Metal Halide Lamps With Ceramic Envelopes: A Breakthrough in Color Control

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THIS PAPER WAS PRESENTED AT THE 1996 IESNA ANNUAL CONFERENCE

Introduction

Most types of metal halide lamps have discharge tube fillings based on sodium and scandium halides or sodium and rare-earth halides. For decades, these halides have been contained within envelopes of fused quartz, henceforth called quartz. These halides provide spectral energy distributions that offer lamp designers a broad choice of color temperatures, color renderings, and luminous efficacies. However, these properties depend on the vapor pressure of the halides and hence on the operating temperature of the discharge tube. The higher the temperature, the better the color rendering, the smaller the color spread lamp-to-lamp, and the higher the efficacy, as shown in **Figure 1**. However, higher operating temperatures can cause severe color shift and reduce lamp lifetimes. The challenge to lamp designers is to improve the color control by minimizing the color spread and color shift, while maintaining lamp lifetimes that customers require. This can hardly be realized by using quartz discharge tubes. To achieve a breakthrough in color control, a new envelope material is needed.

Limits of quartz technology

The types of halides that offer good photometric properties cannot be well contained at elevated temperatures in discharge tubes made of quartz, due to various chemical interactions.

Two major types of interactions between the quartz glass and the halide filling may be distinguished (**Figure 2**).

- Reactions of scandium or rare-earth halides with quartz may form silicates and silicon halide. The silicon halide decomposes at the hot electrode tip, forming metallic silicon, which readily dissolves in the tungsten. This chain of reactions causes depletion of the scandium or rare-earth part of the filling.[1,2]
- Sodium may permeate through the quartz wall. This causes depletion of the sodium part of the filling.[1]

Both depletion mechanisms contribute to considerable color shift over lifetime. Moreover, depletion of sodium also causes considerable lamp voltage rise.

Opportunities for ceramic technology

The interactions of halides with quartz glass, which limit the color quality of these lamps, do not occur with ceramic envelopes of alumina.

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- Reactions of the rare-earth elements with alumina form, analogous to quartz, aluminates and aluminum halide. However, in contrast to silicon, aluminum hardly dissolves in tungsten, and so the reaction is self-limiting. Therefore there is minimal depletion of the metallic part of the filling (**Figure 3**).
- Permeation of sodium through the alumina tube wall is negligible, in contrast to the situation with quartz tubes. The following experiment, comparing the permeation of sodium through quartz and alumina discharge tubes, demonstrates this huge difference. Metal halide discharge tubes, made of quartz and alumina, were equipped with antennas, as shown in **Figure 4**. A bias voltage of 50 V was imposed between the antenna and one electrical connection of the discharge tube. Both discharge tubes were operated for several hours, and their lamp voltages were monitored, also shown in **Figure 4**. The discharge tube made of alumina did not exhibit any significant voltage rise, whereas the quartz discharge tube extinguished due to voltage rise after only a few minutes.

Elimination of both depletion mechanisms guarantees a stable halide composition and thus a small initial color spread and an excellent color stability over lifetime. This color control throughout lifetime will be demonstrated in a later section.

This chemical stability of alumina allows discharge tubes to be operated at higher temperatures. It is difficult to provide a meaningful comparison of the temperature profiles of quartz and alumina discharge tubes, but a comparison of the cold-spot temperatures does provide some insight (see **Figure 1**). Typical cold-spot temperatures of alumina discharge tubes are 980–1020 °C, while those of quartz are much lower.

Alumina, as a material for the discharge tubes of metal halide lamps, not only shows a huge difference in its chemical properties; the thermal properties of these materials are very different as well, as shown in **Table 1**.

These differences have two consequences. First, the thermal distributions in the discharge tube chambers are very different, and so the chambers must have differ-

Table 1—Thermal properties of quartz and alumina at 930 °C[3-5]

Thermal properties	Quartz	Alumina
Thermal conductivity W/mK	4	12
Thermal emission	0.35–0.55	0.15–0.35
Thermal expansion K^{-1}	$4 * 10^{-7}$	$8 * 10^{-6}$

