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INTERNATIONAL STANDARD

colour inside

Organic light emitting diode (OLED) displays –
Part 5-3: Measuring methods of image sticking and lifetime

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INTERNATIONAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ORGANIC LIGHT EMITTING DIODE (OLED) DISPLAYS –

Part 5-3: Measuring methods of image sticking and lifetime

FOREWORD

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International Standard IEC 62341-5-3 has been prepared by IEC technical committee 110: Electronic displays.

This second edition replaces the first edition published in 2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) the measurement vehicle for lifetime is only for the module;
b) the measurement method for monitor or TV devices is modified;
c) the digital signage display is included as an example of OLED devices;
d) the measurement method with HDR (high dynamic range) for image sticking is added;
e) the analysis method with CIEDE 2000 is added for image sticking;
f) the information method for evaluating image sticking is modified.

The text of this standard is based on the following documents:

FDIS	Report on voting
110/1134/FDIS	110/1154/RVD

Full information on the voting for the approval on this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 62341 series, under the general title *Organic light emitting diode (OLED) displays*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

ORGANIC LIGHT EMITTING DIODE (OLED) DISPLAYS –

Part 5-3: Measuring methods of image sticking and lifetime

1 Scope

This part of IEC 62341 specifies the standard measuring methods for determining the image sticking and lifetime of organic light emitting diode (OLED) display panels and modules, except finalized display products for end customers, such as TV sets, monitor sets and mobile phones. The measuring method for the lifetime mainly applies to modules.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-845, *International Electrotechnical Vocabulary (IEV) – Part 845: Lighting* (available at <http://www.electropedia.org>)

IEC 62341-1-2, *Organic light emitting diode (OLED) displays – Part 1-2: Terminology and letter symbols*

IEC 62341-6-1:2017, *Organic light emitting diode (OLED) displays – Part 6-1: Measuring methods of optical and electro-optical parameters*

ISO 11664-1, *Colorimetry – Part 1: CIE standard colorimetric observers*

CIE 15, *Colorimetry*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62341-1-2 and IEC 60050-845 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
equivalent current density
average current density of a certain pixel calculated from a varying luminance per frame image in a moving picture so that luminance degradation becomes similar at the same time

Note 1 to entry: See Annex A.

3.1.2
equivalent signal level
digital code value from 0 to 255 (in the case of 8 bits) transformed from the normalized luminance of a certain pixel by a specified opto-electronic transfer function (OETF)

Note 1 to entry: See Annex A.

3.2 Abbreviated terms

For the purposes of this document, the following abbreviated terms apply.

APL	average picture level
CIELAB	CIE 1976(L*a*b*) colour space
DUT	devices under test
EOTF	electro-optical transfer function
FWHM	full-width-at-half-maximum
HDR	high dynamic range
LMD	light measuring device
OETF	opto-electronic transfer function
OLED	organic light emitting diode
PQ	perceptual quantizer
SDR	standard dynamic range

4 Measuring configuration

4.1 General

The system diagrams and/or operating conditions of the measuring equipment shall comply with the structure specified in each item. The measuring system and its arrangement are shown in Figure 1. The details are given in Clause 5.

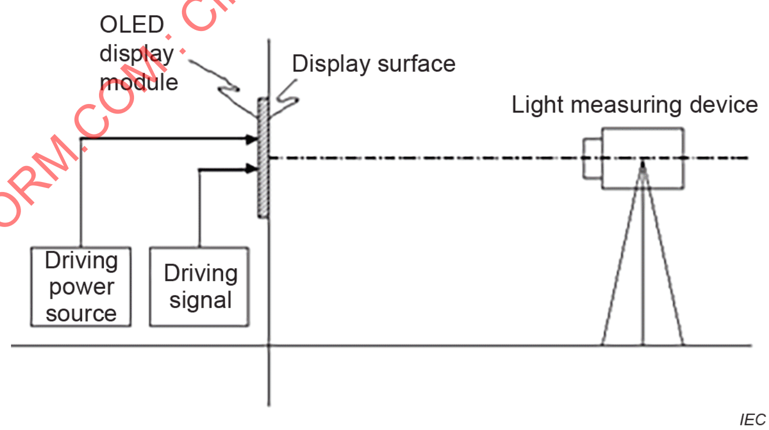


Figure 1 – Measuring system and arrangement

4.2 Light measuring device

The optical properties of displays shall generally be expressed in photometric or colorimetric units using the CIE 1931 standard colorimetric two-degree observer (see ISO 11664-1). Luminance can be measured by a photometer, and the CIE tristimulus values (X, Y, Z) or CIE chromaticity coordinates by a colorimeter. A spectroradiometer can also obtain photometric and colorimetric values through a numerical conversion of the measured spectral radiance data (see, for example, [1][1]). The following requirements are given for these instruments:

The LMD shall be a luminance meter, colorimeter, or a spectroradiometer. For DUTs that have sharp spectral peak full-width-at-half-maximums (FWHMs) smaller than 20 nm, a spectroradiometer should be used. A filter colorimeter should generally not be used for light sources with sharp spectral peaks. If they are used, the colorimeter shall be calibrated with a narrow bandwidth spectroradiometer to give the same results for the specific spectrum. Report the characteristics of the spectroradiometer which is used for calibration. For light sources with sharp spectral peaks, the maximum bandwidth of the spectroradiometer shall be ≤ 5 nm. The higher resolution spectroradiometer produces a more accurate colour measurement. In those cases, the wavelength accuracy shall be within ±0,5 nm. The spectroradiometer shall be capable of measuring spectral radiance over at least the 380 nm to 780 nm wavelength range, with a maximum bandwidth of 10 nm for smooth broadband spectra (i.e. broad spectrum with no sharp spikes).

Care shall be taken to ensure that the LMD has enough sensitivity and dynamic range to perform the required task. Before measuring the DUT, the LMD specification shall be checked.

