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Enhancement Study on Lumen Depreciation & Thermal Management System in Commercial LEDs Bulb from a Product Lifecycle Perspective

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Abstract

In the dynamic realm of LED technology, this paper embarks on a detailed exploration of material engineering and thermal dynamics, key drivers in augmenting the performance and ecological viability of LED lighting. Our investigation is anchored in the study of Polycarbonate (PC) and Polybutylene Terephthalate (PBT) fundamental to LED housing. These materials have been meticulously selected for their exemplary fusion of structural resilience, cost-effectiveness, and advanced thermal management, especially through the use of heat sinks and thermal glue. We thoroughly evaluate their impact on the robustness and functional efficiency of LEDs under diverse thermal conditions and operational stresses. A crucial facet of our study is lumen depreciation, a principal measure of LED longevity. This paper illuminates the intricate relationship between material attributes and the rate of light intensity reduction, thereby dictating the effective operational life of LED units. The durability of PC and PBT in the face of frequent switching cycles is rigorously examined, unearthing vital insights into their adaptability for variable usage patterns. Our comprehensive examination of heat transfer processes, particularly conduction and convection, highlights their pivotal role in the thermal regulation of LEDs, a factor that significantly influences their operational efficiency and service life. By embracing this multi-dimensional approach, our research provides a refined understanding of the LED lifecycle, particularly through a meticulous examination of lumen depreciation and innovative heat design. Our findings aim to propel the future of LED technology towards a horizon of enhanced sustainability and efficiency, setting new benchmarks in lighting solutions.

Keywords

LED Light, Lumen Depreciation, Product Lifecycle, LM80, Residential Lighting.

1. Introduction

As the world grapples with the twin challenges of energy sustainability and environmental preservation, the role of advanced lighting technologies, especially LED (Light Emitting Diodes), comes to the forefront. This research is driven by the urgent need to mitigate the environmental footprint of lighting solutions and the pursuit of greater energy efficiency. LEDs, heralded as the beacon of modern lighting, stand at the cusp of this revolution, but their full potential is shackled by current limitations in material science and thermal management. LED lightings have been widely employed in many fields of application, such as automobiles, biology, streetlighting, scientific research, and the medical industry, thanks to its high luminescence efficiency and longer lifespan compared to incandescent lighting. The demand for high-power LED lighting systems in these applications has grown significantly. [Ju Yong Cho and Won Kweon Jang 2023]

The motivation for this research springs from a critical gap in existing LED technology – the optimization of materials for enhanced performance and sustainability. Traditional materials, while functional, fall short in harnessing the complete suite of benefits that LEDs offer. This study aims to unravel the intricacies of Polycarbonate (PC) and Polybutylene Terephthalate (PBT) in the context of LED housing, scrutinizing their impact on the operational efficacy and longevity of LED units. In parallel, the research seeks to dissect the thermal dynamics of these lighting systems, focusing on heat transfer mechanisms and their role in lumen depreciation, a key factor in the lifecycle of LEDs.

The problems this research endeavors to solve are critical: firstly, to establish a deeper understanding of how the choice of materials like PC and PBT can revolutionize the design and functionality of LEDs, and secondly, to optimize the thermal behavior of these units, thereby extending their lifespan and enhancing efficiency. This exploration is not just academic; it is a necessary stride towards eco-friendly, determine the life cycle of LED and cost-effective lighting solutions, aligning with global energy conservation goals. By bridging these knowledge gaps, the research aspires to illuminate pathways to a more sustainable and enlightened future.

1.1 Objectives

To Evaluate the Impact of Material Selection on LED Performance: This objective involves a comprehensive analysis of Polycarbonate (PC) and Polybutylene Terephthalate (PBT) in the context of LED housing. The aim is to determine how these materials influence the efficiency, durability, and overall performance of LED lights.

To Provide Recommendations for Material Selection and Thermal Design in LED Manufacturing: Based on the lumen depreciation with other findings, this objective is to offer actionable recommendations for the industry, aimed at improving the sustainability and performance of LED technology.

To Investigate the Thermal Dynamics of LEDs: Central to this objective is the exploration of heat transfer mechanisms, particularly conduction and convection, in LED units. Thermal management is a key technology for creating reliable, high lumen, LED systems. Package level and system level thermal management constructs the overall thermal architecture. [Mehmet, Charles,2004] The goal is to understand how these thermal processes affect lumen depreciation and the operational lifespan of LEDs.

To Assess the Longevity and Reliability of LEDs Under Various Operational Conditions: This includes studying the effects of frequent switching cycles on LEDs made with PC and PBT materials. The research aims to provide insights into the resilience of these materials and their suitability for different applications.

2. Methods

First and foremost, abiding by these standards ensures that your LED lamps meet the global criteria for safety and performance. This provides a level playing field in the international market, where your products will be competing with others that also comply with these standards. By ensuring your LEDs meet these criteria, you signal to your customers that your products are trustworthy and high-quality. [Fakir Sheik Zihad 2024]

The IEC 62612:2015 standard sets out the performance requirements for LED lamps, including metrics such as luminous flux, power consumption, lifetime, and color properties. It is an essential benchmark for the efficiency and longevity of LED lamps, and compliance with it ensures that your products deliver on their promises.
Similarly, the IEC 62560:2015 standard specifies the safety specifications for LED lamps for general lighting services. Compliance with this standard ensures that your LED lamps are safe for consumer use, thus reducing the risk of product liability issues and bolstering your brand's reputation. [Fakir Sheik Zihad 2024]

The LM80 standard, officially known as IES LM-80, is a method for measuring the lumen maintenance of LED light sources. Developed by the Illuminating Engineering Society (IES), it's a widely recognized standard in the lighting industry. Lumen maintenance refers to the amount of light output that remains as a light source ages compared to its initial output. It specifies how the testing should be conducted, including the ambient temperature conditions, test duration (typically a minimum of 6,000 hours, and often up to 10,000 hours), and the measurement intervals.