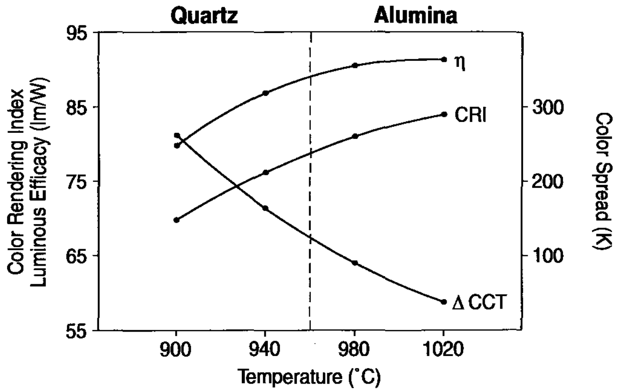


Figure 1—The photometric properties of Na/RE type metal halide lamps as a function of the halide temperature

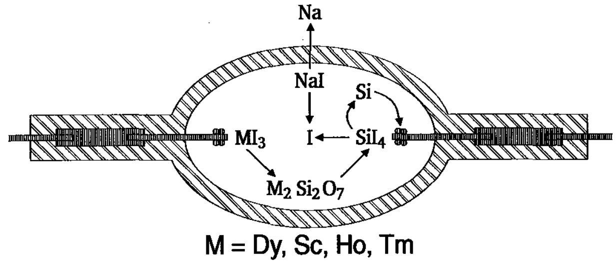


Figure 2—Reaction mechanisms of metal halides with quartz

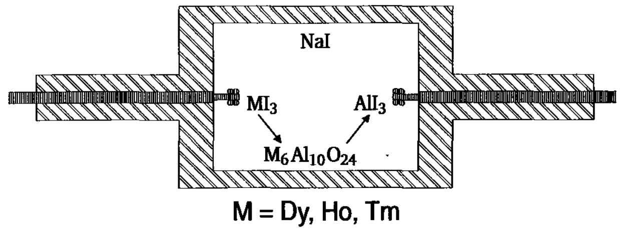


Figure 3—Reaction mechanisms of metal halides with alumina

ent configurations, in order to realize the required cold-spot temperature.

Second, reliable electric feedthroughs require different materials because the halide-resistant lead-through material molybdenum, used in quartz discharge tubes, has a coefficient of thermal expansion smaller than that of alumina. This can cause the formation of cracks in the alumina.

In order to take full advantage of the enormous potential that alumina offers, the discharge tube needs a full redesign. This redesign can best be done by starting from the basic customer requirements.

The design of lamps with ceramic envelopes

As a start the following customer requirements were taken as design criteria:

• The lamps should retrofit on existing ballasts, and so the discharge tubes must meet certain electrical requirements.

• The lamps should produce halogen-like light with a good color control, and so the discharge tubes must meet certain photometric requirements.

• The lifetime of these lamps should be comparable to that of existing metal halide lamps, and so the electric feedthrough must be kept gas-tight.

These requirements can be translated into lamp properties shown in **Figure 5**. These lamp properties can be translated into discharge tube design parameters.

From decades of experience in developing metal halide lamps with ceramic envelopes, it is known that the initial electrical and photometric properties are largely determined by the design of the discharge chamber, whereas the lifetime depends mostly on corrosion of the electric feedthrough. This allowed the split of the design aspects of these lamps in two separate parts—the design of the discharge chamber and the electric feedthrough.

The design of the discharge chamber

The discharge chamber design consists of two sets of major design parameters, as shown in **Figure 5**:

• Discharge-tube geometry (shown in **Figure 7**)

a. Inner diameter of the tube vessel (ID)

b. Arc length (AL)

The electrode tip-to-bottom length (TBL) was fixed at 1 mm.

• Filling

c. Halide composition (ratio of sodium/thallium/dysprosium)

d. Mercury pressure (P_{Hg})

The discharge chamber design was optimized with respect to initial electrical and photometric properties as shown in the following example for a 70 W design.

First, a matrix of discharge tubes was made, with several combinations of inner diameters and arc lengths. The color temperature and lamp voltage of each discharge tube were fixed at 3000 K and 95 V, respectively, by adjusting the halide composition and the mercury pressure.