5 Standard measuring conditions

5.1 Standard measuring environmental conditions

The standard measuring environmental conditions specified in IEC 62341-6-1:2017, 5.1, shall be applied. For image sticking measurements, the environmental temperature shall be controlled at 25 °C ± 3 °C, otherwise a temperature-controlled detector shall be used. (The stability of the LMD shall be less than 1/5 of the intended detecting difference levels of luminance and colour.)

5.2 Standard measuring darkroom conditions

The standard measuring darkroom conditions specified in IEC 62341-6-1:2017, 5.2, shall be applied.

5.3 Standard setup conditions

5.3.1 General

Standard setup conditions are given below. Any deviations from these conditions shall be recorded.

5.3.2 Adjustment of OLED display

The adjustment of the OLED display specified in IEC 62341-6-1:2017, 5.3.2, shall be applied.

1 Numbers in square brackets refer to the Bibliography.

5.3.3 Starting conditions of measurements

Warm-up time is defined as the time elapsed from the moment of switching on the supply voltage until repeated measurements of the display show a variation in luminance of less than 2 %/min. Repeated measurements shall be taken for a period of at least 15 min after starting. The luminance variations shall also not exceed 5 % during the total measurement.

5.3.4 Test patterns

5.3.4.1 SDR displays

The test patterns for SDR display devices such as mobile phones, tablet PCs, monitors, TVs and digital signage are shown in Figure 2. The test pattern for SDR displays is divided into two groups.

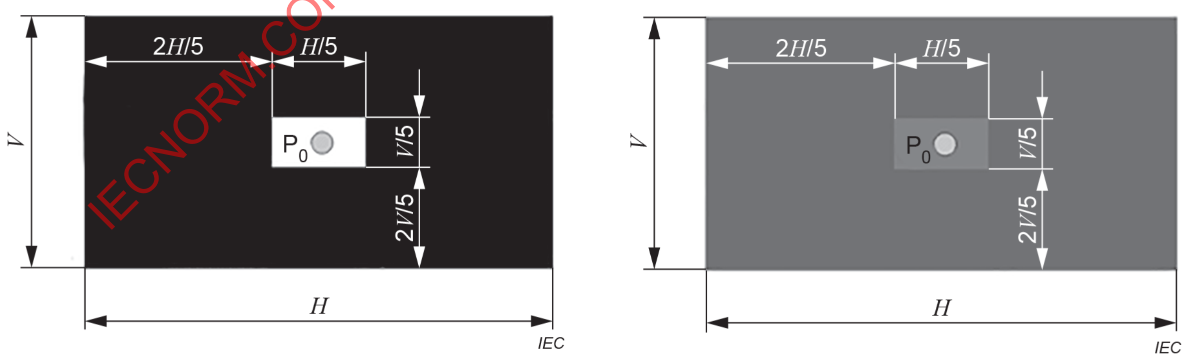
1) Test pattern for mobiles and tablet PC displays

In the case of mobiles and tablet PCs, the measurement distance between the display and the LMD depends on the size of the OLED display panels or modules. The measuring distance and the aperture angle may be adjusted to achieve a measuring field greater than 500 pixels if the setting of the measurement field angle is not applied. For display devices except monitors, TVs and digital signage, the test pattern with a white level at the 4 % window box located in the centre and a black level in the background, is used in Figure 2a).

2) Test pattern for monitors, TVs and digital signage displays

For monitors, TVs and digital signage, the test pattern is extracted by video analysis to reflect the characteristics of the video sample. For the test pattern, the maximum code value is allocated at the 4 % window box in the centre and the average code value is in the background. The examples of the maximum and average gray code values are shown in Table 1. The example of the test pattern is shown in Figure 2b). The maximum and average code values between 0 and 255 (in the case of 8 bits) could be extracted from the accumulating image for all frames of the video sample, which is converted as equivalent grayscale from each colour channel.

NOTE 1 Image sticking is influenced by the characteristics of the OLED displays [5], [7]. Some manufacturers of OLED displays apply various algorithms to optimize the quality of each device, and this also influences the image sticking. To consider the characteristics of an OLED display, the method in Annex A is used for the test pattern reflecting the characteristics of the OLED display.



a) **Test pattern for mobiles and tablet PC displays**

b) **Test pattern for monitors, TVs and digital signage displays**

Figure 2 – Test pattern for SDR displays

Table 1 – Examples of maximum and average code value extracted from video samples

Examples of test video	Maximum code value	Average code value
IEC 62087:2011	107	84
Broadcast video sample	183	102

NOTE 2 For the test pattern, any video samples could be selected as needed. Table 1 shows two kinds of representative examples. The broadcast video sample example is constructed by considering the viewing ratio of the content of TV programmes based on the Korea broadcast media use environmental survey report: entertainment (30,9%), news (20,2 %), drama (16,8 %), and so on [4]. The average gray level and test pattern size are different between SDR and HDR in TVs. Depending on the purpose of the test, Figure 2b) or Figure 4a) would apply.

3) Measuring area

In order to get repeatability of measurement, the measuring area from P_0 to P_4 for displays is set to consider the uniformity of the OLED display panels or modules, as shown in Figure 3. If the centre window size is changed, then it should be reported in Table 2.

