The State of Solid State Lighting: Color Rendering Index and Metamerism Considerations

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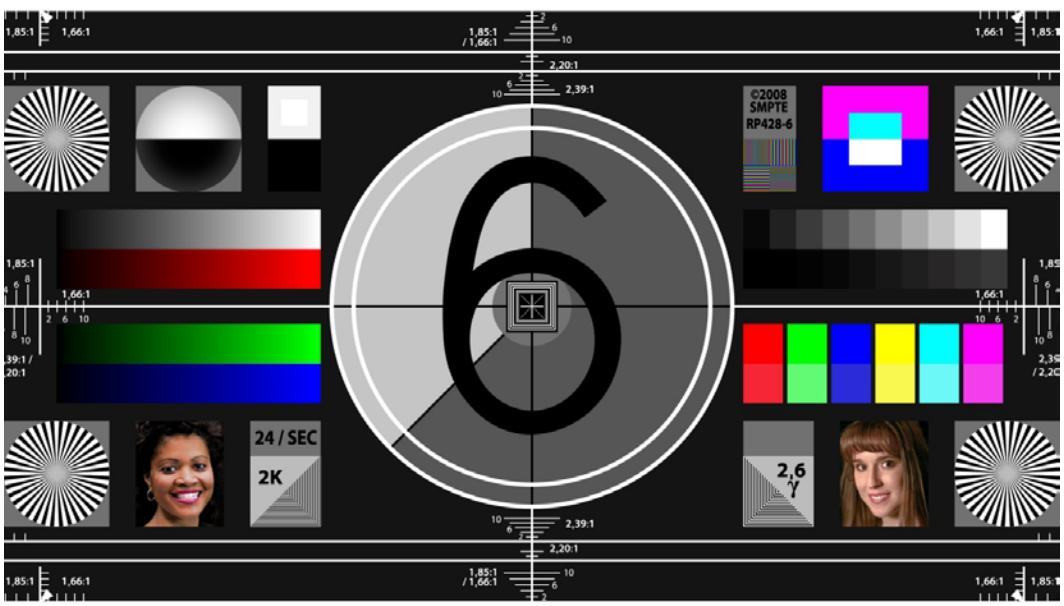
Session: 21st Century Cinematography: New Tools and Trends
Session Chair: John Galt

Thank you Mr. Chairman.

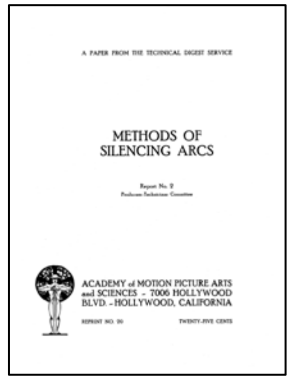
This is the first of what we intend to become a series of reports and assessments on the advent of Solid State Lighting in the motion picture field. This initial report will describe and demonstrate the various types of solid state devices presently available for such applications, identify the developing trends of this technology and assess the potential advantages, e.g. efficacy in terms of power consumption, weight, heat, versatility, etc. and the potential disadvantages, e.g. color rendering issues, frequency, cost, etc.



We're looking at the brand new SMPTE Digital Leader - we've put that up just as a confidence check that our signal is reaching the screen. It's designated RP 428-6 and is available for purchase at this conference. We're delighted that the Academy was able to play a leadership role in the development this new leader.

Science and
Technology
Council

Seven years ago the Academy of Motion Picture Arts and Sciences reconstituted its long dormant Research Council as the Science and Technology Council.


A PAPER FROM THE TECHNICAL DIGEST SERVICE

METHODS OF
SILENCING ARCS

Report No. 2
Producers-Technicians Committee

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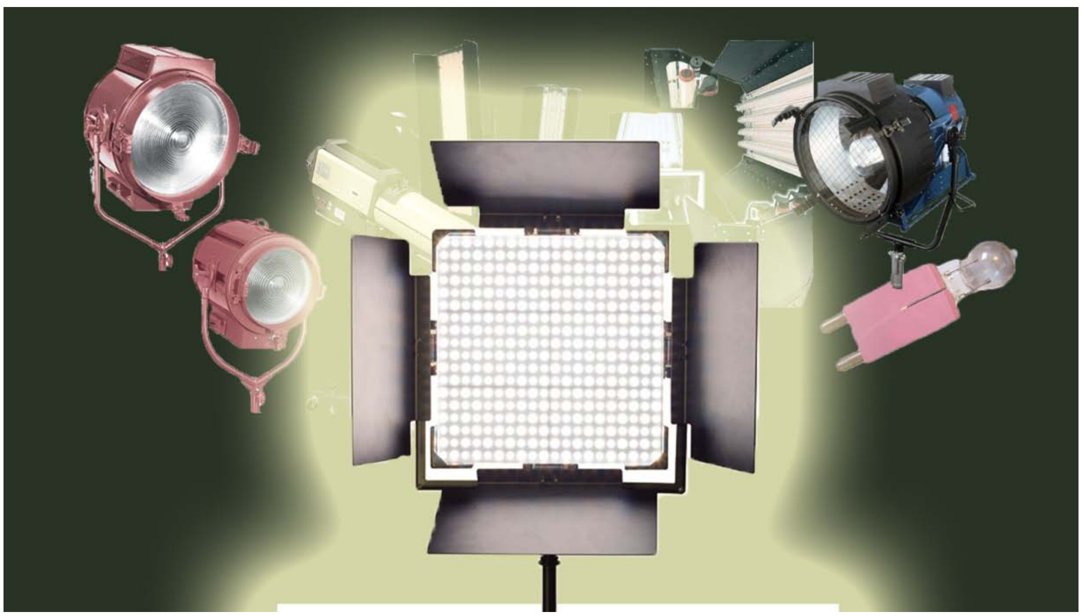
Among the many issues the original Research Council addressed was that of lighting for motion pictures, in particular making noisy arc lights compatible with the new sound recording equipment in the thirties.

In the eighty years that have since passed, motion picture lighting has evolved to include a plethora of sources. The familiar incandescent lamps have been joined by Xenon, HMI, CID, fluorescent and, in just the last few years, Solid State Light, or LED’s.



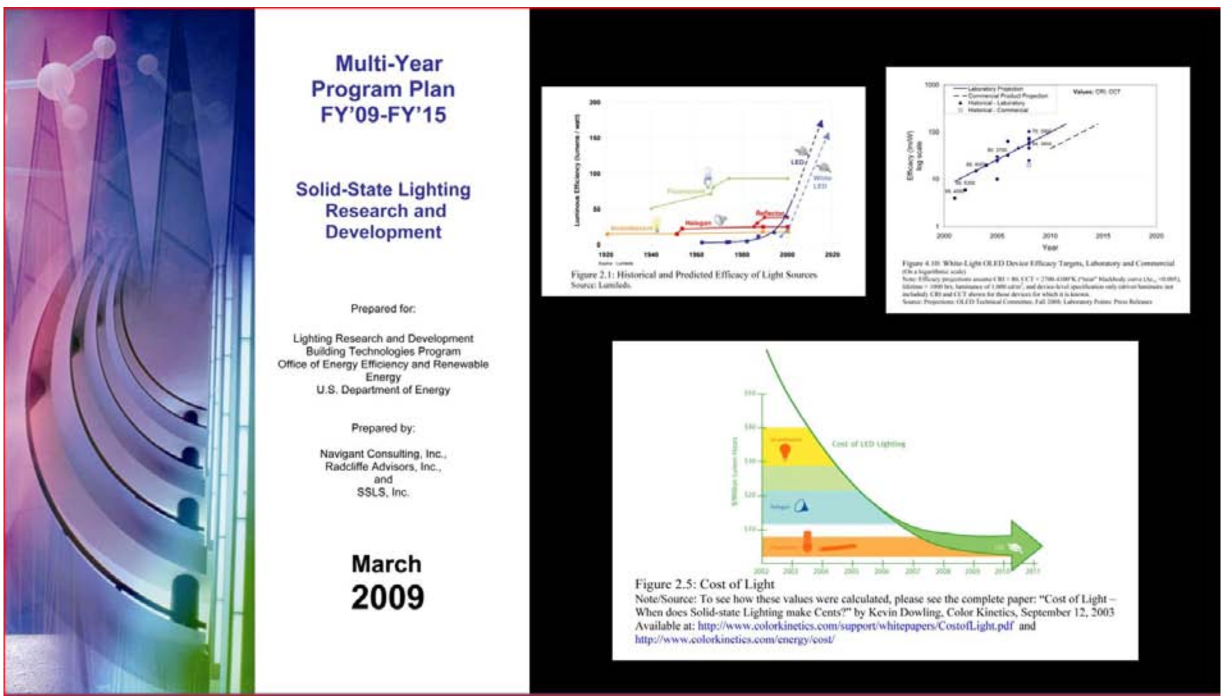
Four years ago, the Council conducted a review of Fluorescent lighting for motion picture applications on behalf of the Academy’s Scientific and Engineering Awards Committee. Much was learned, particularly about the vagaries of such lighting in terms of color rendering. Of course, with fluorescent lighting there are also issues relating to “flicker” frequency, and even the original arc light issue of interference with audio equipment.

With this in mind, the Technology Council felt that, as the introduction of Solid State Lighting as a motion picture illuminant was still in a relatively nascent stage, we should assess the new technology before such problems could become imbedded and possibly intractable.

A committee was empanelled and a “broad sweep survey” of the principal relevant issues was conducted.

