A BAYES APPROACH AND CRITICALITY ANALYSIS FOR RELIABILITY PREDICTION OF AlGaInP LIGHT EMITTING DIODES

M. Sawant[1] and A. Christou[1]

[1] Materials Science Department And Department of Mechanical Engineering
University of Maryland, College Park MD, US.
* E-mail: christou@umd.edu

ABSTRACT

While use of LEDs in fiber optics and lighting applications is common, their use in medical diagnostic applications is very rare. Since the precise value of light intensity will be used to interpret patient results, understanding failure modes is very important. We used the Failure Modes and Effects Criticality Analysis (FMECA) tool to identify the critical LED failure modes. Once the critical failure modes were identified, the next step was the generation of time to failure distribution using Accelerated Life Testing (ALT) and Bayesian analysis.

ALT was performed on the LEDs by driving them in pulse mode at higher current density J and higher temperature T. This required the use of accelerating agent modeling. We have used Inverse Power Law model with J as the accelerating agent and the Arrhenius model with T as the accelerating agent. Such power law dependence originates directly from the electromigration assumption of the failure mechanism, The Bayesian modeling began by researching published articles that can be used as prior information for Bayesian modeling. From the published data, we extracted the time required for the optical power output to reach 80% of its initial value (our failure criteria). Analysis of published data for different LED Materials (AlGaInP, GaN, AlGaAs), the Semiconductor Structures (DH, MQW) and the mode of testing (DC, Pulsed) was carried out. This data was converted to application conditions of the medical environment.

Many of the LED degradation mechanisms occur simultaneously. The weakest link causes the actual failure. This leads us to believe that Weibull distribution is the most suitable distribution for time to failure of the LEDs. We used this rationale to develop the Bayesian likelihood function. In this study, we report the results of our ALT and develop the Bayesian model as an approach for analyzing LED suitability for numerous system applications.

I. INTRODUCTION

In a medical electronics application for LEDs, the precise value of light intensity is used to interpret patient results. Hence understanding critical LED failure modes is very important. Failure Modes and Effects Criticality Analysis (FMECA) technique is commonly used in industry to identify critical failure modes based on their overall system effects (patient results in this case). See sections II.B.5 and V.A for details on FMECA.

There are numerous previous publications on LED reliability. However the application was mostly for lighting or fiber optic communications. Bayesian Analysis allowed us to combine prior published data with Accelerated Life Test (ALT) performed to verify the Medical diagnostic application. Bayesian Analysis involves compiling 'Prior' information, generating the 'Likelihood' function (probability of seeing the Evidence in terms of test data given the underlying failure distribution) and then estimating the 'Posterior' distribution. See sections III, IV.A and V.C for details on ALT and sections IV.B, IV.C and V.D for details on Bayesian Analysis.

II. MATERIALS AND METHODS

A. Materials

Commercially available AlGaInP 640nm MQW LEDs were used in this research. The structure and material combinations of similar LEDs have been previously reported [6, 9, 11, and 12].

B. Methods

1) AlGaInP LEDs were put on accelerated life test as described in section III and in Sawant et al [1].

2) Accelerated Life modeling for current density and temperature is described in section IV.A.

3) Regression analysis of prior published data for AlGaInP, GaN and GaAlAs LEDs is described in Sawant et al [1].
4) Bayesian Theorem and Bayesian Modeling are described in sections IV.B and IV.C respectively. Please refer to Mosleh et al [5] for details.
5) We used FMECA to perform risk analysis for use of LEDs in a medical diagnostic application as described below.

