Halogen-IR Lamp Development: A System Approach

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Introduction

It is well known that the efficacy of incandescent lamps could be greatly increased if the radiated energy in the near-infrared (IR) region could be returned to the tungsten filament and reabsorbed. As a consequence, lamp manufacturers have long searched for coatings to make IR lamps. Coatings for IR-halogen lamps must meet the following requirements:

- thin film filters on the lamp envelope with high infrared reflectance and excellent visible transmittance
- compatibility of the filter with the envelope material, shape, and operating temperature
- functional optical design of the filament/envelope combination to enhance the capture probability of the reflected IR

An excellent review of the types of filters that can be used has been published by Kostlin and Frank.[1] Lamp products using these various types of IR reflecting/visible transmitting filters have been marketed for several years. For example Durotest marketed an incandescent lamp incorporating a TiO_2-Ag-TiO_2 thin film filter on specially made elliptical lamp envelopes.[2] While the silver film gives excellent infrared reflection, it is not suitable for use on the surface of most halogen lamps because of material temperature limitations. Furthermore, the partially reflective nature of this film in the red end of the visible spectrum makes the source color much less than desired for most general lighting applications.

In 1981 GE introduced a line of linear quartz halogen lamps using a multilayer dielectric filter to achieve efficacy increases of 30 to 40 percent.[3] This filter, made with alternating layers of silica and tantala, is compatible with high-temperature envelope materials and can be designed to provide good color. However, in order to obtain layer thickness uniformity, the application process at that time was restricted to long cylinders. With the introduction of 60 and 100-W Halogen/IR PAR38 lamps at the 1989 LIGHTFAIR, this limitation has been overcome allowing a compact, low-wattage, line-voltage halogen source using a transparent heat reflector to be marketed.

The objective of this paper is to highlight the constraints on halogen lamp design introduced by the use of infrared reflecting filters. The sections that follow describe the potential benefits and solutions to design constraints imposed by the use of IR-reflecting thin-film filters. The role of modeling in defining the critical variables that influence lamp performance is accented.

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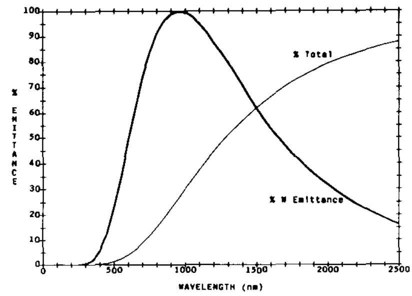

Figure 1—Normalized spectral power distribution of tungsten wire as a function of wavelength at 2800 K. The cumulative fraction of the total radiated power is included.

Efficacy gain potential with IR-films

The basic idea behind the Halogen-IR lamp is to place a spectrally reflecting filter on the outside of a halogen lamp envelope to reflect back a portion of the emitted infrared energy to the filament where a fraction of the reflected energy is absorbed. The absorbed radiation reduces the input electrical power needed to maintain the filament temperature, hence increasing the efficacy. It is clear that the filter, in addition to reflecting the infrared, should transmit nearly all of the visible radiation if the lumen output and color of the light is to be maintained.

Consider the potential reduction in power that can be achieved with such a device. The spectral power distribution of a tungsten filament at 2800 K, typical of general lighting sources, is shown in **Figure 1**; also shown is the cumulative integral of the spectral power distribution. Typical reflectance spectra of a multilayer silica and tantala film placed on the outside of an incandescent or halogen lamp is shown in **Figure 2**. Note that the film effectively reflects radiation between about 750 and 1750 nm.

Further, note from the integral curve of **Figure 1** that 60 percent of the radiation is emitted in this wavelength band. Only 12 percent is emitted in the visible region, less than 750 nm. If the reflectance of

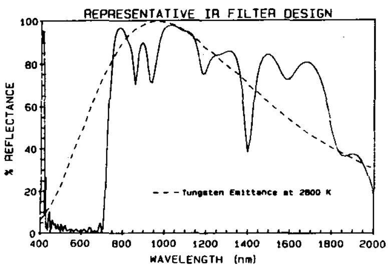

Figure 2—Reflectance spectra of typical multilayer tantala/silica dielectric film.

the filter is 100 percent and the filter covers the entire surface, it is easy to see that, at the same filament temperature, the total radiated power emitted by the filament would be only 40 percent of that without a reflecting filter. Further, assuming that radiation accounts for about 90 percent of the total input power, it is easily shown that the total power is 46 percent of the original. If the filter transmits perfectly in the visible range, the efficacy gain of the lamp would be 217 percent. As is obvious from **Figure 2**, however, the reflectance in the near IR band of a real filter is not 100 percent; 80–85 percent is typical.

