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Official URL:

https://doi.org/10.1109/TIA.2019.2929150

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Modeling the Luminance Degradation of OLEDs using Design of Experiments (DoE)

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Abstract -- **Modeling the lifespan of OLED (Organic Light-Emitting Diode) is a complex task as it depends on different - potentially interacting factors. As the literature on this subject is still scant, new parametric models for calculating the lifespan of OLED are proposed in this work. The Design of Experiment (DoE) methodology is used for cost and accuracy reasons. Different lifespan models based on thermal and electrical experimental aging tests are proposed. As stress factors, current density, temperature and their interactions, which are rarely taken into account in aging studies are simultaneously involved. The analysis of the model parameters highlights the prevalence of temperature compared to current density on the luminance performance of OLEDs. Non-linear models appear as the most accurate.**

Keywords -- **accelerated aging, design of experiments, electrical stress, lifespan prediction, OLED, thermal stress**

I. INTRODUCTION

Nowadays, system and component reliability has become an important issue. A clear understanding, modeling and predicting aging and degradation mechanisms could lead to upgrade the quality and the reliability of the components and avoid system failure. The operational constraints (supply, atmospheric, mechanic, etc.) and their effects on the degradation of components must be studied to predict the lifespan and find solutions to improve the reliability. In the field of electrical engineering, numerous lifespan models have been developed in the literature [1]-[4] but these models present some limitations. Indeed, they depend on the studied material and on its physical properties and they are often restricted or focused to one or two stress factors. Moreover, they do not integrate interactions that may exist between these different factors. The future of light sources will be probably leads by SSL (Solid State Lighting) i.e. LEDs and OLEDs, but those last have a limited lifespan (30,000h to 40,000h) and an aging mode that is still largely unknown. Although this methodology is general and applicable to various components with no prior information on their physical properties, the measurement specifications have to take into account in order to compute a relevant lifespan model.

This paper presents an innovative parametric lifespan models for very recent OLED light sources which the aging characteristics are still largely unknown. The proposed models are inferred from the experimental data obtained through accelerated aging tests involving several stress factors are used to infer the proposed models. Those are innovative because they take into account, not only the effects of the different stress factors, but also, at the same time, their possible interactions. This is rarely done in aging studies. This kind of predictive models is perfectly adapted in studies where there is few and/or expensive samples. Moreover, this methodology allows to maximize the model accuracy with a small learning sets composed by an optimized number and appropriate configuration of experiments in order to reduce the number and the cost of experiments. The significance of the considered parameters onto the stress factors is assesses by a study of the parameters inputs at different lifespan levels. OLED degradations could be leads by two ways: intrinsic and/or extrinsic factors [5]. The first case is related at moisture or oxygen that can induce delamination or oxidation of the electrodes and can generate dark spots. This can be avoided by a good encapsulation. Extrinsic degradations are mainly leading by the supply current and the ambient temperature where this last is considered as the most impacting factor of degradation [6][7]. Depending on the threshold, the temperature can contribute to the OLEDs degradations during use but can also, in the case of high temperature, contribute to degradations during storage [8]. OLEDs are current-controlled components where their luminance is proportional to the supply current level [8]. But the forward current is also the second main degradation factor. Due to the chemical degradation of the organic materials by the flowing current through the layers, their performances decrease gradually over time [9]. The chosen OLED in this work are commercial products and present two

great advantages: they are well encapsulated and show a great repeatability. A good encapsulation can prevent against oxygen and moisture factors, and it allows us to focus our study only on extrinsic degradations. Thus, thermal and electrical stresses remain the most critical degradation factors for OLEDs. When OLEDs are used for lighting applications, the luminance (measured in cd/m²) is, obviously, the most interesting output parameter and also a simple feature to be monitored. The degradation of an OLED is defined by the decay of its luminance over time [10]. It is commonly assumed that the end of life of an OLED is when the luminance degrades by 30% to 50% depending on the application. The corresponding lifetimes are therefore mentioned L70 or L50, corresponding of a decay from the initial value of 30% and 50%, respectively. To date, there is no standard measurement method for OLEDs light source that can be adopted in performance or accelerated aging tests [8], [11]. Some standards and recommendations has been published (as a US standard, in September 2013 [12] that specifies the general safety conditions for the use of OLED lighting panels and an international IEC standard in 2014 [13] about the safety requirements) but the international standard IEC 62922, concerning the evaluation of the performance and reliability of OLEDs, has still not been published.

