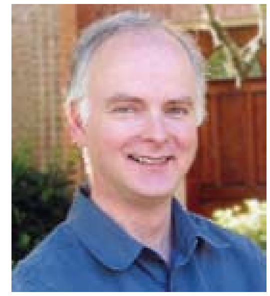
BY **MIKE WOOD**



When white light isn't white

WHITE LIGHT IS WHITE LIGHT ISN'T IT? In the field of entertainment lighting we've long known that isn't true and that white can actually mean a broad range of colors a bit like those 27 shades of white you see in paint charts. Still, in the main, dealing with the differences has been a relatively simple one-dimensional problem. With the rapid expansion of LEDs as viable light sources all that is changing.

Why do I say it's been a one-dimensional problem? Well, the light source that is still by far the most commonly used in entertainment lighting is the incandescent lamp and an incandescent lamp filament emits radiation in a completely continuous spectrum. As the tungsten filament is heated from its cold, black state it changes color in a familiar manner passing through red, orange, yellow and white before finally reaching a bluish-white just before it melts. The color of light emitted by a hypothetical, perfect incandescent black body depends only on its temperature and the color of light produced will always lie somewhere along the Planckian locus (often called the black body line) on a color chart. We use the position along this locus to describe the color of a white light source and refer to that position, measured in Kelvin (K), as its Color Temperature.

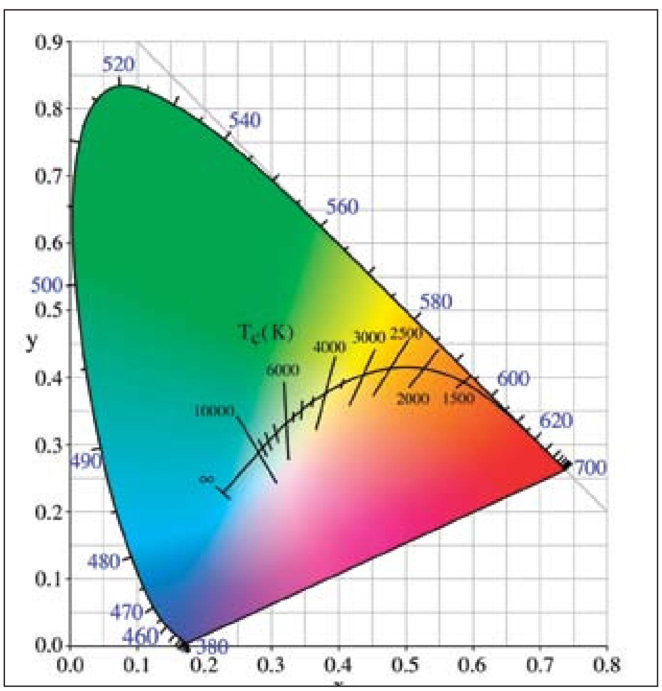


Figure 1 illustrates the Planckian locus on the familiar 1931 CIE chromaticity chart with approximate color temperatures (Tc) marked. The position along that curve is the single value that I have been referring to as the one-dimensional problem.

When we say a lamp has a color temperature of 3200K, we mean that a metal heated to a temperature of 3200K would produce light of about the same color as the lamp. If that same metal is heated to 3700K, it will produce a bluer light. 3700K is pretty much as high as you can go with tungsten as that's close to its melting point (the highest of any metal). Entertainment incandescent lamps are typically in the 2500K to 3200K range where the filament is a little cooler and more robust. Natural daylight, which is also very close to a black body source, has a color temperature which can be anything upwards of 6000K depending on how high the sun is in the sky and how overcast that sky is. Direct sunlight alone, without the contribution from the blue sky and the diffusion from clouds, is a little lower at around 5300K. For normal lighting purposes we often average these out such that the term *daylight* commonly refers to a color temperature of 5600K.

The second-dimension—correlated color temperature

Another group of lamps with which we are very familiar are High Intensity Discharge lamps (HID) such as HMI, MSR, and MSD. These lamps have discontinuous spectra and, although the manufacturers strive to get close, their output color points don't usually fall exactly on the Planckian locus. However those color points are usually close enough to the locus that we can use the concept of correlated color temperature where the correlated color temperature (Tc or CCT) of a source is defined as the temperature of the Planckian radiator whose perceived color most closely resembles that of the source.