Only a portion of the reflected radiation returned to the filament is absorbed as the tungsten wire emissivity is only about 0.3 in the near infrared. The actual absorbency of the filament depends on how it is coiled; typical values are about 0.4. This means that less than half of the reflected radiation returning to the filament will be absorbed; the rest is reflected back. In addition, some reflected radiation misses the filament due to imperfectly achieved geometry, end losses, etc. The situation for a cylinder is shown schematically in **Figure 3**.

The formula for the fraction of radiation, G, returned to a radially centered line source in a cylindrically reflecting cavity, as a function of the length to diameter ratio, L/D, is shown at the bottom of **Figure 3** for both a Lambertian and constant-intensity source. The actual radiation pattern for all filaments is expected to fall between the limits of these two distributions. A plot of G as a function of L/D is shown in

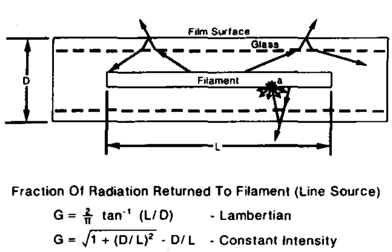

Figure 3—Schematic showing reflection possibilities in a cylindrical system.

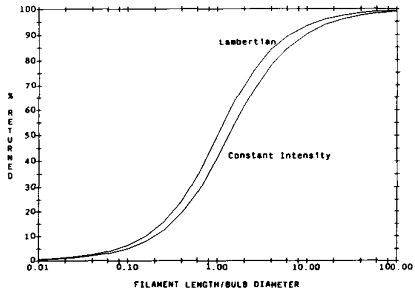

Figure 4—Cylindrical end-loss (geometry) factor as a function of filament length to cylinder diameter ratio.

Figure 4. Note that to obtain $G > 0.8$, L/D values > 3 are needed.

This implies that for cylindrical lamps long coils or very narrow cylinders are needed. The impact of the the filament/envelope construction geometry, based on the magnitude of the fraction of radiation reflected back to the cylinder, is very important in deciding on the lamp design.

As noted, the filament absorbs less than half of the radiation returned to it; the rest reflects. The result of a reflecting filter on the bulb and a reflective filament is a multi-pass reflective system. Due to the inherent reflectivity of the tungsten filament, the filter reflectivity and end-loss fraction have a larger impact than first expected. A model for the fraction of radiation reabsorbed by the filament as a function of the film reflectance (R); the capture probability, or geometry factor (G); and the filament absorptivity (a) can be obtained by simple ray tracing models. **Figure 5** schematically depicts the situation for the first few reflections. Once the pattern for the successive terms for the fraction absorbed and transmitted on each pass is obtained, an infinite sum for each can be generated. The resulting sums are easily solved, resulting in formulae for the fraction of radiation absorbed and transmitted. These are

$$F_{abs} = aGR/[1 - (1\text{-}a)GR] \qquad (1)$$

and

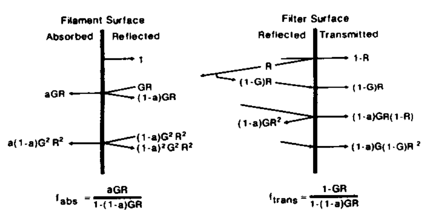

Figure 5—Ray tracing model showing absorption and transmission of a filament in a reflecting cylinder.