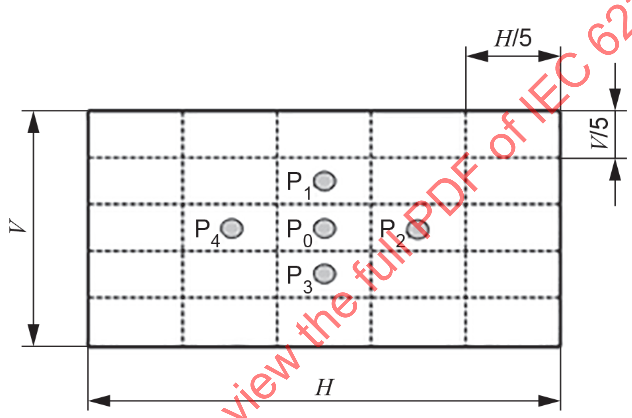


Figure 3 – Image sticking measuring area

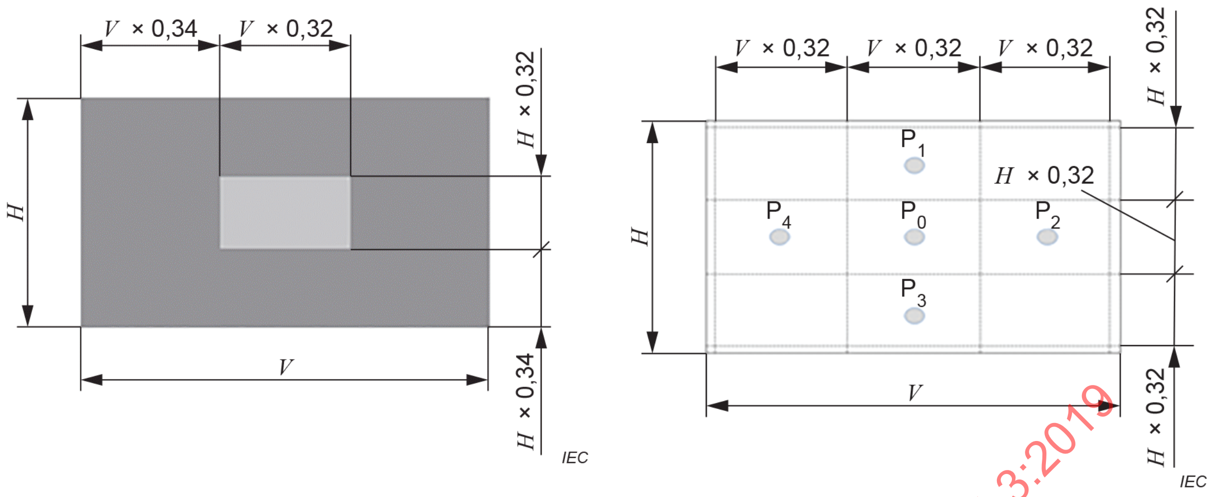
4) Checking the test pattern

For SDR displays, the output luminance can be different although they have the same digital code value inputs. To check the brief information of the selected test pattern, the output luminance for the test pattern should be measured and reported.

Apply the test pattern on OLED displays and measure the output luminance on the measuring area from P_0 to P_4 as shown in Figure 3. The results of the output luminance of the test pattern should be reported in Table 2.

5.3.4.2 HDR displays

In 5.3.4.1, the test pattern for SDR displays is described. The test pattern for HDR displays is shown in Figure 4a). It is based on the PQ curve and 10 bits. The test pattern for HDR displays is proposed separately because the characteristics of the contents of the SDR and HDR are different. The test pattern for SDR or HDR can be used as needed. The background code value should be 510. The size of the box window should be 10 %, which is located in the centre. The code value of the 10 % box window should be 710. The measured luminance of the box window and the background luminance should be reported. To get repeatability of the measurement data, the measuring area from P_0 to P_4 is the centre of the boxes, as shown in Figure 4b). The measurement data should be reported in Table 2.



a) **HDR test pattern** b) **Measurement area**

Figure 4 – Test pattern for HDR displays

NOTE The code value of the 10 % box window and background is the result of the analysed data of HDR contents which are HDR games, drama and documentary.

5.3.5 Conditions of measuring equipment

The general conditions in IEC 62341-6-1:2017, Clause 5, shall be applied.

6 Measuring methods of image sticking

6.1 Purpose

The purpose of this method is to measure the image sticking of an OLED display.

6.2 Measuring method

6.2.1 Measuring equipment

The following equipment defined in IEC 62341-6-1:2017, 5.3.4, shall be used:

a) power supplies and signal sources for driving,

b) LMD.

6.2.2 Measuring procedure

The OLED display shall be set in darkroom conditions for measurement.

a) Initial measurements on full screen pattern

Apply a full white screen driving signal to the OLED display, and set all power supplies to the standard operation conditions.

Measure the initial spectral radiance or tristimulus values at P_0 to P_4 as shown in Figure 3. The initial spectra radiance or tristrimulus values of the primary colours may also be measured individually.

b) Image stress using the test pattern

For image stress, the test pattern based on 5.3.4 for display devices should be applied to the OLED display.

Keep the test pattern until the specified time, considering the luminance degradation curve. For example, the measurement time can be every 1 h during the first 6 h, and every 24 h during the first 120 h, then every 72 h until the target time in the standard measurement condition. Alternatively keep the test pattern until the target time in the standard measurement condition.

c) Measurements on full screen pattern after image stress

Before the measurement, turn off the OLED display and stabilize it to the standard operation condition. Then turn on the OLED display again and apply a full white screen driving signal to the OLED display over the full screen. Set all power supplies also to the standard operation conditions. Measure the spectral radiance or the tristimulus values at the same measuring location as the initial measurement. The initial and final spectra radiance or tristrimulus values of the individual primary colours may also be measured and reported.

For the measurement method, only white tone is considered. For the other primary colours such as red, green and blue, each test pattern should be designed following the methods of 5.3.4, and each full primary colour screen pattern should be used for measurement.

All measurements shall be done at the target time of 500 h and shall be reported. In Figure 5, an example of image stress is shown.

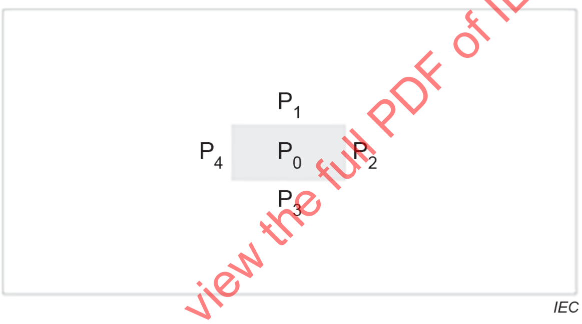


Figure 5 – Example of the resulting image after image stress

6.3 Analysis and report

6.3.1 Analysis

6.3.1.1 Luminance and chromatic deviation method

Image sticking can be characterized by luminance and chromatic deviation.