We found:

Solid State Lighting is very energy efficient. Indeed, LED’s have been identified by the U.S. Department of Energy as a major contributor to energy conservation and is predicted to account for 40% of the national energy “independence” goal, which is to say the reduction of foreign energy imports.

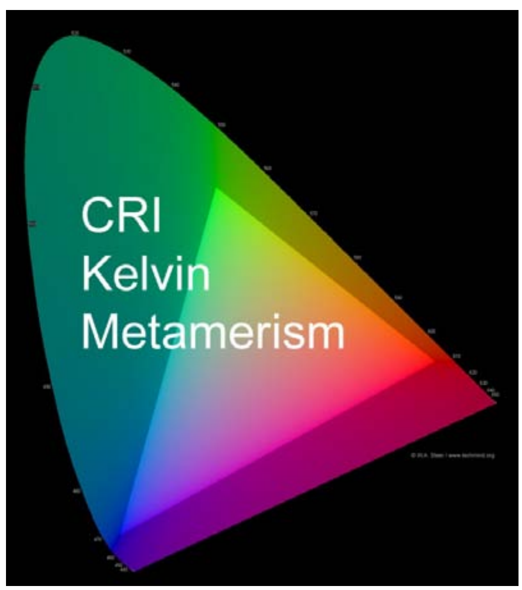


The DOE presently has a program to fund research in Solid State Lighting to the tune of $75 million. With light consuming anywhere from two to ten percent of a motion picture budget, this is a matter of some significance.

Just as an example, it was reported to us that the cost of light for the film Titanic was approximately 10 million dollars.

While the initial purchase cost is still high, LED's promise eventual economy as their service life is vastly greater than their quartz enveloped Tungsten or "discharge" counterparts.

Solid State Lighting is tractable in that power supplies offer considerable control over the light output. Dimming is possible as is a certain amount of control over color. A variety of "special effects" such as strobing, fire simulation and the like are possible. A number of lens possibilities exist and, while not yet a "point" light source, it's possible to approach the abilities of conventional stage lights.



Color rendering, however, presents the greatest impediment to the adoption of Solid State Lighting in motion picture production. The available products have largely inadequately addressed color rendering and discussion of this issue has been confounded by inadequate nomenclature. Terms like Color Rendering Index (CRI), Color temperature (Kelvin) and metamerism are bandied about in connection with the properties of such lights when their application is in fact confusing and irrelevant.

We’ll discuss these various issues in more detail in the course of this, and subsequent papers, but first let’s take a closer look at the core subject here, the diode itself.

While Solid State Lighting has indeed only recently exploded onto the scene as a lighting device, its roots actually go quite far back in time.

The phenomenon that has evolved into the LED appears first to have been observed by Henry Joseph Round in 1907 then working for Marconi. So, we already have a technology over one hundred years old!

A Note on Carborundum.

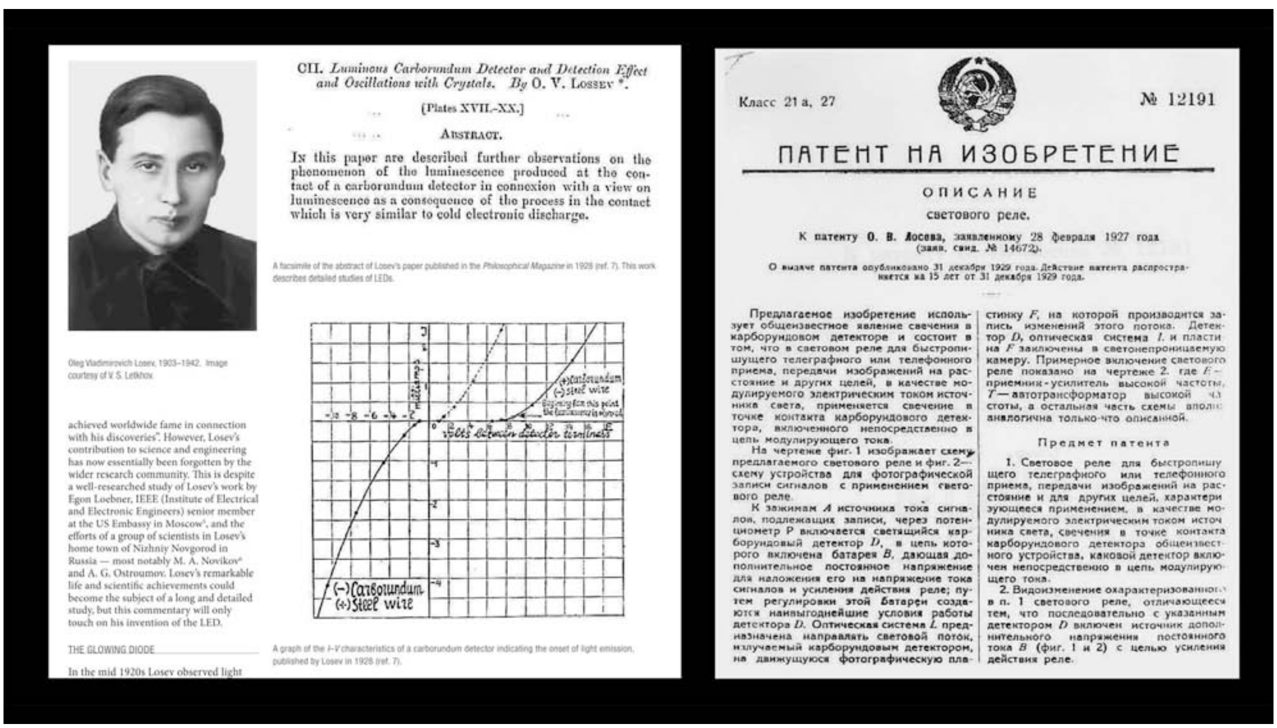
To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

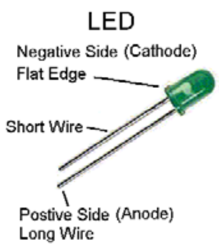
There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

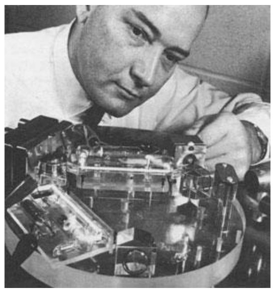
NEW YORK, N. Y. H. J. ROUND.

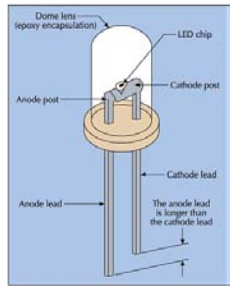
Russian Oleg Vladimirovich Losev, by all accounts a brilliant mind who perished, along with millions, by starvation in Lenningrad in 1942, seems to have made the first deliberate and successful effort to create a LED in 1920.

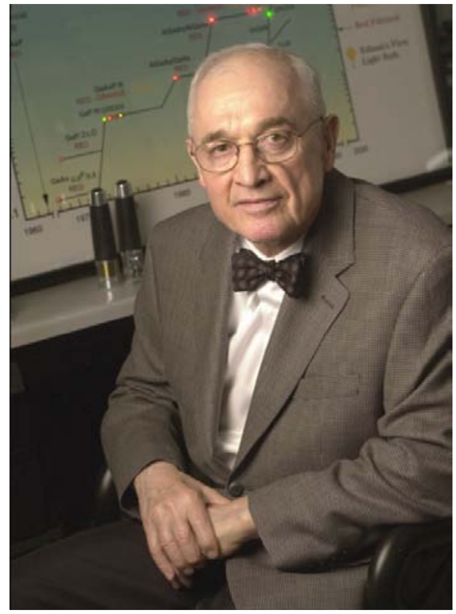


However, the acknowledged “father” of the LED is Nick Holonyak Jr. While working at the General Electric Company in 1962 some fifty-five years after Round’s original observations.



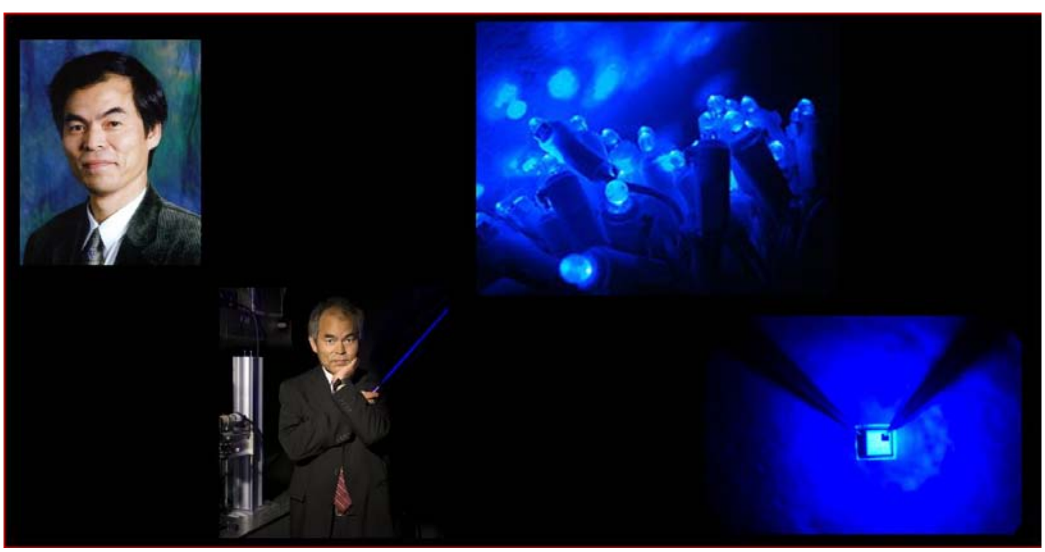




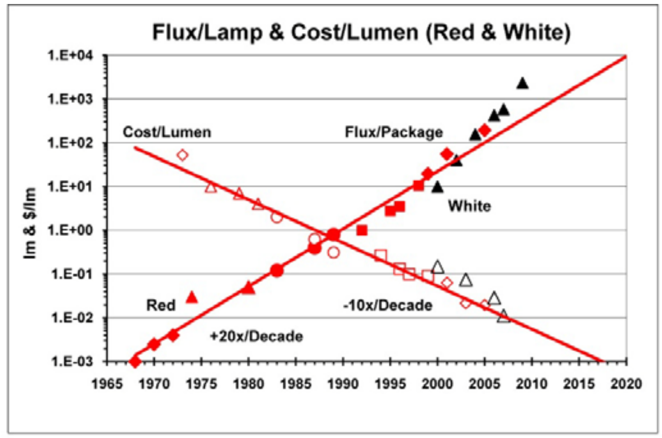


The first commercial applications for the new device, with its relatively low power output, were in the signaling field, and we all became familiar with LED’s as indicator lights and instrument readouts for such as calculators.