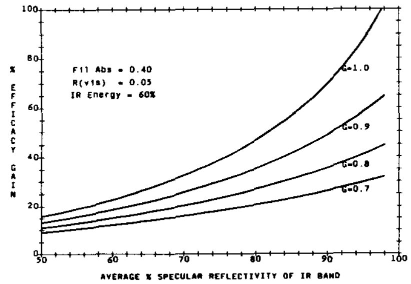

Figure 6—Efficacy gain of centered filament as a function of average IR reflectivity, R, between 750 and 1750 nm, at various values of the geometry factor, G. Filament absorptivity, a, equals 0.4.

$$F_{trans} = (1\text{-}GR)/[1 - (1-a)GR] \quad (2)$$

Note that the effect of R and G are identical, i.e., system geometry is as important as the filter reflectivity. It is concluded that effective use of IR filters on halogen lamps involves obtaining high IR film reflectance in the region of peak radiation and a filament-bulb geometry that captures most of the radiation reflected.

Efficacy gain, assuming constant filament temperature, i.e., inverse power reduction, as a function of filter reflectivity, for various values of the geometry parameter, G, is shown in **Figure 6**. For cylinders the value of G can be related to length and diameter as shown in **Figure 4**. For shaped bulbs this relationship is not as easily defined; however, the concept of a geometry factor can still be used. Given the filter reflectance characteristics shown in **Figure 2**, i.e., 80–85 percent, it is seen from the curves in **Figure 6** that to achieve an efficacy increase of 30–40 percent over that of a non-IR-lamp requires G values approaching 0.9. Thus the optical design requirements for the bulb with integral filter are specified. Next, the problem of performance variability due to filament positioning and film reflectance variability needs to be addressed.

Design constraints

Effect of filament centering

In the above discussion it was assumed that the filament was positioned on the optical axis of the envelope, i.e., optimal results. However, when the filament is offset radially from the axis some reflected radiation that previously reached the filament now misses. The observation is that an image of the filament is formed as shown schematically in **Figure 7**. When the filament is offset radially some emitted radiation requires two or more reflections to return. Due to less than perfect IR reflectance, about 15 percent as shown in **Figure 2**, multiple reflections result in a reduction in the amount of absorbed radiation. The greater the radial offset, the greater the number of reflections with the filter before the radiation is absorbed. It is seen that the consequence of a radial offset in filament position causes a decrease in absorbed energy, hence a decrease in filament temperature, which in turn leads to a loss in lumen efficacy and an increase in life.

In order to attempt quantification of the dependence of lamp performance factors on radial offset, the ray tracing model shown in **Figure 5** was extended. The simplifying assumptions used to model radial offset of the filament are as follows: Assume that the fraction of reflected radiation that misses the filament after the first reflection is proportional to the radial displacement from the axis. Further, assume that when the filament is displaced one diameter from the axis, on average all the emitted radiation reflected from the filter misses the filament.

As noted above, the reflected radiation forms an image of the source. If it is now assumed that the image is the source, it is seen that radiation emitted from the image encounters the real filament after one reflection. Thus, the fraction of radiation that missed the filament after one reflection due to radial offset returns to the filament after two reflections. Note that the model breaks down for offsets larger than one fila-

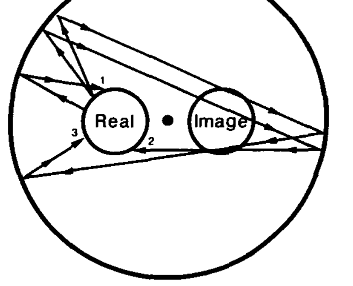

Figure 7—Schematic representation of the effect of radiation when the filament is radially offset.

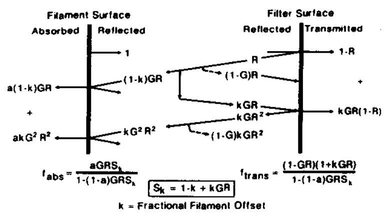

Figure 8—Ray tracing model showing absorption and transmission of a radially offset filament in a reflecting cylinder.