The image sticking of luminance $IS(t)$ for white is calculated as follows:

$$IS(t) = \left| 1 - \frac{\{\sum_{i=1}^{4} L_i(t)\}/L_0(t)}{\{\sum_{i=1}^{4} L_i(t_0)\}/L_0(t_0)} \right| \times 100\ (\%) \qquad (1)$$

where

t is the specified measurement time;

t_0 is the initial measurement time;

L_i is the luminance of the measurement location from P_i.

Chromatic deviation $\Delta u'v'(t)_0$ caused by image sticking at P_0 over time for white is calculated as follows:

$$\Delta u'v'(t)_0 = \sqrt{\{u'(t) - u'(t_0)\}^2 + \{v'(t) - v'(t_0)\}^2} \quad (2)$$

where

t is the specified measurement time;

t_0 is the initial measurement time;

$(u'(t), v'(t))$ is the white chromaticity value at the specified time;

$(u'(t_0), v'(t_0))$ is the white chromaticity value at the initial time.

The average of the chromatic deviation $\Delta u'v'(t)_{AVG}$ caused by image sticking between different measuring locations from P_1 to P_4 for white is calculated as follows:

$$\Delta u'v'(t)_{AVG} = (\sum_{i=1}^{4} \sqrt{\{u'_i(t) - u'_0(t)\}^2 + \{v'_i(t) - v'_0(t)\}^2}) / 4 \quad (3)$$

where

t is the specified measurement time;

$(u'_i(t), v'_i(t))$ are the chromaticity coordinates of the measuring locations of P_i (i = 1, 2, 3, 4).

The value of u' and v' can be calculated from the tristimulus value X, Y, and Z using the following formula:

$$u' = 4X / (X + 15Y + 3Z)$$
$$v' = 9Y / (X + 15Y + 3Z) \quad (4)$$

6.3.1.2 Colour difference method

6.3.1.2.1 General

The image sticking shall be analyzed with ΔE^*_{ab} of the three-dimensional, CIE 1976 $L^*a^*b^*$ colour space (see CIE 15) following the procedure in 6.2.2. Additional three-dimensional uniform colour spaces may also be used and identified in the test report. Each colour point can be plotted on the L^*, a^*, and b^* axes of the CIE $L^*a^*b^*$ colour space by referencing the peak white tristimulus value (X_n, Y_n, Z_n) in the measuring location P_0 at the initial time t_0 and using the following transformation formula:

$$L^*_i(t) = 116 \times f(Y_i(t)/Y_n) - 16$$
$$a^*_i(t) = 500 \times [f(X_i(t)/X_n) - f(Y_i(t)/Y_n)]$$
$$b^*_i(t) = 200 \times [f(Y_i(t)/Y_n) - f(Z_i(t)/Z_n)] \quad (5)$$

where

$$f(x) = \begin{cases} x^{1/3} & x > (6/29)^3 \\ \frac{1}{3}(\frac{29}{6})^2 x + \frac{4}{29} & \text{otherwise} \end{cases}$$

t is the specified measurement time;

$L^*_i\ a^*_i\ b^*_i$ is the CIELAB colour coordinates of the measuring locations of P_i (i = 0, 1, 2, 3, 4);

(X_n, Y_n, Z_n) is the tristimulus value of the reference white in the measuring location P_0 at the initial time t_0.

6.3.1.2.2 CIE 1976

The colour difference formula $\Delta E^*_{ab}(t)_0$ caused by image sticking at P_0 over time for white is calculated as follows:

$$\Delta E^*_{ab}(t)_0 = \sqrt{\{L^*_0(t)-L^*_0(t_0)\}^2+\{a^*_0(t)-a^*_0(t_0)\}^2+\{b^*_0(t)-b^*_0(t_0)\}^2} \qquad (6)$$

where

t is the specified measurement time;

t_0 is the initial measurement time;

$L^*_0 a^*_0 b^*_0$ are the CIELAB colour coordinates of the measuring locations of P_0.

The average of the colour difference formula $\Delta E^*_{ab}(t)_{AVG}$ caused by image sticking between different measuring locations from P_1 to P_4 for white is calculated as follows:

$$\Delta E^*_{ab}(t)_{AVG} = \left(\sum_{i=1}^{4}\sqrt{\{L^*_i(t)-L^*_0(t_0)\}^2+\{a^*_i(t)-a^*_0(t_0)\}^2+\{b^*_i(t)-b^*_0(t_0)\}^2}\right)/4 \qquad (7)$$

where

t is the specified measurement time;

$L^*_i\ a^*_i\ b^*_i$ are the chromaticity coordinates of the measuring locations of P_i (i = 1, 2, 3, 4).

6.3.2 Report

6.3.2.1 Information of test pattern

Before reporting the measurement data, information on the used test pattern should be reported, as shown in Table 2. It includes the type of test pattern, the size of the window box, the allocated code values located at the centre and background, and the output luminance of OLED displays for the test pattern. If other test patterns not listed in 5.3.4 are used, they should be reported in accordance with Table 2.

Table 2 – Information on test pattern

Types of test pattern		(SDR, HDR, etc.)
Size of window box		- %
Code value	Centre	– (based on 8 or 10 bits)
	Background	– (based on 8 or 10 bits)
Output luminance	Centre	(P_0)
	Background	(average of from P_1 to P_4)

6.3.2.2 Measurement data record

The typical value of image sticking can be reported following the format shown in Table 3. For the typical value, the initial data should be reported and other data at the specified time can be selected following the measuring procedure of image stress.

Table 3 – Example of typical value

Time (hour)	**Colour**	**Measurement data**					
		P_0			**Average of P_1 to P_4**		
		X	Y	Z	X	Y	Z
0	White						
1	White						
⋮	White						

6.3.2.3 Image sticking data

Image sticking should be reported with the result of the comparison between the reference luminance ratio, the chromatic deviation, and the colour difference, following the format shown in Table 4. Each result data should be calculated from Formulae (1) to (7), and should be reported in Table 4. The designated time is 500 h. If the time is changed, it should be reported.