II. Existing methods for aging modeling

In the OLED aging literature, the thermal and electrical characteristics of different physical composition OLEDs have been studied to evaluate its thermal degradation [15]. Nevertheless, no modeling is done. Another aging sign for the OLEDs is its luminance degradation. Many articles use this sign as a lifespan indicator. In order to achieve this degradation, most papers use accelerated lifetime tests. The magnitude of stresses, in this case, is much bigger than nominal conditions. Park et al. [10] used accelerated degradation tests to study OLED lifetime. They proposed distribution-based lifespan models (lifetime following Weibull, lognormal, log-spline functions …) along with other methods to study the effect of thermal stress on the aging. Like the previous paper, [14] studied the effect of thermal stress on the accelerated degradation of phosphorescent OLED. It estimated their Mean Time To Failure (MTTF) under normal conditions using a Weibull function for the lifetime distribution and an acceleration factor. Other papers studied the effect of current density on the OLED aging. In [11], the authors suggested that the lifetime is a "power function" of current by plotting the measured lifespans as a function of the applied current. They used this model to characterize OLED panels. A Weibull distribution to model the OLEDs lifespan under constant step current density stresses was proposed in [18] and the same authors defined a lognormal distribution for the OLEDs lifetime under constant current density stress in [19]. OLED lifetime was also

expressed as a Weibull function in [20]. More recently, Kim et al. proposed a statistical modeling of the luminance degradation as an exponential decay [21]. In [22], the lifetime of large OLED panels is estimated as a bivariate model depending on temperature and luminance. In most cases, the distributions parameters include an acceleration factor. Still, the authors of [17] refused to work with accelerated tests, claiming that the degradation mechanism is not the same under accelerated and normal conditions. They proposed another degradation sign, the temperature of the junction. By applying a current density stress on smaller areas OLEDs (having a shorter lifetime than the big panels), Pang et al. determined the degradation in the temperature junction of the big OLED panels at different current density.

So far, all the aging is studied under the influence of a single stressor (temperature or electric current). Moreover, in the literature, few studies are interested in the modeling of OLED lifetimes as a function of stress factors in addition to the evaluation over time of their performances (aging). However, lifespan models that include two or more stressors at once have never been considered for OLEDs in the literature.

The Design of Experiment (DoE) methodology has proved its efficiency to tackle these problems in the case of insulation materials [23], [24], and in the case of white OLEDs [29] where they studied the effect of temperature and current density, as well as their interaction on the L70 lifespan of the OLEDs (30% of degradation).

In this study, a novel application of DoE methodology on OLED light sources is presented. The proposed models include the two accelerated main factors: the temperature, following an Arrhenius law, and the current density, following an inverse power law. Thus, in OLED lifespan models, a logarithmic transformation of lifetimes, a logarithmic transformation of the current density and an inverse temperature transformation in K are applied. Under each test condition (current and temperature), only one OLED was tested for cost and time constraints. It should be noted that manufacturers consider their batches of OLED to be very homogeneous, and that in the literature, only a very limited number of samples are generally tested. Our choice is identical, but the dispersion of the characteristics remains to be tested over time, which can constitute a perspective of this work.

III. Tests performed on OLEDs

A. OLED types tested

This paper proposes a methodology which is applied onto OLED commercial lighting sources Philips Lumiblade OLED Panel GL55. Commercial products offer a fundamental advantage in this kind of study: a great reproducibility that could allow us to have a small dispersion. Our choice of study was focused on large OLEDs because they are made

with organic materials different from small OLEDs, the latter being widely studied in the literature. The tested components are shown in figure 1. Table I summarizes the main electric and photometric characteristics of the Philips Lumiblade OLED panels GL 55.

TABLE I
TECHNICAL CHARACTERISTICS OF PHILIPS GL55 OLEDs

Name	Philips Lumiblade OLED Panel GL55
Color	white
Color temperature	3200K
Size	130.2*47.8 mm² (116.7*35.2 mm² of luminous surface)
Nominal current	390 mA
Maximal current	450 mA
Minimum voltage	6.9 V
Nominal voltage	7.2 V
Maximal Voltage	7.5 V
Lifespan (L_{50}) under nominal current	10000h
Rated Luminance	4200 cd/m²

Fig. 1. Photo of a Philips GL55 OLED

B. Aging factors

The two main stress parameters reported by the literature on OLED lifespan studies about accelerated degradations are the environmental temperature and the electrical current density. The OLEDs were submitted to stress by two ways: pure or combined thermal and/or electrical stresses. Moreover, driven by different sizes, surfaces or geometries of OLEDs, the current density is used as the reference unit (instead of the absolute current). Current density (J) and temperature (T) will therefore be used in our models. We have restricted the ranges of these two parameters to avoid catastrophic degradation (carbonization) when they are applied in the same time at high level:

- Current density: the maximum current (from manufacturer datasheet, with a rated current of 390mA) allowed for normal operation is 450mA, which matches a current density of 11mA/cm². To accelerate the degradation, three current densities were applied: 11.25mA/cm², 13mA/cm² and 15mA/cm² (forward currents of 462, 534 and 616mA, respectively). For current densities above 15mA/cm², a carbonization phenomenon was observed in the injection area (of the order time of only one minute) resulting in the appearance of dark zone, as shown in Fig. 2. OLEDs degradation in storage conditions were also studied with a pure thermal stress (at $J=0$). The measurements to evaluate degradations are performed under rated current.