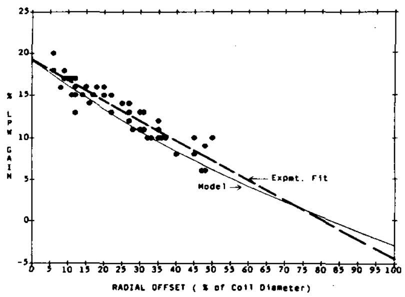

Figure 9—Measured and predicated efficacy gain in percent as a function of radial offset for cylindrical IR lamps.

ment diameter. The above logic, when incorporated into the ray tracing schematic shown in **Figure 5**, results in a ray tracing model as shown in **Figure 8**. Here k is used to denote the fractional radial filament offset in terms of the filament diameter; $k=0$ when axially centered, and $k=1$ when the radial offset equals one filament diameter. By forming the infinite series as done previously, the fraction of radiation absorbed and transmitted from an offset filament is,

$$F_{abs} = aGRS_k/[1 - (1\text{-}a)GRS_k] \quad (3)$$

and

$$F_{trans} = (1-GR)(1+kGR)/[1 - (1-a)GRS_k] \quad (4)$$

where

$$S_k = 1 - k + kGR \quad (5)$$

Numerical Monte Carlo-type ray tracing models verified the predictions of the ray tracing model. Results using cylindrical source emitters in both cylindrical and elliptical reflectors agree amazingly well with those predicted by **Equation 3**. Furthermore the results of measurement of efficacy gain as a function of filament offset for cylindrically coated filament tubes agree very well with predicted radial offset as shown in **Figure 9**. In this figure each circle indicates a photometry and centering measurement on one filament tube. The model results were matched with the experimental best linear fit at the origin, i.e., no offset. Note that in the experimental case the lamps were measured at constant voltage, not constant temperature. Thus, to plot the model curve in **Figure 7**, the change in filament temperature at constant voltage must calculated. This was done by solving for the temperature dependence on the absorbed radiation from the energy balance equation.[4] The observed as well as calculated decrease in efficacy due to displacement by one filament diameter is over 20 percent, i.e., a very large change. In addition to predicting the efficacy as a function of radial offset, once the temperature dependence vs radial offset is known, the dependence of life, lumens, and power on radial offset can be obtained as well. The predicted results are shown in **Figure 10**. Note that life, assuming evaporation as the dominant process, is expected to increase by a factor of more than two at a coil offset of one diameter from the axis. Power input, on the other hand, is not significantly changed. The conclusion reached as a result of radial offset considerations is the following. In order to provide a viable product where variations in lumen output and life are of the same order as present halogen products, it is necessary to limit radial variations of the filament position to a small fraction of its diameter from the optical axis of the filament tube.

The dependence of lumens and life on radial position of the filament was the major constraining factor influencing the choice of a double-ended filament tube. First, it was determined that positioning filaments in present single-ended filament tubes during manufacturing did not achieve the required tolerance. Furthermore, it was not apparent how the process could be modified to achieve tight tolerance control. Thus a double-ended structure was chosen, since holding both ends of the filament provides more accurate filament positioning. In addition, use of small-bore tubing, with specially designed inner leads to provide self-centering, added additional capability for control of radial positioning. Obviously, the insertion of a mount containing two moly foil sections into a tube is inherently a more difficult manufacturing process than that for a single-ended mount. This complication was accepted as a necessary consequence of the need to control variations introduced by the additional reflected IR heat source created by use of IR reflection filters.

Compact coil design

Not only must the initial position of filament be ac-

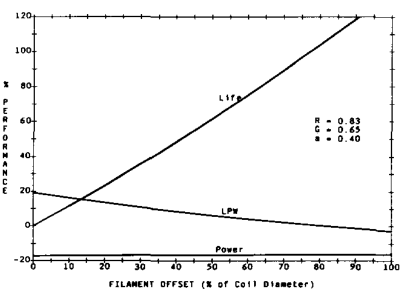

Figure 10—Predicted dependence of power, efficacy, and life on the radial offset of the coil.

curate, the position must also remain near the axis throughout life. Obviously, a badly deformed filament due to sag is equivalent to a poorly positioned filament as far as the radiative processes are concerned. Thus, excellent non-sag coils are needed to make IR lamps a success. Two options appeared viable. One was to make standard size filaments and place these in cylindrical IR-reflecting envelopes. However, obtaining a G value greater than 0.8 requires filaments of at least 20 mm coil body length, assuming 6-mm OD tubing. This filament length requires at least one center support to prevent sag and to achieve adequate radial positioning. While such a design can provide excellent efficacy gain, the attachment of non-distorting center supports on fine-wire coiled-coil filaments proved difficult. More importantly lamps with long filaments are inherently poor candidates for optical sources intended for display applications.