Table 4 – Reporting format of the image sticking data at target time

Time (hours)	**Factor**	**Result data**
500	Luminance ratio (IS)	
	Chromatic deviation $\Delta u'v'(t)_0$ at P_0	
	Average of chromatic deviation $\Delta u'v'(t)_{AVG}$	
	Colour difference $\Delta E^*_{ab}(t)_0$ at P_0	
	Average of colour difference $\Delta E^*_{ab}(t)_{AVG}$	

It is recommended to refer to ΔE^*_{00} using the method in Annex B, if it is necessary to calculate the colour difference with CIEDE2000 instead of ΔE^*_{ab}.

6.3.2.4 Image sticking time

Image sticking can also be reported as the estimated time with the thresholds as shown in Table 5. The thresholds of the image sticking can be set depending on the display size, peak luminance and so on. They can be selected as needed and should be reported.

Table 5 – Reporting format of the image sticking time with threshold

Factor	**Threshold**	**Estimated time**
Luminance ratio (IS)	-	
Chromatic deviation $\Delta u'v'(t)_0$ at P_0	-	
Average of chromatic deviation $\Delta u'v'(t)_{AVG}$		
Colour difference $\Delta E^*_{ab}(t_0)$ at P_0	-	
Average of colour difference $\Delta E^*_{ab}(t)_{AVG}$		

It is recommended to refer to ΔE^*_{00} using the method in Annex B, if it is necessary to calculate colour difference with CIEDE2000 instead of ΔE^*_{ab}.

7 Measuring methods of the luminance lifetime

7.1 Purpose

The purpose of this method is to measure the luminance lifetime of the OLED display modules. The lifetime is the elapsed time required for the luminance to decrease to the specified fraction of the initial luminance set in operation. Unless otherwise specified, half luminance lifetime shall be used for lifetime measurements. When describing the lifetime, the initial luminance, the evaluation temperature and degradation ratio shall be specified.

7.2 Measuring method

7.2.1 Measuring equipment

The following equipment shall be used:

a) power supplies and signal sources for driving,

b) LMD.

7.2.2 Measuring procedure

The OLED display shall be set in the standard measuring conditions. The darkroom conditions shall be applied when the luminance is measured. Apply a full white screen driving signal to the OLED display at 100 % gray level, and set all power supplies to the standard operation conditions. However, for some display applications, the full screen luminance can be reduced, according to IEC 62341-6-1:2017, 6.3.

Measure the initial luminance, keep the above operating conditions and measure the luminance of the DUT at the specified time. The specified time can be (1, 2, 5, 10, 20, 50, 100, 200, 500, 1 000 and 2 000) days. In Figure 6, an example of the luminance behavior in operation is shown. When measuring the luminance lifetime, an acceleration method can be acceptable (see A.2.2). If an acceleration method is applied, the acceleration condition, the acceleration ratio and the theoretical basis of the method shall be reported.

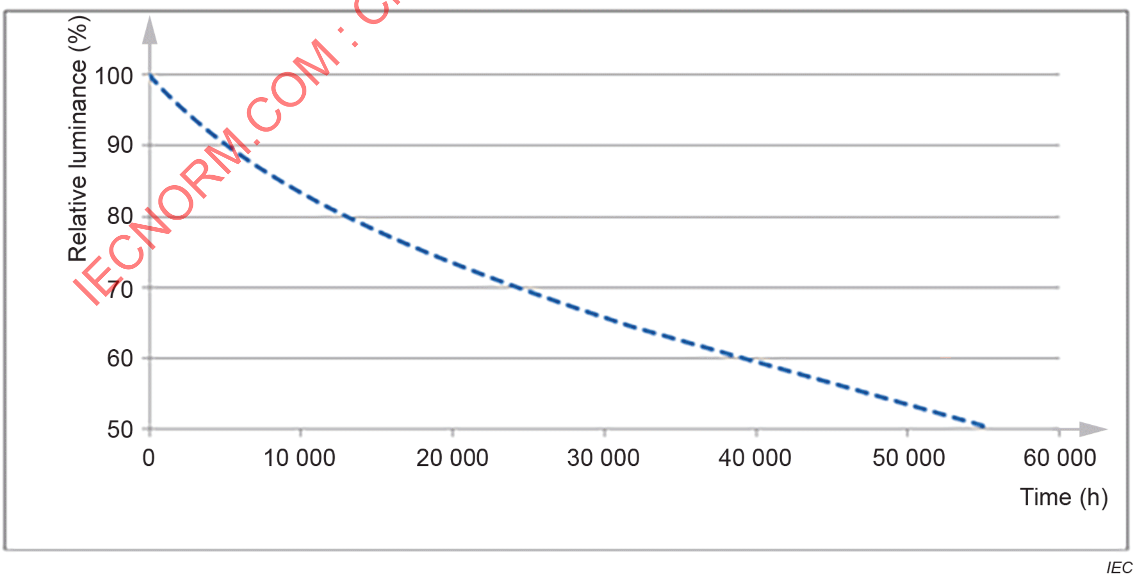


Figure 6 – Example of luminance behavior in operation for an OLED display module

7.2.3 Estimation of luminance lifetime

The direct measurement of luminance lifetime would typically take an impractically long time, exceeding several tens of thousands of hours of panel operation. Extrapolation methods are applied to shorten the measuring period. Luminance lifetime is a degradation phenomenon of the light emission from OLED displays. An extrapolation method can be applied to estimate the lifetime by using a formula which models the degradation with time. This method is based on the knowledge of the degradation phenomenon.