- Temperature: one set of four OLEDs was tested at room temperature (23°C) and the two others, at 40°C and 60°C respectively. At temperatures above 60°C, the tested OLEDs do not support combined thermal and electrical stresses (with current density over 11mA/cm²).
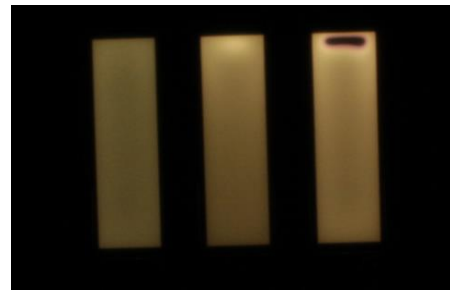

Fig. 2. Catastrophic degradation under strong current (carbonization area appearance)

C. Experimental bench

An innovative experimental device was developed at the LAPLACE laboratory to apply thermal and electrical stresses with a high accuracy, homogeneity and stability, to the OLED and allowing simultaneously in situ electrical and photometric characterizations. In order to discriminate the thermal and/or the electrical influence, OLEDs have been subjected to combined electrical and thermal stresses, but also to pure thermal and electrical stresses.

To apply the thermal stress, OLEDs were placed in thermal controlled caissons where the temperature is regulated with accuracy under 1°C. The temperature was controlled by a regulator and measured using a thermocouple (K type). The homogeneity is assured by a strong wind blower. Three different temperatures were applied simultaneously in three steel caissons (23 °C, 40 °C and 60 °C) that ensure, in the same time, EMC protections during measurements. Each OLED are supplied by one DC laboratory power supply at various electrical stresses but simultaneously at the same temperature except for the one with a pure thermal stress. Four OLEDs are subjected to the same temperature in the same chamber but under different current densities (zero current, 11.25mA/cm², 13mA/cm² and 15mA/cm².). The

caissons are thermally isolated and painted inside in black to allow in situ photometric measurements and avoid any light reflection. Finally, each box is equipped with a time counter. The different parts of this experimental bench dedicated to these tests are presented in Fig. 3, 4 and 5.

D. Lifespan measurement method

During the accelerated aging of OLEDs, measurements were done very frequently the first weeks in order to follow the evolution and degradation of the OLEDs performances over time. Regular measurements of the electrical and photometric characteristics were carried out and, according to an estimation rate of degradation based on the previous measurements, those were performed with a longer time period. The rate of degradation was not the same at the beginning and at the end, and between each OLED, depending on the stress level (the degradation rate of OLEDs with strong constraints (and moreover for ones with, simultaneously, both stresses) was faster than that of OLEDs with lower constraints).

All the characterizations were performed outside the climatic chamber, and at room temperature (no thermal or electrical stress, only under the rated current) but this measurement time was very short compared to the total duration time of an aging test. It is assumed that these very short time measurements do not impact the aging rate of the OLEDs. It should be noted that this kind of measurement protocol constitute a de facto thermal and electrical cycling and those effects should be studied more precisely in a future work. However, according to the very low frequency of the measurements and the short measurement time compared with the aging time under stresses, this cycling effect will be neglected here. Nevertheless, the study of cycling will be an interesting perspective of this work. Among the different characterizations of OLEDs carried out regularly over time (mainly electrical characterizations allowing to study the evolution of the parts of electrical equivalent model or the structural characterization done at the end (destructive tests)), the measurement of luminance is the most pertinent parameter used to characterize their lifetime because to enlighten is the aimed of an OLED. In each experimental configuration, regardless of the kind of stress applied, the luminance was measured by powered the OLED with the nominal current density ($9.5 mA/cm^2$) through a SourceMeter Keithley 2602A to ensure a high current quality and perform electrical characterizations in the same time. The degradation rate of the luminance expressed in percentage gives the corresponding index of the lifetime; if the luminance reaches x% (and thus with a downshifting of $(100-x)$ % from the nominal value at $t=0$) of its initial value, the corresponding lifetime is noted L_x. Thus, each L_x corresponds to a lifespan model as a function of the stress factors. This allows us to follow, through the evolution of luminance for a given stress, the evolution of the effects of stressors (current and temperature) over time.
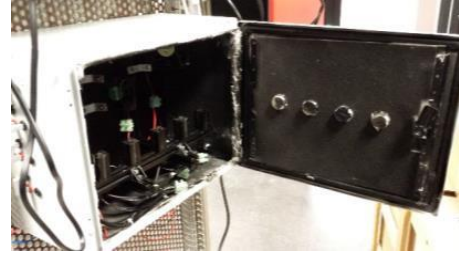

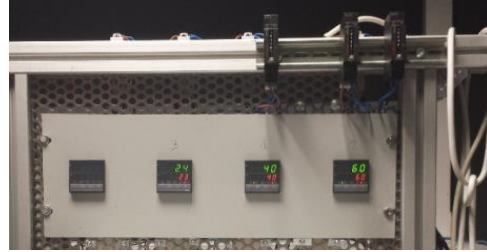Fig. 3. Insulated Steel caissons equipped for in situ measurements

Fig. 4. Temperature controllers and elapsed time counters (in hours)

Fig. 5. Experimental bench of OLED aging tests (overview)

E. Configuration of tests and measurement results

As described in [25], we applied 4 different currents (from 9.5 mA/cm^2 to 15 mA/cm^2) and 3 kinds of thermal stresses (23°C, 40°C and 60°C) that lead to 12 combinations. OLEDs were thus tested in these 12 configurations corresponding to pure or combined stresses. For each configuration, an OLED was tested and different measurements of lifetimes were recorded. Fig. 6 and Fig. 7 show the evolution of the relative luminance (ratio of the measured luminance on the initial luminance) for the different aging tests with different rates of degradation of the luminance. The vertical axis corresponds to the percentages 60%, 65%, 70%, 75%, 80% and 85% as aging indices (luminance decay compared to initial value at $t=0$).