The other option is to place a compact coil on the axis of a shaped bulb, e.g., elliptical, to achieve high G values. Compact coils are less likely to require center supports than long coils made from the same length of wire since the amount of sag experienced is more sensitive to lead spacing than bend stiffness, everything else being equal. However, processing large mandrel ratio coiled-coils, needed for compacting coil length, required significant innovation in wire and coil processing to achieve compact low-sag filaments. This becomes even more difficult in IR-lamp applications because the filament length increases and the wire diameter decreases in proportion to the efficacy gain of the IR filter for constant voltage designs at the same lumen and life values.

For a given lamp design, the coil diameter generally increases in proportion to the decrease in coil length. Since radial offset is scaled in terms of filament diameter, a short coil is less sensitive to a given coil offset, which is another major advantage for compact coils. Compact coils are also much more desirable for beam applications. The development of a process to make fine-wire, low-sag compact coils was the key item, along with the IR filter development, that made the Halogen-IR product possible.

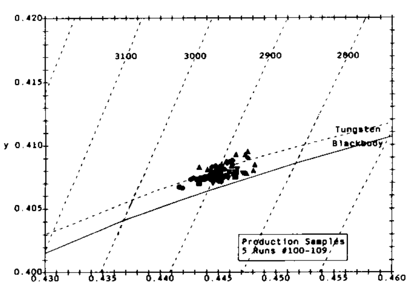

Figure 11—Chromaticity coordinates of 120-V, 60-W IR filament tubes.

A concern with elliptical reflectors is that the return radiation is predicted to be somewhat axially nonuniform. A nonuniform return leads to a nonuniform filament temperature distribution that would be expected to lower lamp life over that of a more uniform distribution. However a number of tests comparing elliptically shaped filament tubes with and without IR filters have not revealed the presence of a large enough nonuniformity in the temperature to show a correlation with lamp life.

Color

If the spectral transmission of the film were constant across the visible spectrum no change in the apparent color of the source would be observable. This ideal characteristic is difficult to obtain in practice with actual filters. First, the actual filter as made will have some variation in transmission with wavelength compared to the theoretical design. Also, variability in the film process leads to variation in spectral reflectivity in the visible range, affecting the color perceived. Furthermore, radiation traversing the filter at an angle to the normal shifts the reflection edge to smaller wavelengths in proportion to the angle of incidence. If the reflection edge is too close to the visible this leads to some reduction in red transmission. In addition, film imperfections tend to scatter light, particularly in the blue region, thus reducing the blue transmission.

The cumulative effect of these factors, with typical filter designs, is to shift the chromaticity coordinates toward a more yellow or green-yellow color. This is considered undesirable in lamps in general but especially for lamps intended for display applications. In order to minimize the reduction in red transmission due to off-normal radiation and reduce the effect of process variability, a film design with the reflection-transmission edge between 750 and 800 is desired. The design must accomplish this without moving the other reflection edge into the visible blue, i.e., above 400 nm.

An IR-reflecting filter design and manufacturing process that meets the above criteria for the visible region has been developed by GE Lighting. A measured reduction of 20–30 K in color temperature of the lamp with filter compared to that of a lamp without filter operating at the same filament hot resistance, i.e., temperature, is observed. The chromaticity coordinates remain near the black body locus as demonstrated in **Figure 11** for a set of 75 measured lamps from five different filter production runs.

The distribution in chromaticity values tends to be 30–50 percent higher than that for standard halogen

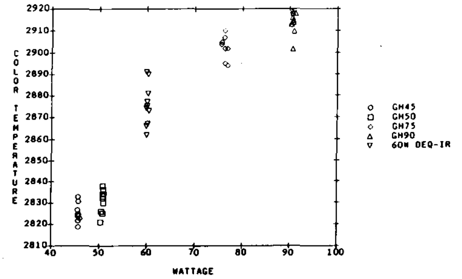

Figure 12—Color temperature measurements of a number of different halogen lamps, including Halogen-IR, all with 2000-hr design life.

lamps as expected, but the performance easily falls within the required two-step oval. Furthermore, as is shown in **Figure 12**, the observed color temperature from the halogen-IR lamp is as high, if not higher, than that expected from a 60-W halogen lamp. This is demonstrated by the plot of color temperature for a variety of glass-halogen lamps all having a design life of 2000 hrs.