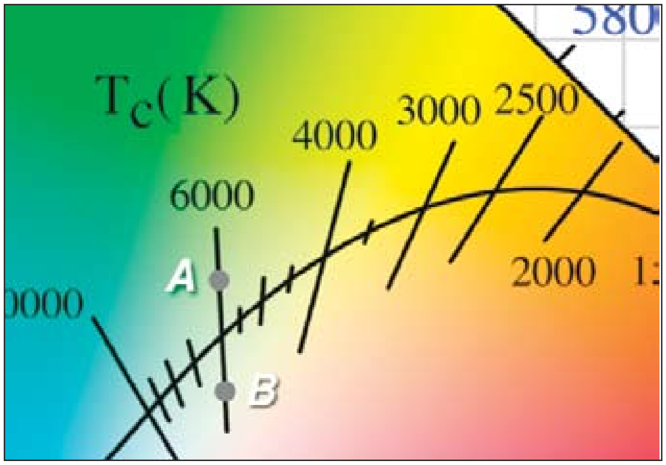


Figure 2 – Correlated Color Temperature

This is an approximation of course but one that works well in practice. In **Figure 2** the lines of equal correlated color temperatures are the short lines crossing the Planckian locus and points A and B are both on the 6000K line. Once we are back on the Planckian locus then we can use our earlier definitions and treat the source as if it were a black body radiator and we can be comfortable with using gels to correct color temperature up and down the Planckian locus to increase (CTB) or decrease (CTO) the color temperature.

> "How much color variation are we prepared to accept between similar whites?"

The use of correlated color temperature isn't the whole story though, especially if the color coordinates are a long way from the Planckian locus. You can see from **Figure 2** that two lamps (shown as points A and B) whose color co-ordinates fall either side of the Planckian locus, one above and one below, could have the same correlated color temperature but still look very different. One, A, would appear greenish and the other, B, slightly magenta or pinkish. It's not uncommon to see this problem with discharge lamps used in followspots or automated lights and TV and film practitioners are very familiar with using "minus green" gels to try and correct the problem. A green tint in what is supposed to be white light is usually to be avoided at all costs, our eyes are particularly sensitive to green and it makes skin tones in particular look very unnatural. If there has to be an error it is usually better for a light source to err on the magenta side than the green one.

This green correction is a second-dimension of correction and, although we know about it, unless you are working in the television or film areas of our industry and using large HID lamps, it's not something we are dealing with every day. However the almost inevitable takeover by LEDs as the ubiquitous light source for the 21st century will force us to deal with this problem all the time.

My LED is white, but what about yours?

Like HID sources LEDs give us a discontinuous spectrum, and often one with even bigger gaps. This is particularly obvious when using an LED luminaire which uses a mix of red, green and blue emitters to produce a white; but is also the case when using so called white LEDs. Currently there are two common techniques for producing white LEDs. The first technique just mimics the RGB luminaire and uses multiple wavelengths of different LED dies mounted in a single package to mix an approximation to white light, while the second uses a deep blue (InGaN) or UV (GaN) LED die with a phosphor coating to create white light. The phosphor technique is becoming very common and is now pretty much the norm for white LEDs. The development and manufacture of these phosphors owes a lot to the R&D done on the similar phosphors used in fluorescent lamps and, although they are getting better every day, they suffer from many of the same problems with gaps in the spectra and a propensity to appear green.

Whichever way you make white light from your LEDs you now not only have to worry about the first-dimension of correlated color temperature but also the second-dimension of green/magenta shift. To make matters worse the manufacture of these LEDs is an inexact science with a wide variation in the product coming off a single production line. The LED manufacturers deal with this by *binning* where they measure the output of the LEDs and sort them into various ranges, or bins, before sale. The size of each of those bins and the subsequent range of colors each one encompasses is critical in determining how close a match the LEDs we use in our lights will have to each other and thus how much color variation we are going to see between units.

We now have to ask ourselves a question. If we can't have an exact match, how much color variation are we prepared to accept between similar white LEDs? It's a question with more than one answer depending on what you are lighting and how. This question has been extensively studied with fluorescent lamps and there is now an ANSI standard (*NEMA ANSLG C78.377-2008, Specifications for the Chromaticity of Solid State Lighting Products for Electric Lamps*) recommending a series of bins based on 7-step MacAdam ellipses as the color-tolerance criterion for solid state lighting—that's a huge variance! The standard also discusses perhaps tightening this to a 4-step ellipse in the future but, although better than 7, that's not too tight a tolerance either. A single step MacAdam ellipse represents a region plotted on a color space diagram showing where colors are perceived to be the same by the average viewer and, logically, a 4-step ellipse is four times larger—in other words a color difference that is four times more than the minimum color difference we can see. But what should we use for LEDs? Just because a standard works (somewhat) for fluorescent lamps doesn't mean it works for LEDs. As an example the red ellipse plotted in **Figure 3** illustrates approximately what a 4-step MacAdam ellipse looks like on the CIE chart. Any sources within that ellipse would be classified as being the same color.