3. Data Collection, Results and Discussion

Diffuser Material:

In LED bulb design, the selection of materials for the diffuser component is critical to the performance and longevity of the bulb. Polycarbonate (PC) is a favored material for diffusers due to its outstanding physical, mechanical, thermal, and optical properties. PC has an excellent transparency rate (80% at 1mm thickness), which ensures minimal light loss when used as a diffuser, thereby maintaining the LED bulb's brightness and efficiency.

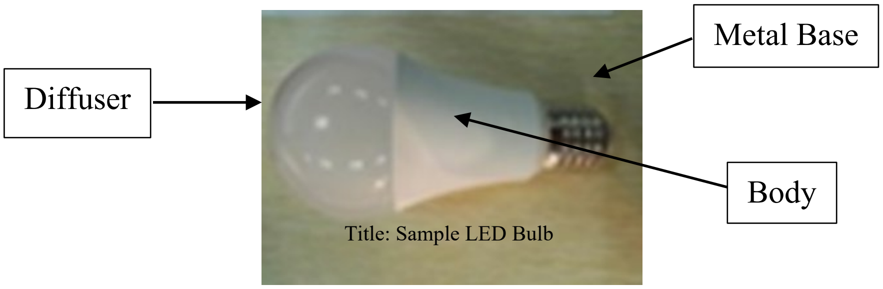
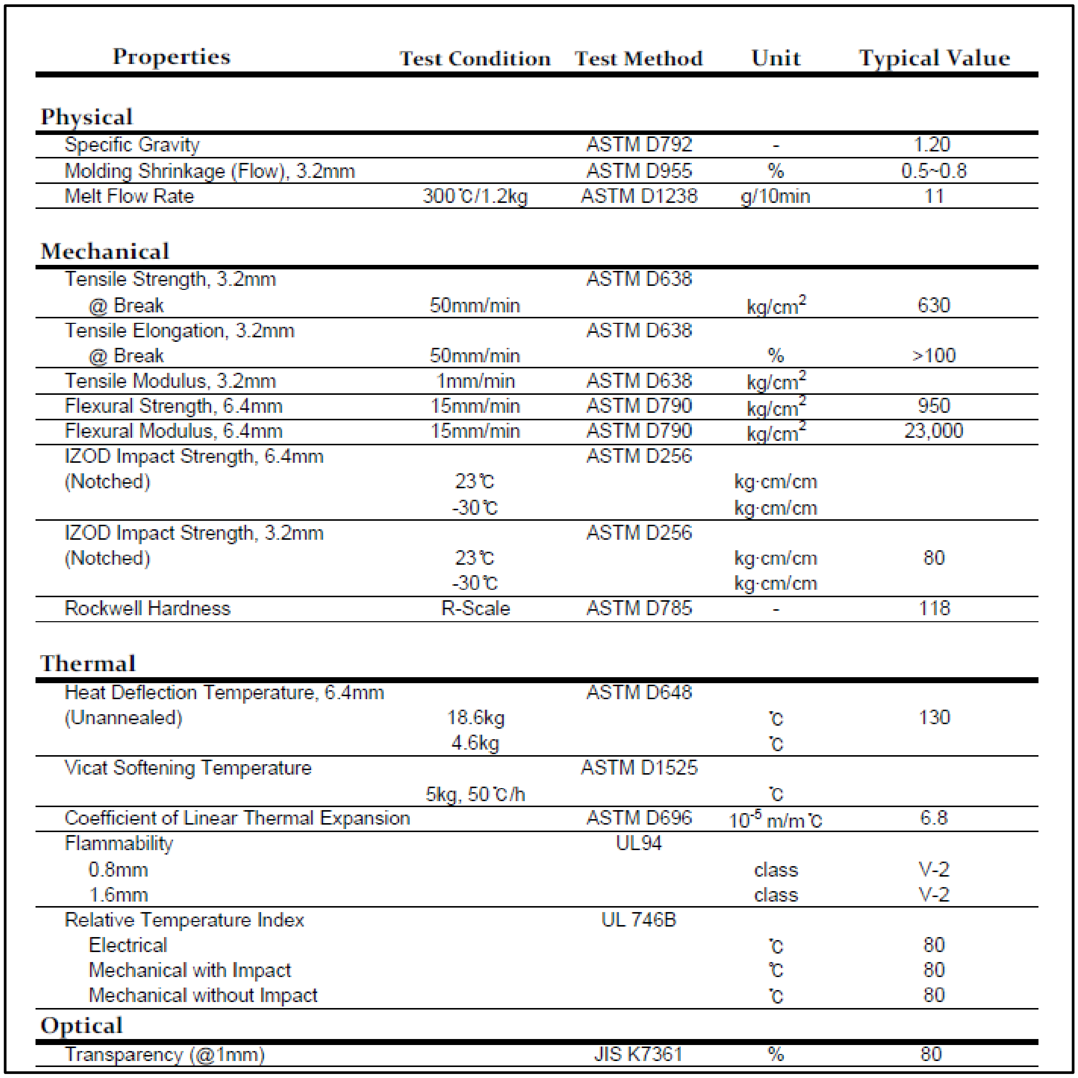