FMECA is a bottoms up approach, which identifies failure modes at a component level (LED in this context), and analyzes the system level effects (failure or partial failure of the medical diagnostic instrument in this case). The competing failure modes/mechanisms were degradation of: active layer [6, 7 and 12] where electron-hole recombination occurs to emit light, P-N contacts [2] which provide electrical contact to the semiconductor chip, Indium Tin Oxide surface layer [16] used to improve current spreading & light extraction, plastic encapsulation [21] which is a protective polymer layer and packaging failures [2] such as bond wires & heat sink separation. A FMECA table is constructed and the criticality is calculated by estimating the failure effect probability (β), failure mode ratio (α), failure rate (λ) and the operating time (t). Criticality is given by equation (1). The results of the FMECA are provided in section V.A.

$$Cm = \beta\alpha\lambda t \qquad - (1)$$

III. EXPERIMENTAL

AlGaInP LEDs were Accelerated Life Tested simultaneously in 3 Environment Chambers. The LEDs were tested in batches with 15 LEDs in each batch. The LEDs were driven in a pulse mode with a duty cycle of 0.2%. Testing was done at 3 temperatures (35°C, 55°C and 75°C) and 2 Peak currents (Batch2: 483mA=418.1A/cm^2, and Batch3: 725mA=627.2A/cm^2). The results are reported in Sawant et al [1] and we used them with some transformation for Bayesian Analysis.

IV. THEORY & CALCULATIONS

A. Modeling for Current Density & Temperature Acceleration

We have used Inverse Power Law (IPL) model with current density J as the accelerating variable. Since the prior published data spans over decades, use of current density (instead of current) normalizes the effect of die size increase to a great extent. The IPL is given as:

$$TTF = A.J^{-n} \qquad - (2)$$

Where TTF=Time to failure in hrs, J=LED Current density in Amps/cm^2, A & n are +ve constants.

The Acceleration Factor for Inverse Power Law Model is given by

$$AF_1 = \frac{TTF_{Use}}{TTF_{Acc}} = \left(\frac{J_{Acc}}{J_{Use}}\right)^n \qquad - (3)$$

For temperature acceleration, the Arrhenius reaction rate model was used as given by:

$$TTF = Ce^{\left(\frac{Ea}{KT}\right)} \qquad - (4)$$

Where T=Temperature in °K, Ea=Activation energy of the LED degradation, K=Boltzmann's constant, C=constant.

Acceleration Factor for Arrhenius Reaction Rate Model is given by:

$$AF_2 = \frac{TTF_{Use}}{TTF_{Acc}} = e^{\frac{Ea}{K}\left(\frac{1}{T_{Use}}-\frac{1}{T_{Acc}}\right)} \qquad - (5)$$

Since we had multiple data points at different temperatures and currents, we performed regression analysis to accommodate the results of both the accelerating variables. The overall Acceleration Factor is given by

$$AF = AF_1 x AF_2 = \left(\frac{J_{Acc}}{J_{Use}}\right)^n e^{\frac{Ea}{K}\left(\frac{1}{T_{Use}}-\frac{1}{T_{Acc}}\right)} \qquad - (6)$$

We used equation 6, published data and use conditions of the medical device application (i.e. temperature = 35°C and current density = 21.6Amps/sq2) to get the TTF distributions (given in Table 2) for AlGaInP-DH-DC, AlGaInP-MQW-DC, GaN-DH-DC, GaN-DH-DC etc. We used the same approach for analyzing our ALT data.

B. Baye's Theorem

For two events X and E, the probability of X AND E (represented by X•E) is the product of probability of X given E has occurred and probability of E

$$\Pr(X \bullet E) = \Pr(X|E)\Pr(E) \qquad - (7)$$

Similarly,

Pr(E•X) = Pr(E|X)Pr(X) - (8)

Since Pr(X•E) = Pr(E•X), we have

Pr(X|E)Pr(E) = Pr(E|X)Pr(X) - (9)

Rearranging (9) gives the Baye's Theorem

$$\Pr(X \mid E) = \frac{\Pr(E \mid X)\Pr(X)}{\Pr(E)} \quad - (10)$$

Now Pr(E) = Σ Pr(E|X)Pr(X) for all possible values of X, this gives

$$\Pr(X \mid E) = \frac{\Pr(E \mid X)\Pr(X)}{\sum \Pr(E \mid X)\Pr(X)} \quad - (11)$$