Next, the four most important properties (including

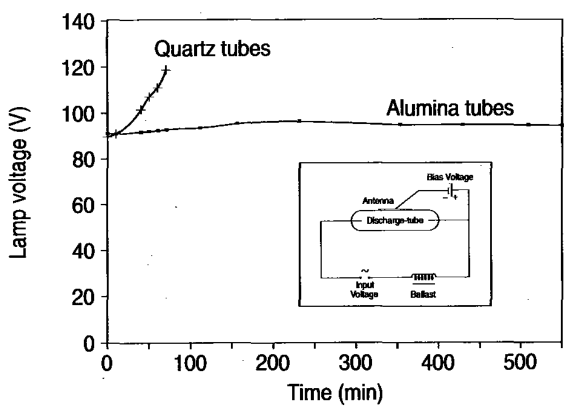


Figure 4—Comparison of the effect of sodium depletion in quartz tubes and alumina tubes on the lamp voltage

Table 2—Requirements for initial lamp properties, derived from customer requirements

Lamp properties		Requirements
Photometric properties	Color temperature - K	3000
	Color spread (lamp-to-lamp) - K	< 150
	Color Rendering Index	> 80
	Luminous efficacy - lm/W	> 70
Electrical properties	Lamp voltage - V	90–100
	Reignition voltage - V	< 200

efficacy, color spread, color rendering, and reignition voltage) were measured for each point within this matrix. Comparing the results of the measurements with the requirements for these properties, shown in **Table 2**, determined the areas of the matrix that met these requirements. These areas are shown in **Figure 6** marked as the unshaded parts of the matrix. The potentially useful part of the matrix is further limited by the allowable mercury pressure which may not exceed the strength of the alumina tube.

Finally all matrices were combined to reveal the free design area, from which in principle, any design could be used. The final choice for the geometry of the 70 W lamp was made for the design that offered the best lumen maintenance. This design minimizes the free convection in the tube chamber. This can be realized by maximizing the arc length (thus minimizing the mercury pressure) and minimizing the inner diameter.

The design of the electric feedthrough

The feedthrough construction of alumina discharge tubes used in high pressure sodium lamps is not suitable for metal halide lamps. The niobium feedthrough and the sealing frit are rapidly corroded by the liquid and gaseous halides, causing leakage. These corrosion processes can be stopped by employing a special feedthrough design, shown in **Figure 7**. This design is a variation of the feedthrough construction of the white high pressure sodium lamps.[6] The construction consists of an extended plug, a niobium lead-in, a molybdenum lead-through, and the sealing frit. The sealing frit completely covers the niobium and a part of the molybdenum. The voids between the plug hole and the molybdenum lead-through are filled with liquid halide during operation.

This construction reduces the frit temperature to an acceptable level and protects the niobium by a layer of frit that reduces the transport rate to and from the niobium surface. The corrosion of the frit is further reduced by choosing a more resistant type based on mixtures of aluminum, silicon, and rare-earth oxides.[8]

The potential danger of this construction, the formation of cracks in the alumina plug due to differences in the coefficients of thermal expansion between the molybdenum lead-through and the alumina plug, can be avoided in either of two ways: by using a coiled molybdenum lead-through which redirects the stresses, or by using molybdenum-alumina composite material that has a coefficient of thermal expansion which closely matches that of alumina.

Properties of metal halide lamps with ceramic envelopes

Metal halide lamps with ceramic envelopes, made according to the design method described above, offer interesting photometric properties. These properties provide lamps with improved color rendering, color control, and luminous efficacy, both initially and throughout lifetime. All improvements can best be illustrated by a comparison of three types of metal halide lamps, containing quartz envelopes with sodium/scandium fill, quartz envelopes with sodium/rare-earth fill, and alumina envelopes with sodium/rare-earth fill, shown in **Table 3.**

Color rendering

The differences in color rendering among the three types of metal halide lamps are reflected by their spectra.