The degradation phenomenon shows exponential degradation as follows [1,6]:

$$L(t) = L(0)\exp\left[-\left(\frac{t}{a}\right)^{\beta}\right] \qquad (10)$$

where

t is the operating time;

$L(t)$ is the luminance value of the degradation phenomena at time t;

$L(0)$ is the initial luminance value of $L(t)$;

a is the constant (relaxation time);

β is the coefficient.

In Formula (11), there is a linear relation between log [ln ($L(0)/L(t)$)] and log (t).

$$\log\left[\ln(L(0)/L(t))\right] = \beta\log(t) - \beta\log(a) \qquad (11)$$

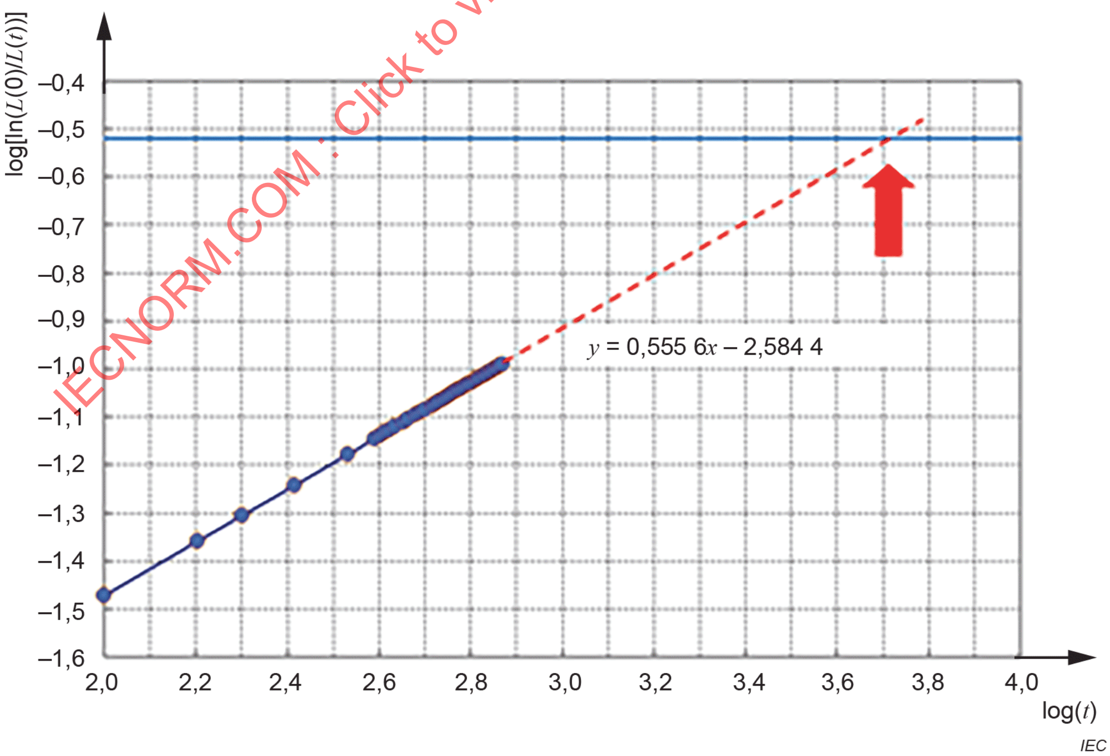


Figure 7 – Example of lifetime estimation with the extrapolation method

With the linear relation, the lifetime can be estimated, using the extrapolation method (Figure 7). For example, the formula y = 0,555 6x – 2,584 4 is defined based on the real measurement data. y could be -0,541 47 by calculating log [ln ($L(0)/(0{,}75 \times L(0))$)]. After calculating the formula to get the time, it is possible to estimate the life time which is about 4 753 h where $L(t)$ is 0,75 times $L(0)$. To check the suitability of the degradation formula, the drift of the estimated lifetime should be used. If the formula is appropriate, there will be no significant drift of the estimated value with the driven time. Examples are shown in Figure 8.