In Reliability applications, events X and E are represented by distributions. Summation is used for discrete distributions and integration is used for continuous distributions as shown below.

$$\pi_1(X \mid E) = \frac{L(E \mid X)\pi_0(X)}{\int L(E \mid X)\pi_0(X)dX} \quad - (12)$$

C. Bayesian Modeling of LED data

Many of the LED degradation mechanisms occur simultaneously. The weakest link causes the actual failure. This leads us to believe that Weibull distribution is the most suitable distribution for time to failure of the LEDs. For the first posterior, using Uniform Prior distribution for α & β is a good choice. Since only MTTF values were available, min-max values for α & β were estimated using engineering judgment. New test data was used as Evidence and a joint α-β posterior distribution was calculated using Bayesian updating. This joint α-β distribution gave a series of Weibull time to failure distributions. The predictive posterior failure distribution for the LEDs was estimated by averaging over the range of α-β values. Numerical techniques were used for various computations.

If the random variable *T* represents time to failure of the LED, the Weibull PDF f(*t*) and the Reliability R(*t*) are given by

$$f(t \mid \alpha, \beta) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad - (13)$$

$$R(t) = 1 - F(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad - (14)$$

where α = scale parameter & β = shape parameter

Consider a life test in which *n* LEDs are put on test and *r* out of *n* fail at failure times *t1, t2,…,tr*. The test is terminated at time *tc* at which point *n-r* LEDs did not fail. The only thing we know about these 'survived' LEDs is that their failure time is greater than *tc*. The failure times *t1, t2,…,tr* and the suspend time *tc* is the Evidence for the Bayesian Analysis.

The likelihood of r LEDs failing at ti (i = 1 to r) and n-r LEDs surviving time tc is given in (15) and (16) below

$$L(E \mid \alpha, \beta) = \prod_{i=1}^{r} f(t_i \mid \alpha, \beta) \prod_{i=1}^{n-r} R(t_c \mid \alpha, \beta) \quad - (15)$$

$$L(E \mid \alpha, \beta) = \beta^{r} \alpha^{-\beta r} \left(\prod_{i=1}^{r} t_{i}\right)^{\beta-1} \exp(-\alpha^{-\beta} T) \quad (16)$$

where $T = \sum_{i=1}^{r} t_i^{\beta} + \sum_{i=1}^{n-r} t_c^{\beta} = \sum_{i=1}^{r} t_i^{\beta} + (n-r)t_c^{\beta}$

The Uniform Prior distribution for α & β is given by equation below -(17)

$$\pi_0(\alpha, \beta) = \begin{cases} \dfrac{1}{(\alpha\ \max - \alpha\ \min)(\beta\ \max - \beta\ \min)}, & \alpha\ \min \le \alpha \le \alpha\ \max,\ \beta\ \min \le \beta \le \beta\ \max \\ 0, & otherwise \end{cases}$$

The posterior distribution for α & β can be estimated by using the Baye's theorem given is equation - (18)

$$\pi(\alpha, \beta \mid E) = \frac{L(E \mid \alpha, \beta)\pi_0(\alpha, \beta)}{\int_{\beta}\int_{\alpha} L(E \mid \alpha', \beta')\pi_0(\alpha', \beta')d\alpha' d\beta'}$$

Our final goal is to estimate the Weibull distributed time to failure. The joint posterior distribution of α and β then allows the posterior predictive distribution to be calculated as given by PDF equation (19) and CDF equation (20)

$$\overline{f}(t) = \int_{\beta}\int_{\alpha} f(t \mid \alpha', \beta')\pi_1(\alpha', \beta' \mid E)d\alpha' d\beta'$$

$$\overline{F}(t) = \int_{\beta}\int_{\alpha} F(t \mid \alpha', \beta')\pi_1(\alpha', \beta' \mid E)d\alpha' d\beta'$$

V. RESULTS & DISCUSSION

A. FMECA for LED in medical application

During our initial FMECA (based on our literature review and our knowledge of the medical diagnostic instrument), we estimated packaging heat sink de-lamination and degradation of the active region as the critical failure modes. After we performed ALT, we now believe that plastic encapsulation and active region degradation as the critical failure modes. Either of these failure modes will cause system level effects such as excessive drift requiring unscheduled calibration and delayed medical test results. See Table 1 as reproduced from Sawant et al [1].