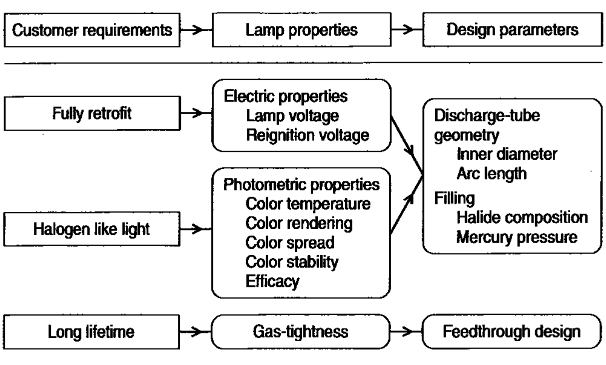


Figure 5—The link between the customer requirements and the ceramic lamp design

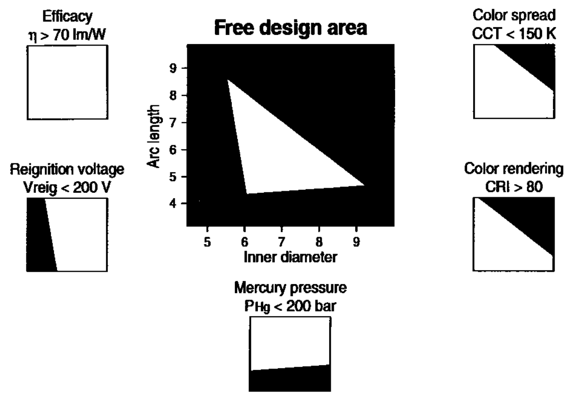


Figure 6—The design area for a 70 W discharge tube, according to the customer requirements

Figure 8 shows a comparison of some examples of typical spectral power distributions of the three types of lamps. The lamps with alumina envelopes show a higher continuum radiation throughout the spectrum, and especially in the red part of the spectrum.

Color control

The improved color control of lamps with ceramic envelopes is manifested as reduced color spread and improved color stability.

Figures 9 and **10** show a comparison of the color stability as a function of operating position and as a function of the input voltage. Lamps with ceramic envelopes show a significantly better stability than lamps with quartz envelopes and sodium/scandium fill.

Figure 11 shows a comparison of typical values of initial color spread for the three types of lamps. The very small color spread of the ceramic metal halide lamps is a direct consequence of the higher halide temperature.

This figure also shows a comparison of typical values of color spread and color shift at a lifetime of 5000 hrs. The permanently small color spread of alumina lamps is a direct consequence of the chemical resistivity of the alumina.

Luminous efficacy and lumen maintenance

The luminous efficacy of lamps with ceramic envelopes, as shown in **Table 3**, is significantly higher than that of lamps with a quartz envelope, due to the higher operating temperature of the former. **Figure 12** shows that lamps with alumina envelopes also have a better maintenance throughout lifetime. The real cause of this better maintenance is still unknown, and may be a consequence of the unique chemistry of the ceramic metal halide lamp.

Conclusions

The chemical resistance of ceramic envelopes allows increased discharge-tube operating temperatures. The design of the ceramic discharge chamber takes advan-

Table 3—Typical properties of 70 and 100 W universal metal halide lamps.*

Discharge-tube material	Quartz	Quartz	Alumina
Filling	Na/Sc	Na/Tl/RE	Na/Tl/RE
Color temperature - K	3200	3000	3000
Color spread (lamp-to-lamp)- K	360	250	150
Color rendering index	65–70	75–80	82–85
Luminous efficacy - lm/W	75–80	75–80	90–92

****Values of color temperature, color rendering index, and luminous efficacy indicate catalog values of lamps of major lamp manufacturers. Values of color spread indicate three-sigma values of measurements of at least 10 lamps.***

