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Visibility of exit signs and low-location lighting in smoky conditions

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ABSTRACT

The International Maritime Organization (IMO) requires that – in addition to the emergency lighting – all passenger ships in international traffic should have low-location lighting at all points of the escape route. IMO gives guidelines for the evaluation, testing and application of low-location lighting. To support the guidelines, the International Organization for Standardization (ISO) is preparing a standard for approval, installation and maintenance of low-location lighting systems. There are, however, no international standards for testing the *performance* of the lighting system. In all corridors for example, the low-location lighting system is required to provide visible delineation along the escape routes. For verifying the visible delineation of semicontinuous systems, national standards are not even available.

In the present project a method of defining the maximum acceptable distance between any two light sources is presented along with several measurements of the visibility of a few light sources at different viewing angles, distances and smoke densities. The method can be applied to verify the visible delineation of semicontinuous systems.

PREFACE

This report is updated from the draft final report of the NORDTEST Project No. 1174-94 (8th August 1995). The project was initiated because no standards for testing the performance of semicontinuous low-location lighting systems are available. More specifically, the requirement of lighting systems with visible delineation may exclude all semicontinuous systems simply because the visible delineation cannot be verified in a standardized way.

Some preliminary testing on the visible delineation had been conducted earlier at VTT under contract research. In the present project the issue was studied in a more systematic way. The test method presented was originally suggested by Mr. Tapani Timonen, Senior Research Scientist at VTT. He also evaluated the results of the luminance measurements in this study. The measurements were carried out by Mr. Raul Kempe. All the practical arrangements and smoke density measurements were made by Mr. Risto Latva.

Maarit Tuomisaari

CONTENTS

LIST OF SYMBOLS

A	surface area [m^2]
d	distance between light source and observer [m]
D	distance between wall with light sources and observer [m]
E	illumination [lx]
I	luminous intensity [cd]
k	extinction coefficient [m^{-1}]
L	luminance [cd/m^2]
m	optical density [dB/m]
n	number density of smoke particles [m^{-3}]
OD	optical density [m^{-1}]
T	light transmission [-]

Subscripts

0	clean air
s	smoky air

Greek symbols

α	viewing angle
ω	solid angle
σ	effective absorption cross section [m^2]
Φ	radiant flux [lm]

1 INTRODUCTION

1.1 DEFINITIONS

A low-location lighting (LLL) system is defined as an electrically powered (EP) lighting system or photoluminescent (PL) indicators placed at all points of the escape route to readily identify all routes of escape.

An EP system requires electrical power for its operation; such systems include those using incandescent lamps, light emitting diodes (LED), electro-luminescent strips or lamps, fluorescent lamps, etc.

A PL material contains a chemical that has the property of storing energy when illuminated by visible light. It gives off the stored energy by emitting visible light when the ambient light source is less effective. Without the light source to re-energise it, the PL material gives off all the stored energy for a period of time with diminishing luminance.

1.2 LOW-LOCATION LIGHTING ON BOARD PASSENGER SHIPS

The IMO Resolutions MSC.24(60) /1/ and MSC.27(61) /2/ require that all passenger ships in international traffic should have a low-location lighting system by Oct 1, 1997. These resolutions are incorporated into the regulations II-2/28, paragraph 1.10 and II-2/41-2, paragraph 4.7 of the 1974 SOLAS Convention, as amended /3/, that require the following:

"In addition to the emergency lighting... the means of escape, including stair-ways and exits, shall be marked by lighting or photoluminescent strip indicators placed not more than 0.3 m above the deck at all points of the escape route... The Administration shall ensure that such lighting or photoluminescent equipment has been evaluated, tested and applied in accordance with the guidelines developed by the Organisation."

The IMO Resolution A.752 (18) /4/ gives the guidelines referred to, for the evaluation, testing and application of low-location lighting. The guidelines require that

“The Administration should ensure that the LLL systems meet the requirements of international standards acceptable to the organisation.”

However, since no international standards are available for testing the performance of low-location lighting systems, national standards – like UL 1994 /5/ – should be applied. To support the Res.A.752 (18), ISO/TC 8/SC 1: Lifesaving and Fire Protection is preparing a standard /6/ for use in approving low-location lighting systems installed in accordance with the Assembly resolution. Laboratory test procedures are to be implemented into the standard, but in the draft standard submitted to the 41st session of the IMO Sub-Committee on Fire Protection (1996) no procedures were given yet.

Both continuous and semicontinuous systems are allowed, the semicontinuous system, however, should be tested to demonstrate a visible delineation. No international or even national standards are available to demonstrate the delineation and yet, e.g. in a Norwegian study /7/, a green semicontinuous system was found to be the best visual one. Another study /8/ shows that a travelling flashing of light sources at less than 1 m spacing is a powerful tool for safety evacuation.

In this project, a test method is suggested for defining the requirements for a semicontinuous system. In practice, a method is described to determine the maximum distance between any two light sources so that the next one is visible at the point of the first one.

The report is organised as follows. The necessary definitions and equations are given in Chapter 2. Chapter 3 includes the experimental details of the test arrangement and procedure, and in Chapter 4 the test results are evaluated and a method to define the maximum distance between the light sources is suggested. Chapter 5 includes the conclusions.

2 LIGHT SOURCE VISIBILITY IN SMOKE

2.1 SMOKE DENSITY

Many different units are used for measuring smoke density. In the literature the definitions and names are used in a somewhat random way and when comparing smoke density values of various authors one should be careful to check what definition has actually been used.

All the definitions are related to one basic concept, i.e. the extinction coefficient

$$k = \sigma n \ . \tag{1}$$

The attenuation of light in smoke may be described by Beer-Lambert's law

$$I_s = I_0 e^{-kd} \ . \tag{2}$$

Hence, the extinction coefficient can be determined by measuring the luminous intensities

$$k = \frac{1}{d} \ln \frac{I_0}{I_s} \ . \tag{3}$$

In the literature, in addition to the extinction coefficient, other definitions appear. Optical density is defined as

$$OD = \frac{1}{d} \log \frac{I_0}{I_s} \ . \tag{4}$$

In the European standard for testing the fire sensitivity of smoke detectors, EN 54-9 /9/, optical density *m* is defined as

$$m = \frac{10}{d} \log \frac{I_0}{I_s} \ . \tag{5}$$

The ratio of the luminous intensities is the light transmission

$$T = \frac{I_s}{I_0} \tag{6}$$

but it is meaningless if the distance over which the transmission is measured is not known.

All the definitions above are related to the extinction coefficient and each other by simple equations. In the present study the smoke sensitivity test room and instrumentation, which are in accordance with EN 54-9, were used. Hence, the corresponding optical density *m* is also adopted.

The following values give an idea of the magnitudes of the optical smoke density. Smoke detectors are classified according to EN 54-9 /9/ into classes A, B and C if (among other requirements) the optical smoke density *m* at the time of alarm has not reached a certain upper limit, which for the most sensitive detector (Class A) is 0.5 dB/m (k = 0.12 1/m). The corresponding limits for Class B and C detectors are 1.0 dB/m (k = 0.23 1/m) and 2.0 dB/m (k = 0.46 1/m), respectively. If the smoke density at the time of alarm has been or is over 2.0 dB/m, the detector has failed the test. In practice the smoke detectors are installed at the ceiling level where the smoke density is highest. The air close to the floor may still be almost clean and at the time of alarm, people have time to escape.

A Japanese study /10/ concludes that the maximum allowable smoke density for people unfamiliar with the escape route is m = 0.65 dB/m (k = 0.15 1/m) and that for people familiar with the route m = 2.2 dB/m (k = 0.5 1/m).

