Understanding Light Quality: ***Color Temperature and Color Rendering Index***

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There is growing recognition by the public that fluorescent lighting, with its high energy efficacy and long lamp life, saves money over time and, by reducing demand for electric power, minimizes many of the environmental impacts that accompany utility scale electric power generation—toxic pollution, waste, habitat loss, and greenhouse gas emissions. In most industrial, commercial, and institutional settings, where economic imperatives often take precedence, energy efficient fluorescent lighting has become standard practice. In the residential sector and among building occupants, however, the technology faces tougher scrutiny and somewhat less overall acceptance.

When people return home from a day devoted to the demands of the workplace, they frequently want to relax and unwind. As we all know, light plays a central role in setting the mood. From a purely aesthetic point of view, people often prefer the "warm" glow of energy intensive incandescent lamps, and are willing to pay more in the long run—and pollute more—to have this effect. The all-too-common perception of fluorescent light, resulting from the early expressions of the technology, is one of poor light quality; as one participant in a 1998 tour through the Energy Efficient Fixtures Lab at Lawrence Berkeley National Laboratory put it, "Aren't those the expensive, dim, flickering, humming, poor-color, strange-looking, hard-to-find lamps that make me tired, give me headaches, and don't fit into any of the fixtures in my house?"[1]

The reality of today is that there are fluorescent lamps available which produce light quality characteristics to suit most any need—without the flicker or the hum—even matching the "warm" glow of the standard incandescent bulb. Dissatisfaction arises because people simply don't understand how fluorescent light quality is rated, and therefore cannot select the option best suited to their particular needs. The problem is further complicated by the fact that enhancements to fluorescent lighting technology are being introduced to the marketplace at a pace that even building design professionals and product merchandisers are hard pressed to keep up with. As a result, stores may stock only one variety of fluorescent lamp—quite likely the one that won't create that pleasant, warm and cozy feel in the home. Even when choices are available, the selection process boils down to a shot in the dark decision, which risks leaving many consumers turned off to fluorescent technology.

To understand how light quality is rated it is essential to grasp several concepts developed by physicists over the years. Light quality is characterized by its *color temperature* (measured in Kelvin's—a unit of temperature not unlike Fahrenheit or Celsius) and by its *color rendering index* (no units here). Naturally, the average person has no idea what these terms mean. Many building professionals, though probably familiar with the basic definitions, may not be aware of how these indexes are derived and as a result, may be making decisions based on misconceived notions.

Let's take a glance at the common definitions, and then consider the reasoning behind these important terms.

Color Temperature

The Illuminating Engineering Society of North America (IESNA) defines color temperature, in non-technical terms as, "*a numerical measurement of its color appearance…based on the principle that any object will emit light if it is heated to a high enough temperature and that, as the temperature increases, the color of that light will change in a predictable way.*[2]" Color temperature is determined by comparing the light source in question to a standard source, known as a *black body radiator*.

This definition begs the question: What is a black body radiator? Here lies the key to arriving at a better functional understanding of how light quality is characterized.

A black body is a theoretical construct that physicists have created in their minds, but can only be closely approximated in the laboratory. Simply put, it is a device that absorbs all electromagnetic radiation that strikes it, reflecting or transmitting none. Visible light is a range of electromagnetic radiation of wavelengths 700 nm (red) down to 400 nm (blue-violet)—that's *nano*-meters or *billionths* of a meter. So, a blackbody will absorb (not reflect, not transmit) all wavelengths of visible light that strike it. The science of physics informs us that black objects absorb visible light, and white objects reflect visible light. In reality, all real objects, even objects that appear black to the human eye, will reflect some wavelengths of light. A black body is, theoretically speaking, truly black. A small hole leading into a dark cavity closely approximates an ideal black body.[3]