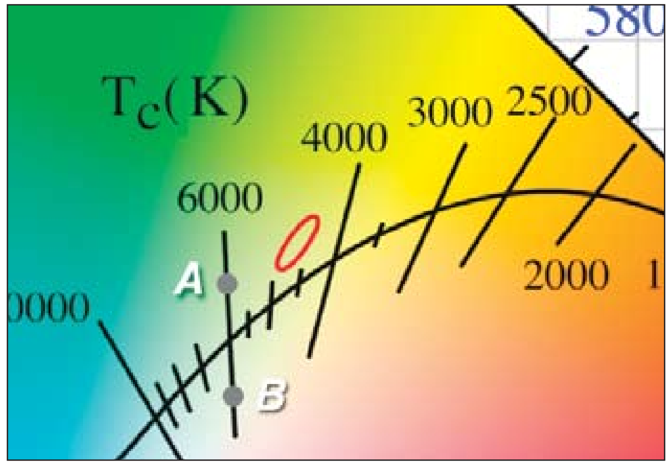


Figure 3 – MacAdam Ellipse

The LRC study

Establishing these criteria is not a simple task—we are dealing with human perception and all the natural variation that implies. The Lighting Research Center of the Rensselaer Polytechnic Institute has taken on the task and recently published preliminary results on a study to determine these criteria and reported as follows (text extracts quoted with permission from LRC). In the study, LRC researchers conducted experiments to develop

> "Green is great for efficiency but awful for skin tones . . ."

color-tolerance criteria for white LEDs. The criteria define at what point a normal human observer would see a just-noticeable color difference between LED light sources. Their study also investigated the impact of light level, spectrum, correlated color temperature (CCT), and visual complexity of the illuminated scene on the color tolerance range. This information was then used to establish recommended color-binning criteria for white LEDs. As an example of currently available binning, **Figure 4** shows the white color-binning currently offered by Lumileds for its Luxeon emitters, these bin sizes vary between four and six step MacAdam ellipses. Is this good enough?

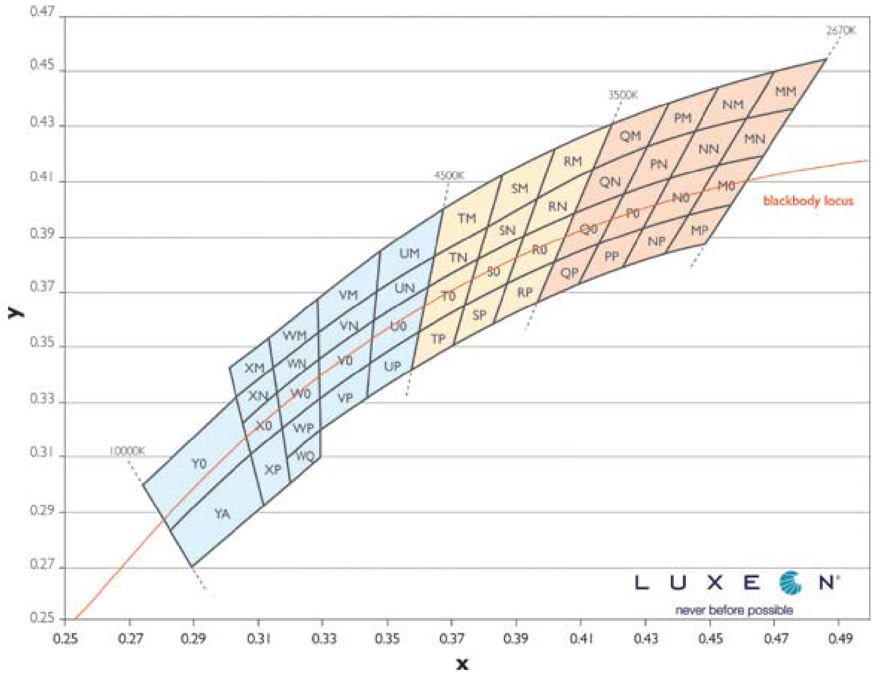


Figure 4 – Luxeon binning

To carry out the tests LRC researchers built a display cabinet with two side-by-side compartments. Using RGB LED panels, MR16 halogen lamps with RGB filters, and a variety of white and multicolored backgrounds, test subjects compared the color of white light in one compartment against the other. The reference compartment showed a constant white light color at a specific x, y chromaticity value. This same value was used as the starting point for the adjacent test compartment light source. The test compartment then changed color systematically in incremental steps. At each step, subjects were asked whether they saw a color match or noticed a color difference. If subjects saw a color difference, they commented on how different the two compartments appeared.