From these data, we have observed that:

- a deterioration of 85% at the highest temperature (60°C) and highest current density (15 mA/cm2) takes more than one week (187h),
- a pure thermal stress up to 60°C does not degrade the luminance of the tested OLEDs; the tests corresponding to these conditions (green curves on Fig. 6 and Fig. 7) were therefore stopped after 2500h (104 days i.e. three and a half months) since the luminance was not degraded throughout this period,
- the current alone (at 23°C), on the contrary, can degrade the luminance of OLEDs as displayed in Fig.6. (it should be noted that the current also induces thermal effects itself but these last can't easily dissociate).
- Three points are at steady temperature or current at the most and can therefore be used to validate the forms of the two stress factors, as shown below.
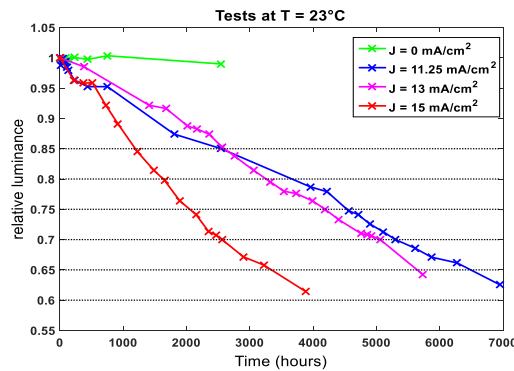

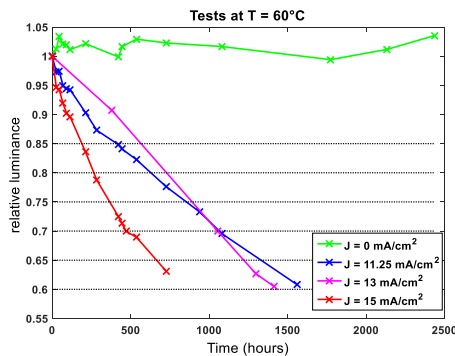Fig. 6. Test results: relative luminance at T = 23 C for different current densities

Fig. 7. Test results relative luminance at T = 60 C for different current densities

F. *Experimental results discussions*

Previous experimental results showed that accelerated degradations under thermal and electrical stresses affect both electrical and photometrical characteristics [25, 28, 29]. Concerning the electrical characteristics, our electrical equivalent model shows the increase of the serial and parallel resistances and the decrease of the parallel capacitances correlated to the I-V curve evolution. On the other hand, photometrical measurements, namely the luminance, the light distribution on the OLED surface, the evolution of the

spectrum and the colorimetry, show a correlated decrease in the amount of light and a better homogeneity over time, but also a shift of the color linked to a significant reduction of the blue emitter with no shift of any other wavelength peak position. The structural characterizations carried out by energy dispersive spectroscopy (EDX) showed that both electrical and photometrical characteristics of the OLED are affected by the indium and oxygen diffusion inside the hole transport layer (HTL) that change concomitantly the discrete parts of the electrical equivalent model and the luminance whereas the evolution of the *J-V* characteristics is linked to the increase in density of the bulk traps, which reduces the charge mobility and the *C-V* characteristics by a decreased colorimetry of the injected charges. These degradations are not linear and are mostly affected by the heat generated initially by the current but where the ambient temperature plays a secondary, albeit important role.

Fig. 8 and 9 present two graphs which validate the respective forms of current and temperature that are considered in the life models from two different indices of life duration. Unfortunately, since only one measurement per test condition is available so far, it is not possible to evaluate statistical properties of the data such as dispersion or distribution. However, for the models, we assume that lifetimes are distributed lognormally, as it is commonly used in the literature.
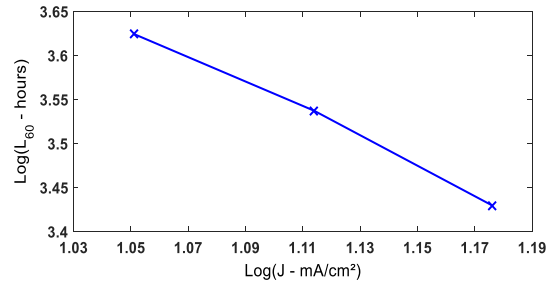
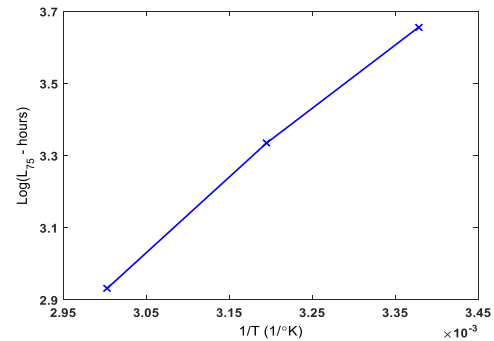Fig. 8. Linear variation of *Log(L)* versus *Log(J)* at *T* = 40 C