In 1995 the development of a viable blue LED by Shuji Nakamura of Nichia Corporation completed the spectrum, enabled the white LED, opened the world of display screens and this provided an enormous capital investment incentive to further develop the technology.



There is now a new "law," analogous to Moore's law, called Haitz's Law, named after Dr. Roland Haitz, a now-retired scientist at Agilent Technologies, which states that every decade, the cost per lumen (unit of useful light emitted) falls by a factor of 10, the amount of light generated per LED package increases by a factor of 20, for a given wavelength (color) of light. (A little later in this presentation, however, we'll take a look at how this equation may have to be revised.)



Haitz' Law updated Feb. 2009

For a concise description of the Fundamentals of Light-Emitting Diodes we have this from Michael Davidson of the National High Magnetic Field Lab in Tallahassee, Florida.

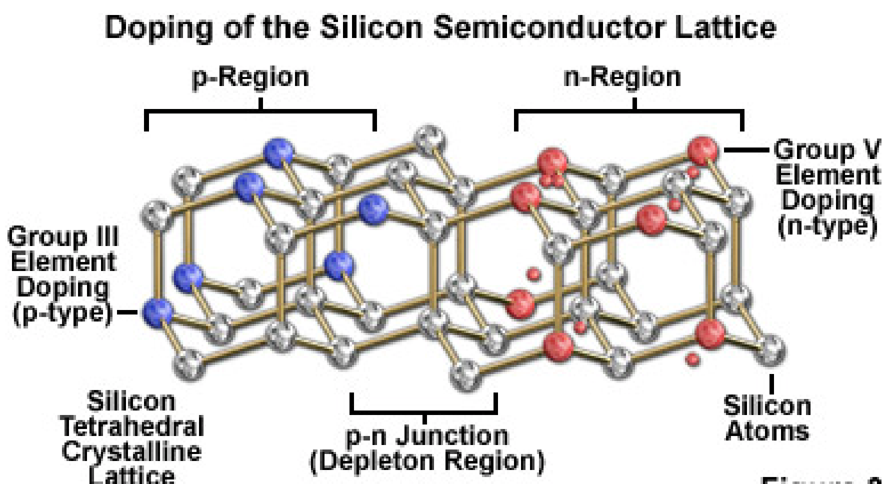


Figure 3

"At the heart of a light emitting diode is a semiconductor chip fabricated in a manner similar to that of common integrated circuits. The diode semiconductor contains several very thin layers of material that are sequentially deposited onto a supporting substrate (usually silicon or doped gallium), the first semiconductor material that is deposited onto the substrate is doped with atoms containing excess electrons to yield what is termed an n-type semiconductor. A second doped material, containing atoms having too few electrons (a p-type semiconductor), is then deposited onto the first semiconductor to form the diode. The region created between the doped semiconductor materials is known as the active layer.

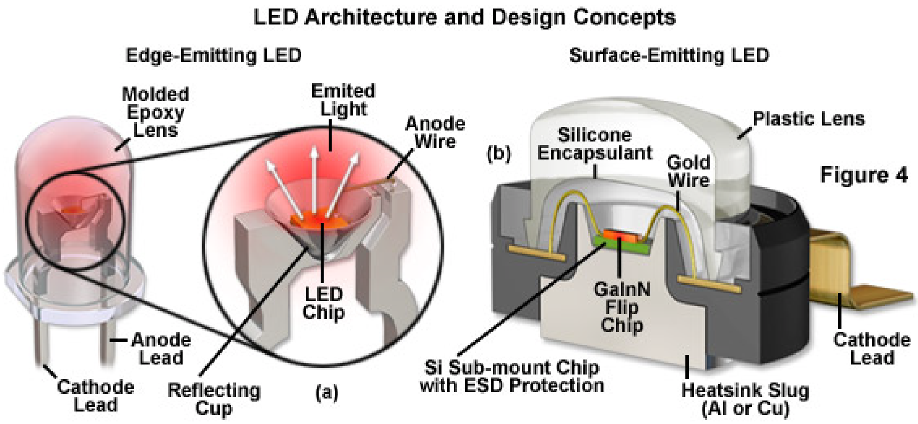


Figure 4

When a voltage is applied to the diode, holes (positive charges) from the p-type region and electrons (negative charges) from the n-type region meet in the active layer to produce light. The wavelength of light emitted by the diode is dependent upon the chemical composition and relative energy levels of the doped semiconductor materials that comprise the p and n regions. By varying the composition of the doped semiconductors, a wide range of emitted wavelengths can be generated that represent every primary color in the visible light spectrum.

After being fabricated, the semiconductor diode chip is mounted in a reflector cup connected to a lead frame, and is bonded to the anode and cathode terminals of the frame through miniature bonding wires. The entire assembly is then encased in a solid epoxy dome lens that enables emitted light to be focused in a single direction."

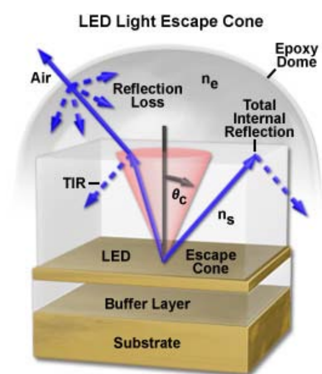
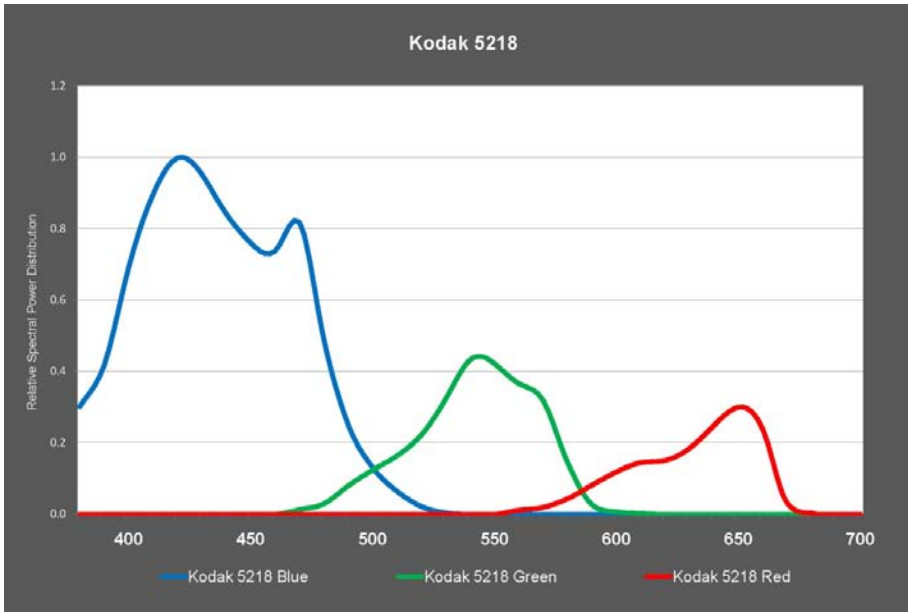


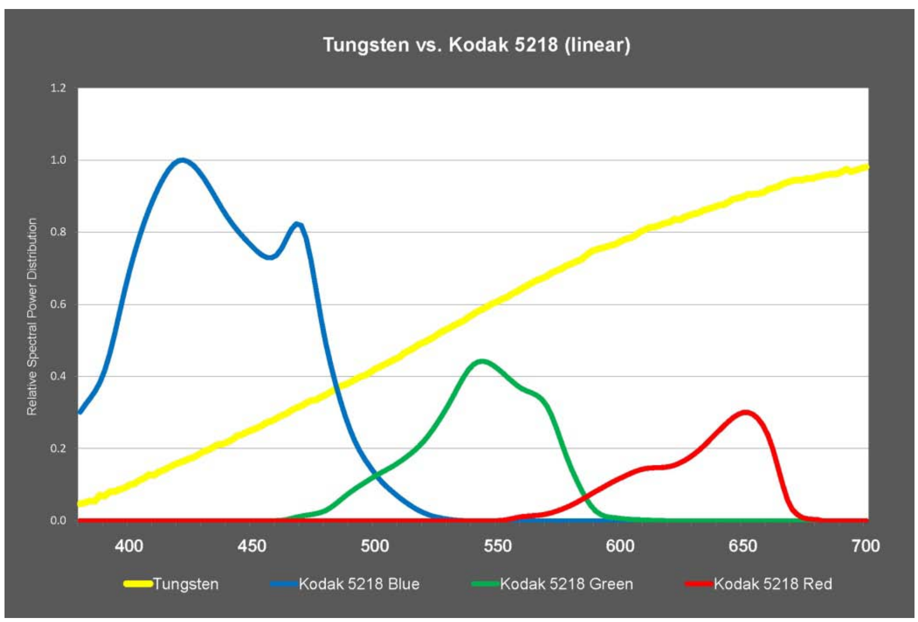
Figure 6

Our thanks to Mr. Davidson.