Summary

A compact-coil, double-ended quartz halogen lamp, incorporating a multilayer dielectric oxide film to reflect infrared radiation to the filament, has been developed. The efficacy increase obtained by the IR-film lamp, for 60 and 100-W designs, is over 35 percent. The chromaticity obtained with the filter is equivalent to other non-IR-film IR halogen lamp sources.

This efficacy increase, coupled with the better optical performance of the compact coil, provides a PAR38 source that delivers the same beam lumens at 60 W as that obtained from the standard halogen 90-W PAR.

Engineering tests on the performance and variability for the 60-W design indicate the following.

- Lumen output variability is found to be up to 50 percent greater than that of comparable non-IR halogen lamps.
- Variability in power is the same as for halogen lamps.
- Life is greater than 2000 hrs for both horizontal and vertical orientations; variability in life is not found to be any higher than that obtained in standard halogen lamps.
- Color temperature is 2900 K with a variability giving a standard deviation of about 30 K. A schematic of the double-ended quartz filament tube is shown in **Figure 13**.

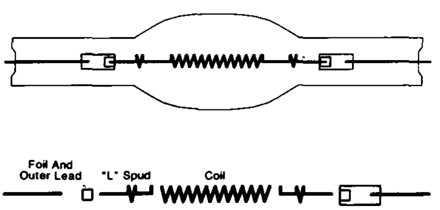

Figure 13—Halogen-IR lamp schematic showing compact coil in shaped double-ended quartz filament tube. IR filter is placed on outside of quartz envelope. Mount component parts are also shown.

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Discussion

The author is to be commended for the approach used in this work to analyze the many parameters involved in this unique lamp design. In this paper it is stated, "The efficacy increase obtained by the IR-film lamp, for 60 and 100-W designs, is over 35 percent." What is used as a reference to arrive at this figure?

One way to arrive at an efficacy increase is to compare an IR-film lamp to one not using an IR film. For example, the beam of a 90-W PAR38 is nearly equivalent to the 60-W IR-film lamp referred to in this paper. Beam equivalence implies that the 67 percent wattage decrease is offset by a 150 percent increase due to the more compact 60-W coil and the efficacy increase obtained by its IR film. Using data,[1] the 60-W coil should contribute a 1.2 factor (+20 percent). This leaves an efficacy increase of only 25 percent that can be attributed to the IR film. If the film efficacy increase is 35 percent, a loss of 8 percent would leave a net increase of 25 percent. If this analysis is correct, could the 8 percent loss be due to a filament offset within the ellipse?

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Philips Lighting

Reference

1. Benson, Gagnon, and Johnson. 1989. PAR lamps using compact filaments. *LD*+A 19(no. 8):15–19.

Author's response

To P. Johnson

The stated >35 percent efficacy increase due to the IR filter is that due to the action of the filter only. It is measured as follows. Photometric data on a lamp made before applying an IR filter are obtained at a given voltage, i.e., a given hot resistance. The IR filter is then applied to the same lamp, and photometric data are again obtained by adjusting the voltage to obtain the same hot resistance. The ratio of the efficacies before and after applying the filter at the same hot resistance is used as the quoted gain, e.g., 35 percent gain. The efficacy gain is due to a decrease in input power slightly larger than the efficacy increase since there is normally a 2 to 5 percent loss in lumens due to the filter application. At this time tens of measurements of this kind have been done resulting in an average measured efficacy gain of between 35 and 40 percent for production lamps.

In addition to the efficacy gain due to the filter, there are extra benefits due to using a compact coil in reducing heat loss by convection and, more importantly, in increasing the center beam candlepower of a PAR38 lamp. These improvements, while important, have not been included in the performance gain of >35 percent quoted in the paper.