Figure 1. Sample LED Bulb

A diffuser in the context of LED lighting is a critical component designed to spread the light emitted from the LED bulb evenly across a space. The efficiency of a diffuser is measured by its ability to transmit light. Good diffusers maintain high luminous efficacy, ensuring minimal loss of luminous output from the LED source to the point of use. A well-designed diffuser allows for optimal light transmission while minimizing glare. The diffuser scatters the LED's point-source light, converting it into a wide, uniform, and soft light, which is more comfortable for human eyes. The design and material of the diffuser can affect the overall efficiency of the LED bulb. A balance must be struck between sufficient diffusion to soften and spread light and maintaining high efficiency by minimizing the loss of total light output. PC diffusers can offer excellent impact resistance and can endure high temperatures, making them ideal for various lighting conditions that's why we chose PC material.

According to the provided datasheet, the following attributes of PC are particularly pertinent:



Properties	Test Condition	Test Method	Unit	Typical Value
Physical				
Specific Gravity		ASTM D792	-	1.20
Molding Shrinkage (Flow), 3.2mm		ASTM D955	%	0.5~0.8
Melt Flow Rate	300℃/1.2kg	ASTM D1238	g/10min	11
Mechanical				
Tensile Strength, 3.2mm		ASTM D638		
@ Break	50mm/min		kg/cm^2	630
Tensile Elongation, 3.2mm		ASTM D638		
@ Break	50mm/min		%	>100
Tensile Modulus, 3.2mm	1mm/min	ASTM D638	kg/cm^2	
Flexural Strength, 6.4mm	15mm/min	ASTM D790	kg/cm^2	950
Flexural Modulus, 6.4mm	15mm/min	ASTM D790	kg/cm^2	23,000
IZOD Impact Strength, 6.4mm		ASTM D256		
(Notched)	23℃		kg·cm/cm	
	-30℃		kg·cm/cm	
IZOD Impact Strength, 3.2mm		ASTM D256		
(Notched)	23℃		kg·cm/cm	80
	-30℃		kg·cm/cm	
Rockwell Hardness	R-Scale	ASTM D785	-	118
Thermal				
Heat Deflection Temperature, 6.4mm		ASTM D648		
(Unannealed)	18.6kg		℃	130
	4.6kg		℃	
Vicat Softening Temperature		ASTM D1525		
	5kg, 50℃/h		℃	
Coefficient of Linear Thermal Expansion		ASTM D696	10^{-5} m/m℃	6.8
Flammability		UL94		
0.8mm			class	V-2
1.6mm			class	V-2
Relative Temperature Index		UL 746B		
Electrical			℃	80
Mechanical with Impact			℃	80
Mechanical without Impact			℃	80
Optical				
Transparency (@1mm)		JIS K7361	%	80

Figure 2. Title: Technical Datasheet of PC Materials

PC's low molding shrinkage rate (0.5-0.8%) is crucial for manufacturing precision, ensuring that the diffuser fits accurately within the LED bulb assembly.
A reasonable melt flow rate (11 g/10min) allows for easier processing and molding of the PC into the complex shapes often required for diffuser components.

After making the Diffuser, we tested ten samples with the following parameters which are given below:

Table 1. Diffuser Material Performance Test Result

Sl No.	Sample taking time	Power (Watt)	Current(A)	Power Factor	Lumen	Efficacy	CCT	Ra	Remarks
1	9:00Am	*8.94*	*0.041*	*0.931*	*955.8*	*106.9*	*6523*	*77.9*	*Comply*
2	9:00Am	*9.03*	*0.042*	*0.931*	*923.2*	*102.3*	*6530*	*78.2*	*Comply*
3	9:00Am	*9.00*	*0.042*	*0.931*	*948.3*	*105.4*	*6587*	*78.3*	*Comply*

4	9:00Am	*8.93*	*0.041*	*0.934*	*952.3*	*106.7*	*6543*	*78.1*	*Comply*
5	9:00Am	*9.00*	*0.042*	*0.931*	*966.6*	*107.5*	*6713*	*78.5*	*Comply*
6	9:00Am	*8.98*	*0.042*	*0.930*	*944.6*	*105.2*	*6613*	*78.4*	*Comply*
7	9:00Am	*8.98*	*0.042*	*0.931*	*942.0*	*105.0*	*6629*	*78.6*	*Comply*
8	9:00Am	*8.97*	*0.042*	*0.931*	*939.2*	*104.7*	*6639*	*78.6*	*Comply*
9	9:00Am	*8.92*	*0.041*	*0.934*	*971.7*	*108.9*	*6652*	*78.2*	*Comply*
10	9:00Am	*8.92*	*0.041*	*0.938*	*965.4*	*108.2*	*6676*	*78.4*	*Comply*

Additionally, these parameters were also checked after making the diffuser:

Table 2. Physical Checking Criteria of Diffuser

Checking Parameters	Sample 1	Sample 2	Sample 3	Remarks
Diffuser locking system with the body	√	√	√	Comply
Scratch	√	√	√	Comply
Bubble / Spot	√	√	√	Comply
Plastic Color	√	√	√	Comply

So, here the attributes of PC not only contribute to the diffusion of light to achieve a uniform light distribution but also ensure that the diffuser can withstand environmental and operational conditions typical to LED bulbs. Thus, Polycarbonate emerges as an exemplary material that aligns with the goals of durable, efficient, and safe LED lighting solutions.

