White Paper

Development of Graphite Foam Cooled Light-Emitting Diode (LED) Streetlight

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Background

Our product is an enhanced light-emitting diode (LED) streetlight that is cooled with graphite foam developed at ORNL. Graphite foam is a specially prepared carbon material that provides very high thermal conductivity and lightweight thermal management to LED solid-state components, reducing their temperatures and significantly increasing their lifetimes. Graphite foam (see Fig. 1) is a porous structure that is nearly 80% air, but the solid ligaments are more than 4 times as thermally conductive as copper. The overall structure has a density of ~0.7 g/cm^3, making the foam about 25% the weight of aluminum. The bulk thermal conductivity of the graphite foam can be up to 240 W/mK, or nearly 30% higher than the aluminum alloys used as heat sinks (aluminum 6061 has a conductivity of 180W/mK). More importantly, in terms of mass, the thermal response of the foam is more than 5 times faster than that of copper. In other words, a block of foam will respond to a heat impulse 5 times faster than copper, thus preventing thermal spikes more efficiently.

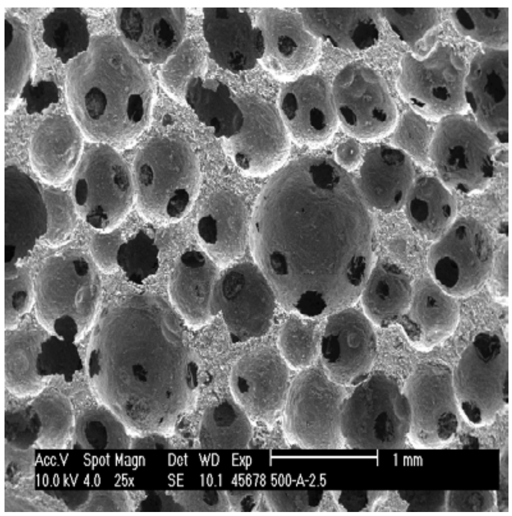

Fig. 1. Electron micrograph of graphite foam shows its large air spaces and ligaments for wicking heat from one side to the other.

Our product uses graphite foam to rapidly move the heat from the LED board to the aluminum housing of the streetlight more efficiently than aluminum by itself, effectively reducing temperatures. Our tests comparing graphite foam with aluminum for LED cooling have shown a temperature drop of approximately 22˚C under steady-state conditions when using a thermal adhesive and 18˚C without any thermal adhesive on the foam-cooled LED. These temperature decreases induced by graphite foam and the thermal adhesive will more than double the reliability and life of the LED components.

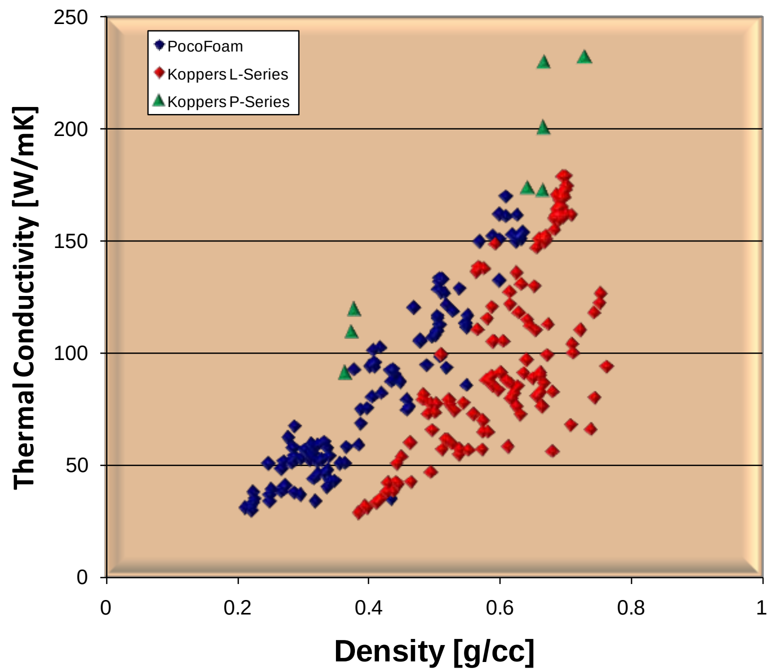

Fig. 2. Thermal properties of graphite foams

Program Objectives

In a LED streetlight, there are two elements that get hot – the LED board itself, and it's driver that converts the alternating current (ac), to direct current (dc) that powers the LEDs. Our product uses a very thin layer of graphite foam as an interface between both elements and their aluminum housing. See Figures 3 through 6. The components of our product are simple in concept. Graphite foam is used to replace as much aluminum as possible because, compared with the metal, the foam has 30% more thermal conductivity and 25% the weight. The technology to implement this modification is rather complex. The design of the foam structures and the task of interfacing these to the aluminum housings in the initial products can be difficult. The reason for this is that our goals have been to maximize the surface area between the foam and the aluminum, while minimizing the amount of foam used, which can be expensive. However, these concepts will allow future designs that are rather radical. For example, if foam-cooled LED streetlights could have plastic instead of aluminum housings, causing a large reduction in weight minimizing the effects of wind-caused vibrations of lights on poles, reducing their maintenance. Because they are more efficient and longer lasting, LEDs cooled with graphite foam could be attractive replacements for fluorescent light bulbs and other indoor light sources.