Fig. 9. Linear variation of *Log (L)* versus $1/T$ (*T* in K) at *J* = 11.25 mA / cm²

IV. DoE FOR LIFESPAN MODELLING

A. *DoE principles*

The parametric modeling of a response influenced by a number of factors at a lower experimental cost is based on the Design of Experiments (DoE) method. The DoE method was

introduced in 1925 [26] with Fisher's work on agronomy. This method is an experimental planning strategy for studying the effects of factors and their interactions on the response in an efficient and cost-effective manner [27]. The models presented in this paper derive from this method, which has been introduced in [29]. Different types of models can be proposed such as first order model (1) or second order model. For a factorial plan 2², the response Y can be written in a first order model, expression (1)

$$Y = M + E_1 X_1 + E_2 X_2 + I_{12} X_1 X_2 \qquad (1)$$

B. Plans for Response Surfaces (RS)

There are many cases and for which second-order mathematical models must be considered leading to a better description of the phenomenon studied, as in the case of our statistical modeling of OLED lifespan. The response surface method is a good candidate. Based on [29], quadratic effects of factors in addition to their main effects and interactions could be take into consideration and are included in (2):

$$Y = M + \sum_{i=1}^{k} E_i X_i + \sum_{i=1}^{k} I_{ii} X_i^2 + \sum \sum_{i=1<j} I_{ij} X_i X_j \qquad (2)$$

The parameters of this model can be estimated thanks to the OLS method. For k factors, q parameters must be estimated:

$$q = \frac{(k+2)!}{k!\,2!} = \frac{(k+2)(k+1)}{2} \qquad (4)$$

Then, at least q experimental points are necessary to be able to estimate these q parameters. Optimal configurations of these plans have been proposed in the literature to be able to establish that kind of second-order model with interactions. Test configuration and data base for lifespan modeling

This methodological approach is applied to the OLEDs. As current density and temperature are the most influential factors on the life of OLEDs - they will be considered in our aging tests. The variation domain of these two factors is chosen in order to accelerate the aging of the OLEDs without causing sudden failures. Table II presents the accelerated aging tests for constructing the lifespan models The specific experiments corresponding to zero current have been removed. Measured (black) and interpolated (linear interpolation between the nearest points when the corresponding measurement has not been made, in red) lifespan for different percentages of the luminance degradation rate are provided.

The combined electrical and thermal stress tests were configured to be able to construct the 1st and 2nd order models with interactions. Experimental points 1 to 9 of Table II plotted in Fig. 10, form a 3-level experiment plan: with 2 factors (Temperature T and current density J) for which 3²=9 experiments are necessary. This arrangement of the experimental points makes it possible to obtain:

- a first order model with interactions as in (1) by using the classical plan 2² with the extreme levels -1 and +1 (exp. 1, 3, 7 and 9), called model M1;
- 4 models of the first-order with interactions (as in (1)) using the 4 classical 2² plans consisting of the levels (-1; 0) and (+1; 0). It is important to notice that these normalized levels have to be recalculated each time at (-1; +1) to cope with the theory and obtain an orthogonal matrix, called models M2.1 to M2.4;
- another model of the first-order with interactions but using the whole 3-level DoE (all the experiments, n°1 to n°9), called model M3;
- and finally, a second order model, with interactions as well, based on expression (3). This last model is based on all the experimental points: the extreme factorial plan 2² (exp.1, 3, 7 and 9), the 4 axial points (exp. 2, 4, 6 and 8) and the only central point (exp. no 5). It is called model M4.

Only one sample (OLED) per experimental point was tested because of the cost (each tested OLED costs €100), because of the duration of the experiments (the longest one lasted one year), and because of material availability. Consequently, it was not possible to achieve any statistical analysis on the lifespan models. The different normalized levels of the 3-level factorial design for each of the real stress values are listed in Table III.

TABLE II
OLED ACCELERATED AGING TEST CONFIGURATIONS (WITHOUT PURE THERMAL TESTS) MEASURED (BLACK) AND INTERPOLATED (RED) LIFETIMES

| Exp. Nb. | Constraints | | Measured lifespan (in hours) | | | | |
	J (mA/cm²)	T (ºC)	L_{85}	L_{80}	L_{75}	L_{70}	L_{65}
1	11.25	23	2543	3660	4562	5298	6489
2	13	23	2566	3325	4191	5063	5644
3	15	23	1225	1654	2051	2468	3343
4	11.25	40	1234	1657	2166	2917	3488
5	13	40	860	1192	1517	1955	2702
6	15	40	949	1266	1576	1872	2377
7	11.25	60	423	628	855	1082	1331
8	13	60	567	733	893	1055	1221
9	15	60	187	270	367	471	665