As might be expected the type of visual background has a major impact on the color tolerance range. Complex visual backgrounds using different colors allow for much greater variations in white light color before we notice a color difference than a plain white background. Taking all this into account, LRC proposed the following two criteria for color binning white LEDs:

- **2-step MacAdam ellipse**—For applications where the white LEDs (or white LED fixtures) are placed side-by-side and are directly visible, or when these fixtures are used to illuminate an achromatic (white) scene. Accent lighting a white wall and lighting a white cove are some examples.
- **4-step MacAdam ellipse**—For applications where the white LEDs (or white LED fixtures) are not directly visible, or when these fixtures are used to illuminate a visually complex, multicolored scene. Lighting a display case and accent lighting multicolored objects or paintings are some examples.

LRC were not specifically considering entertainment lighting of course but I would argue that, for many of our applications particularly when lighting critical skin tones, we fall in the first category and should be looking at 2-step

> **"Color consistency will become a major concern, if not a headache, for us all."**

MacAdam ellipses. Until very recently this was a much tighter tolerance than the binning offered by the major LED manufacturers; however the LED manufacturers are responding with moves in the right direction and Osram recently announced a new initiative to move to 3-step binning for white LEDs which they claim is the finest binning in the industry. If this

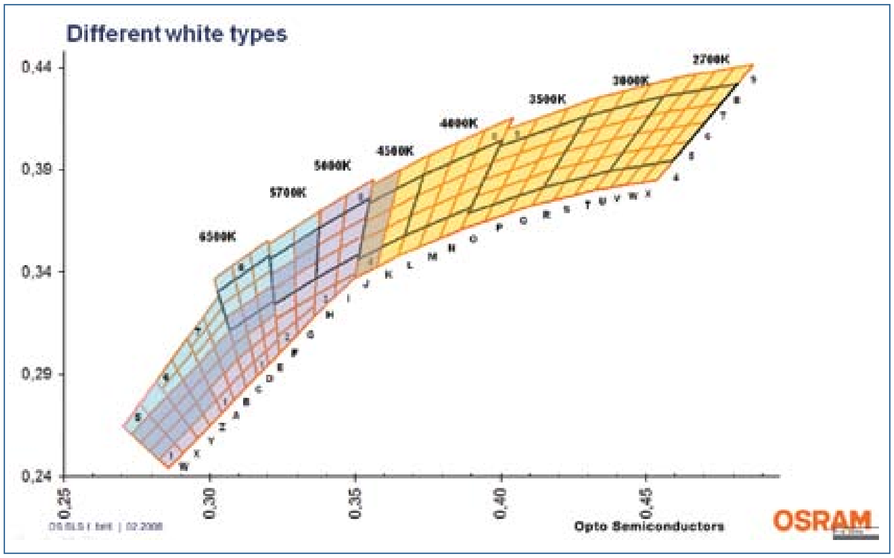


Figure 5 – Osram "Fine White" binning

initiative is successful I'm sure the other manufacturers will follow and perhaps improve even more.

Figure 5 shows the proposed Osram binning structure superimposed on the eight rectangular bins (black quadrilaterals) recommended in NEMA ANSLG C78.377-2008 and shows just how big those bins are. You can also see from **Figure 4** just how many of those bins are on the green side of the Planckian locus. As discussed earlier, whatever we *do* want in a white LED the one thing we *don't* want is green—errors on the magenta side of the locus are always more acceptable to the eye than errors on the green side. Unfortunately the phosphors used for white LEDs, like those used for fluorescents, tend to be most efficient on the green side so that's where the manufacturers like to be as it gives the most lumens per watt! Green is great for efficiency but awful for skin tones….

Only a year ago the use of LEDs in entertainment lighting was pretty much restricted to direct view and display applications and for lighting backings and set pieces, much of the time in deep colors, so none of this was of concern. Now LEDs are bright enough to be used to light performers and to be used as a white light source, color consistency will become a major concern, if not a headache, for us all. We have been accustomed to not having to worry about it with incandescent lamps so the question isn't usually in the forefront of our minds. Time to learn about that second-dimension!

Thanks to the Lighting Research Center of the Rensselaer Polytechnic Institute, Troy, NY for permission to quote extracts from their research which was sponsored by the Alliance for Solid-State Illumination Systems and Technologies (ASSIST). ■

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