So, we've established that Solid State has matured to the point of being feasible for motion picture lighting from the perspective of efficiency, service life, and versatility. All highly desirable attributes. But what of Color? Arguably the most important attribute for an illuminant in our field.

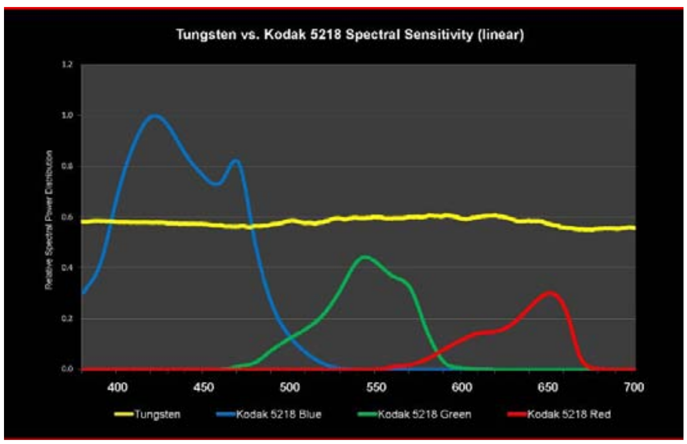


Let’s take a look at the spectral sensitivity curves for 5218. To which we can add the line for Tungsten.

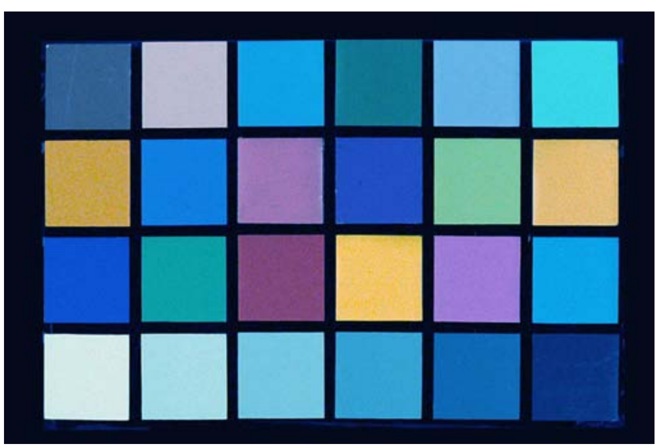


Well, that’s pretty straightforward. So let’s take a look at a Macbeth chart together with the 5219 sensitivity curves showing how the chart would look if exposed to the 32K Tungsten light.

However, now we'll alter the Kelvin value of the source and move it in the direction of daylight.

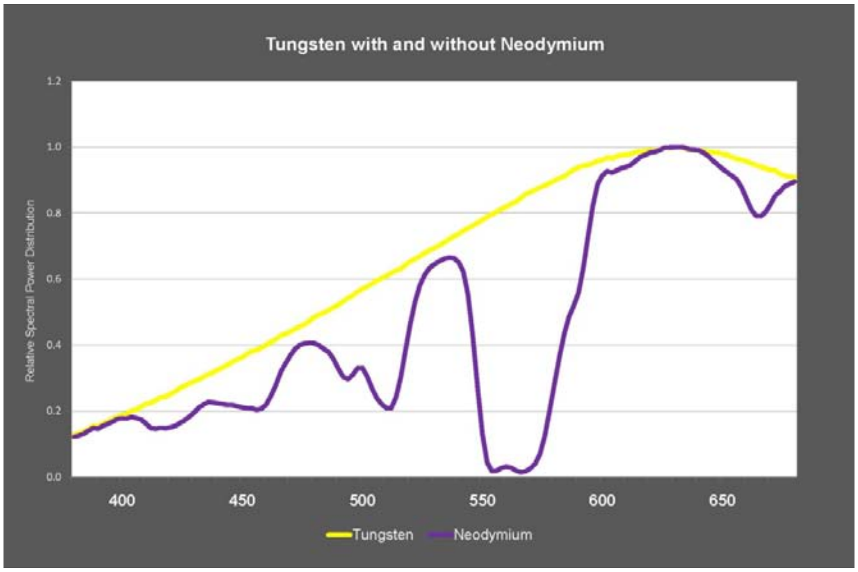


So this is what happens to color rendering with changes to a continuous curve source.

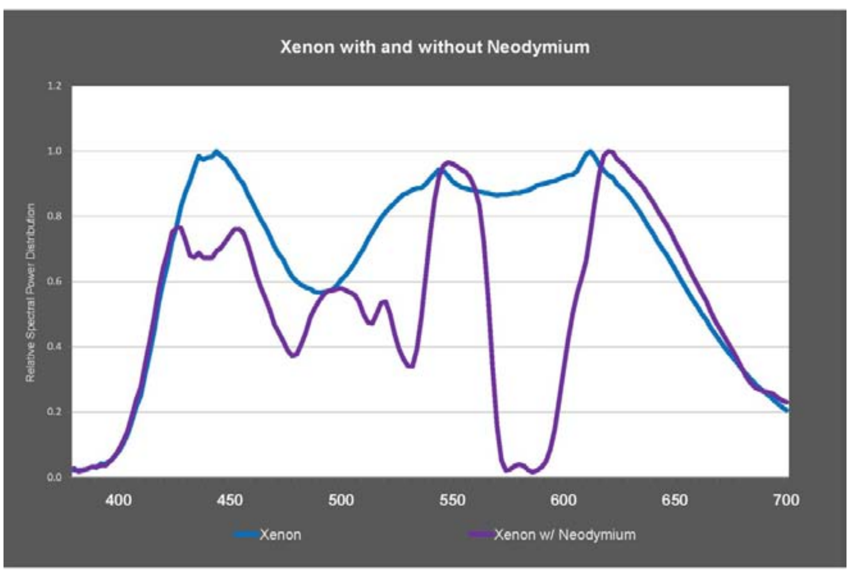


What then happens if the source is not continuous?

Many of us are familiar with a camera filter called the “Enhancer.” Actually this is a glass filter containing the element neodymium, and its spectral curve looks like this.

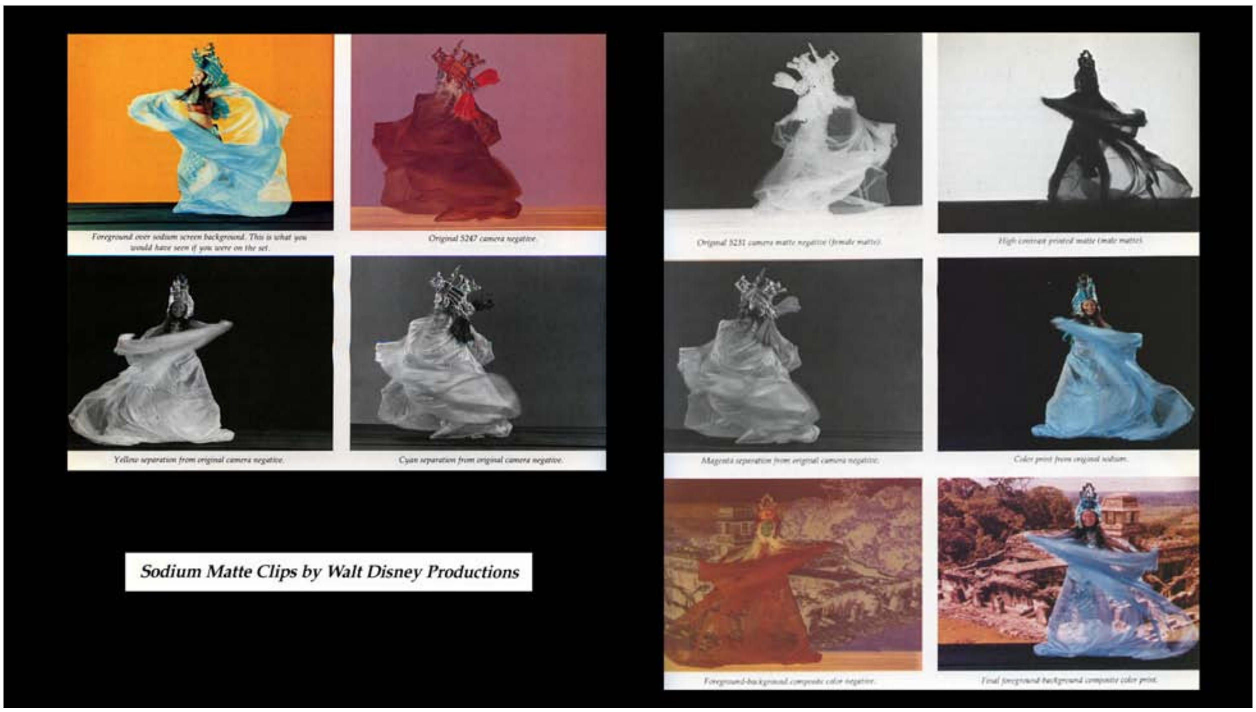


As you can see it’s quite interesting. It has the ability to transform a continuous source, in this case Tungsten, into a discontinuous source.