In the UL 1994 /5/ the low-location light is required to be visible to observers at of 3.66 m a distance in smoke with the transmission T = 0.5, which corresponds to m = 0.8 dB/m.

According to a Norwegian study /7/ smoke density as high as m = 15 dB/m (k = 3.5 1/m) can be regarded as a survival limit, because in denser smoke it will be difficult to keep the eyes open and the probability of survival diminishes dramatically.

2.2 LUMINANCE

A measure of the brightness of a light source is the illumination which it produces on the surface of the observer's eye, and it is defined as

$$E = \frac{\Phi}{A_{observer}} \quad . \tag{7}$$

The radiant flux is defined as

$$\Phi = \omega I \quad . \tag{8}$$

For a point source the illumination may be expressed as

$$E = \frac{I}{d^2} \quad . \tag{9}$$

The visibility of a light source is determined by its luminance, which is defined as the emitted luminous intensity per unit surface area of the light source

$$L = \frac{I}{A_{source}} \quad . \tag{10}$$

The higher the luminance value is, the brighter the light source appears in clean air. The luminous intensity and hence also the apparent luminance decrease in smoke according to Beer-Lambert's law (Eq.2).

Equation 5 may be reformulated to give the following dependence for the apparent relative luminance in smoke

$$\frac{L_s}{L_0} = 10^{-md/10} \quad . \tag{11}$$

The above dependence is shown in Figure 1.

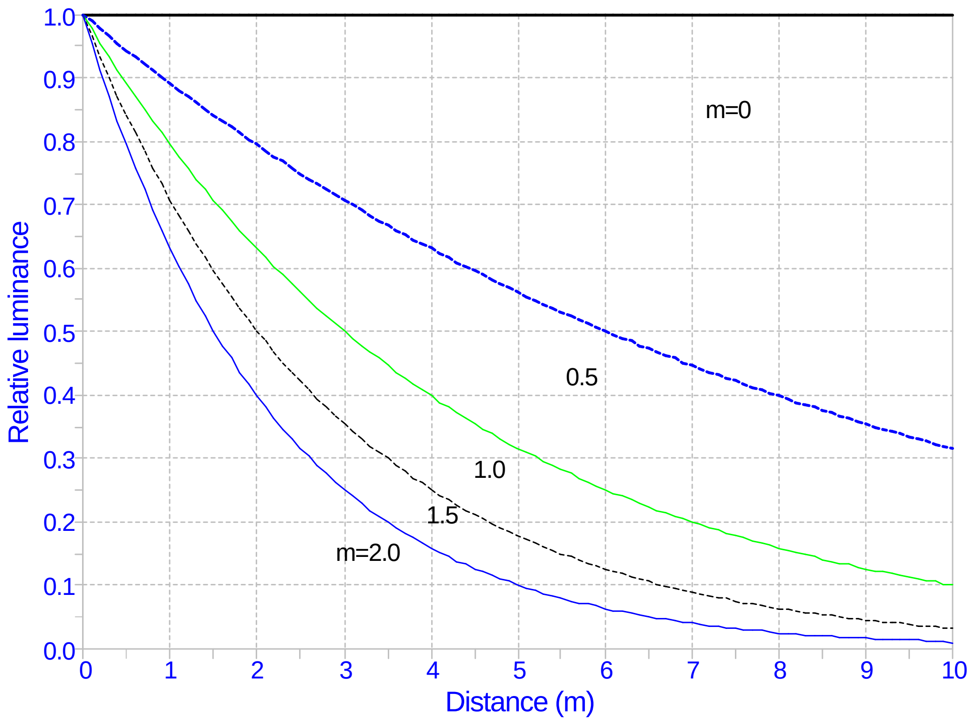


Figure 1. Apparent relative luminance in smoke (L_s/L_0) as a function of viewing distance at different optical smoke densities.

For a completely diffusing flat light source the luminance is constant when viewed at any angle, whereas the illumination decreases as a cosine of the viewing angle. In practice, the luminance also decreases with increasing observation angle, and Eq.11 may be applied at any angle:

$$\frac{L_{s,\alpha}}{L_{0,\alpha}} = 10^{-md/10} \quad . \tag{12}$$

Equations 11 and 12 are the basic equations used in the present study. The reliability of actual measurements in smoke is tested against them.

2.3 REQUIREMENTS

UL 1994 /5/ requires that an EP light source should be visible to observers at 7.62 m a distance of for at least 1.5 hours in clean air and under conditions of total darkness. The same requirement applies to PL light sources just after being energised. In smoky conditions (50 % of the light transmitted, m = 0.8 dB/m) the as received and conditioned light sources should be visible at 3.66 m. No requirements for the luminance are set in these tests, the judgement of visibility is made by observers.

According to DIN 67510 /11/, within the first 10 min without ambient lighting the luminance of a PL light source may not decrease below 11.5 mcd/m^2. The corresponding value in ISO/WI 15370:1996 /6/ is 15 mcd/m^2. Both standards require that the PL system should continue to provide luminance values greater than 2 mcd/m^2 for 60 min.

For EP systems the ISO/WI 15370:1996 requires that the active parts should have a minimum luminance of 10 cd/m^2.

3 EXPERIMENTAL

3.1 LIGHT SOURCES

Three different types of light sources were tested. Figures 2 a and b show the two EP light sources, i.e. the LED and fluorescent lamp operated signal lights, respectively. Pieces of a photoluminescent (PL) strip and plate are shown in Figure 3.

The LED light source was of type Wikrolux 940-L and the fluorescent lamp light source of type Wikrolux 940-A with a TC-E 5 W fluorescent lamp. The average luminances of the signal lights with the two light sources in clean air were measured to be about 2.4 cd/m^2 and 220 cd/m^2, respectively.

The two PL light sources were of the same type (PermaLight). The luminance of a PL material is much lower than that of any EP light source and it decreases with time. The luminance of the present materials after 10 min was 10 ... 14 mcd/m^2 and after one hour slightly above 2 mcd/m^2.

Higher luminance means better visibility at low smoke densities, but at higher smoke densities (m > 10 dB/m) the viewing distance becomes the most decisive factor /7/. At high smoke densities one has to be very close to any light sources and then PL systems become competitive with brighter light sources.

Signal lights with symbol patterns like those shown in Figures 2 a and b cause some uncertainties in the luminance measurement because the analysed area contains both white and green areas. It should also be born in mind that it is not only the luminance that affects the recognition of the symbol pattern. There are many other important factors to be considered, such as the contrasts, the colours and ambient lighting. No requirements are available for most of these factors.

3.2 TEST APPARATUS

3.2.1 Test room

The tests both in clean air and in smoke were carried out in the smoke sensitivity test room of the fire technology laboratory at VTT. The room meets the requirements of EN 54-9 /9/. The dimensions of the room are 9.5 m $\times$ 6.3 m and the ceiling height was 2.05 m for the present tests.

A schematic drawing of the test room with the instrumentation (described below) is shown in Figure 4. Figure 5 shows the arrangement before starting a test with the light sources at the farthest position measured (6 m). The black strips on the floor show the other measurement positions. Smoke was always generated by a source on the floor at the centre of the room, at the position of

a) LED operated signal light.

b) fluorescent lamp operated signal light.

Figure 2. The two EP signal lights.