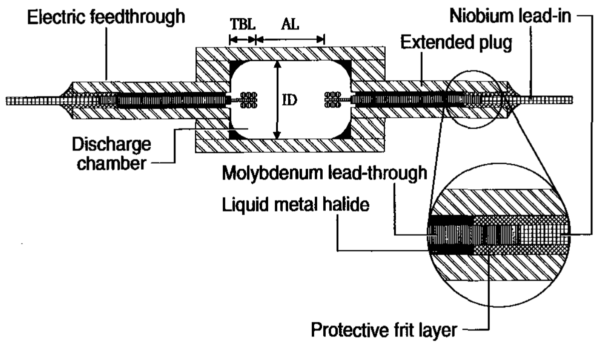


Figure 7—The design of the ceramic metal halide discharge tube

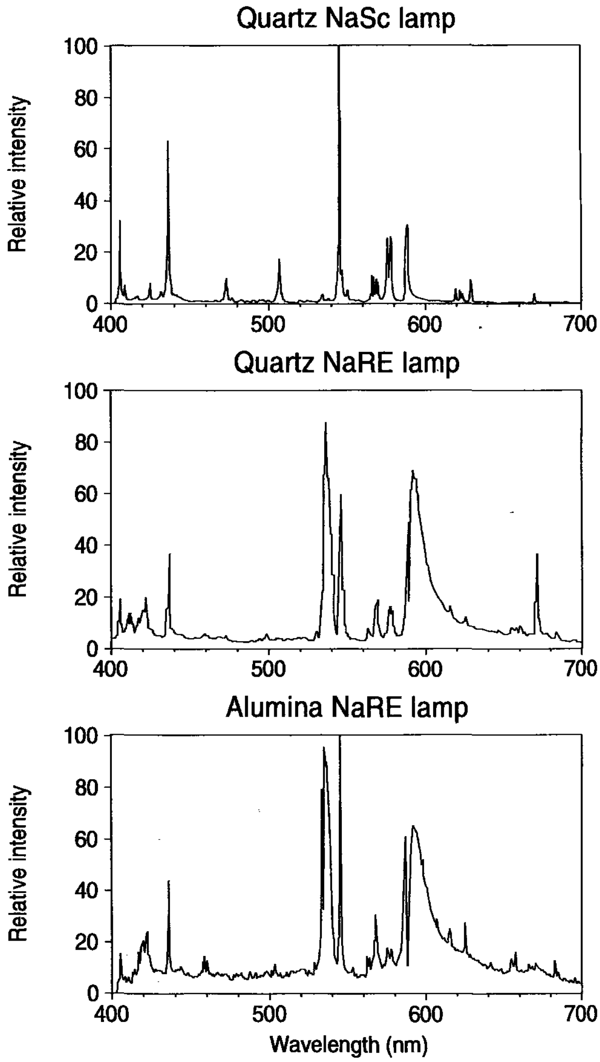
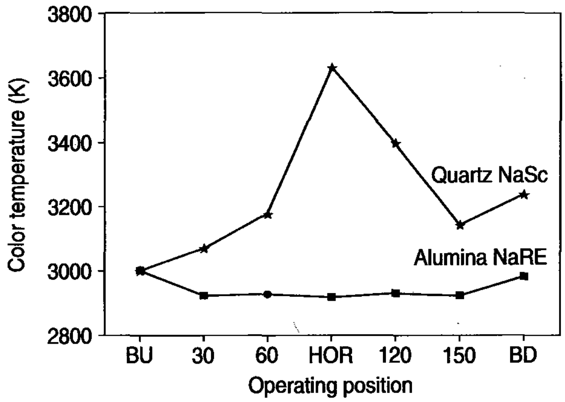
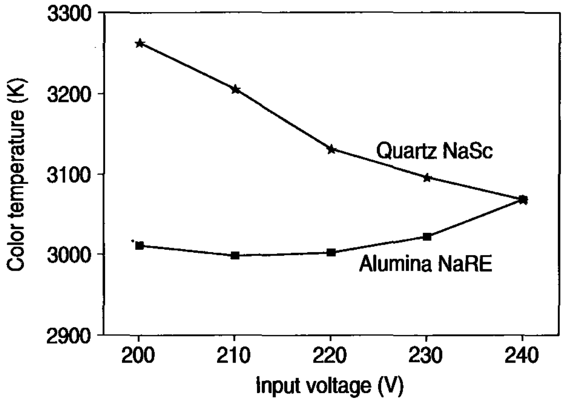


Figure 8—Comparison of the spectral power distribution of the three types of metal halide lamps



'igure 9—Color stability of 100 W universal metal halide lamps as function of operating position. Values of the lamps of quartz ith sodium/scandium fill represent the average of measurements f three lamps each from three major lamp manufacturers. Values f the lamps of alumina with sodium/rare-earth fill represent the verage of measurements of three lamps



igure 10—Color stability of 100 W universal metal halide lamps s a function of input voltage. Values of the lamps of quartz with odium/scandium fill represent the average of measurements of hree lamps each from three major lamp manufacturers. Values of he lamps of alumina with sodium/rare-earth fill represent the verage of measurements of three lamps

