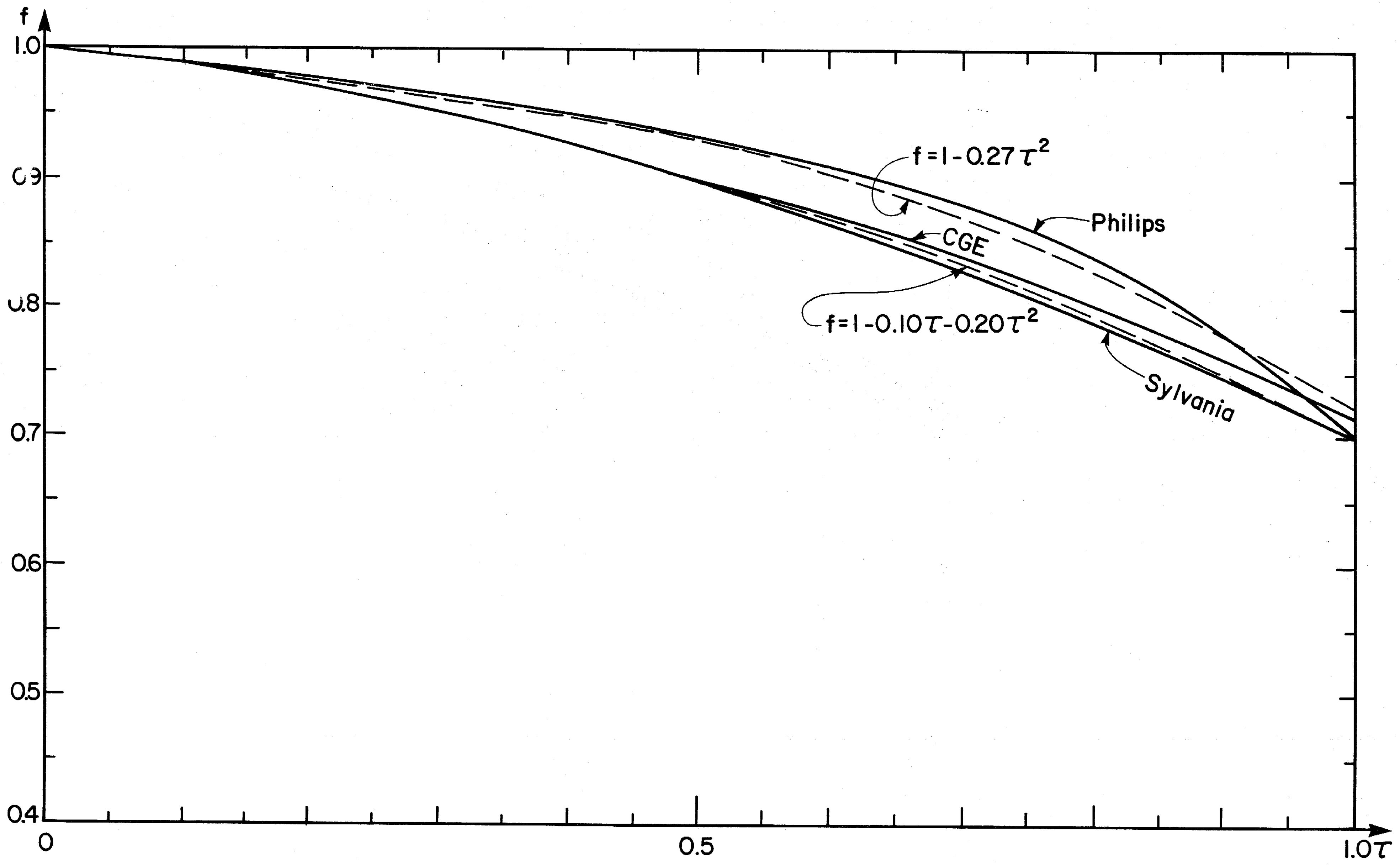


Figure 4, Normalized LLD - Functions for HPS Lamps, 150 W to 1000 W