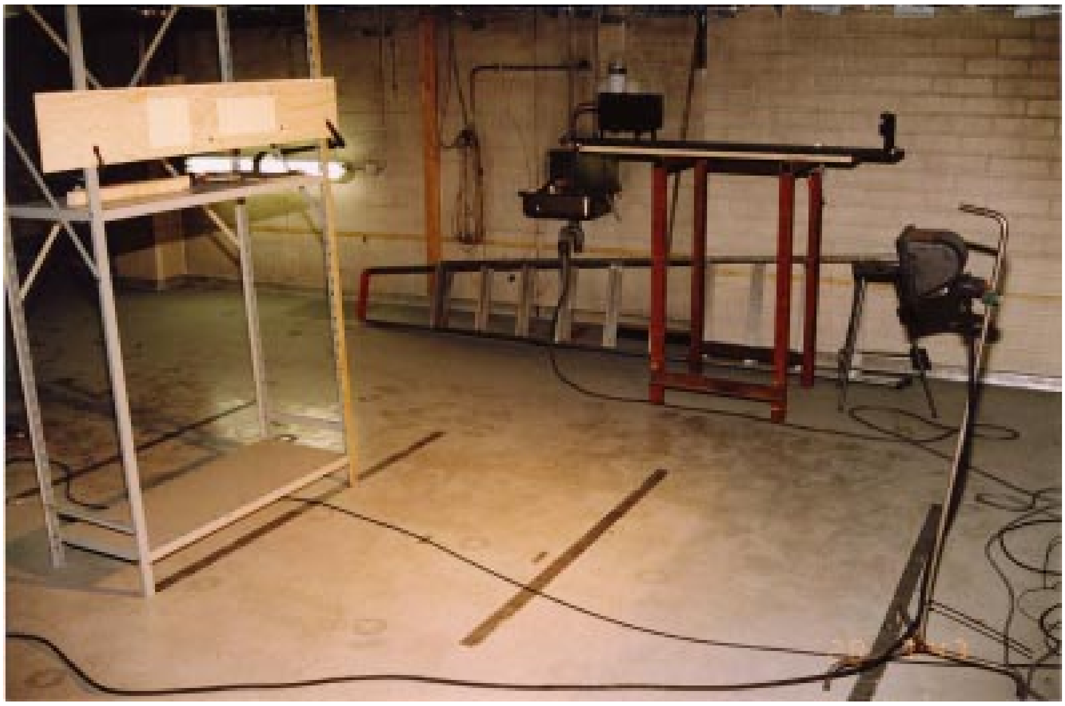


Figure 3. The PL plate and strip being attached to a plywood panel. The 500 W lamp on the right was used to energise the PL material (at 2 m, for about 20 h).

the red brick in Figure 5. Therefore, depending on the measurement distance, smoke was produced either in front of or behind the light sources.

During the tests the lighting of the test room and the ventilation were turned off. Observations were made through the window at the other end of the room.

3.2.2 Smoke density measurement

Smoke density was measured at two different positions (see Figure 4) by the obscuration method. One smoke density monitor was of type MIREX V3.2 manufactured by Cerberus AG, and the other one of type SICK RM 61-01 manufactured by Erwin Sick GmbH. Both monitors measure attenuation of light within the infrared wavelength range 800 - 950 nm over a distance of 2 m. The (black) MIREX monitor at a height of 1.25 m is seen in Figure 3 on the red stand and the (orange) SICK monitor in Figure 5 attached to the ceiling behind the signal lights.

The outputs of the smoke density monitors were connected to a printer. Both outputs are proportional to the light transmission T (Eq.6), which was converted to the optical density m (Eq.5). Since the monitors were measuring the local smoke density at different positions, their readings were a measure of the smoke homogeneity in the test room.

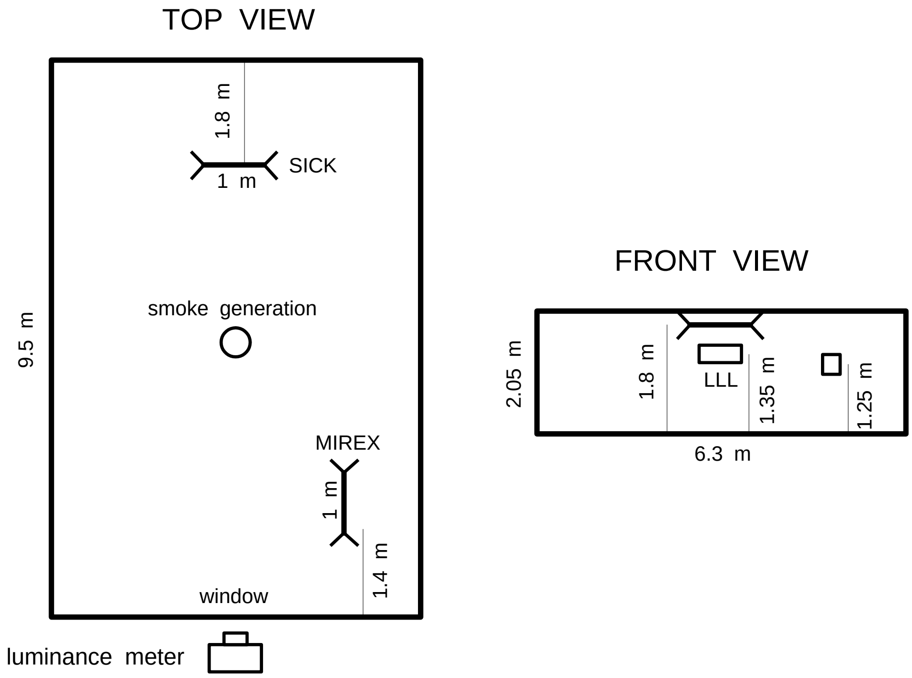


Figure 4. The test room.
The distance of the LLL from the luminance meter varied between 1 m and 6 m.

Figure 5. Test arrangement before a test.

3.2.3 Luminance measurement

The luminance was determined by measuring the luminous intensity with a Spectra Pritchard photometer (Model PR-1980A) which was positioned outside the test room next to the window. The aperture of the photometer was chosen to be large enough for the whole illuminating surface of the signal light to be inside the measuring field. The average luminance of the signal light was calculated from the readings of the photometer.

3.3 TEST SMOKES

Three different types of smoke were used. The first type was produced by Brandax VS smoke bombs (diameter 32 mm, length 65 mm, burning time 5 min) manufactured by Björnax AB, Sweden. Smoke produced by a smoke bomb is originally hot and rises upwards. However, since there are no other heat sources except for the small bomb, the smoke cools down quickly and is eventually distributed all over the volume. Therefore, in this report the smoke produced by smoke bombs is referred to as "cold smoke". Figure 6 shows the situation at an early stage of smoke generation.

Figure 6. Smoke generation with a smoke bomb.

Different smoke densities were reached by using different numbers of bombs. With 1, 2, 4, and 6 bombs the smoke density *m* stabilised to a value of approximately 1.5, 3.5, 7.5, and 9.0 dB/m, respectively. The smoke was allowed to stabilise for about 10 min before the first measurement. As will be seen later, however, the smoke density never quite reached a stable value.

The two other types of smoke were produced by smouldering wood and flaming polyurethane. The smoke generation in each case was in accordance with the EN 54-9 test fires TF2 and TF4 /9/. The hot smoke produced rises towards the ceiling level and since the burning fuel is an efficient heat source, the smoke is far from being homogeneously distributed in the test room at any stage of smoke production. In this report the smokes produced by TF2 and TF4 test fires are referred to as "hot smoke".

3.4 TEST PROCEDURES

The angular dependence of the luminance in clean air was determined for the EP signal lights with observation angles 0, ±45°, ±60°, and ±80°. The results were compared with those measured earlier /12/ for the same signal lights (with different light sources). The angular dependence of the apparent luminance in smoke was determined at a distance of 3 m .