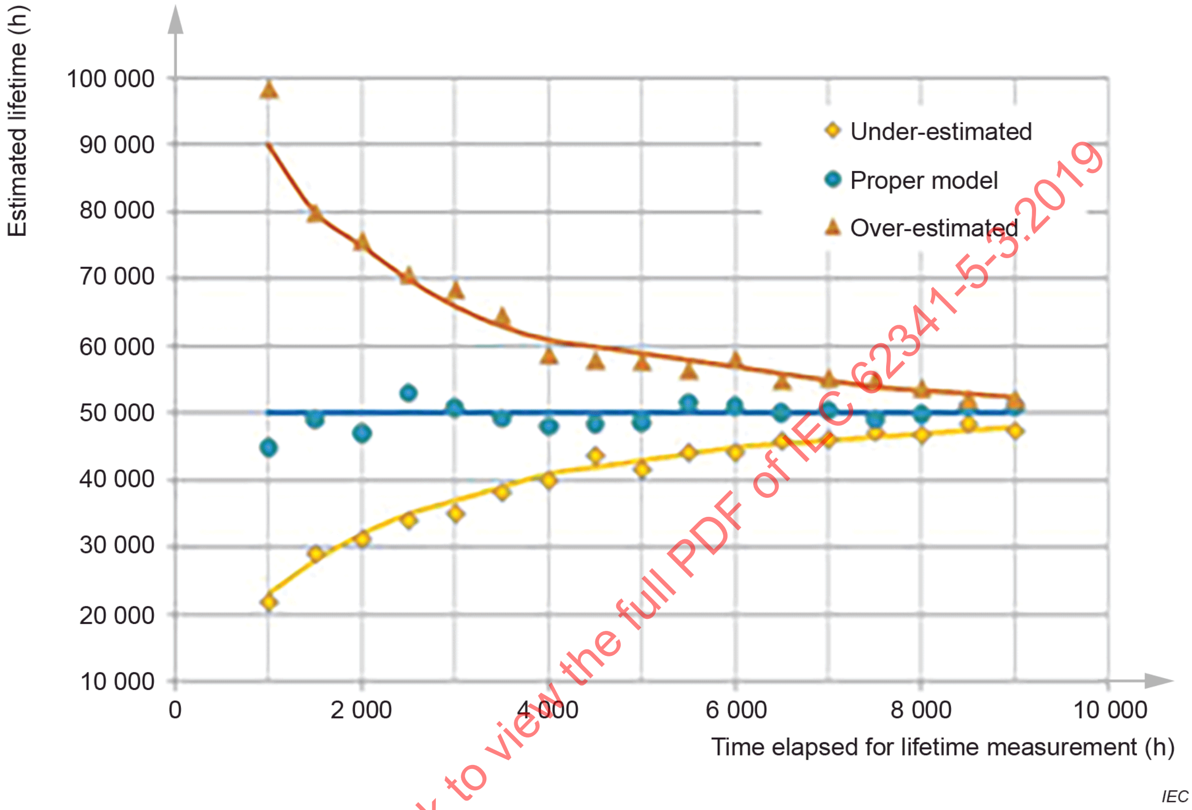


Figure 8 – Examples of estimated lifetime depending on the time elapsed

Annex A
(informative)

Calculating method for equivalent signal level to reflect the characteristics of the OLED display

A.1 Purpose

The purpose of this method is to define the procedure for calculating the equivalent signal level for the image sticking of monitors, TVs, or digital signage devices using video samples. Through the calculation of the equivalent signal level, the characteristics of the OLED display can be reflected.

A.2 Determining the equivalent signal level

A.2.1 General

Since OLED degradation is generally not proportional to current density, the quantities of normalized luminance intensity and equivalent current density, which are proportional to OLED degradation, are defined [6]. It is possible to apply this quantity to the usage model-based image sticking measuring method. The normalized luminance intensity is in the RGB linear space and can be converted to the equivalent signal level to apply linear to non-linear conversion. Further, accurate image sticking simulation for a specific application can be achieved by computing one image in terms of normalized luminance intensity or equivalent current density of various kinds of the actual usage images and image sources.

A.2.2 Calculation of the normalized luminance intensity

The equivalent current density is calculated using the OLED degradation function. The OLED degradation function that is normalized by initial luminance is given empirically by the stretched exponential function:

$$\frac{L(t)}{L(0)} \propto A\exp(-KJt^{m}) \tag{A.1}$$

where $L(0)$ is the initial luminance, A, K and m are fitting coefficients depending on the device, J is the current density of the OLED device in subpixel, and t is the time of the test duration. K and m are determined from the measurement data. m = β: β is the coefficient according to Formula (10) and Formula (11). Figure A.1 shows the measured luminance degradations and fitted lines according to Formula (A.1).

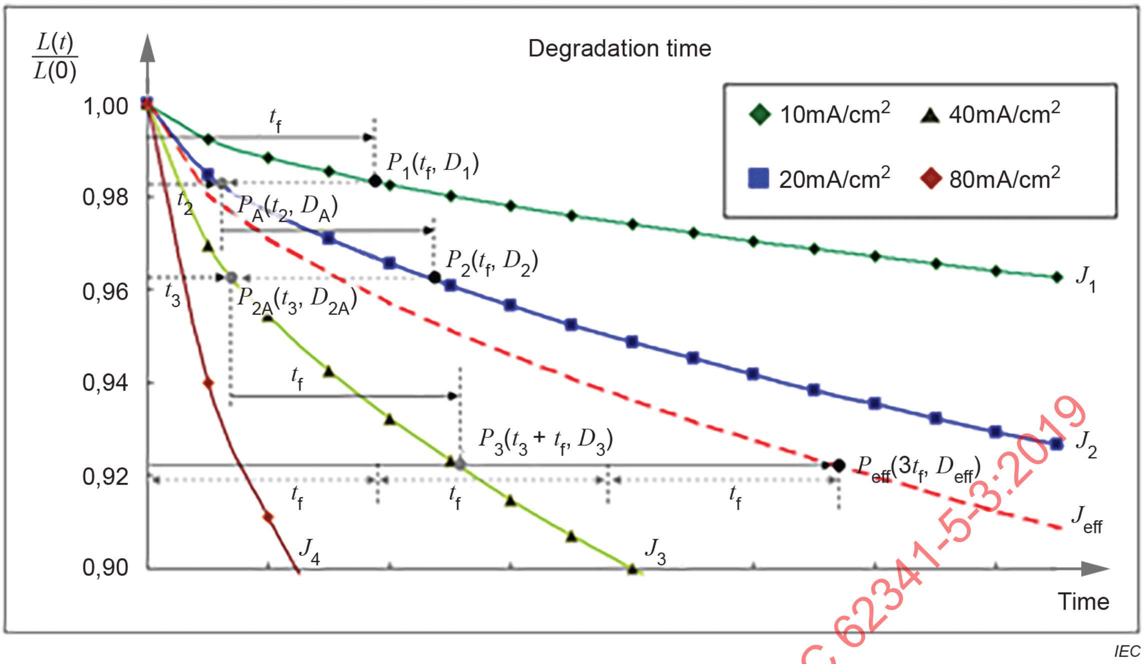


Figure A.1 – Measured 10 mA/cm² to 80 mA/cm² OLED degradation values and corresponding modelled functions with m = 1 / 1,7

As shown in Figure A.1, this model accurately accounts for the degradation of the OLED as a function of both time and current density for a typical OLED. By applying this model and assuming that degradation is additive, one can derive a degradation function for a subpixel which is degraded by exposure to multiple current densities over time. Therefore, D_n, which is the degradation of a pixel by the temporal sequence of current densities $J_1, J_2, J_3 \ldots J_n$ and N over a time period t_f is defined. D_n is calculated as follows.