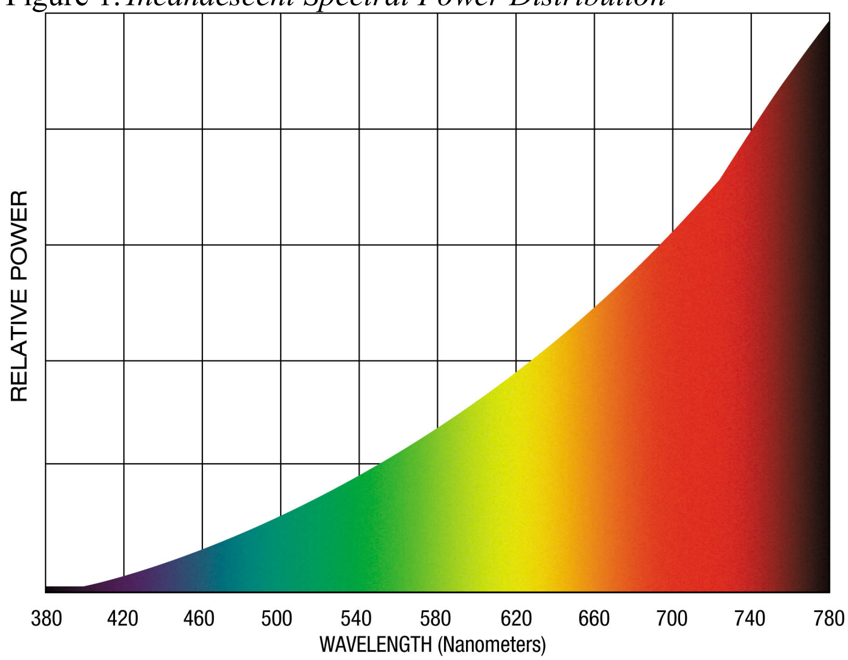
As far as lamps are concerned, the relevant understanding about black bodies is that they are not merely ideal absorbers of radiant energy; they are also ideal emitters of radiant energy. Imagine a small hole leading into a furnace. As the furnace is heated, a continuous spectrum of all wavelengths of light will be emitted from the hole, however not all wavelengths will be equally represented. The so-called *spectral power distribution* of the black body radiator will depend entirely upon the temperature. For example, a black body at 98.6 ºF (310 K)—the temperature of the human body—will emit a continuous spectrum of, predominantly, infrared radiation, which our eyes cannot see, but our sensory system can perceive as warmth. As the temperature of a black body is increased, the spectral power distribution of radiant energy shifts toward emission of higher frequency—shorter wavelength—radiation.

Below 1,112ºF (873 K), the radiation emitted by a black body is in the infrared range (>700nm) and is not visible. Between about 1,112 ºF and 1,292 ºF (973 K), long wavelength visible energy begins to radiate and the black body glows a dull red. With increasing temperature, the visible light emitted by a black body shifts from red, to orange, to yellow, to white, and finally—to bluish white. This means that light emitted by a black body with a lower *color temperature* (973 K) appears more red or yellow, while a black body of higher color temperature, say 10,340 ºF (6000 K) appears more bluish-white.[4]

Candles, campfires and standard incandescent lamps radiate low color temperature light (2,700 K or less). The noontime sun is a good example of high color temperature light (about 6,000 K). Ironically, artists, photographers, and yes, even lighting engineers like to describe *low* color temperature light—that's reddish-white light—as *warm* light, and *high* color temperature light—that's bluish-white light, as *cool* light.[5] That's because we tend to associate the color red with warmth, and the color blue with the coolness of ice.

Most any dense substance, such as the tungsten metal filament of an incandescent lamp, when heated will behave like a black body radiator, not ideally so, but very closely. The color temperature of the filament in an incandescent bulb is about 2,700 K producing all visible wavelengths (white light), but with a red (700nm) emphasis in its spectral power distribution, as shown in figure 1. A tungsten *halogen* incandescent bulb has a hotter filament, with a color temperature of about 3000 K. Even at 3000 K, however, the spectral power distribution strongly emphasizes red wavelengths.

Figure 1. *Incandescent Spectral Power Distribution*[5]