The apparent luminance was also determined perpendicular to the symbol pattern at distances of 1, 2, 3, 4, and 6 m at different smoke densities. (Only after the tests, was the 1 m measurement distance found to be too close because the measuring field of the photometer did not cover the whole surface area.) The light sources were cleaned and the test room was well ventilated before each test.

Before starting a measurement in smoke, the smoke density was allowed to stabilise as much as possible. Typically the first measurement point was taken at 6 m, after which the light unit was moved to the next position and the smoke density was again allowed to stabilise. These steps were repeated, typically during one smoke generation for 2 - 4 distances. In total, nearly 30 measurement points were obtained.

The luminance was measured both before and after the tests in smoke to see the effect of soot.

4 TEST RESULTS

4.1 LUMINANCE IN CLEAN AIR

Luminance of the two EP light sources in clean air (perpendicular to the light source) was measured to be about 220 cd/m^2 for the fluorescent lamp and 2.40 cd/m^2 for the LEDs. The angular dependence of the luminance for both of the signal lights (with different light sources) had been already measured earlier /12/ but a few points were double-checked. The results presented in the form of relative luminance ($L_{0,rel}(\alpha) = L_{0,\alpha}/L_{0,0}$) are shown in Figure 7. The solid curve represents the (smoothed) experimental results of the earlier set of measurements and the symbols show the results of the present measurements for the LED operated signal light with an arrow pattern. Two different power sources were applied: (i) supply from mains 230 V, 50 Hz or (ii) supply from accumulator. The + and - signs indicate the opposite rotational directions of the signal light around its vertical symmetry axis.

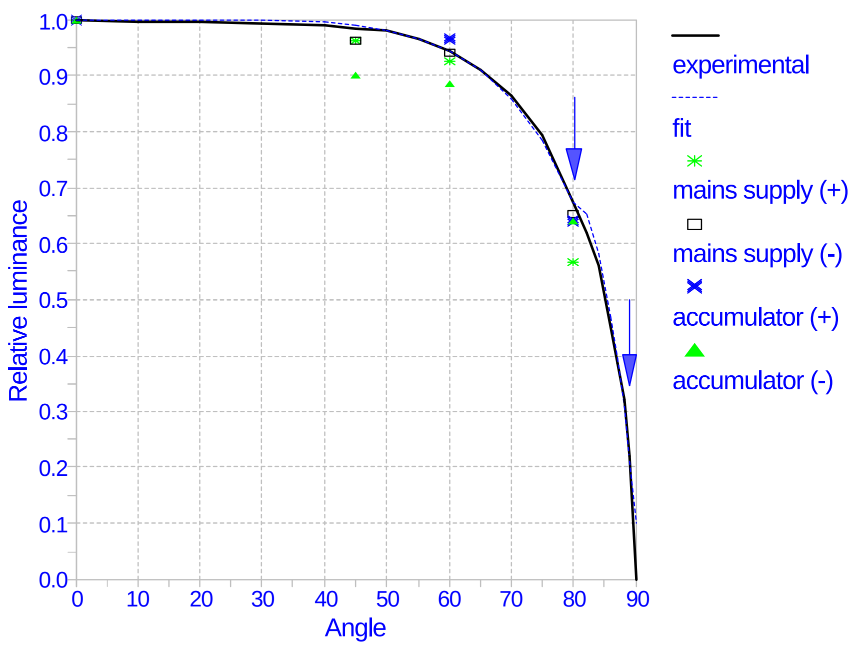


Figure 7. Relative luminance $L_{0,rel}(\alpha)$ in clean air.
For a description, see text.

The present results follow reasonably well the curve measured earlier, and therefore the curve was taken to represent the angular dependence for both of the present EP signal lights. To facilitate the use of the results of Figure 7, a simple fit to the curve was calculated and is shown in the figure as a dashed line (mostly it falls within the thick experimental line and does not show). The fit in the present case was the following

$$L_{rel}(\alpha) = 1.0 - 1.204 \cdot 10^{-12} \alpha^6 \quad . \tag{13 a}$$

between 0 ... 80^o, and

$$L_{rel}(\alpha) = 0.675 - 5.74 \cdot 10^{-3} (\alpha - 80)^2 \, . \tag{13 b}$$

between 80 ... 89^o. The arrows in the figure point to the positions 80^o and 89^o to show the ranges where Eqs.13 are valid.

It should be noted that Figure 7 and Eqs.13 are valid only for the present signal lights and should be separately measured for any other signal light.

The few results of a PL light source in clean air are presented along with the results in smoke in Chapter 4.2.3.

4.2 SMOKY CONDITIONS

4.2.1 Smoke density in the test room

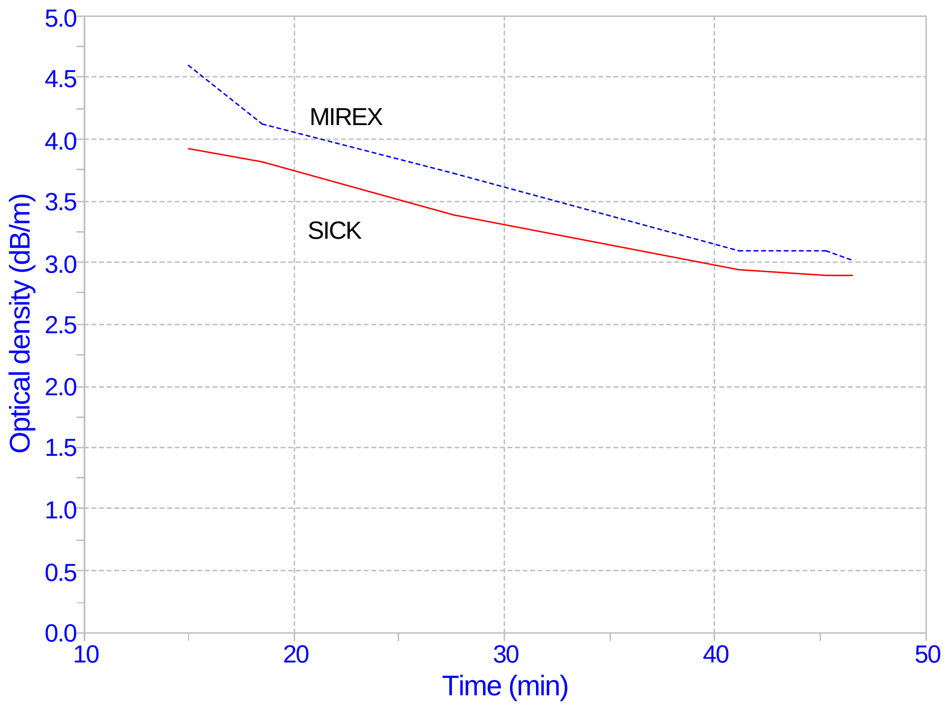
Figures 8 a and b show the measured optical density *m* for a cold smoke (two smoke bombs) and a hot smoke (TF4), respectively. Two curves for each case are shown, one measured with SICK, the other with MIREX. For the cold smoke the optical densities are reasonably close to each other, which indicates that the smoke was more or less evenly distributed over the room volume. The average smoke density *m* measured with SICK was 3.3 dB/m and with MIREX 3.6 dB/m. The smoke density is as stabilised as it could be, but it is seen to decrease with time.

The same decreasing tendency is seen in the hot smoke results. As expected, SICK at the ceiling level measures higher smoke densities than MIREX, the averages being 1.5 dB/m and 1.0 dB/m, respectively.