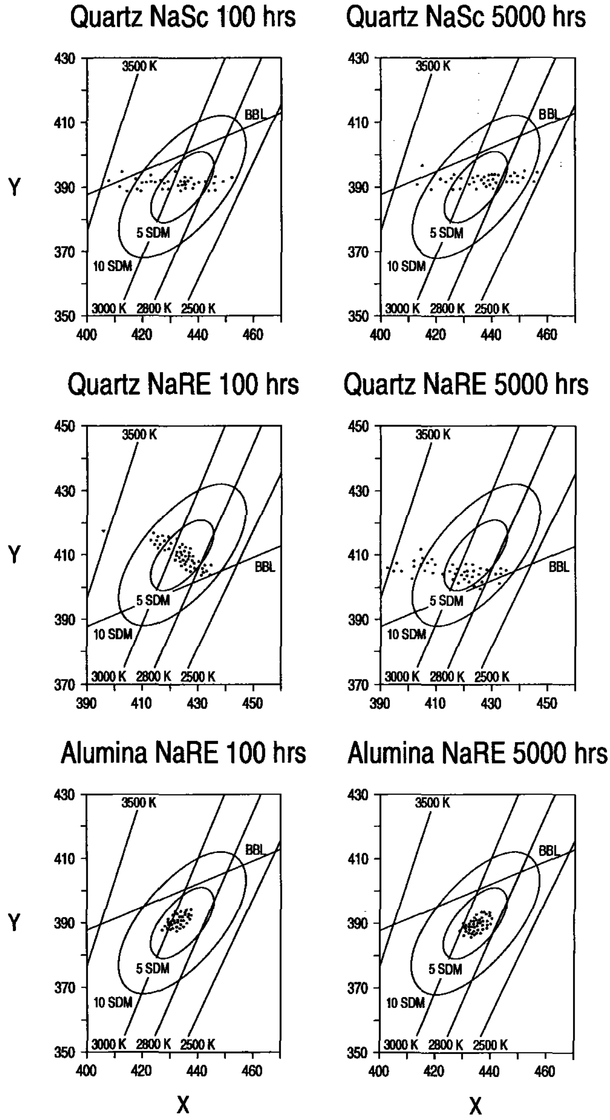


Figure 11—Comparison of the color spread (initially and after 5000 hrs lifetime) of the three types of metal halide lamps.

age of this fact to optimize photometric properties that ire important to customers, like a good color rendering, n excellent color control, and a higher luminous flux, oth initially and throughout lifetime. A special eedthrough design ensures that the lamps achieve the ustomers' required lifetimes.

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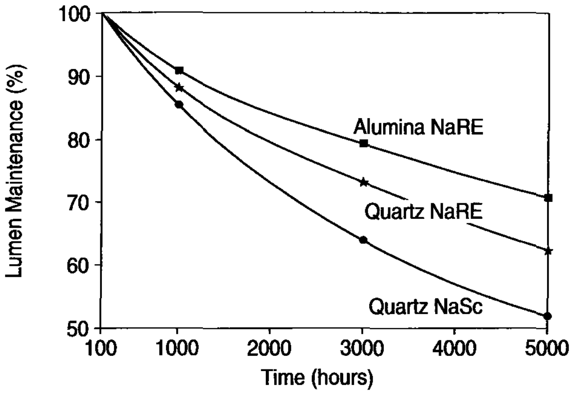

Figure 12—Comparison of the lumen maintenance of the three types of metal halide lamps

Discussion

When the design space was chosen, what was the rationale for > 150 K color spread lamp-to-lamp (why not tighter)? Also, how much variation can be expected in the x and y coordinates?

An issue often discussed at length with respect to metal halide lamps is open versus closed fixtures. Does the ceramic arc tube increase, decrease, or not change the probability of arc tube rupture? Will there be open fixture ceramic lamps or will two versions (enclosed only and open/enclosed) be available?

Figure 10 seems to exhibit the promise of nearly constant color dimming of ceramic metal halide lamps. Can the authors comment on the dimmability of ceramic metal halide lamps (effects on life, color, light output, etc.).[7]

R. Barton
GE Lighting

The authors present very significant results on the development of new types of metal halide lamps in ceramic envelopes with a special feedthrough design. The main advantage of these new lamps is an improved color control in terms of minimal initial lamp-to-lamp color spread and smaller color shift over lifetime.

Would the authors please respond to the following questions?