Table 1 FMECA table after Accelerated Life Test

Sr.#	Failure Modes/Mechanisms	Causes	Local Effects at LED level	System Effects in Medical equipment	Severity	Failure Effect Probability (_)	Failure Mode Ratio (_)	Failure Rate	Operating Time (T) in hrs	Criticality #
1	Packaging failure (Heat Sink)	Heat sink de-lamination	- Decrease of optical output - Local heating effects	- Unscheduled module replacement - Delayed medical test results	3	0.4	0.3	1.8E-11	31500	6.7E-08
2	Degradation of plastic encapsulation	- Discoloration - Carbonization - Polymer degradation at high temperature	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	3	0.6	0.7	1.8E-11	31500	2.3E-07
3	Degradation of ITO layer	- Loss of Oxygen from ITO - De-adhesion	- Decrease of optical output - Non-uniform light emission	- Unscheduled module replacement - Delayed medical test results	4	0.3	0.1	1.8E-11	31500	1.7E-08
4	Packaging failure (Bond Wires)	- Electro-migration of bond wires - Burnout due to excessive current - Void formation at the solder metal stem - Reaction of solder metal with package electrodes	- Abrupt LED failure	- Unscheduled module replacement - Delayed medical test results	4	0.9	0.1	1.8E-11	31500	5.0E-08
5	Degradation of active layer	- Dislocation growth - Metal diffusion in AlGaInP - Heating effects of AlGaInP active region resulting in enhanced current injection	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	4	0.6	0.6	1.8E-11	31500	2.0E-07
6	Degradation of P-N metal contacts	- Interdiffusion	- Change in IV characteristics	- Design will accommodate minor changes in IV characteristics	5	0.4	0.2	1.8E-11	31500	4.5E-08

B. Thermal Shift of active layer Bandgap (Eg)

Reliability testing of AlGaInP/InP MQW LEDs resulted in a shift of Bandgap towards the longer wavelength when driven at high current and high duty cycles. The spectral FWHM also increased. Characterization of the shift showed that it was temporary and dependant on the junction temperature.

C. Logarithmic degradation of LED output

The optical power decreased with time due to degradation of the LED chip as well as the encapsulation. See Fig 1 and Fig 2. The rate of degradation followed a logarithmic function in agreement with Yanagisawa et al [31]. 20% degradation was considered failure for the medical application. For LEDs that did not reach 20% degradation in a reasonable time (suspend data), the logarithmic function was used to extrapolate TTF. Using regression analysis of ALT data, the activation energy 'Ea' was found to be 1.15eV and 'n' for IPL was 4.48. Note that a few LEDs showed extremely low degradation rates. LEDs not failed during ALT were excluded from the analysis since the focus was FMECA.