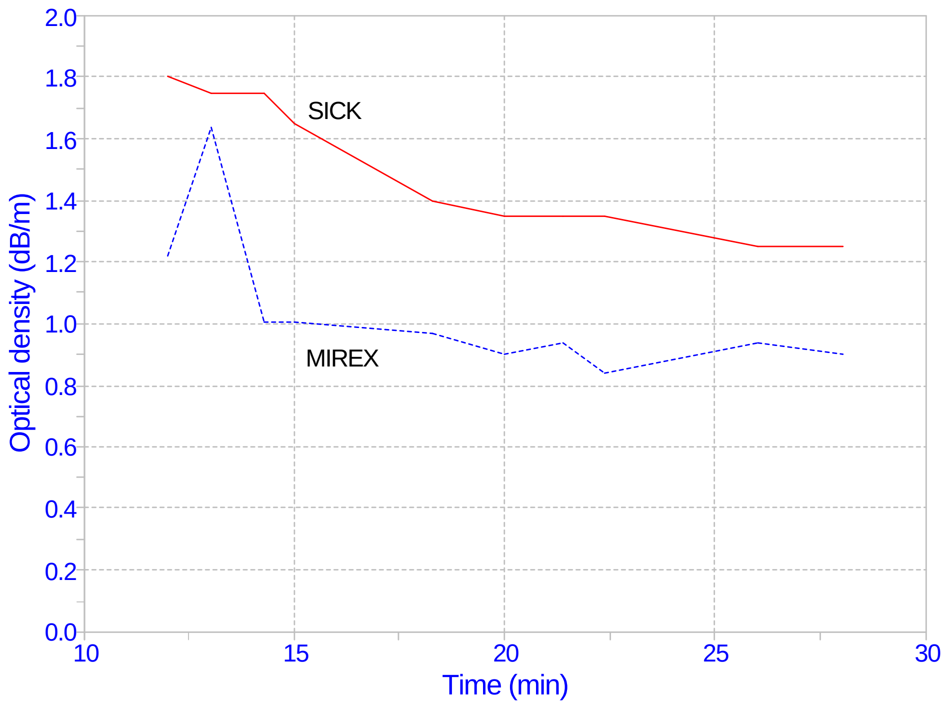
4.2.2 EP light sources in smoke

In total, six different sets of measurements were carried out to check how well actual measurements in smoke follow Eq.11. In the tests, different smokes and smoke densities were generated (*m*-dependence) and the luminous intensity was measured at different distances (*d*-dependence).

As is shown in Figures 8, the smoke density varies considerably even in the so-called stabilised situation. A 5 % error in the optical density around m = 3 dB/m causes a 4 % error in the luminance at 1 m but already a 20 % error at 6 m. During one set of measurements the optical density could vary as much as 25 % (see Figure 8 a)!



a) Cold smoke (two smoke bombs).



b) TF4 (flaming polyurethane)

Figure 8. Smoke density during a measurement period.

Figures 9 a and b show the correlation between the measured apparent luminance in cold smoke and the luminance calculated with Eq.11. The measured smoke density at the time of the luminance measurement is applied in each case. Fitting the results to a straight line by linear regression gives the following slope coefficients (ideally the coefficient is 1) and r^2 values:

Table 1. Linear regression parameters for the data in Figures 9.

	fluorescent lamp		LED	
	slope	r^2	slope	r^2
SICK	1.288	0.952	0.806	0.726
MIREX	1.026	0.911	0.657	0.677

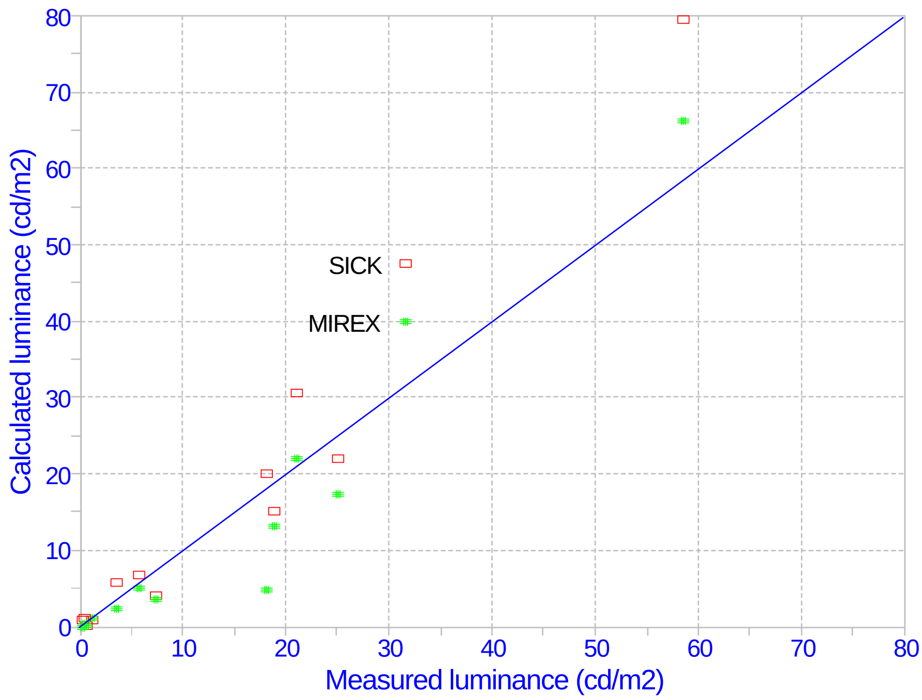
A reasonably good overall agreement between the measured and calculated luminance is found for the fluorescent lamp. The agreement is poorer for the LEDs because of the uncertainties in the luminance measurement (apparent luminance in smoke was close to the detection limit) and fewer measurement points (the light source was not resolved at longer distances). Even though the average overall behaviour of the data is reasonable, there are considerable variations in the individual data points. The scatter is most probably due to the different locations of the measurement devices and hence the uncertainty in the actual smoke density on the path of light to the photometer.

As the measured *local* smoke densities may vary considerably – much more than the *average* smoke density between the light source and the photometer – the luminance was recalculated by using a constant smoke density for each test. The constant density was taken to be the average of the measured SICK and MIREX averages (see e.g. Figure 8 a: the SICK-average is 3.6 dB/m, the MIREX-average is 3.3 dB/m – hence the average smoke density in the calculations is about 3.4 dB/m). The luminances thus calculated are shown in Figures 10 a and b. The fits to a straight line give the following slope coefficients and r^2 values:

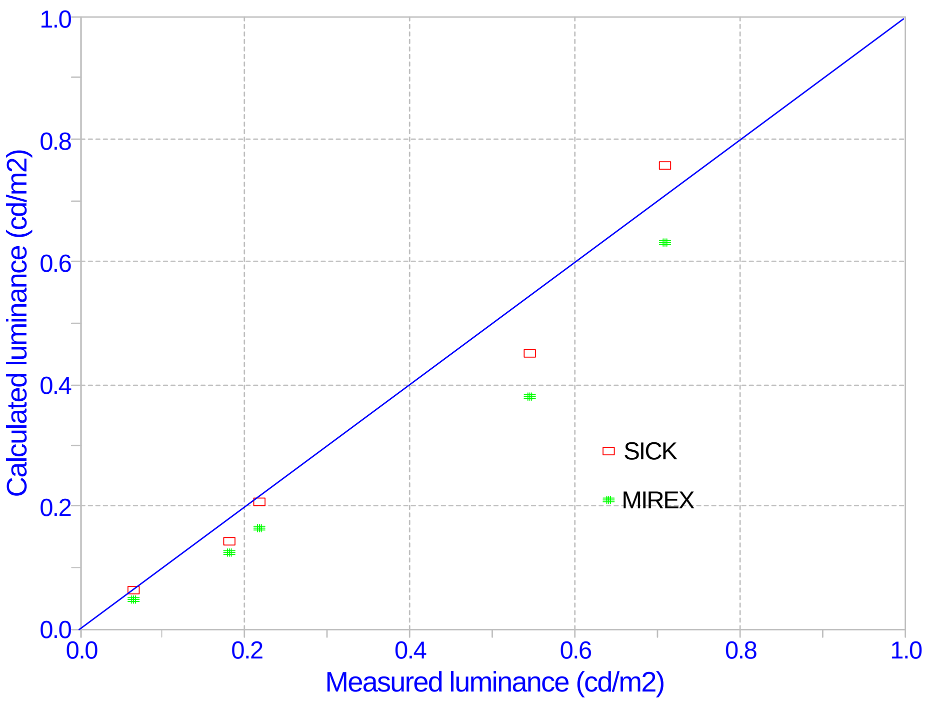
Table 2. Linear regression parameters for the data in Figures 10.