Fig. 3. Streetlight as received by LED North America

Fig. 4. Streetlight as received by LED North America showing the location of the LED board on the aluminum housing

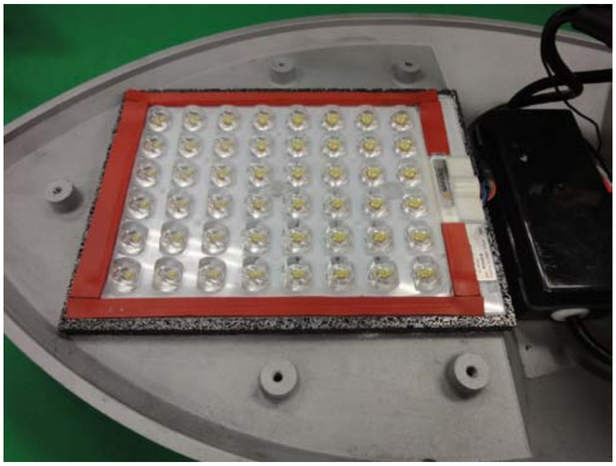

Fig. 5. Streetlight modified by LED North America showing the LED board in a graphite foam base

Fig. 6. The Streetlight modified by LED North America prepared for delivery.

By wicking the heat as quickly as it is generated to a larger sink, such as the aluminum housing, the temperature rise of the back side of the LED board will be much smaller. **This reduction in temperature enhances the reliability of** the solid-state components, which are predicted to fail according to the standard Arrhenius Law (the rate of failure drops by a factor of 2 for roughly every 10˚C drop in temperature). Thus, the life of the LED devices will be increased significantly.

In 1889 Nobel Laureate and Swedish chemist Svante Arrhenius developed a simple equation that reveals the dependence on temperature of any rate of an elementary chemical reaction. His formula is:

$$R = Ae^{\left(-E_a/kT\right)}, \qquad \text{eq 1.}$$

where the rate of reaction (R) is equal to a constant (A) times the fraction of vibrations ($e^{\left(-E_a/kT\right)}$) that have an energy that exceeds a threshold "activation energy" (Ea) at a temperature of T (in kelvins). The term k is the Boltzmann constant. The Arrhenius equation can also relate how increased temperature accelerates the aging of a product more than does its normal operating temperature. In electronics, there are many modes of failure, such as short circuits, open circuits, wear, crack propagation, migration of lubricants, and spalling. In our LED case, the main source of failure is electrochemical in nature, involving interactions between components and voltage breakdown effects, such as those occurring in varistors. The typical activation energy of most electrochemical breakdown effects ranges from 0.5 to 1.3 eV, as discussed by [**reference here**]. When equation 1 is evaluated at two different temperatures (T1 and T2), it can be rewritten to give equation 2. From this equation, determining the effects of temperature on the rate of failure, or degree of reliability, of LED electronic components is easy.

$$\frac{R_2}{R_1} = \frac{Ae^{\left(-E_a/kT_2\right)}}{Ae^{\left(-E_a/kT_1\right)}} = e^{\left(\frac{-E_a}{k}\left[\frac{1}{T_2}-\frac{1}{T_1}\right]\right)} \qquad \text{eq. 2}$$

Program Tasks

We compared the LED streetlight containing our product with the standard LED streetlight. As shown in the table in figure 7, the temperature at the back surface of the LED board cooled by graphite foam was nearly 8˚C lower than that of the standard light. Next, we inserted a ¼ in. thick piece of foam between the driver and the aluminum housing as well, and the temperature of the driver dropped 12˚C and the temperature of the LED board fell another 10˚C. This finding indicates that the heat from the driver will contribute to the temperature rise of the LED board, as well, and that use of the graphite foam to conduct heat from the driver further cools the LED board. Finally, a thermal interface adhesive (Aremco 568) was used to bond the foam to the aluminum housing to further enhance the heat transfer. As can be seen, with thermal adhesive between the foam and the housing, driver, and LED board, the temperatures of the driver and LED board were reduced by 18˚C and 22˚C respectively, a very significant improvement in heat transfer.

	TEMPERATURE READINGS AFTER 3 HOURS OF CONSTANT RUNTIME		
LED APPLICATION	**LED TOP**	**UNDER LED**	**UNDER DRIVER**
Baseline Streetlight	66.3° C	85.7° C	68.9° C
Foam under LED	63.1° C	77.7° C	68.4° C
Foam under LED and Driver	62.7° C	67.2° C	54.4° C
Foam under LED and Driver using Thermal Adhesive	52.6° C	63.2° C	50.2° C

Fig. 7. Temperature of LED streetlight before and after various applications of graphite foam

For our example, we can assume that our LED light normally operates at a temperature (T1) of 353 K (85˚C) and at the reduced temperature (T2) of 350 K (or 77˚C) with graphite foam cooling. The Boltzmann constant is 8.62×10^{-5} eV/K. Assuming an average activation energy of 0.75 eV, equation 2 shows us that an 8˚C change in temperature at these temperatures yields an approximately 1.82 times increase in the life of the LED. Consequently, dropping the temperature of the LED further to 63.2˚C results in an increase in LED life of nearly 5 times. Hence, a light that is usually replaced after 2 years could last up to 10 years with cooling by graphite foam. Imagine the cost savings to a major city such as San Francisco. A Department of Energy Gateway Demonstration Report completed in December 2008 for the City of San Francisco concluded that the annualized maintenance cost for one High-pressure sodium (HPS) luminaire would be $24.44. A large metropolitan city with 40,000 HPS streetlights, such as San Francisco, would therefore have a maintenance cost of $977,600 annually. This expenditure would be drastically reduced, if not eliminated, by installing LED streetlights with a long rated life. Clearly, increasing the life of the LED components of streetlights will result in significant savings for many municipalities around the United States and the world.