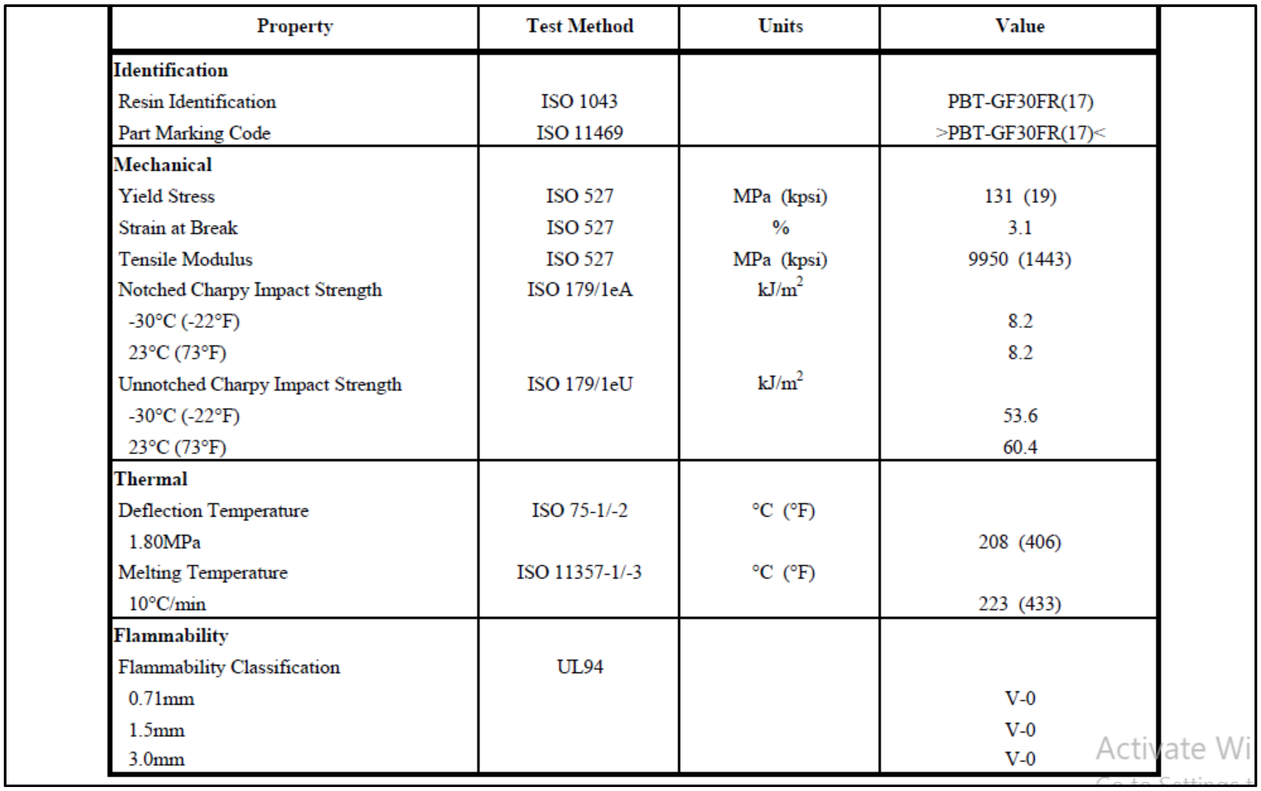
LED Bulb's Body Material:

Polybutylene Terephthalate (PBT) is a type of thermoplastic polyester that is often chosen for LED Bulb's body manufacturing due to its balance of mechanical, electrical, and thermal properties. This material consists of a 30% glass fiber reinforced flame retardant PBT, here are some reasons why PBT is suitable material for an LED bulb body:

PBT has a good thermal stability indicated by a high melting temperature (223°C or 433°F) and a deflection temperature under load (208°C or 406°F). These characteristics mean it can withstand the heat generated by LEDs without deforming. The flame retardancy of PBT, as evidenced by its UL94 V-0 classification, is crucial for safety in electrical applications. This would help to contain any potential fires that could arise from electrical malfunctions.
PBT possesses a good balance of mechanical properties, such as a high yield stress and tensile modulus. The 30% glass fiber reinforcement would further enhance its rigidity and dimensional stability, ensuring the bulb maintains its shape and integrity throughout its use.

The material has notable notched Charpy impact strength, meaning it can resist breakage upon impact which is important for handling during installation and use. Typically, PBT has excellent electrical insulating properties, although not specifically listed in the datasheet you provided, this characteristic is inherent in PBT and important for LED bulb applications to prevent electrical hazards.
PBT is resistant to various chemicals and solvents which can ensure longevity and durability in various environments. PBT resins usually have low shrinkage rates, which make them suitable for precision parts that require tight tolerances, such as LED bulb bodies.