It does the same thing with daylight also. It particularly chops out an area of yellow here at 580 nm. region.

(For those familiar with the history of motion picture matting, this is the filter that was used in conjunction with the Sodium Vapor process. Sodium producing a narrow band emission at, that's right, 589nm. This process employed a Technicolor camera provided with a beamsplitter that separated the "sodium" silhouette, or matte image, from the regular color image and thus produced, in camera, a perfect matte with translucency on one film, together with a full color image on the other film.)

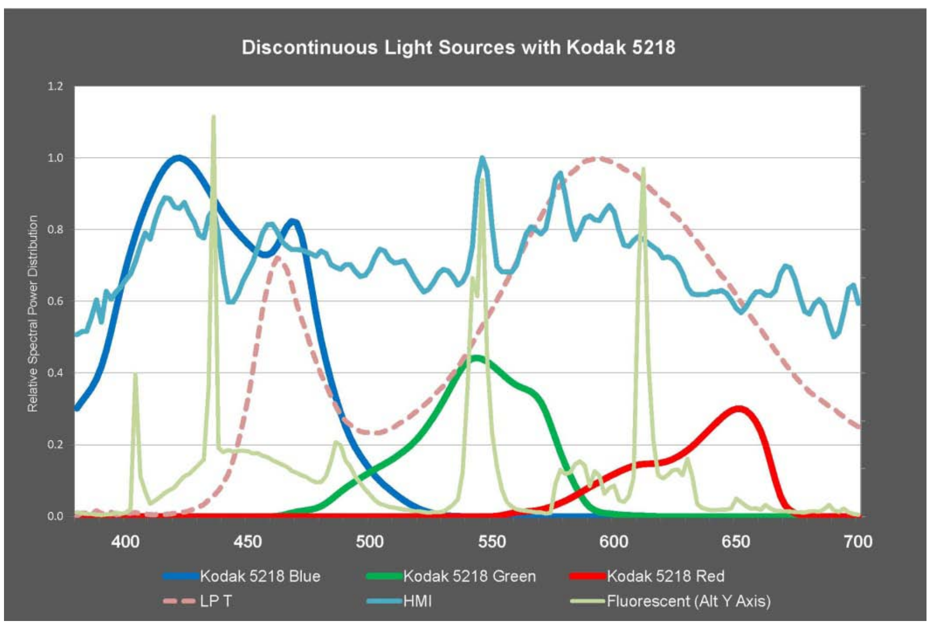


So with this filter we can produce a discontinuous source from a continuous one. It's called the "Enhancer" because the reduction of yellow tends to flatter human flesh tones. Conversely, humans illuminated solely with Sodium Vapor light, such as found in parking lots, look absolutely hideous!

For several years now it's been possible to buy lamps with neodymium built into the glass envelope. They're sold under various trade names, such as, Chromalux, "Reveal," is the G.E. version, and "Daylight Plus" is the Osram Sylvania version.

But the point of this demonstration is that disrupting the continuous emission spectrum will have an effect on color rendering; flattering, or not, as the case may be. When it's a deliberate choice, and under our control, it's an artistic effect; if not, it's an "artifact," and as such it can incur incredible expense to "fix" in post, if indeed it's possible at all. This is very much in the same vein as the case of "bleach by-pass" which, if it happens by accident at the lab would be regarded as a catastrophic error, resulting in lawsuits; whereas, if called for by the Director of Photography, it's "art."

There are various ways of providing a discontinuous source light. Most discharge lighting has a discontinuous spectral energy distribution (SED). This includes HMI,



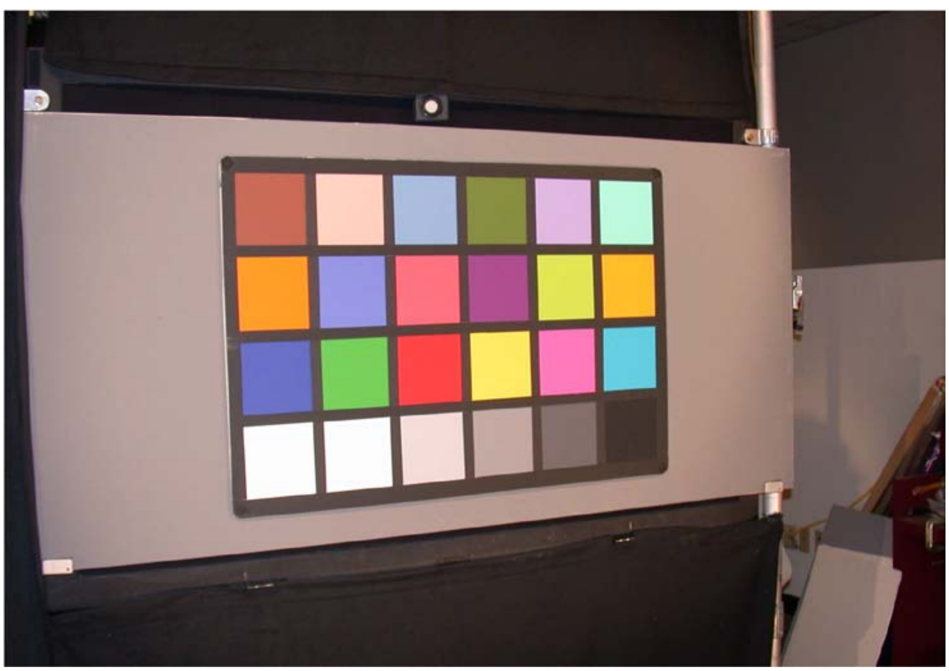
Fluorescent and (if we can classify them as such) Solid State lights.

I mentioned earlier that the Council had conducted a survey of fluorescent sources.

The Council performs such projects at the Academy Pickford Centre on the Esmeralda Stage, a laboratory for testing many aspects of cinema technology. We covered this lab in some detail at last year's SMPTE Conference.

To assess lighting technology we employ a special set-up as shown here.

This is a split screen Macbeth.

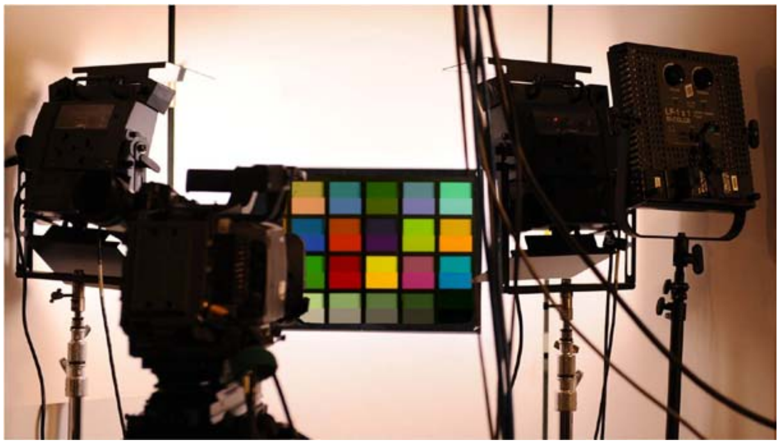


For those not familiar with it, an oversize Macbeth Chart (app. 40" wide and as such possibly the largest Macbeth chart in the world!) is mounted on the main easel.

a tri-fold flat is placed between the camera and the main easel.

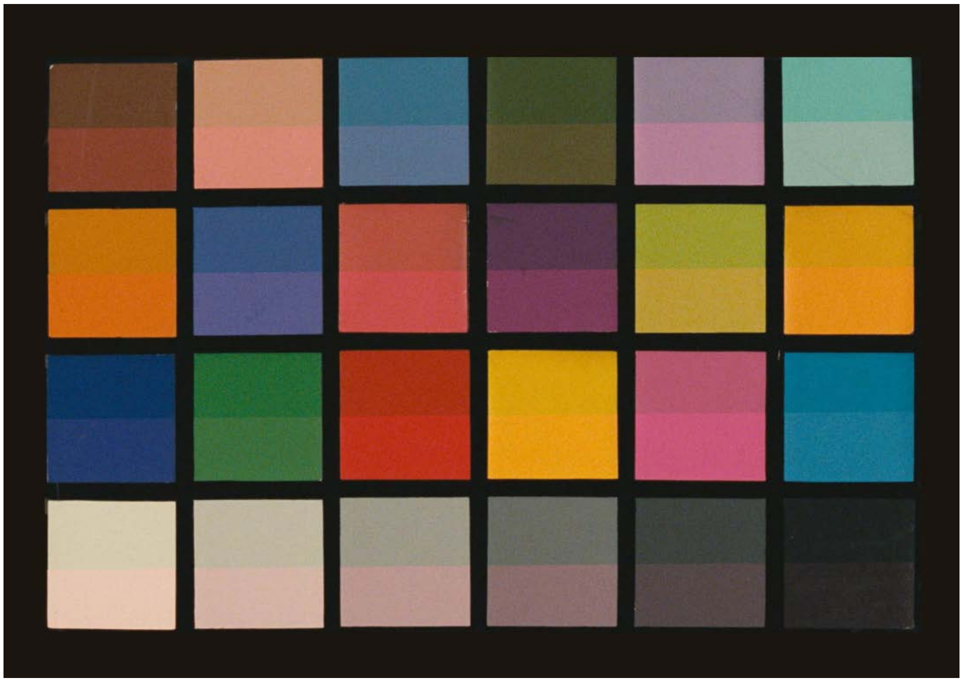
The center panel of the tri-fold flat contains a smaller version of the Macbeth Chart (app. 18" wide) with the upper half of each color chip removed.