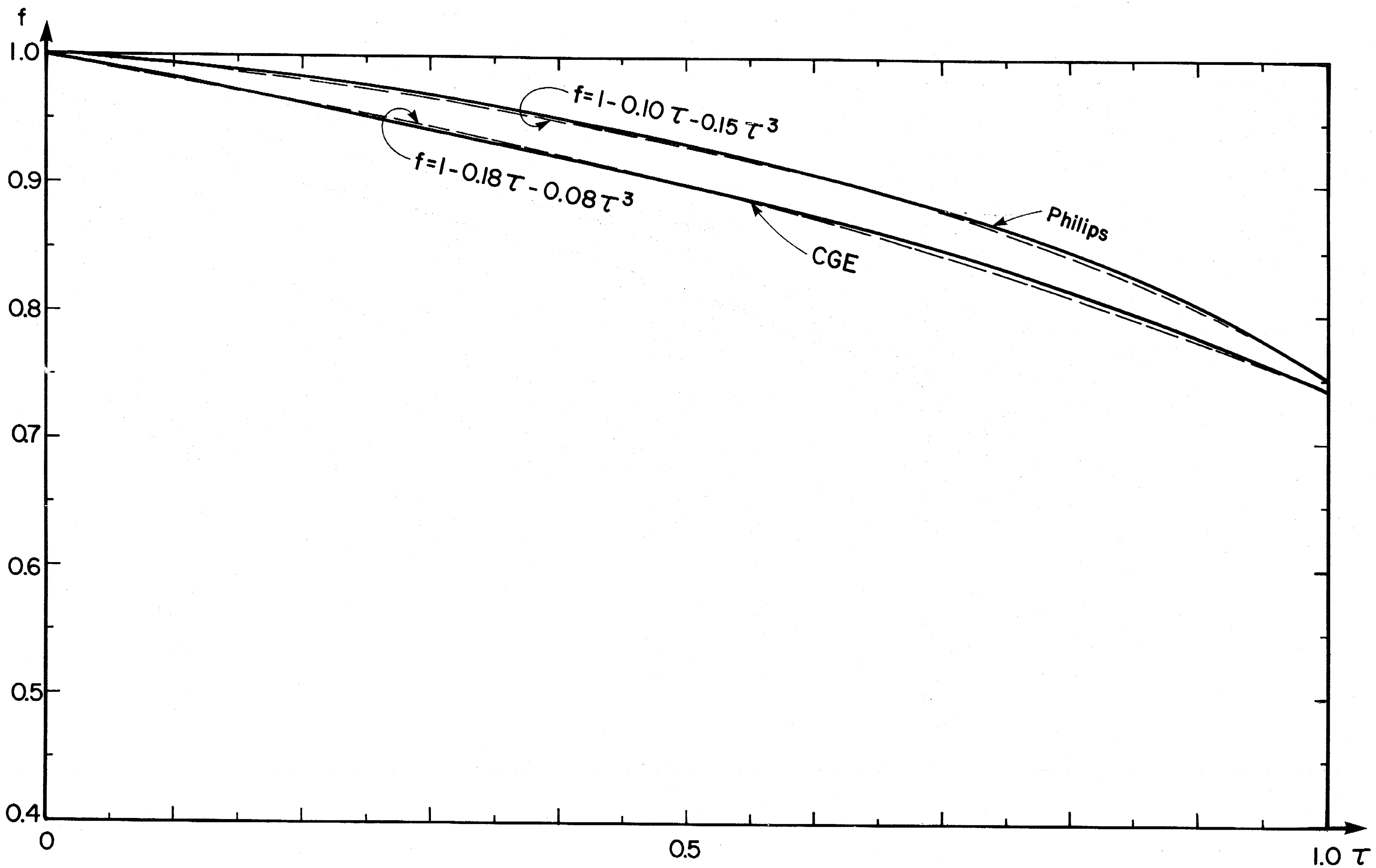


Figure 5, Normalized LLD - Functions for HPS Lamps, 70 W and 100 W