a) Consider a first degradation of an OLED, resulting from exposure to current density J_1 over a time period t_f. This degradation is expressed as:

$$D_1 = A\exp\left(-KJ_1 t_f^{\,m}\right) \tag{A.2}$$

b) Consider an alternative degradation D_A of an OLED resulting from current density J_2 over a time period t_2. This degradation is expressed as:

$$D_A = A\exp\left(-KJ_2 t_2^{\,m}\right) \tag{A.3}$$

t_2 can now be defined, such that it is the time required to make D_1 equal to D_A. Accordingly t_2 can be calculated from Formula (A.2) and Formula (A.3), and is expressed as:

$$t_2 = \left(J_1 / J_2\right)^{1/m} t_f \tag{A.4}$$

Using Formula (A.4), time period t_2 can be scaled to account for differences between current densities J_1 and J_2. Therefore, after an OLED is exposed to J_1 for a first time period and J_2 for a second time period, the resulting degradation can be expressed as:

$$D_2 = A\exp\left(-KJ_2\left(t_2 + t_f\right)^m\right) = A\exp\left(-K\left(\frac{J_1^{1/m} + J_2^{1/m}}{2}\right)^m \left(2t_f\right)^m\right) \tag{A.5}$$

c) Consider the degradation of an OLED over a third time interval t_3 with exposure to current density J_3. Degradation D_{2A} can then be expressed as:

$$D_{2A} = A\exp\left(-KJ_3 t_3{}^m\right) \tag{A.6}$$

Again, defining t_3 such that it is the time required to make D_2 and D_{2A} equal, t_3 is calculated from Formula (A.5) and Formula (A.6) and is expressed as:

$$t_3 = \left(\frac{J_1{}^{1/m} + J_2{}^{1/m}}{2}\right)\frac{1}{J_3{}^{1/m}}(2t_f) \tag{A.7}$$

Therefore, after the third time interval, the degradation D_3 is expressed as:

$$D_3 = A\exp\left(-KJ_3\left(t_3 + t_f\right)^m\right) = A\exp\left(-K\left(\frac{J_1{}^{1/m} + J_2{}^{1/m} + J_3{}^{1/m}}{3}\right)^m (3t_f)^m\right) \tag{A.8}$$

Thus, after N intervals, D_n is expressed as:

$$D_n = A\exp\left(-KJ_{eff}\left(Nt_f\right)^m\right) \tag{A.9}$$

where J_{eff} is the equivalent current density and is expressed as:

$$J_{eff} = \left(\sum_n \frac{(J_n)^{1/m}}{N}\right)^m \tag{A.10}$$

Similarly, since intensity is proportional to current density (i.e., current density can be computed by scaling intensity by the efficiency, luminance, and area of the OLED), normalized luminance intensity I_{eff} in the RGB linear space can also be expressed as:

$$I_{eff} = \left(\sum_n \frac{(I_n)^{1/m}}{N}\right)^m \tag{A.11}$$

The normalized luminance intensity I_{eff} can be transformed to the equivalent signal level I'_{eff} by using the Formulae (7) and (8) specified in IEC 61966-2-1:1999 as follows:

If $I_{eff} \leq 0{,}003\ 130\ 8$

$$I'_{eff} = 12{,}92 \times I_{eff} \tag{A.12}$$

or if $I_{eff} > 0{,}003\ 130\ 8$

$$I'_{eff} = 1{,}055 \times I_{eff}{}^{1{,}0/2{,}4} - 0{,}055 \tag{A.13}$$

where signal level I'_{eff} is the normalized value from 0 to 1.

Another linear to non-linear conversion can also be used for the normalized luminance intensity to the equivalent signal level transformation.

NOTE Some OLED displays control the peak luminance differently by the APL of the input signal. In this case, the luminance intensity I_n for each frame of video could be influenced by its characteristics. The characteristics of the OLED display which control the peak luminance by APL could be measured following the measurement method of luminance loading in [7].

A.2.3 Examples of extracted equivalent signal level

Examples of extraction of the maximum and the average equivalent signal levels are demonstrated by using the IEC 62087:2011[2] 10-min video loop. If the another video is used, then it should be following this method. Assuming the experimental data of m = 1/1,7, and the transformation Formula (8) specified in IEC 61966-2-1:1999 for non-linear to linear and linear to non-linear conversion, OLED device primaries are the same as that in IEC 61966-2-1, and take both the RGB and RGBW formats. The maximum and the average equivalent signal levels are summarized in Table A.1. For example, the values are shown in the case where m = 1/1,7, gamma is 2,2, and the signal is 8 bits. m is the experimental value, so the maximum and the average equivalent signal levels are recalculated from Formula (A.10) or Formula (A.11) in the case of another m value. They are also re-calculated from Formula (A.12) and Formula (A.13) in case of another gamma value. The images and distribution of signal levels are shown in Figures A.2 and A.3. In the case of an RGB pixel format display, the test input signal to the OLED display panels or modules can be set to generate 143, 137, and 142, respectively, as the maximum equivalent signal level over the 4 % window located in the centre of the display and 121, 117, and 116, respectively, as the average equivalent signal level over the remaining area simultaneously. However, for the case where the OLED display panels or modules have more than three primaries (i.e. RGBW), the procedure should be separated into multiple procedures with the multiple combination of the equivalent signals as follows:

Procedure A: 102, 0, 0 as the maximum signal level, 81, 0, 0 as the average signal level

Procedure B: 0, 77, 0 as the maximum signal level, 0, 65, 0 as the average signal level

Procedure C: 0, 0, 100 as the maximum signal level, 0, 0, 80 as the average signal level

Procedure D: 135, 135, 135 as the maximum signal level, 114, 114, 114 as the average signal level

Table A.1 – Examples of the maximum and the average equivalent signal levels (8 bits)

	RGB pixel format		RGBW pixel format	
	Avg. signal level	Max. signal level	Avg. signal level	Max. signal level
Red	121, 0, 0	143, 0, 0	81, 0, 0	102, 0, 0
Green	0, 117, 0	0, 137, 0	0, 65, 0	0, 77, 0
Blue	0, 0, 116	0, 0, 142	0, 0, 80	0, 0, 100
White	-	-	114, 114, 114	135, 135, 135

2 This publication has been withdrawn.