When properly aligned and viewed from the camera position, the foreground chart lines up perfectly with the background chart.



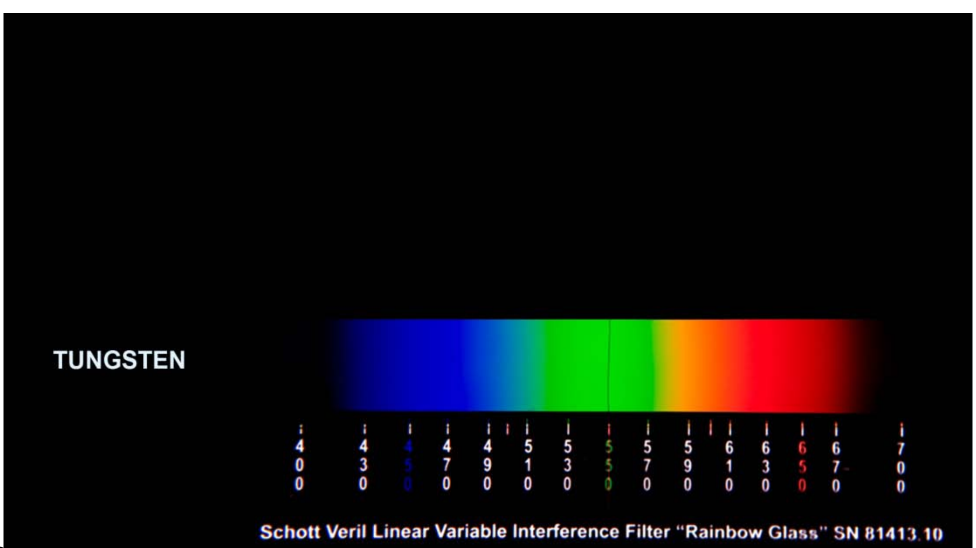
It’s then possible to illuminate the foreground chart with the illuminant source of interest (e.g. a fluorescent lamp, HMI, LED or other) and the background chart with a standard reference illuminant (e.g. incandescent).

Images are then recorded on the media of interest (e.g. different filmstocks or digital cinema cameras, etc.). I should mention that the several iterations of Macbeth charts we use on the Esmeralda stage are made from the same stock of material and are monitored by spectra-radiometry to ensure accuracy.

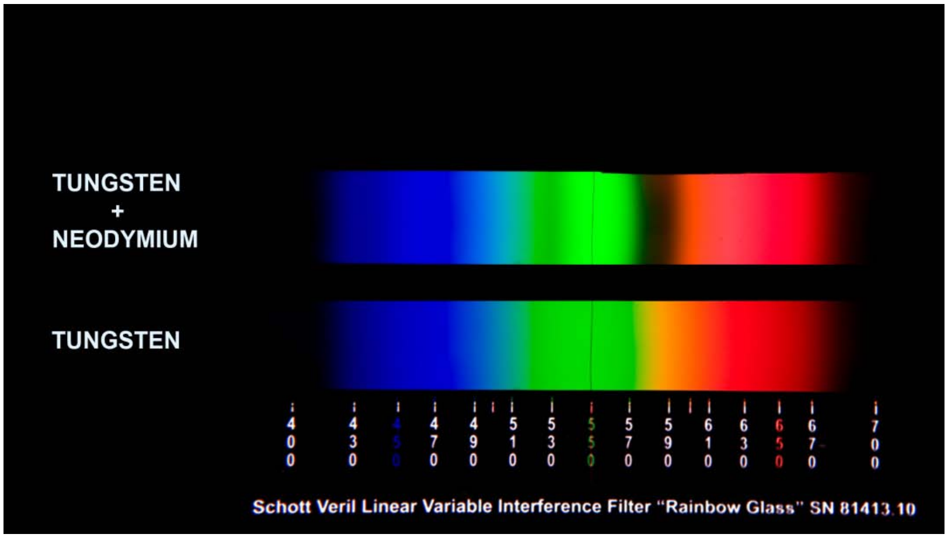


So, here is our split Macbeth showing the effect of the Enhancer, or neodymium filter in the lower portion with the normal continuous Tungsten emission in the upper half.

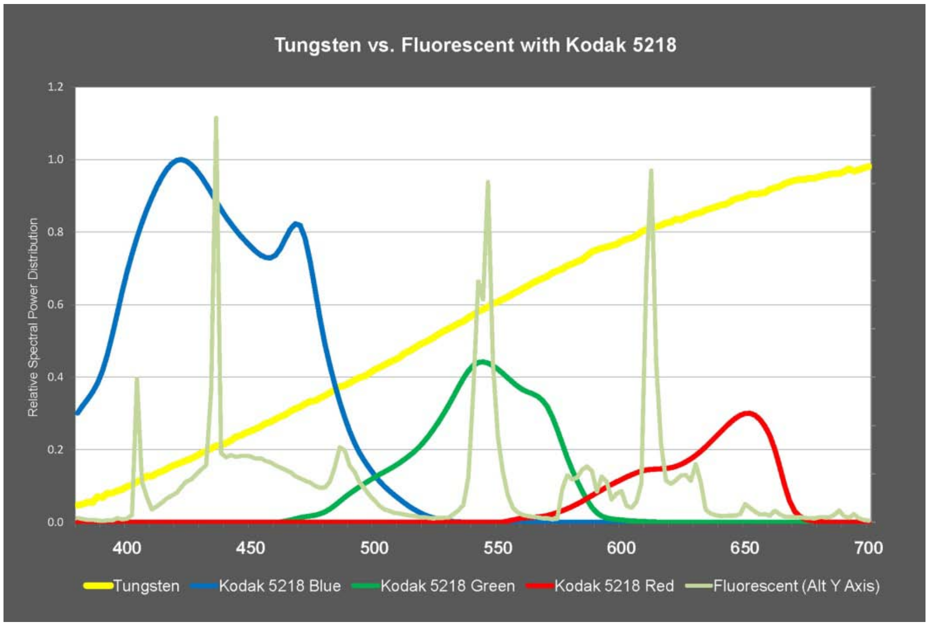
Another way to perceive the effect of a discontinuous source is to view it through what's called a "Rainbow" glass. Technically, a Schott Veril Linear Variable Interference Filter. This is such a filter with a standard Tungsten source.



And here we can see the effect of introducing the Neodymium filter. It's obvious the 580 nm region is essentially wiped out.



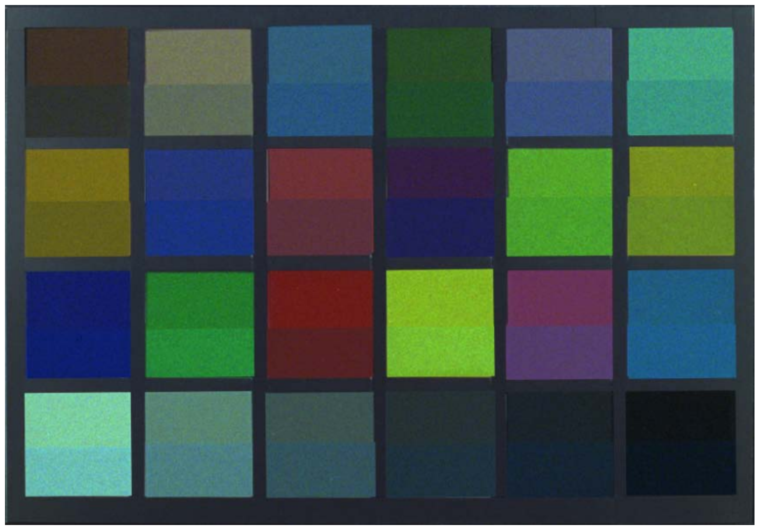
O.K let's now take a look at a fluorescent light source using these two techniques.



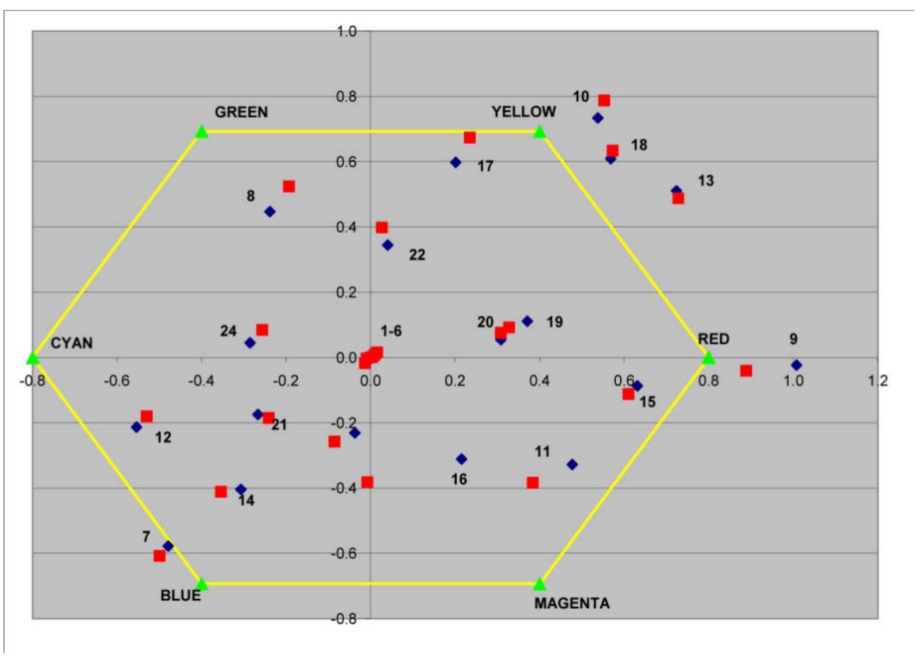
It can readily be seen that the spectral emission distribution (SED) of the fluorescent and the Spectral Sensitivity Curve for the filmstock are not entirely in accord.