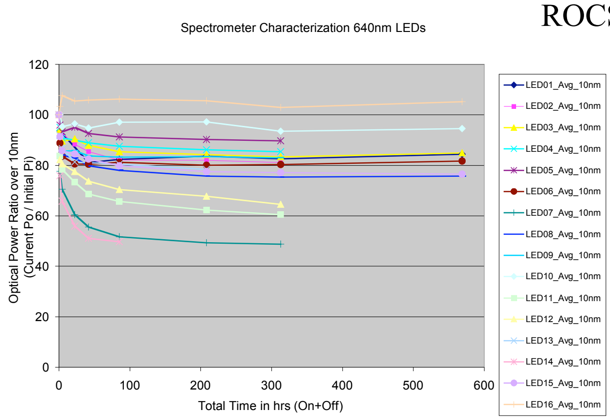

Fig 1 ALT for Batch2, 483mA

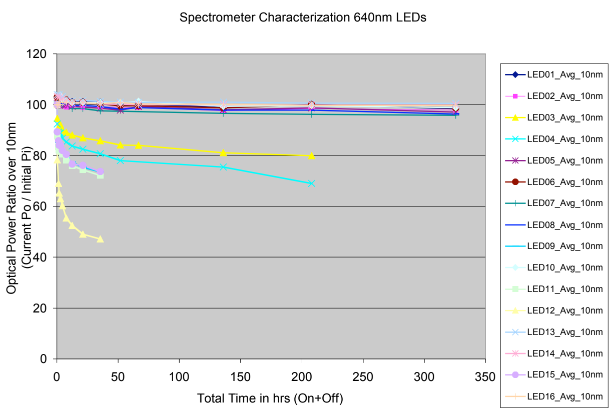

Fig 2 ALT for Batch3, 725mA

D. Bayesian Modeling

Results of prior published data and ALT as reported in Sawant et al [1] will be used in the Bayesian modeling. We have relied on Mosleh et al [5] for the Bayesian theory. In Table 2, Sr.# 1-4 represents prior data (normalized to current density and temperature values) under dc driving conditions where as Sr.#5 represents ALT data (normalized to current density and temperature values) under pulse (0.2% duty cycle) driving conditions. Since LED life under dc conditions was much shorter compared to pulse conditions, we had to transform Sr#.1-4 data in to Sr.#:1A-4A to allow using in our Bayesian model. This exact method of transformation will be covered in future work. For now, we will assume a simple multiplier of 500 (1 hr at 100% duty cycle is equivalent to 500hrs at 0.2% duty cycle).

Table 2: Results of Prior published data & ALT

Sr. #	**LED Material-Structure-Driving**	**Wei-bull α**	**Wei-bull β**	**Wei-bull MTTF Hrs**
1	AlGaInP-DH-DC	2.76E4	0.50	1.33E4
2	AlGaInP-MQW-DC	7.82E5	0.89	5.17E5
3	GaN-DH-DC	-	-	-
4	GaN-MQW-DC	1.61E5	0.57	8.47E4
5	ALT: AlGaInP-MQW-Pulsed (0.2%)	1.55E9	0.50	7.50E8
1A	AlGaInP-DH-Pulse-Transformed	1.38E7	0.5	6.65E6
2A	AlGaInP-MQW-Pulse-Transformed	3.91E8	0.89	2.59E8
3A	GaN-DH- Pulse-Transformed	-	-	-
4A	GaN-MQW-Pulse-Transformed	8.07E7	0.57	4.24E7

In this article, Bayesian updating involves computation of posterior joint α-β distribution by combining the prior joint α-β distribution with new Evidence/Likelihood function.

We started with a Uniform prior joint α-β distribution with α taking values between 5E7 to 9E9 and β taking values between 0.1 to 2. Uniform distribution implies that the probabilities are constant for the entire range. Further, since the Bayesian updating is done using a SW program that we wrote (to implement equation 18), we had to discreetize the α & β values. Now we used the actual data represented by Sr.# 2A in Table 2 as evidence to compute the 1st posterior joint α-β distribution as shown in Fig 3.

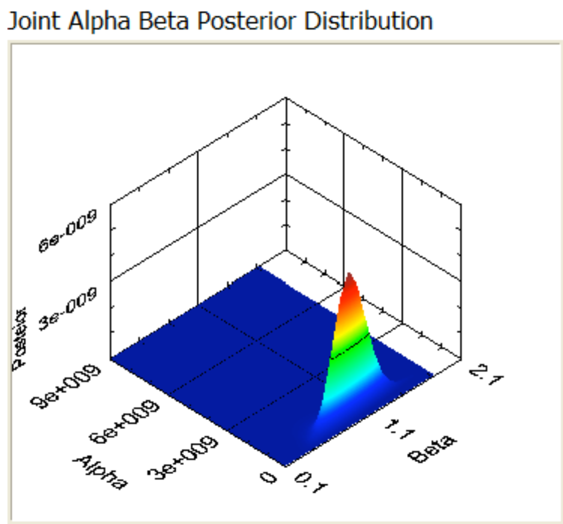

Fig 3. 1st Posterior Joint α-β distribution for AlGaInP-MQW-Pulse-Transformed

We used the 1st posterior joint α-β distribution to compute the Average Predictive distribution of the LED time to failure (TTF) using equations 19 and 20. See Fig 4 for the CDF of LED TTF.