fluorescent lamp		LED	
slope	r^2	slope	r^2
1.022	0.919	0.881	0.718

The constant smoke density did not improve the agreement.

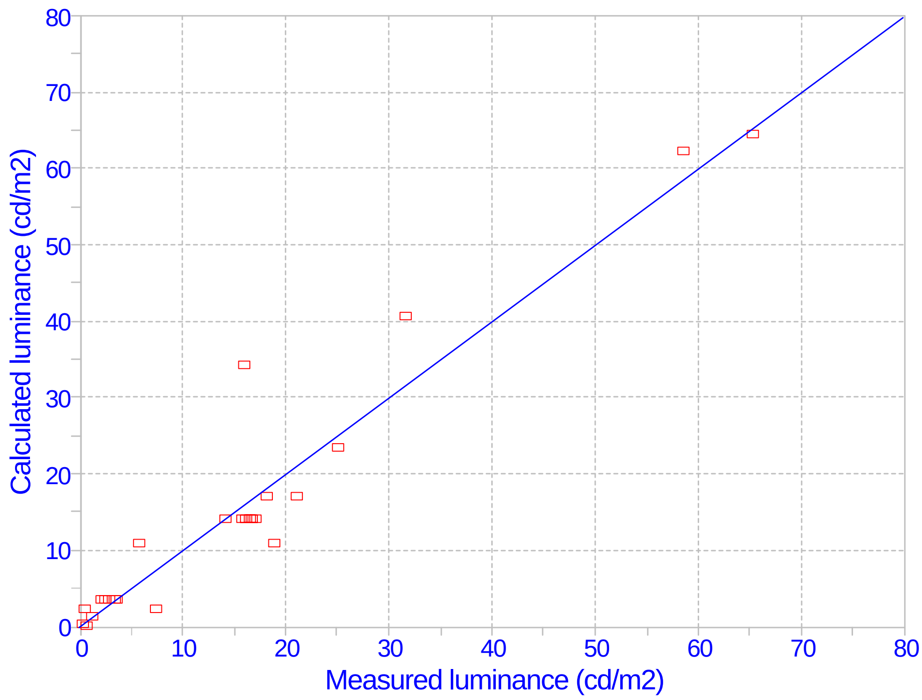


a) Fluorescent lamp

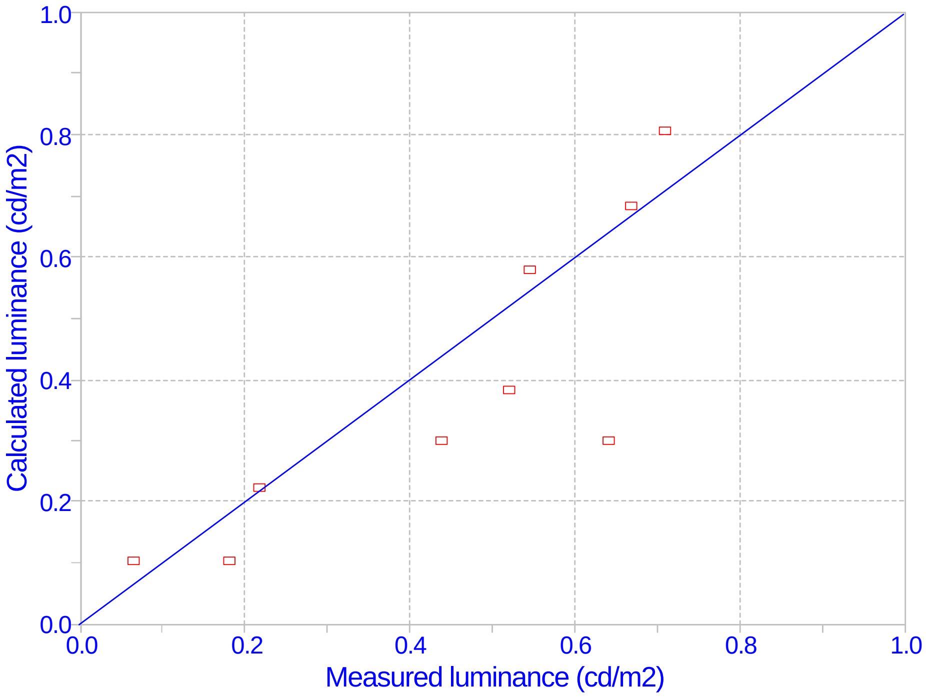


b) LED

Figure 9. Correlation between the calculated luminance (from the smoke density data at each point, Eq.11) and the measured apparent luminance.



a) Fluorescent lamp



b) LED

Figure 10. Correlation between the calculated luminance (from the average smoke density data, Eq.11) and the measured apparent luminance.

It may be concluded that the results of the luminance measurements for the fluorescent lamp fit reasonably well to Eq.11. The agreement between the LED results and Eq.11 is considerably poorer, most probably because of the low luminance level and only nine measurement points.

Accurate measurements in smoke are difficult since the smoke itself is not stable in time or in space. The smoke also scatters light which causes errors in the measured apparent luminance. This was seen especially when measuring the angular dependence of the apparent luminance in smoke. Due to the light scattering, the apparent surface area viewed by the photometer does not change as a function of cos(α) as in clean air.

Figure 11 clarifies the practical difficulty: the measured angular dependence of the relative apparent luminance ($L_{s,rel}(\alpha) = L_{s,\alpha}/L_{s,0}$) measured at 3 m is presented. The solid curve with crosses (x) shows the calculated results based on Eqs.12 and Eq.13 a. The measured results for both signal lights are shown for first rotating the light in one direction and then back to the original position. Rotating the light source from the perpendicular position seems to increase the apparent luminance (+) and when the light source is rotated back (-) large hysteresis is seen, and at the original position the measured luminance has increased considerably.