TABLE III
VALUES OF STRESS FACTORS AND ASSOCIATED LEVELS

X_i level	$U_J = Log(J)$ (mA/cm²)	$U_T = 1/T$ (°K)
-1	Log(11.25)	1/(23+273.15)
0	Log(13)	1/(40+273.15)

| +1 | Log(15) | 1/(60+273.15) |

TABLE IV
LEVELS OF THE FACTORS FOR THE DOE AND EXPERIMENTAL RESULTS

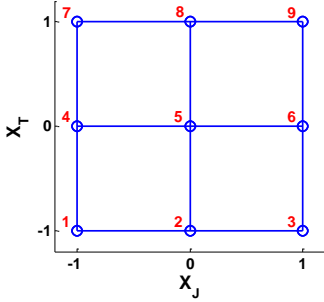| Exp. N°	X_J	X_T	L_{85} (hr)	L_{80} (hr)	L_{75} (hr)	L_{70} (hr)	L_{65} (hr)
1	-1	-1	2543	3660	4562	5298	6489
2	0	-1	2566	3325	4191	5063	5644
3	1	-1	1225	1654	2051	2468	3343
4	-1	0	1234	1657	2166	2917	3488
5	0	0	860	1192	1517	1955	2702
6	1	0	949	1266	1576	1872	2377
7	-1	1	423	628	855	1082	1331
8	0	1	567	733	893	1055	1221
9	1	1	187	270	367	471	665

Fig. 10. Experimental points of Table IV in 2D space

Table IV presents the 9 experiments where the levels of the factors are designated by X_J and X_T for the current density and the temperature respectively.

V. OLED LIFESPAN PARAMETRIC MODELS

In all the following models, L_x denotes the lifespan measured at $x\%$ of the initial luminance in hours. Here, two lifespan will be used, the first is for $x = 85\%$ lifespan and the second is for $x = 70\%$ lifespan. X_J and X_T are the respective levels of Log (J), and $1/T$ as shown in Table III.

A. Model of the first order with interactions (model L1)

The first-order model with interactions is given by expression (4). It is based on experiments 1, 3, 7 and 9 Table IV. These experiments are the four extreme points of the square in Fig. 10

$$M1 = Log(L_x) = M + E_J X_J + E_T X_T + I_{JT} X_J X_T \qquad (4)$$

The unknown parameters of this model are the constant M, the coefficients E_J, E_T associated with the effects of the density of the current and the temperature respectively. The coefficient I_{JT} is associated to the effect of the interaction between current density and temperature. Thanks to OLS method, the model coefficients are given in Table V for the two studied luminances L_{85} and L_{75}, measured at 85% and

70% of the initial luminance in hours respectively. For this first model, the test base is composed of experiments 2, 4, 5, 6 and 8 which are not part of the learning set, i.e. which have not been used to calculate the model coefficients. Table VI and Table VII give the relative errors between measured Log (L_{70}) and $Log(L_{80})$ and their corresponding prediction by model M1.

TABLE V
ESTIMATED NORMALIZED COEFFICIENTS OF MODEL L1 BUILT FROM EXTREME POINTS OF THE FIRST ORDER 2 FACTOR DoE

	L_{70}	L_{85}
M	3.206	2.848
E_J	-0.173	-0.168
E_T	-0.352	-0.399
I_{JT}	-0.007	-0.009

TABLE VI
RELATIVE ERRORS OF MODEL L1 ON THE L_{70} TEST BASE

Exp. Nb.	$Log(L_{70})$ measured	$Log(L_{70})$ predicted	Relative error
2	3.704	3.558	4.0%
4	3.465	3.379	2.5%
5	3.291	3.206	2.6%
6	3.272	3.033	7.3%
8	3.023	2.854	5.6%

TABLE VII
RELATIVE ERRORS OF MODEL L1 ON THE L_{85} TEST BASE

Exp. Nb.	$Log(L_{85})$ measured	$Log(L_{85})$ predicted	Relative error
2	3.409	3.247	4.7%
4	3.091	3.016	2.44%
5	3.934	2.848	2.95%
6	2.977	2.68	9.98%
8	2.754	2.449	11.05%

An analysis of the coefficients of this model show that temperature has a stronger effect than current density between levels -1 and +1 of each of the factors (11.25 mA/cm² < J < 15 mA/cm² and 23 °C < T < 60 °C. Moreover, it seems that the interaction between the two factors is negligible with respect to the main effects. All the relative errors in Table VI and VII are generally small (< 8%) except for the 6th and 8th experiments for of L_{85} probably because interpolated values are considered rather than measurements. On that account, the considered form of the model and the two factors is validated.

B. Four 1° order models with interactions (M2.1 to M2.4)

Fig. 10 could be separated into 4 factorial plans (the 4 inscribed squares of Fig. 10). Then, it is easy to build 4 first order models with interactions from these 4 squares. Table VIII list the learning sets of these 4 models (designated by M2.1 to M2.4).