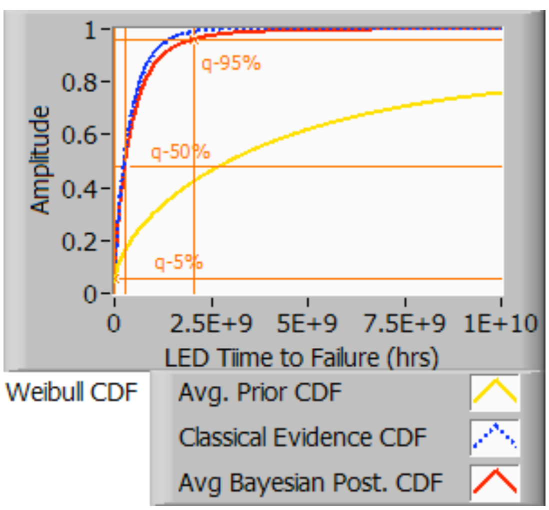

Fig 4. 1st Average Predictive Posterior of LED TTF

For the 2nd Bayesian updating, we used the 1st posterior joint α-β distribution as the prior distribution and the data representing Sr.# 5 in Table 2 as evidence. Fig 5 shows the 2nd Posterior Joint α-β distribution for AlGaInP-MQW-Pulse-ALT. Comparing Fig.3 and Fig.5, quickly reveals that the uncertainty in the Joint α-β distribution has decreased after 2nd Bayesian updating.

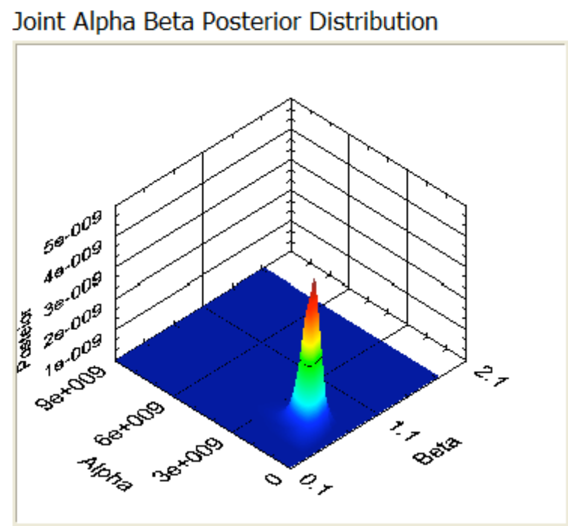

Fig 5. 2nd Posterior Joint α-β distribution for AlGaInP-MQW-Pulse-ALT

We can now compute the 2nd Average Predictive posterior distribution of the LED time to failure (TTF) using equations 19 and 20. See Fig 6 for the CDF of LED TTF. Again, comparing Fig 4 and Fig.6 reveals that 50th percentile of LED TTF changed from 2.75E8 to 6.38E8 hrs between 1st and 2nd Bayesian updating.