The use of such a material helps to ensure that the bulb will perform reliably over its intended lifespan, even under thermal and mechanical stresses that are typical in both the manufacturing process and during end-use.



Property	Test Method	Units	Value
Identification			
Resin Identification	ISO 1043		PBT-GF30FR(17)
Part Marking Code	ISO 11469		>PBT-GF30FR(17)<
Mechanical			
Yield Stress	ISO 527	MPa (kpsi)	131 (19)
Strain at Break	ISO 527	%	3.1
Tensile Modulus	ISO 527	MPa (kpsi)	9950 (1443)
Notched Charpy Impact Strength	ISO 179/1eA	kJ/m^2	
-30°C (-22°F)			8.2
23°C (73°F)			8.2
Unnotched Charpy Impact Strength	ISO 179/1eU	kJ/m^2	
-30°C (-22°F)			53.6
23°C (73°F)			60.4
Thermal			
Deflection Temperature	ISO 75-1/-2	°C (°F)	
1.80MPa			208 (406)
Melting Temperature	ISO 11357-1/-3	°C (°F)	
10°C/min			223 (433)
Flammability			
Flammability Classification	UL94		
0.71mm			V-0
1.5mm			V-0
3.0mm			V-0

Figure3. Technical Datasheet of PC Materials

5.2 Graphical Results

The life cycle test is a very important and crucial factor for determining the warranty period of an LED and with a long time use, the product remains safe throughout its lifespan, not just when it is new. Life-cycle testing ensures that LED products meet specific quality and durability standards before they are brought to market. This testing helps manufacturers identify and correct potential defects, leading to higher customer satisfaction and lower warranty costs. It confirms that the LED maintains its brightness and color over time and that its performance degrades at an acceptable rate, as indicated by the lumen depreciation tests. For LED Life cycle analysis, we have done 3 types of tests which are given below:

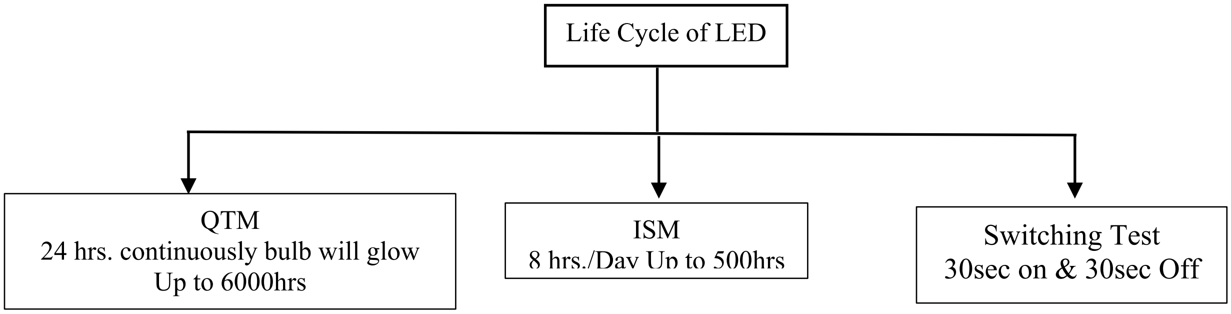


Figure 4. LED Life Cycle Test Types

These tests provide data on the reliability of the LED product, allowing manufacturers to predict the lifespan and schedule maintenance or replacements accordingly.

QTM:

QTM test, refers to a long-term endurance test where the LED bulb is kept on continuously, 24 hours a day, until it reaches 6,000 hours of operation. The results from QTM tests guide manufacturers in product development and inform consumers about product performance. It also plays a role in warranties and product claims. One of the primary focuses is on lumen maintenance, which is how well the bulb maintains its brightness over time. A lumen depreciation of 30% (often referred to as L70) is a common benchmark for the end of life for many commercial LEDs.

$$\text{Here \% of Lumen Depreciation Calculation} = \frac{\text{Initial Lumen} - \text{Lumen After a Certain Period}}{\text{Initial Lumen}} \text{ X } 100$$

Noted that the ambient air temperature must be maintained at 25 °C ± 3 °C, with minimal airflow. LEDs are temperature sensitive and large temperature fluctuations or excessive air flow can result in errors in lumen maintenance measurements.

Table 3. Lumen Depreciation Test of QTM up to 3000hrs

SN.	Item Name	Power (W)	Initial lumen (Avg.)	Initial Efficacy (Avg.)	Wattage after 300 Hr.	Lumen after 300Hr.	% of Lumen Depreciation after 300Hr.	Wattage after 500Hr.	Lumen after 500Hr.	% of Lumen Depreciation after 500Hr.
1	9W AC LED Bulb	8.20	943.2	114.97	8.2	921	2.35%	8.2	901	4.47%
2		8.27	966.2	116.84	8.26	938	2.92%	8.26	917	5.09%
3		8.25	922.0	111.80	8.25	907	1.63%	8.25	884	4.12%

SN.	Item Name	Power (W)	Initial lumen (Avg.)	Initial Efficacy (Avg.)	Wattage after 1000Hr.	Lumen after 1000Hr.	% of Lumen Depreciation after 1000Hr.	Wattage after 1250Hr.	Lumen after 1250Hr.	% of Lumen Depreciation after 1250Hr.
1	9W AC LED Bulb	8.20	943.2	114.97	8.1	897	4.90%	8.01	881	6.59%
2		8.27	966.2	116.84	8.2	909	5.92%	8.11	891	7.78%
3		8.25	922.0	111.80	8.14	874	5.21%	8.06	865	6.18%