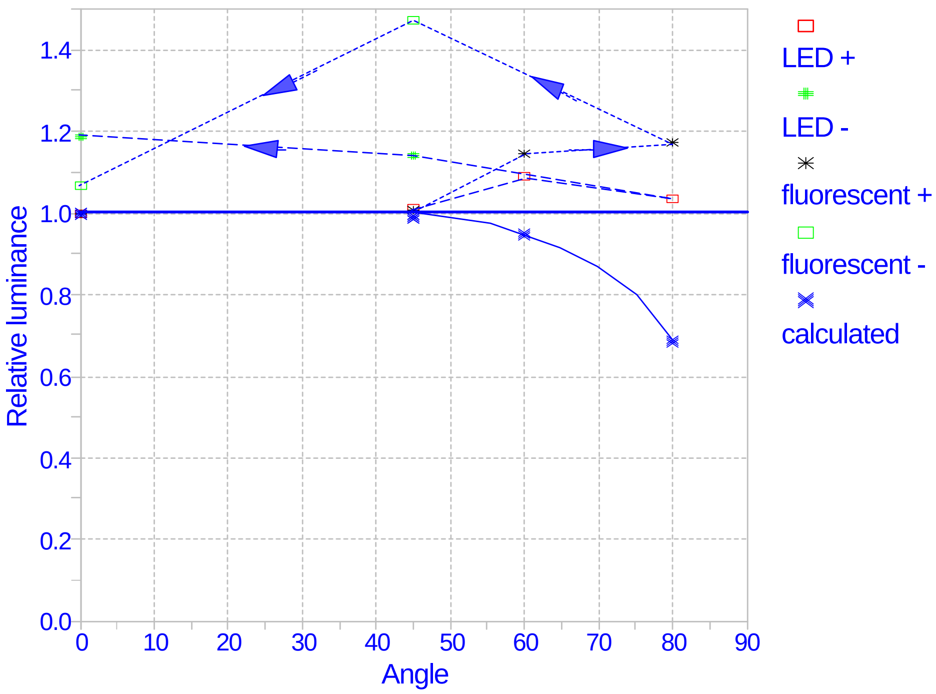


Figure 11. Measured angular dependence of the apparent relative luminance $L_{s,rel}(\alpha)$ in smoke. The results are presented only to quantify the practical difficulties in the measurements, the results do not have any physical significance. For details, see text.

This trend is to be expected since the smoke density decreases and the apparent luminance increases with time: the original point at 0^o is measured at a higher smoke density than the last point at 0^o after the whole rotation circle. Table 3 gives the smoke densities measured at the first and last measurement point within the test runs.

Table 3. The optical smoke density m at the beginning and end of the test runs. (Cold smoke, one smoke bomb)

	fluorescent lamp		LED	
	before rotation	after rotation	before rotation	after rotation
SICK	1.5	1.4	1.7	1.5
MIREX	2.6	1.5	2.2	1.6

Due to practical problems caused by the smoke itself, it seems to be extremely difficult to measure the "real" angular dependence of the apparent luminance in smoke.

The soot in the present smokes had a minor effect, if any. The original luminances in clean air measured through the window were 2.16 and 227 cd/m^2 for the LEDs and fluorescent lamp, respectively. The corresponding values after a smoke bomb test (6 bombs) were 2.06 and 229 cd/m^2 and, after cleaning the surface of the signal light, 2.14 and 229 cd/m^2.

4.2.3 Photoluminescent material in smoke

Only one systematic set of measurements was made for the PL material (plate 8.9 cm $\times$ 9 cm) in smoke (generated by one smoke bomb). Figure 12 shows the apparent luminance as a function of time measured at a distance of 3 m. The figure also shows the luminance measured in clean air for both the PL plate and the strip, and the corresponding calculated values in smoke (Eq.11). In the calculations an average optical density of 1.9 dB/m was applied. The actual *m* measured by SICK varied from 2.2 dB/m at 10 min to 1.2 dB/m at 45 min. The values measured by MIREX were more or less stable around 1.6 dB/m, but there was a peak of 2.2 dB/m between 15 and 20 min. The agreement between the measured and calculated luminance in Figure 12 is surprisingly good probably because of there were no symbol patterns, which (among other things) scattered the results measured for the EP signal lights.

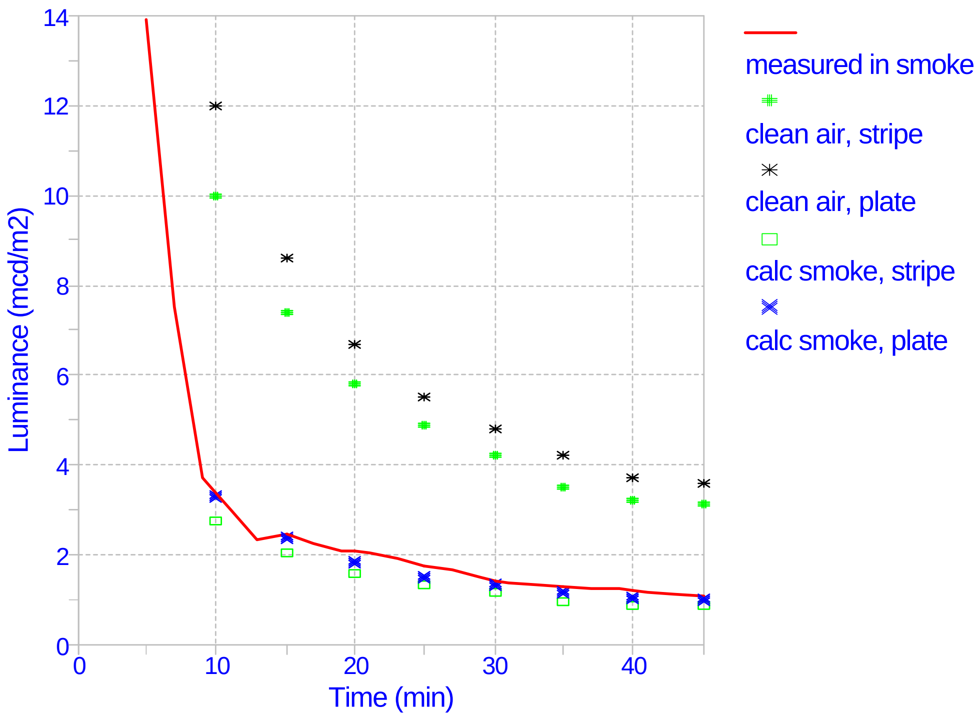


Figure 12. PL luminance in clean air and smoke.

4.3 MAXIMUM DISTANCE BETWEEN LIGHT SOURCES

The measured apparent luminance in smoke of a flat light source with a symbol pattern is in reasonably good accordance with the luminance calculated from the smoke density data, when the measurement is made perpendicular to the surface of the signal light. The discrepancies in the results are caused by the instability of the smoke both in space and time. The angular dependence in smoke, however, is almost impossible to measure because of light scattering in smoke.

For determining the maximum distance between light sources, the angular dependence is crucial, and more accurate and reproducible methods should be applied. A method that requires luminance measurements only in clean air is presented below.

The method is based on the geometry shown in Figure 13. Two adjacent light sources of a semicontinuous low-location lighting system (LLL) are shown. Assuming that a person is passing the light sources at a distance *D* from the wall and can see the light source LLL 2 at the point of LLL 1, the maximum distance between the light sources may be written as $D \tan \alpha$.

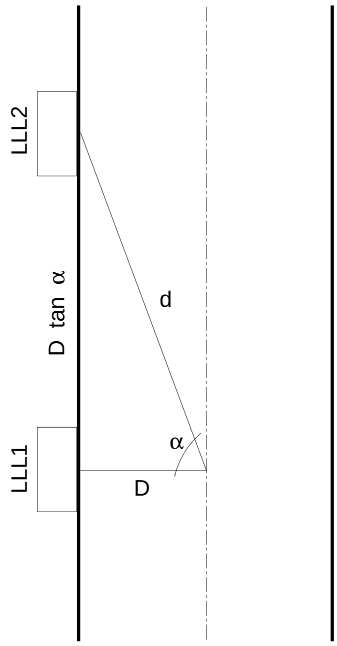


Figure 13. Geometry to define the maximum distance between two light sources.