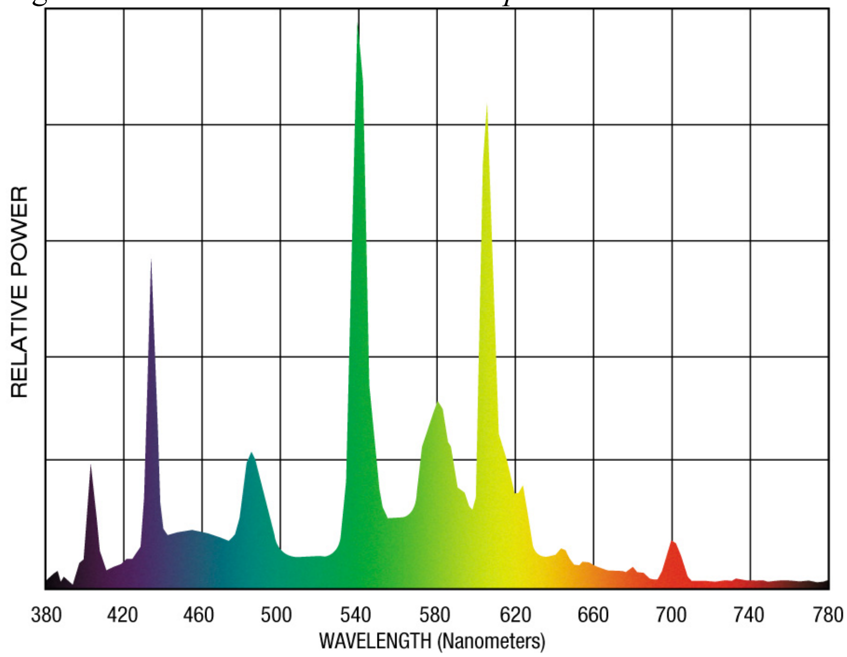
Charts and illustrations courtesy of OSRAM SYLVANIA Inc

Determining the color temperature of a fluorescent lamp is not as straightforward. Because this technology does not rely on heating a dense solid filament to a high temperature, it does not mimic the behavior of a black body radiator.

Instead, fluorescent lamps are gas discharge tubes, where a high voltage electric arc is placed across a gas which, due to the energetic excitation of the individual atoms, emits wavelengths of light characteristic of the identity of the gas. The mercury vapor contained inside the fluorescent lamp will emit very specific wavelengths of radiant energy, not a continuous spectrum; many of these wavelengths happen to fall in the ultraviolet range, and are invisible to human eyes.

The inside of the glass tube is coated with a complex mixture of chemicals that contain phosphorous. These phosphors, as they are commonly called, are what give the glass of fluorescent lamps their chalky white appearance. The purpose of the phosphor coating is to absorb the ultraviolet light emitted by the excited mercury vapor and re-radiate the energy at longer, visible wavelengths (reds, yellows, and blues). The resulting spectral power distribution is not smooth; instead some wavelengths are weakly represented, while others dominate. Figure 2 shows the spectral power distribution of a 4100 K fluorescent lamp with a tri-phosphor coating.

Figure 2. *Octron 4100 K Fluorescent Spectral Power Distribution*[5]



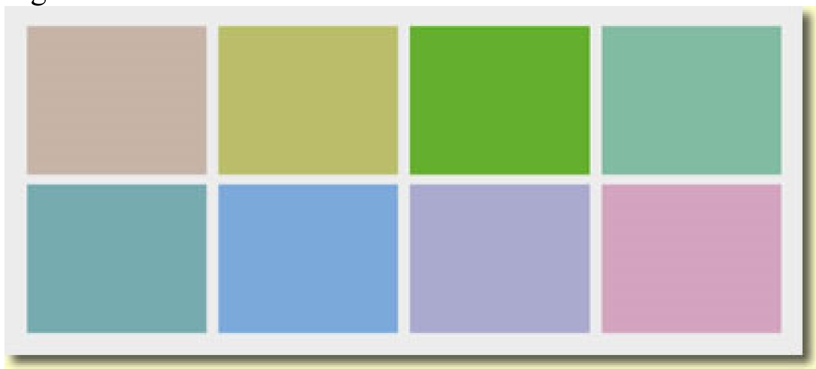
Charts and illustrations courtesy of OSRAM SYLVANIA Inc

The color temperature of a fluorescent lamp is approximated by matching the appearance of the lamp's light output to that of the black body temperature that it most closely resembles. Whereas incandescent lamps really do radiate energy at their rated black body color temperature, fluorescent lamps are always at a much lower real thermal temperature than their rated color temperature suggests. Due to this, and in light of the fact that the spectral power distribution of a fluorescent lamp never matches that of a black body radiator, the term *correlated color temperature* is more accurately applied to fluorescent lamps. By modifying the mixture of chemical phosphors, the spectral power distribution of fluorescent lamps can be adjusted to mimic the light output of a wide range of black body color temperatures, from warm light quality (2,500-3,500 K) to cool light quality (4,000-6,000 K).