SN.	Item Name	Power (W)	Initial lumen (Avg.)	Initial Efficacy (Avg.)	Wattage after 1500Hr.	Lumen after 1500Hr.	% of Lumen Depreciation after 1500Hr.	Wattage after 2000Hr.	Lumen after 2000Hr.	% of Lumen Depreciation after 2000Hr.
1	9W AC LED Bulb	8.20	943.2	114.97	7.96	870	7.73%	7.86	852	9.66%
2		8.27	966.2	116.84	8.01	883	8.61%	7.91	867	10.27%
3		8.25	922.0	111.80	7.90	854	7.37%	7.81	838	9.11%

SN.	Item Name	Power (W)	Initial lumen (Avg.)	Initial Efficacy (Avg.)	Wattage after 2500Hr.	Lumen after 2500Hr.	% of Lumen Depreciation after 2500Hr.	Wattage after 3000Hr.	Lumen after 3000Hr.	% of Lumen Depreciation after 3000Hr.
1	9W AC LED Bulb	8.20	943.2	114.97	7.78	834	11.58%	7.71	817	13.37%
2		8.27	966.2	116.84	7.80	849	12.13%	7.72	831	13.99%
3		8.25	922.0	111.80	7.76	820	11.06%	7.69	803	12.90%

Table 4. Lumen Depreciation Test of QTM from 3500hrs to 6000hrs

SN.	Item Name	Power (W)	Initial lumen (Avg.)	Initial Efficacy (Avg.)	Wattage after 3500Hr.	Lumen after 3500Hr.	% of Lumen Depreciation after 3500Hr.	Wattage after 4000Hr.	Lumen after 4000Hr.	% of Lumen Depreciation after 4000Hr.
1	9W AC LED Bulb	8.20	943.2	114.97	7.63	799	15.29%	7.57	781	17.19%
2		8.27	966.2	116.84	7.64	814	15.75%	7.58	795	17.71%
3		8.25	922.0	111.80	7.59	784	14.97%	7.48	767	16.81%

SN.	Item Name	Power (W)	Initial lumen (Avg.)	Initial Efficacy (Avg.)	Wattage after 4500Hr.	Lumen after 4500Hr.	% of Lumen Depreciation after 4500Hr.	Wattage after 5000Hr.	Lumen after 5000Hr.	% of Lumen Depreciation after 5000Hr.
1	9W AC LED Bulb	8.20	943.2	114.97	7.49	762	19.21%	7.41	742	21.33%
2		8.27	966.2	116.84	7.51	777	19.58%	7.43	760	21.34%
3		8.25	922.0	111.80	7.40	749	18.76%	7.32	731	20.71%

SN.	Item Name	Power (W)	Initial lumen (Avg.)	Initial Efficacy (Avg.)	Wattage after 5500Hr.	Lumen after 5500Hr.	% of Lumen Depreciation after 5500Hr.	Wattage after 6000Hr.	Lumen after 6000Hr.	% of Lumen Depreciation after 6000Hr.
1	9W AC LED Bulb	8.20	943.2	114.97	7.32	724	23.56%	7.22	704	25.36%
2		8.27	966.2	116.84	7.33	746	22.79%	7.24	727	24.76%
3		8.25	922.0	111.80	7.21	712	22.78%	7.11	695	24.62%

Table 5. Cumulative Summery of QTM Test

SN.	Avg Lumen Depreciation Result	Standard	Remarks
1	After 500hrs is 4.56%	10%	Comply
2	After 1000hrs is 5.34%		
3	After 1500hrs is 7.90%		
4	After 2000hrs is 9.68%	20%	
5	After 2500hrs is 11.59%		
6	After 3000hrs is 13.42%		
7	After 3500hrs is 15.34%	25%	Comply
8	After 4000hrs is 17.24%		
9	After 4500hrs is 19.18%		
10	After 5000hrs is 21.13%	30%	
11	After 5500hrs is 23.04%		
12	After 6000hrs is 24.91%		

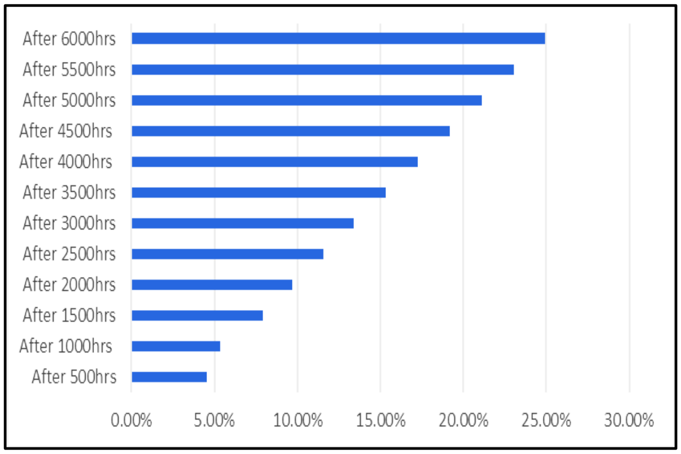


Figure. 5 Title: QTM Test Result

Initially, the LED product exhibits a 4.56% reduction in luminosity after 500 hours, which is well within the acceptable 10% margin. As the operational duration extends, an incremental escalation in lumen depreciation is observed. Notably, at 1,000 and 2,000-hour intervals, the depreciation remains below the 10% and 20% thresholds, respectively, indicating adherence to the standards. Beyond the 2,000-hour mark, the standard permits a more liberal 20% reduction, which is not surpassed until after 2,500 hours of use. This trend continues with the product maintaining performance within the permissible depreciation margins up to 4,500 hours, correlating to a standard of 25%.