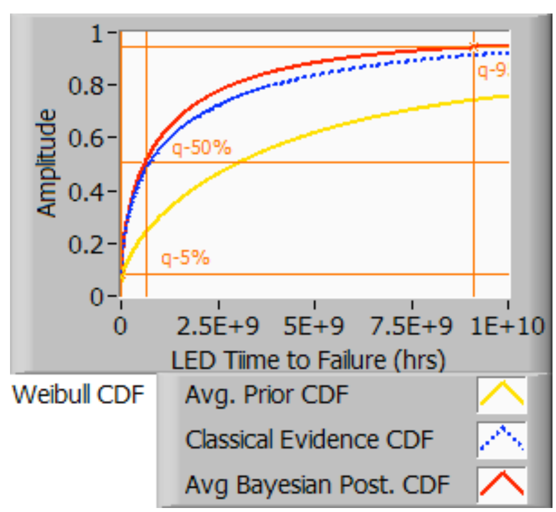

Fig 6. 2nd Average Predictive Posterior of LED TTF

VI. CONCLUSIONS

FMECA approach, widely used for risk analysis, has been successfully applied to LED reliability and physics of failure investigation. Degradation of the plastic encapsulation and the active region were found to be the critical failure modes. These failures could cause unscheduled calibration of the diagnostic instrument and would cause delay in patient medical test results.

To simulate the medical diagnostic application, LEDs were driven in pulse/burst mode during Accelerated Life testing. The degradation rate was found to be logarithmic and this was used to estimate TTF of suspend data. From the graphs or tabular data in prior published articles, we extracted the time required for the optical power output to reach 80% of its initial value. The activation energy 'Ea' and 'n' value during ALT are comparable. However, the time to failure during ALT is much higher compared to published data due to low duty cycle (0.2%).

Finally, we present Baye's approach to assessing the time to failure distribution of LEDs. Many of the LED degradation mechanisms occur simultaneously and the weakest link causes the actual failure. This leads us to believe that Weibull distribution is the most suitable distribution for time to failure of the LEDs. For the first posterior, using Uniform Prior distribution for α & β is a good choice. For successive Bayesian updating, prior published data and ALT data (converted to medical application conditions) were used. The power of Bayesian modeling comes from the fact that as new evidence/test data becomes available, successive Bayesian updating allows us to improve our LED TTF estimates.

VII. REFERENCES

[1] Sawant et al. 'Failure Modes and Effects Criticality Analysis and Accelerated Life Testing of LEDs for Medical Applications', Special ISDRS2011 Solid State Electronics Issue, 2012 (to be published).

[2] Mitsuo Fukuda, 'Reliability & Degradation of Semiconductor Lasers & LEDs', 1991

[3] Shuji Nakamura & S.F. Chichibu, 'Introduction to Nitride Semiconductor Blue Lasers & LEDs', 2000

[4] K. Wada & S.W. Pang, 'Defects in Optoelectronic Materials', 2001

[5] Ali Mosleh, 'Bayesian Methods for Risk and Reliability', 2007

[6] Vanderwater et al. 'High-brightness AlGaInP light emitting diodes', Proceedings of the IEEE, Vol. 85, Issue 11, Pages 1752-1764, Nov. 1997

[7] Grillot et al. 'Sixty Thousand Hour Light Output Reliability of AlGaInP LEDs', IEEE Transactions on Device and Material Reliability, Vol. 6, No.4, Pages 564-574, Dec 2006

[8] Kish et al. 'Highly reliable and efficient semiconductor wafer-bonded AlGaInP/GaP LEDs', Electronics Letters, Vol. 32, Issue 2, Pages132–136, Jan 1996.

[9] Chang et al. 'AlGaInP multiquantum well light-emitting diodes', IEE Proc.-Optoelectron., Vol. 144, No. 6, December 1997

[10] Kish et al. 'High luminous flux semiconductor wafer-bonded AlGaInP/GaP large-area emitters', Electronics Letters, Vol. 30, Issue 21, Pages 1790-1792, October 1994

[11] Krames et al. 'Status and Future of High-Power LEDs for Solid-State Lighting', Journal of Display Technology, Vol. 3, Issue 2, Pages 160–175, June 2007

[12] Streubel et al. 'High Brightness AlGaInP Light-Emitting Diodes', IEEE Journal of Selected Topics in Quantum Electronics, Pages 321–332, March-April 2002

[13] Altieri et al. 'Analysis of internal quantum efficiency of high-brightness AlGaInP LEDs', The 4th International Conference on Numerical Simulation of Optoelectronic Devices Proceedings NUSOD '04, Pages 13-14, August 2004

[14] Liang et al. 'Comparison of temperature dependent electroluminescence of InGaN/GaN and AlGaInP based LEDs', Optoelectronics, The 6th Chinese Symposium Proceedings Pages 196-199, Sept. 2003.