Color Rendering Index

A second term, color rendering index, assesses how a light source influences the color appearance of objects. It is arrived at by illuminating a set of eight standard color plates (Figure 3), with the light source in question, and by a black body radiator of the same correlated color temperature.

Figure 3.



The color rendering index is set at its highest rating of 100 only if the appearance of the color plates remains unchanged by the two light sources. Any change in the color appearance of the plates evokes a lower color rendering index; the greater the discrepancy, the lower the CRI.

Though relatively simple in concept, this technique for characterizing the capacity of a light source to render colors can be easily misinterpreted. For example, since the underlying technology of incandescent lamps—heating a dense, solid filament—closely approximates the radiation of an ideal black body, the CRI of these lamps is always 100, the maximum rating. This may lead to the conclusion that incandescent lamps reveal the true color of objects exceptionally well, but this is simply not the case. In fact, incandescent lamps, with their inherently reddish-white light (color temperature 2,500-3,500 K) are not very well suited to render the true colors of objects, especially if the object is blue! Physics tells us that light dominated by red wavelengths, when shined on a blue object will shift its perceived color to a darker shade, it may even appear black.

In Contrast, fluorescent lamps—phosphor-coated gas discharge tubes—do not possess the thermal properties of a black body radiator, and never have a CRI of 100. The best fluorescent lamps today typically have a CRI of 85 or higher.

Nothing renders an object's true color like the mid-day sun, a high color temperature light source (about 6,000K), with a CRI of 100 because the sun behaves very much like a black body radiator. The sun at noon renders colors well because it emits lots of short wavelength blue light, in addition to lots of yellows and reds. Since all visible wavelengths are well represented in the sun's spectral power distribution, the true colors of objects can be accurately perceived. A high color temperature fluorescent lamp with a CRI of 85 or better can achieve a similar effect, and save energy, money, and the environment. Energy hungry incandescent lamps cannot achieve this effect because, at 6,000 K, the tungsten filament would melt.

Concluding Recommendations

What follows are a few simple suggestions, intended to provide some final clarity on the matter of selecting and using a fluorescent lamp. Fluorescent lamps are a technology that will save you money, reduce toxic emissions from power plants, and reduce greenhouse gas emissions. In some cases, particularly when purchasing compact fluorescent lamps, you may need to contact the manufacturer to determine color temperature and color rendering index, as the indices are not always reported on the lamp or its packaging.

- Unless light quality makes no difference, always shop for high CRI (85 or better) fluorescents. Very low CRI fluorescent lamps should cost less, and may be adequate in storage rooms, warehouses, and other non-living spaces where light quality is of little concern.
- If you are looking to simply mimic the light quality of your existing incandescent lamps, shop for low color temperature fluorescent lamps (2,500-3,000 K).
- If you wish to create a “warm” mood in your occupied space, such as dining areas and bedrooms, choose low color temperature fluorescent lamps. This will make reds and yellows appear vibrant, while greens and especially blues will be de-emphasized by comparison. Sharp color contrasts, often associated with a sense of alertness, will also be reduced.
- If you desire to render the colors of objects as accurately as possible, perhaps in a kitchen, workshop, or artist’s studio, go with higher color temperature lamps (4,000-6,000 k). Walk in closets and dressing rooms are another good place for high color temperature lamps. Color accuracy and color contrasts will be maximized, adding to a sense of alertness.
- As far as the selection process is concerned, the most important take home message is to understand the meaning of color temperature and color rendering index, how they are based on scientific theory and how they are applied to light technology. Armed with this understanding, informed buyers can exercise good judgment in choosing the most appropriate lamp for a particular purpose.

References

[1] Erik Page. Changing Attitudes on Changing Lamps. Home Energy Magazine Online. May/June 1998.

[2]Illuminating Engineering Society of North America. Educational Opportunities: Discover Lighting. www.iesna.org

[3] Paul A. Tipler. Physics for Scientists and Engineers. Worth Publishers. 33 Irving Place. New York, New York. 1991

[4] Black Body Physlet, an online Java tutorial. Created by S.G. Urquhart. Davidson College. http://www.usask.ca/chemistry/courses/243/links/BBR/BBR.html

[5] Lightpoints Understanding the Science and Technology of Light. Osram Sylvania. http://www.sylvania.com