Remarkably, the product continues to comply with the escalating standards, with depreciation remaining below 30% at the 5,500-hour checkpoint. By the conclusion of the 6,000-hour test period, the LED demonstrates a lumen depreciation of 24.91%, which is under the maximum allowed 30% depreciation, thus reflecting the product's durability and robustness over extended use. In essence, the table confirms that the LED product in question maintains luminous efficacy within the acceptable bounds set by industry standards throughout its evaluated lifecycle, thereby corroborating its compliance and reliability.

ISM:

The Initial Screening Method (ISM) with 8 hours per day testing is designed to simulate typical consumer use of LED bulbs, reflecting an average daily usage pattern. This method is part of the life cycle testing that aims to evaluate the lumen maintenance, which is the ability of the LED bulb to retain its brightness over time. By operating the LED bulbs for 8 hours each day and measuring the lumen output at specific intervals, researchers like us can assess how quickly and to what extent the luminosity decreases from the initial value. This gradual decrease in light output, or lumen depreciation, is a critical factor in determining the bulb's longevity and overall performance. The ISM thus provides valuable data that can help predict the bulb's behavior under normal usage conditions and is an important aspect of product development and quality assurance for LED lighting solutions.

Table 6. Initial Screening Method Test (8hrs/day)

SN	Initial Lumen	After 100hr Lumen Depreciation	%	After 200hr Lumen Depreciation	%	After 300hr Lumen Depreciation	%	After 400hr Lumen Depreciation	%	After 500hrs Lumen Depreciation	%
1	927	919.49	0.81%	915.88	1.20%	910.41	1.79%	900.30	2.88%	891.49	3.83%
2	963	956.35	0.69%	950.29	1.32%	945.18	1.85%	934.30	2.98%	925.54	3.89%
3	924	917.35	0.72%	912.72	1.22%	908.57	1.67%	900.71	2.52%	890.09	3.67%

This table details the lumen depreciation of three LED bulbs over a 500-hour period with a daily usage of 8 hours. Each bulb starts with a different initial lumen output (927, 963, and 924 respectively) and shows incremental lumen depreciation at intervals of 100 hours. After 500 hours, the lumen output for Sample 1 has depreciated by 3.83%, Sample 2 by 3.89%, and Sample 3 by 3.67%. All samples display a lumen depreciation within acceptable limits, indicating they have passed the test for maintaining sufficient brightness over the assessed period.

Switching Cycle Test:

The switching test is vital for assessing the durability of LED bulbs in conditions where they are frequently turned on and off. This test simulates the stress experienced by LEDs in applications like motion-activated lighting, where the frequency of switching can significantly impact the lifespan of the bulb. It measures not only the lumen depreciation but also the electronic and thermal components' resilience to the thermal cycling caused by rapid changes in temperature.

Table 7. Switching Cycle Test

SN	Standard	Initial Lumen	Lumen Depreciation After 30,000 Switching Cycle	%	Remarks
Sample 1	30 sec ON & 30 sec Off	940	923.11	1.83%	Comply
Sample 2		961	942.86	2.2%	Comply
Sample 3		920	904.45	1.69%	Comply

The table presents the outcomes of a lumen depreciation test under a 30-second on-off switching cycle, with all samples successfully meeting the standard requirements. Sample 1 showed a lumen reduction of 1.83%, Sample 2 a 2.2% decrease, and Sample 3 a 1.69% decline after 30,000 cycles, indicating that the LED bulbs can sustain frequent use while maintaining their brightness within the compliance threshold. The ability of an LED bulb to withstand a high number of switching cycles is a critical aspect of its overall reliability and performance in real-world applications. This test ensures that the product will hold up under the varied and sometimes demanding conditions that it may encounter once installed.

Thermal Management System:

For the attainment of satisfactory longevity in LED applications, it is imperative to gauge the temperatures of LEDs under authentic operational circumstances. This practice ensures that the empirical temperature data aligns with the manufacturer's lumen depreciation projections. Moreover, to preemptively exclude the prospect of premature malfunctions, it is advisable to conduct extensive testing of multiple product units during the initial stages of the design process. We advocate a minimum of 2000 hours of uninterrupted test operation as a benchmark for evaluating the endurance of these lighting solutions. Such rigorous testing protocols are crucial in certifying the reliability and sustained performance of LED products before market release.