1. What are the reasons for a smaller lamp-to-lamp color spread at higher salt temperatures as shown in **Figure 1**? Are the data points for the color spread in **Figure 1** taken from **Table 3**? What was the lamp's age? Does the color spread reflect production tolerances at zero hours or is it the result of wall reactions early in life as mentioned in paragraph four? How was the halide temperature measured?

2. Why do the lamps with ceramic envelopes show better color stability as a function of operating position than lamps with quartz envelopes? What was the tip-off orientation for horizontally burning quartz lamps? What was the stabilization time for lamps under test in differe positions before photometry?

3. What are the main life limiting factors for the ne lamps? Your literature quotes 20 percent failure rate a 50 percent life. What is a typical failure mode?

4. **Figure 6** requires more detailed explanations for a average reader; otherwise it looks like pieces of a puzzl that are not easy to put together. For example, what do the term "reignition voltage" describe—voltage spik during warm-up or during steady-state—and how does relate to the arc tube geometry? The wall temperatur change must be dramatic within the "free design are because the surface area is decreasing in half by movin to the lower left corner (wall loading is increasing fro 20 to 40 W/cm^2). Can the authors comment on this?

Z. Krask
OSRAM Sylvani

Authors' response

To R. Barton

1. The rationale for the design space for color sprea of ± 150 K was the fact that this color spread within th tolerance is acceptable for the human eye. Color sprea of ± 150 K corresponds to x,y < ± 0.005 in the chr maticity diagram.

2. We continue to investigate the rupture characteri tics of this well-known arc-tube material in this new lam type. Testing to date suggests a very low propensity fo rupture in typical applications, but we do not yet mak definitive claims.

3. Indeed, the potential for dimming is one of the fe tures of ceramic arc tubes. At 50 percent lamp powe reduction, for example, the luminous flux decreases b 60 percent. The color shift is mainly in the y directio and is much smaller compared to that of most quar metal halide lamps. The acceptance of this color shift wi surely depend on the application. Our testing to dat shows no dependence of lamp life on dimming, but ou testing is not finished.

To Z. Krasko

1. The reasons for the smaller lamp-to-lamp colo spread at high salt temperatures are still a bit of a my tery. The best explanation boils down to the assumptio that small differences of the partial halide pressures o the mixture, caused by small differences in the compos tion and/or halide temperature, give larger spectral di ferences for a line spectrum than for a more continuo spectrum.

The data points for color spread in **Figure 1** and **Tabl 3** are taken from the same lamp type. The data on th color spreads presented in the figure, however, represen the one-sigma value, whereas the data presented in th table represent the three-sigma value.

The lamp age was 100 hrs, because this is the standard reference.

We continue to identify the contributors to the relatively narrow zero-hour color spread. While known variables such as salt composition play a part, there are undoubtedly other contributors. Since the color spread of ceramic arc tubes is significantly less than that of quartz arc tubes, the usual important quartz variables cannot be reliably assigned to this new design approach.

The halide temperature was measured by measuring the outer tube wall temperature at the location of the liquid halide. The actual temperature measurement was by means of infrared pyrometry.

2. The better color stability as a function of operating position is the consequence of higher halide temperature. Assuming that halide temperature changes, caused by changing the operating position, are similar for quartz and alumina tubes, it can be demonstrated that these changes at high temperatures (alumina tubes) cause a smaller color shift than similar changes at low temperatures (quartz tubes).

The tip-off orientation of quartz tubes was up.

The stabilization time for lamps at different operating positions was at least 1 hr. Moreover, the stabilization was checked by monitoring lamp parameters like x,y and the lamp voltage during this time.

3. Leakage of the discharge tube is the typical failure mode.

4. The reignition voltage as given in **Figure 6** describes the maximum lamp voltage immediately following the transition from one-half cycle to the following half cycle (see definition in ANSI C82.9) during stable operation. Its mathematical relation to the arc tube geometry (arc length and inner diameter) is best shown by the line that forms the border between the shaded and unshaded areas. This line is in fact the iso-voltage line at 200 V.

The wall temperature change within the "free design area" is indeed large, estimated to be a few hundred degrees. This may well have its repercussions on the (expected) lifetime of the lamps. In this view, the term "free design area" may be a little misleading, because it suggests that attainable lifetime will be similar throughout the entire area. This is of course not the case.

Generally speaking, it is our experience that longer lifetimes result from lower arc-tube temperatures, and this consideration is included in our designs.