The design of a fluorescent "Tungsten" lamp (pale green line) attempts to match the spectral trace for actual Tungsten (yellow line). The "spikey" nature of the combination of phosphors and the mercury emission basic to the fluorescent lamp SED make a perfect match impossible. Cascade that discrepancy with the differing spectral sensitivity curves for a variety of filmstocks (blue, green & red lines), or for various digital cameras, and the engineering task becomes formidable, as relatively minor changes of any factor can produce a significantly different result.

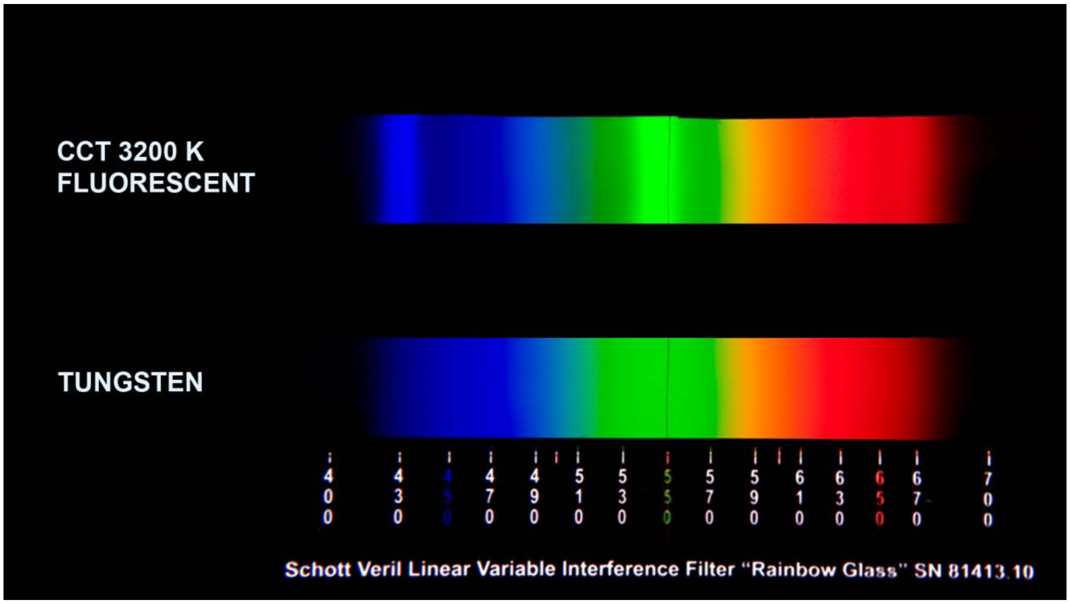
The effect can be seen in the split screen Macbeth here.



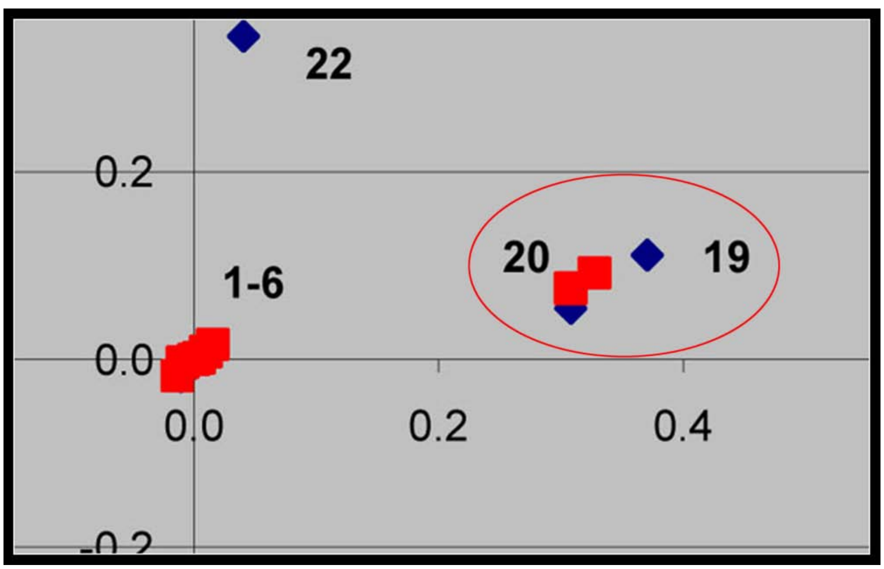
And in the tri-linear plot here.



The disparity between the Tungsten distribution and the Fluorescent is quite obvious when we look at the Rainbow glass image.



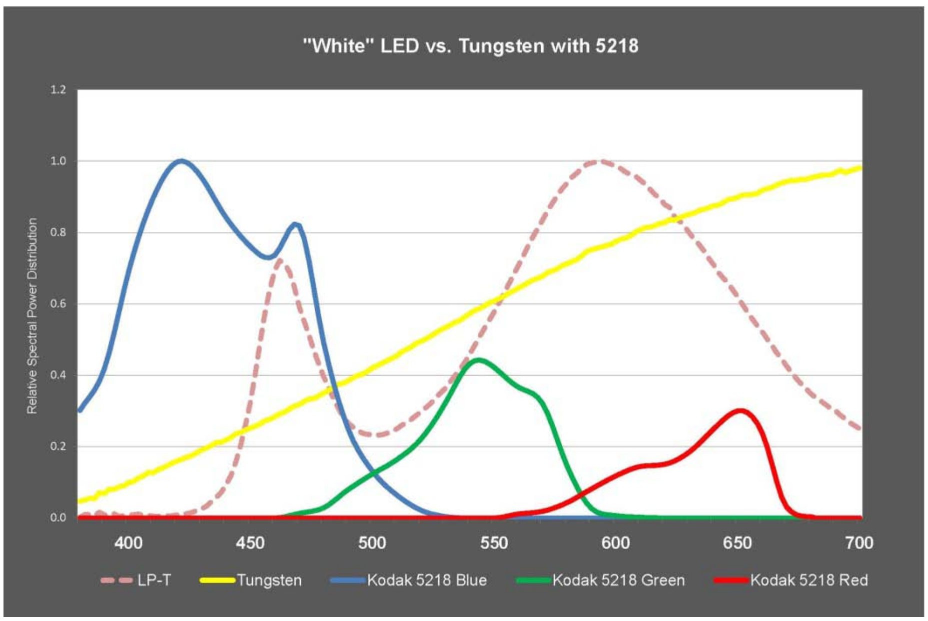
Of particular importance is the situation shown here:



This represents two Macbeth chips, the light and dark human flesh chips that have been recorded as essentially identical in this particular fluorescent light. To those who may be contemplating that a 3 D LUT offers the prospect of correcting for the anomalies described here, this is the situation for which there is no such remedy.

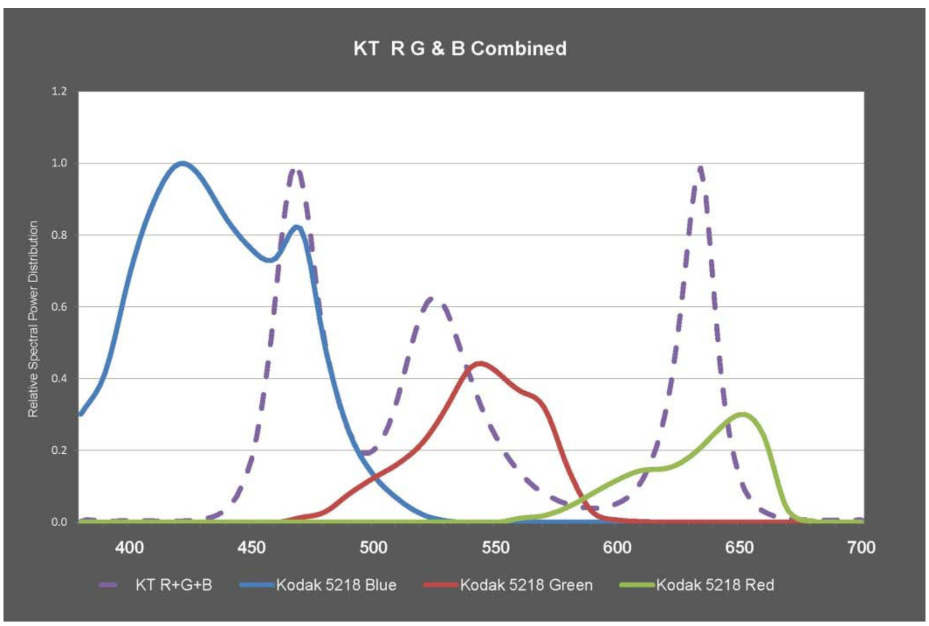
Our study concluded that it is probably only possible to create a match between a particular filmstock and a particular fluorescent lamp and Tungsten. It would require another custom blend of phosphors to match another filmstock, and likewise a specific blend for each flavor of digital camera. Unless it were possible to conform all these image recording devices to a common spectral sensitivity. Which seems extremely unlikely.