TABLE VIII
LEARNING BASICS OF THE 4 FIRST ORDER DOES 2^2

Model nb.	J levels	T levels	Exp. nb. in the learning base
M2.1	[-1 ; 0]	[-1 ; 0]	1, 2, 4, 5
M2.2	[0 ; 1]	[-1 ; 0]	2, 3, 5, 6
M2.3	[0 ; 1]	[0 ; 1]	5, 6, 8, 9
M2.4	[-1 ; 0]	[0 ; 1]	4, 5, 7, 8

The 4 DoE models M2.1 to M2.4 have the same form as (1) and their coefficients estimated by OLS are given by the diagram of Fig. 11. For comparison purpose, the levels of J and T are brought back by changing variables at levels -1 (for the low level) and +1 (for the high level) when calculating each model. It can be seen in these diagrams shows the similarity in magnitude of that the effects have similar magnitude for both lifespans, although they are not equal. The effect of the temperature (in green) is confirmed as stronger than that of the current density (in blue), whatever the experimental domain is. Unlike the first DoE model M1, the interaction between the two factors is significant in each of the four plans. Finally, the effect of the current density (respectively the temperature) increases when the current levels (respectively the temperature levels) go from [-1; 0] to [0; 1]. This phenomenon is easily observed by comparing E_J between M2.1 and M2.4, on the one hand, and M2.2 and M2.4 on the other hand. The same type of comparison on E_T between M2.1 and M2.2, on the one hand, and M2.3 and M2.4 on the other hand (Fig. 11) leads to the same conclusion.
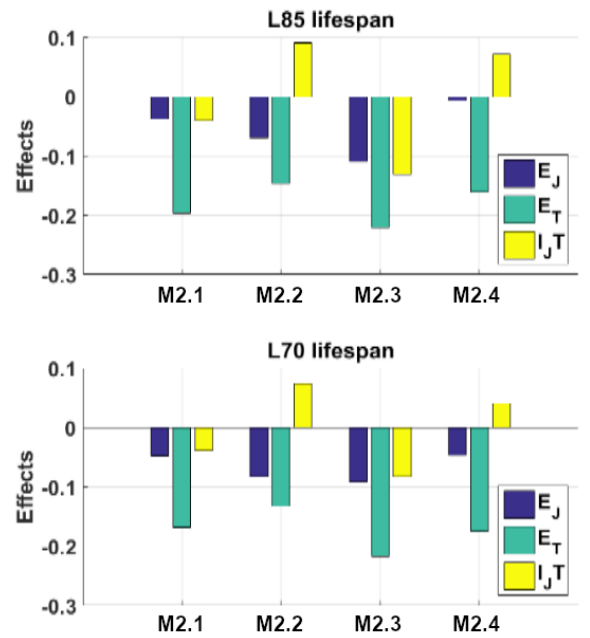

Fig. 11. Estimated coefficients of the four first order model M2.1 to M2.4 for the L_{85} and L_{70} lifespans

C. Model of the first order with 3 levels and interactions (model M3)

The decomposition of the 3-level plan into four 2-level plans reveals non-linear effects of the current and temperature density as along with strong interactions between these two factors. Consequently, another first-order (but a little bit more complex) model was built, based on a 3-level DoE, in order to confirm these results. This model, named M3, has the following form expressed in (5) and is piecewise linear [25]:

$$M3 = Log(L_x) = M + \begin{bmatrix} E_{J_{-1}} & E_{J_0} & E_{J_{+1}} \end{bmatrix}[X_J]$$
$$+ \begin{bmatrix} E_{T_{-1}} & E_{T_0} & E_{T_{+1}} \end{bmatrix}[X_T]$$
$$+ [X_J]' \begin{bmatrix} I_{J_{-1};T_{-1}} & I_{J_{-1};T_0} & I_{J_{-1};T_{+1}} \\ I_{J_0;T_{-1}} & I_{J_0;T_0} & I_{J_0;T_{+1}} \\ I_{J_{+1};T_{-1}} & I_{J_{+1};T_0} & I_{J_{+1};T_{+1}} \end{bmatrix} [X_T] \tag{5}$$

Expression (6) gives some examples of the formula used for the calculation of the different coefficients of this model according to the methods presented in [25] Table X lists the corresponding coefficients values of model M3.

$$E_{11} = \frac{1}{3}(Y_1 + Y_2 + Y_3) - M$$
$$E_{21} = \frac{1}{3}(Y_1 + Y_4 + Y_7) - M$$
$$I_{11;21} = Y_1 - M - E_{11} - E_{21} \tag{6}$$
$$I_{12;21} = Y_4 - M - E_{12} - E_{21}$$
$$I_{13;21} = -(I_{11;21} + I_{12;21})$$

TABLE IX
COEFFICIENTS OF MODEL M3 FOR A 3^2 DOE

L_{85}		L_{70}	
$M = 2.95$		$M = 3.287$	
Main factors	Interactions $X_J X_T$	Main factors	Interactions $X_J X_T$
$E_{T-1} = 0.35$	$IJ_0 T_0 = -0.15$	$E_{T-1} = 0.32$	$IJ_0 T_{-1} = 0.04$
$E_{T1} = -0.4$	$IJ_1 T_0 = 0.15$	$E_{T1} = -0.38$	$IJ_1 T_{-1} = -0.04$
$EJ_{-1} = -0.09$	$IJ_0 T_1 = 0.12$	$EJ_{-1} = -0.12$	$IJ_0 T_0 = -0.11$
$EJ_0 = -0.08$	$IJ_1 T_1 = -0.11$	$EJ_1 = -0.17$	$IJ_1 T_0 = 0.10$
$EJ_1 = -0.17$			$IJ_0 T_1 = 0.06$
			$IJ_1 T_1 = -0.06$

It can be seen in Table IX, that the effects of X_J and X_T are not the same if the interval [-1; 1] is decomposed into two intervals [-1; 0] and [0; 1], Moreover, it can be noticed that the effects of the interactions (specially the interaction with the level 0) are significant. Nevertheless, the effects do not vary a lot from the L_{85} model to the L_{70} one. However, the effect of the current, at level -1 increase mostly with aging which can indicate a snowballing effect of the current density with time.