LEDs that run at excessive temperatures will have very short lifetimes and fail to produce adequate light after a few short weeks or months of operation. Two Heat Flow basics in LED which is the conduction & convection processes. Conduction – transfer of heat through matter by communication of kinetic energy from particle to particle. An example is the use of a conductive metal such as copper to transfer heat. Convection – heat transfer through the circulatory motion of a liquid or gas in contact with a hot surface. Air surrounding a hot object removes heat by conduction and convection, where gas molecules flow past the surface and remove heat energy. Good circulation is important to good heat transfer. Heat sink – any thermally conductive element designed to transfer heat from a heat source (the LED) to the ambient environment. Heat sinks with fins are common and work by creating a large surface area. [Technical Notes: Lighting Global,2010]

Table 8. Thermal Test

Sl No.	**Parameters**	**Required Value**	**Sample-1**	**Sample-2**	**Average**	**Remarks**
1	LED Chip junction Temperature (After 1hour) with Thermal Conductive Glue	≤75˚C	68	69	68.5	Comply
2	Body Temperature (After 1 hour) with Thermal Conductive Glue	≤55˚C	54	55	54.5	Comply

In the context of the provided test results, both the LED chip junction temperatures and the body temperatures with glue are within the required operational thresholds after one hour of running time, showcasing the efficacy of the heat dissipation design. When glue is used—a substance with its own conductive properties—it likely enhances the transfer of heat away from the LED chip and the body. This indicates that the glue serves not only as an adhesive but also as a thermal bridge that assists in the conduction of heat away from critical components, maintaining temperatures below the specified maximums of 75°C and 55°C, respectively.

For the LED chip junction temperature with glue, the results show an average of 68.5°C, which is compliant with the set requirement. The body temperature with glue shows even better performance, with an average temperature of 54.5°C, well below the 55°C limit. This suggests that the material of the bulb body, possibly a polymer like ABS, effectively conducts heat away from the LED chip to the surrounding environment, preventing heat accumulation.

These observations affirm that good thermal design, utilizing principles of conduction effectively, can prevent the early degradation of LEDs due to excessive heat. It's crucial for extending the operational life of LEDs, as high temperatures can accelerate lumen depreciation and lead to early failure. The materials used in the LED's construction, along with the incorporation of conductive adhesives like thermal glue, play a pivotal role in managing heat through conduction, thereby ensuring the reliability and longevity of the lighting device.

5.3 Proposed Improvements & Validation

While thermal conductive glue has proven effective in enhancing the thermal management of LED bulbs, its cost implications warrant the exploration of more economical yet efficient alternatives. One promising avenue is the use of emerging materials such as thermally conductive polymers or bio-based composites.

Thermally Conductive Polymers can be integrated directly into the bulb's body, potentially reducing the need for additional thermal interface materials. They offer a dual advantage of intrinsic thermal conductivity and ease of manufacturing, which could result in cost savings at scale. Further research into the formulation of these polymers to meet the specific thermal conductivity requirements of LED bulbs is suggested.

Additionally, with an increasing demand for sustainable manufacturing practices, bio-based composites represent a forward-thinking solution that could reduce environmental impact. Their natural thermal dissipation properties, combined with the potential for carbon neutrality, make them an area ripe for development. Investigations into the thermal performance of these composites in comparison to conventional thermal glues would not only align with ecological goals but might also uncover cost efficiencies.

The transition from thermal conductive glue to these innovative materials could signify a strategic improvement in LED manufacturing. It is proposed that subsequent studies evaluate the thermal conductivity, structural integrity, and cost-effectiveness of these materials through a series of comparative analyses and practical testing. This initiative could culminate in a significant advancement in LED bulb technology, balancing performance with sustainability and cost considerations.

By integrating these advanced materials into the design of LED bulbs, manufacturers could maintain the necessary heat dissipation capabilities and adhere to safety standards, potentially reducing the overall cost of the product. Future studies should focus on the comparative analysis of these materials in terms of thermal conductivity, environmental impact, and cost implications to validate their practical application in LED bulb manufacturing

6. Conclusion

This research meticulously delves into the intricate relationship between material engineering, thermal dynamics, and their collective influence on the efficacy and life cycle of commercial LED bulbs. Our comprehensive analysis highlights the pivotal role of material choices, notably Polycarbonate (PC) and Polybutylene Terephthalate (PBT), and the integration of sophisticated thermal management techniques, in bolstering the functional lifespan and reliability of LED lighting.

Our results demonstrate that the harmonious combination of PC and PBT materials with thermally conductive glue successfully addresses the key thermal challenges inherent in LED operation. This synergy effectively counters the risks of premature LED failure due to overheating. Through extensive lumen depreciation testing under a variety of operational scenarios, we've established that these material choices ensure the preservation of LED luminosity well within the accepted industry standards for a prolonged duration.

Employing a testing regimen that mirrors real-life usage patterns—including continuous, intermittent, and high-frequency switching—our study has methodically quantified the endurance and resilience of LED bulbs. This rigorous evaluation affirms that the light output of these LEDs not only remains robust over time but also aligns with the expectations of durability and performance set by consumers and industry benchmarks alike.
Looking ahead, this paper advocates a progressive shift towards innovative alternatives like thermally conductive polymers and bio-based composites. These emerging materials beckon with the potential of paralleling, if not surpassing, the thermal efficiency of traditional options while also offering avenues for cost reduction and environmental sustainability.

In essence, this study encapsulates the successful amalgamation of strategic material selection with advanced thermal management strategies, paving the way for future enhancements that aim to redefine the paradigms of sustainability and economic viability in LED technology. The methodologies and insights gleaned from this research not only contribute significantly to the body of knowledge in LED lighting but also provide a robust framework for future exploration and innovation in this dynamic field.

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