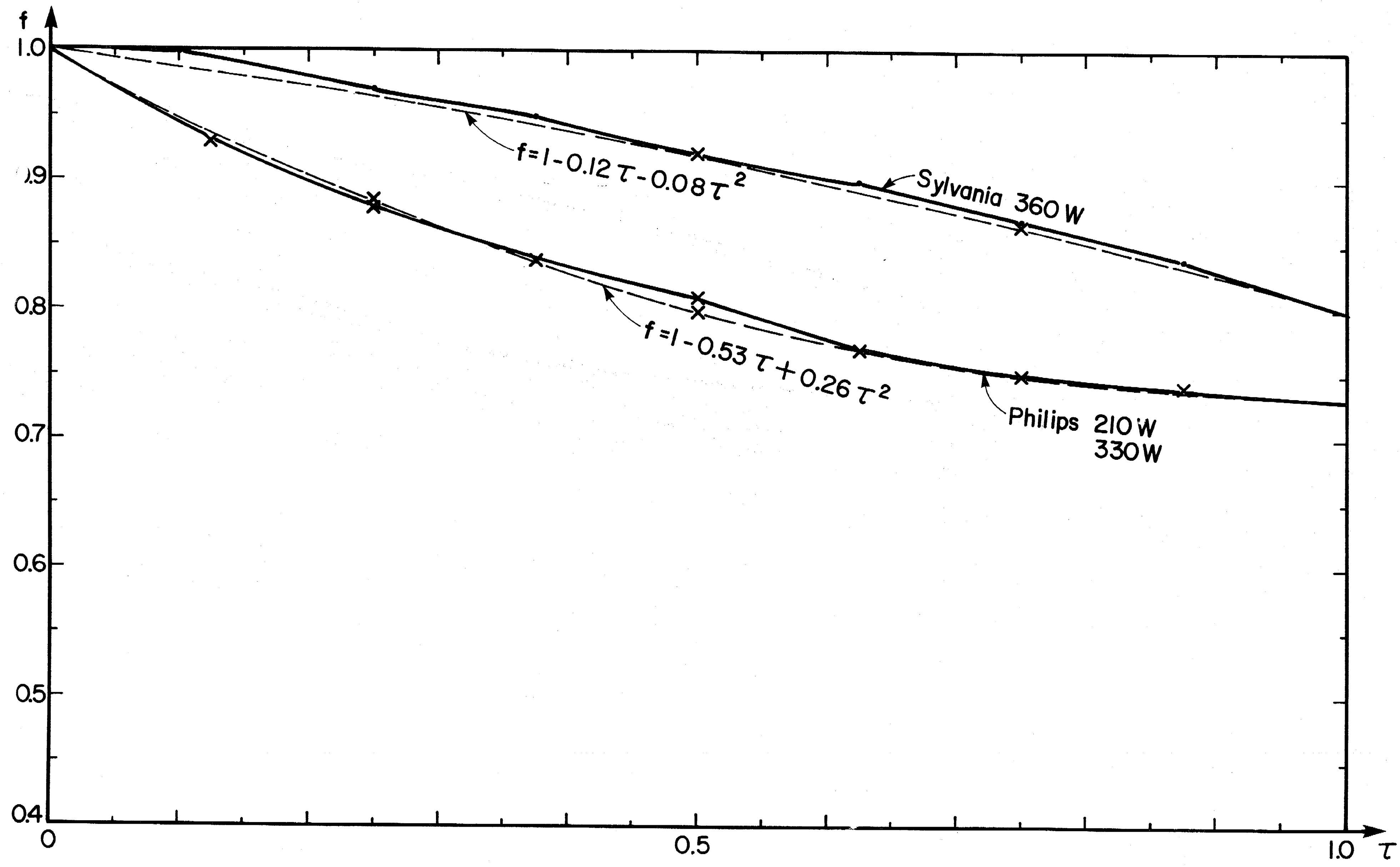


Figure 6, Normalized LLD - Functions for HPS Lamps on Mercury Ballast