D. Model of the second order with interactions based on Surface Response (model M4)

The factorial plan with 3 equidistant levels (-1, 0 and 1) can be the basis of a new DoE including quadratic effects on each of the factors, in order to introduce some non-linear effects. The model is given by (7) according to the Surface Response method [28]. Experiments 1 to 9 of Table V were used to estimate is coefficients:

$$M4 = Log(L_x) = M + E_J X_J + E_T X_T + I_{JJ} X_J{}^2 + I_{TT} X_T{}^2 + I_{JT} X_J X_T \quad (7)$$

The quadratic effects of current density and temperature are I_{JJ} and I_{TT} respectively. Table X lists all the coefficients estimated by OLS.

TABLE X
ESTIMATED COEFFICIENTS FOR MODEL M4

	L_{70}	L_{85}
M	3.396	3.083
E_J	-0.148	-0.131
E_T	-0.348	-0.375
I_{JJ}	-0.079	-0.122
I_{TT}	-0.084	-0.075
I_{JT}	-0.007	-0.009

Temperature appears as the most influential parameter with the strongest effect when compared to that of current density. A large quadratic effect of both factors is also put in evidence and the values of I_{JT} estimated by models M1 and M4 are the same.

E. Discussion

Fig.12 shows a comparison between the lifespan models M1 to M4 for both luminances L_{70} and L_{85} where it can be seen that most of the errors remain under 25%.

These models can be classified with respect to their accuracy, from the least to the most: M2.x<M1<M3<M4. The global conclusion is that non-linear models are more accurate than linear models. Indeed, M2.x type models, all the four models created from specific parts of the experimental plan are the less accurate for lifespan estimation even if their maximum error remains anyway under 30%. M1 model leads to maximum errors up to 12%. This is certainly due to the non-linear relationship between lifespan and the two stress factors, temperature and current density. The model M4 tends to be the best model therein, proving that the lifetime model is not of the first order p. The model M3 has zero percentage errors, which is normal because all the experiments are used in the learning set and there is no test set. Therefore, the errors cannot be comparable, despite having the ability to cope with a nonlinear phenomenon. Future work will test this model with additional test points.

Another possible conclusion is that, the errors between the L_{85} and L_{70} lifespans differ, despite having a similarity. It can be assessed that the differences in the lifespans show that the degradation of the OLEDs is a time varying process, even when the constant stress levels.
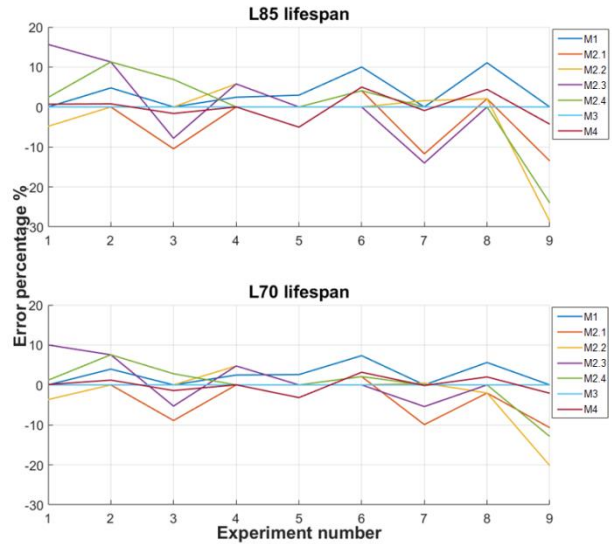

Fig. 12. Maximum percentage of error on lifespan modeling with the 7 models M1, M2.1 to M2.4, M3 and M4

The proposed method was able to provide good lifespan predictions. This confirms the accuracy of the forms used to model the link between the lifespan and the temperature and current density. The results show a high dependency between the lifespan and the operation

temperature, as already spotted in [30]. The model is build using experimental data with the assumption of the relation form between the lifespan and the stressors only. However, this might be a limitation for the proposed methodology if these relations are unknown.

VI. Conclusion and perspectives

Thanks to DoE, this work enriches the previous studies on OLED lifespan modeling. The method proves to be very helpful for this purpose. Several models have been proposed and compared allowing the study of the relative importance of stress factors. Temperature has the strongest effect compared with that of current density and their possible interactions. The proposed models show good rather performance for lifespan prediction in most of the tested cases and non-linear models appear as the most accurate.

Future work will test a larger number of OLEDs for each experiment making possible a deeper analysis of the predictive quality of the models. The variability and statistical significance of models will be studied. Additional test points randomly configured would also allow the analysis of the dispersion and distribution of the lifespan and thus refine the choice of the model. Other parameters than luminance such as color rendering index or equivalent electrical model parameters could be tested according to the proposed protocol. Finally, considering a time varying model can unite the values of the effects without the need of testing different lifespan levels.

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