[15] Philips, 'LUXEON Reliability Datasheet RD25', Pages 9-10, July 2006

[16] Lin et al. 'Highly reliable operation of indium tin oxide AlGaInP light emitting diodes', Electronics Letters, Vol. 30, No.21, October 1994

[17] Su et al. 'High Reliability of AlGaInP LEDs with tensile strain barrier-reducing Layer', IEEE Photonics Technology Letters, Vol. 16, Issue 1, Pages 30–32, Jan. 2004

[18] Lacey et al. 'The Reliability of AlGaInP visible LEDs', Quality & Reliability Engineering, Vol. 16, Issue 1, Pages 45 – 49, 2000.

[19] Dutta et al. 'High Brightness and Reliable AlGaInP-Based LED for POF Data Links', IEEE Photonics Technology Letters, Vol. 9, No 12, December 1997.

[20] Meneghini et al. 'A review on the Reliability of GaN based LEDs', IEEE Transactions on Device and Materials Reliability, Vol. 8, No. 2, June 2008.

[21] Meneghini et al. ' A review on the physical mechanisms that limit the reliability of GaN based LEDs', IEEE Transactions on Electron Devices, Vol. 51, Issue. 1, Jan 2010.

[22] Levada et al. ' Analysis of DC Current Accelerated Life Tests of GaN LEDs Using a Weibull-Based Statistical Model', IEEE Transactions on Device and Materials Reliability, Vol. 5, No. 4, Dec 2005.

[23] Buso et al. 'Performance Degradation of High-Brightness LEDs Under DC and Pulsed Bias', IEEE Transactions on Device and Materials Reliability, Vol. 8, No. 2, June 2008.

[24] Trevisanello et al. 'Accelerated life test of High Brightness LEDs', IEEE Transactions on Device and Materials Reliability, Vol. 8, No. 2, June 2008.

[25] Meneghesso et al. 'Degradation mechanisms of GaN-based LEDs after accelerated DC current aging', Electron Devices Meeting Digest, Pages 103-106, Dec 2002.

[26] Levada et al. ' High Brightness InGaN LED degradation at high injection current bias', 44th Annual International Reliability Physics Symposium Proc., Pages 615-616, Mar 2006.

[27] Meneghesso et al. 'Failure mechanisms of GaN-based LEDs related with instabilities in doping profile and deep levels', 42nd Annual International Reliability Physics Symposium Proceedings, Pages 474-478, April 2004.

[28] Osinski et al. 'AlGaN/InGaN/GaN blue light emitting diode degradation under pulsed current stress', Applied Physics Letters, 69 (7), August 1996.

[29] Barton et al. 'Life tests and failure mechanisms of GaN-AlGaN-InGaN LEDs', 35th Annual International Reliability Physics Symposium Proc, Pages 276-281, April 1997.

[30] Barton et al. 'Degradation mechanisms in GaN/AlGaN/InGaN LEDs and LDs', 10th Conf. on Semiconducting & Insul. Materials Proc., Pages 259-262, June 1998.

[31] Yanagisawa T., 'Estimation of the degradation of InGaN/A1GaN Blue LEDs', Microelectronic Reliability, Vol. 37, No. 8, pp. 1239-1241, 1997.

[32] Yanagisawa T. ' The degradation of GaAlAs red LEDs under continuous and low-speed pulse operations ', Microelectronics Reliability 38, pp. 1627-1630, 1998.

[33] Narendran et al. 'Life of LED-Based White Light Sources', IEEE/OSA Journal of Display Technology, Vol. 1, NO. 1, September 2005.