To be able to quantitatively calculate the distance, the following parameters are needed:

- "Design smoke density", i.e. which smoke density is taken as the reference smoke density at which the light sources are to be resolved.
- "Design viewing distance", i.e. at what distance *D* from the wall the low-location lighting system is supposed to be viewed.
- The luminance of a single light source at different angles in clean air.
- Minimum acceptable luminance for smoky conditions, i.e. is the minimum apparent luminance that can be resolved by eye in smoke.

The third parameter, the angular dependence can be measured, while the other parameters are a matter of definition. With all the information needed, Eq.12 can be applied to calculate the maximum acceptable distance.

No requirements for the values above are set in any standard. As a demonstration, however, the minimum acceptable luminance is taken to be 0.2 cd/m^2 /12/ which represents a conservative approach. In the present tests, for example, the signal light was still seen by eye when the apparent luminance was 0.07 cd/m^2. Distance from the wall is taken to be $D = 1$ m. If the corridor width is over 2 m, low-location lighting is required on both sides.

With the assumptions above, Figure 14 shows the maximum distance *D tanα* as a function of the smoke density *m* for light sources of different luminances in clean air. The higher the luminance is, the longer may the distance be. When the clean air luminance is as low as 1 cd/m^2, the luminance at 1 m and $m > 7$ dB/m is already less than the required 0.2 cd/m^2.

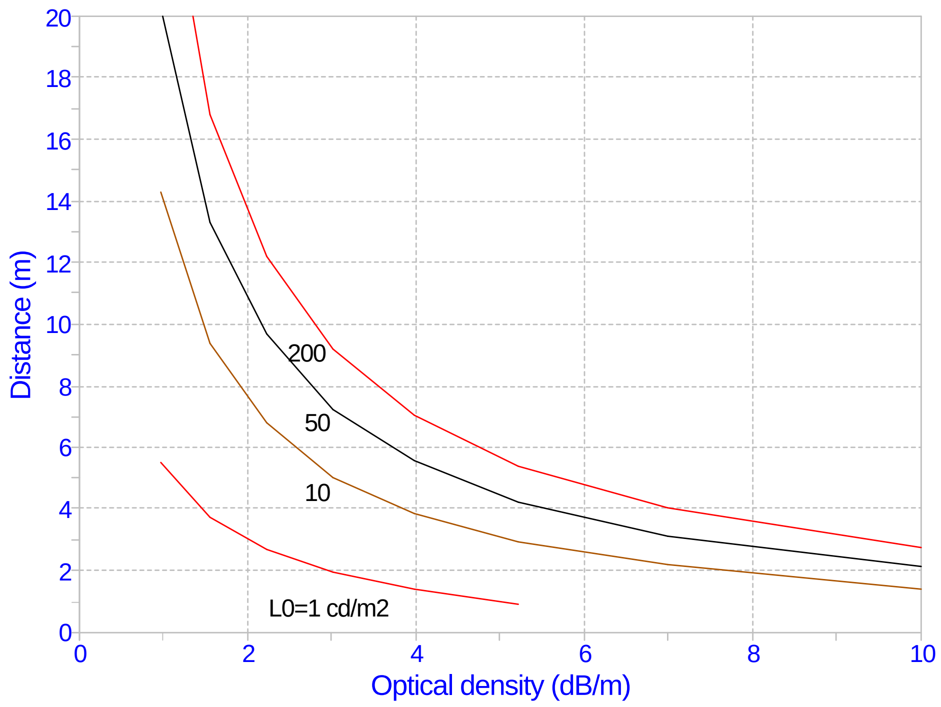


Figure 14. Maximum distance between signal lights of different luminance. (Minimum acceptable luminance 0.2 cd/m^2, viewing distance 1 m)

5 CONCLUSIONS

The objective of this project was to define requirements for the visibility of low-location lighting in smoky conditions. More specifically: a method to define the maximum acceptable distance between any two light sources to provide visible delineation was determined.

Several measurements for three different types of light sources, i.e. a fluorescent lamp, LED and photoluminescent material were conducted. The experiments revealed serious practical problems associated with measurements in smoke:

- Well defined, stable and reproducible smoke conditions are extremely difficult to achieve: the smoke density varies both in space and time, i.e. the smoke density distribution in an enclosure is inhomogeneous and it changes with time.
- Smoke particles scatter light, which affects especially the angular dependence measurements of the apparent luminance. This effect varies with the type of smoke, whereas the effect of the light source itself is insignificant.

In spite of the practical difficulties, the apparent luminance measured *perpendicular* to the flat light source agreed reasonably well with the luminance calculated using the measured smoke density data. For light sources covered with symbol patterns, the brighter the light source was the better the correlation. Also, for low luminance PL material (no symbol patterns) a good correlation was found.

The *angular dependence* of the apparent luminance in smoke could not be measured reliably, and yet the angular dependence is one of the desicive properties that define the maximum installation distance between the light sources. It was concluded that a reproducible test method cannot involve measurements in smoke – except for demonstration purposes.

Hence a test method was presented that requires only an angular dependence measurement for the luminance in *clean* air. The principle is simple, and it reveals the maximum acceptable distance between any two light sources. To apply the test method for determining quantitatively the distance, a few design parameters need to be defined, i.e.:

- minimum acceptable luminance for smoky conditions,
- “design viewing distance”,
- “design smoke density”.

Defining conservative and yet realistic design parameters would require a set of measurements in smoke with test persons making observations.

The luminance of PL materials is low, probably lower than the minimum acceptable luminance above. Low-location lighting systems that use PL materials are continuous systems and, in any case, to see the strips in smoke, people need to be very close to them. In reference 7 it was found that at very high smoke densities (m > 20 dB/m), PL strips are superior to semicontinuous distinct lights. Therefore, an ideal low-location lighting system might consist of both a semicontinuous EP system (effective at the earlier stages of the fire) and a PL system as a supplementary system (effective at the very early stage of the fire and later in dense smoke).

REFERENCES

1. MSC 60/21 Annex 3, Resolution MSC.24(60), International Maritime Organization, London, 1992, 7 p.

2. MSC 61/21/Add.1 Annex 2, Resolution MSC.27(61), International Maritime Organisation, London, 1992, 20 p.

3. *SOLAS, The International Convention for Safety of Life at Sea*, International Maritime Organisation, London, England, Consolidated Edition 1992, 543 p.

4. IMO Resolution A.752 (18) *Guidelines for the evaluation, testing and application of low location lighting on passenger ships*, International Maritime Organisation, London, 1993, 5 p.

5. UL 1994, *Standard for low level path marking and lighting systems*, 1st edition, Underwriters Laboratories Inc., 1991, 53 p.

6. ISO/WI 15370:1996 *Ships and marine technology – Low-location lighting on passenger ships – Arrangement*, International Organisation for Standardisation, 1996, 9 p. Work item, under development.

7. Jensen G., *Evacuating in smoke*, IGP A/S, Trondheim 1993, 41 p.

8. Jin T., Yamada T., *Experimental Study on Effect of Escape Guidance by Travelling Flashing of Light Sources*, Fire Safety Science, Proceeding of the 4th International Symposium, Ottawa, Canada, 13-17 June, 1994, pp.705-714, International Association for Fire Safety Science, 1994.

9. EN 54-9, *Components of automatic fire detection systems. Part 9: Fire sensitivity test*, European Committee for Standardisation, 1982, 10 p.

10. Jin T., *Studies of Emotional Instability in Smoke from Fires*, Journal of Fire & Flammability, Vol.12, pp.130-142, 1981.

11. DIN 67510: Part 3, *Photoluminescent pigments and products; escape route system*. Deutsches Institut für Normung, 1994.

12. VTT Research Report No. SÄH1012/93, confidential.