So now, let's try this with our LED's

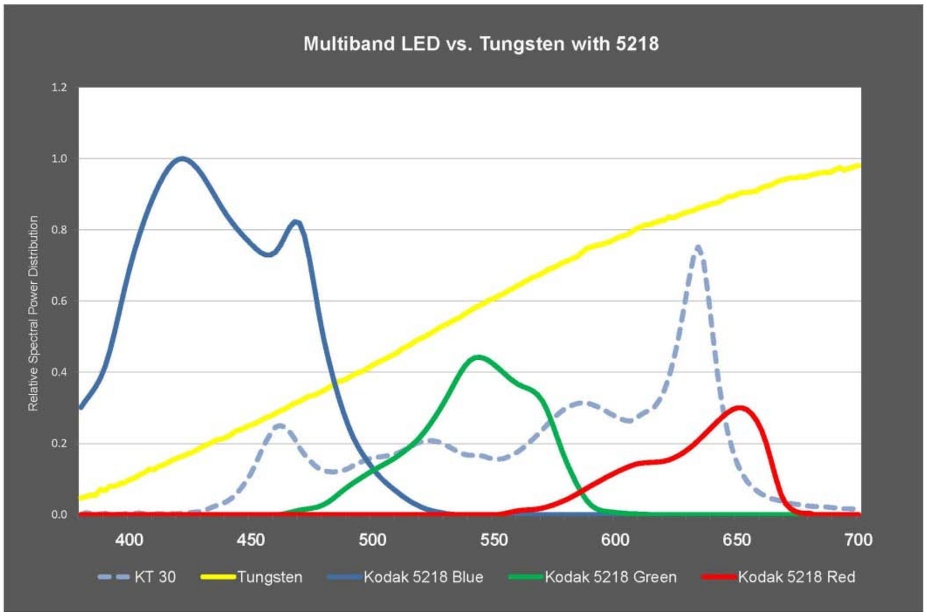


There are three basic types of LED illuminators currently available to our industry. A "White" LED created by a powerful emission of blue energy which excites phosphors to complete the spectrum, much like a fluorescent lamp. The trace looks like this. We can see that, while the Blue emission of the LED will be effectively captured by the Blue sensitive layer of the film, the "phosphor" emission straddles the Green and Red film sensitivity but "favors" the Green record. The Red emission of the LED has diminished substantially by the time it reaches the peak sensitivity for the Red record.

We can see how the split screen Macbeth recorded the result. And also how the Macbeth chip on the tri-linear plot correspond to the standard tungsten locations.



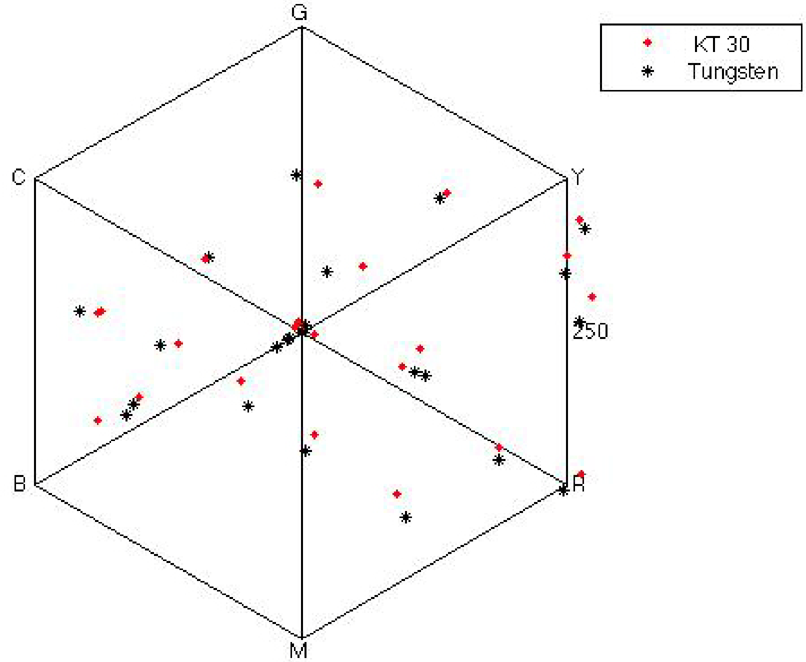
Then there is the Red Green Blue LED with a trace like this. In this trace we can see that the Blue and Red emission corresponds well with the film sensitivity, the Green emission is off the Green sensitivity peak.



Finally there is the multi-band approach which employs the same white LED but is supplemented with a variety of additional devices at different wavelengths. This approach allows for a degree of “tuning” of the overall emission distribution.

Here we can see that, while we still do not have a good match for the Green recording peak, we should be able to adjust the total emission to achieve a reasonable balance.

Even so, that balance would not be to 32K Tungsten per se, but rather to a particular filmstock or digital camera. So such a light would need to be adjusted to match each particular detector. Needless to say, Tungsten set to 32K will perform the same way for any detector looking at it.

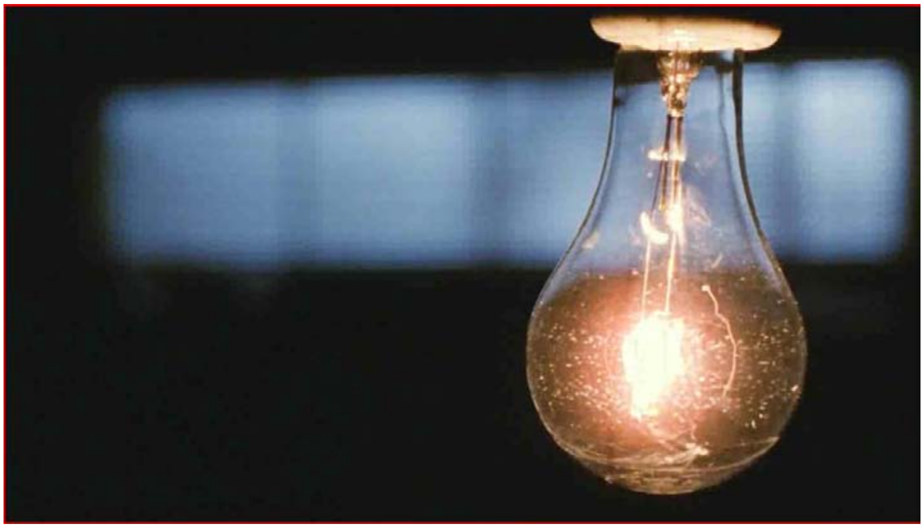


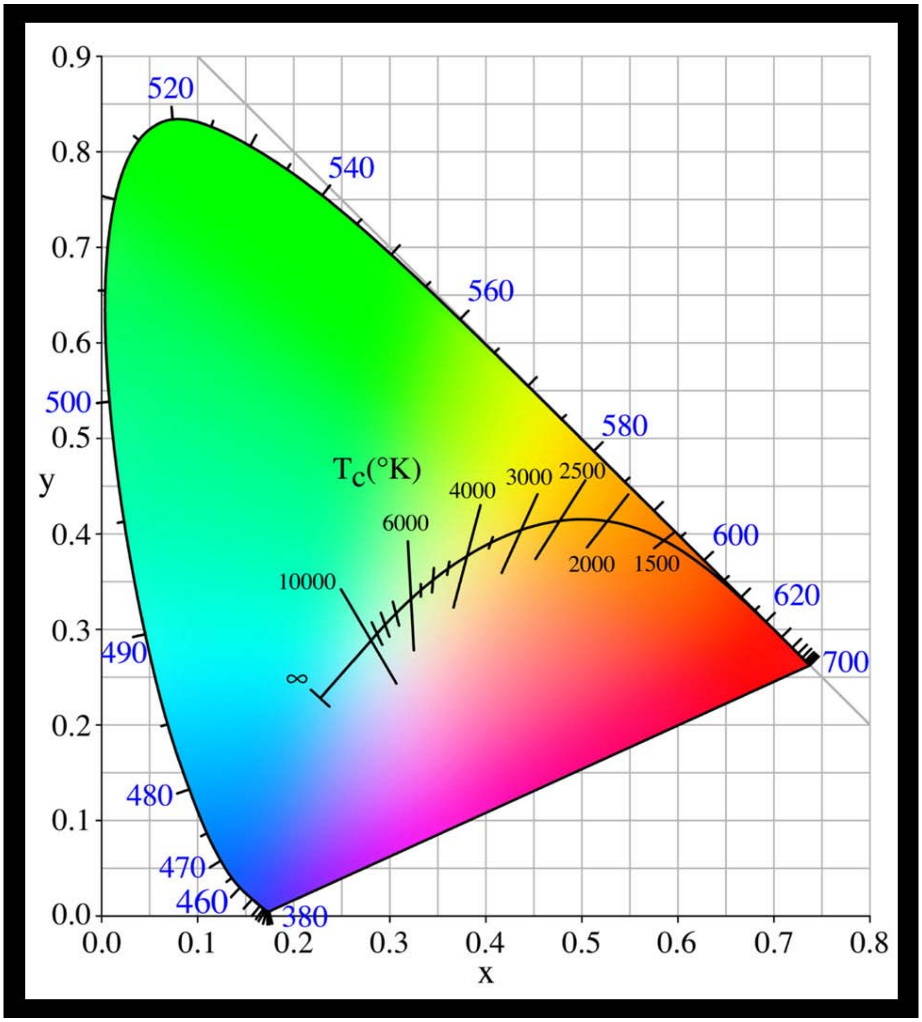
So, as with the fluorescents, there is not a lot of conformance between these peaks and the filmstock curves, especially for Green and Red.

Now that we've seen how difficult it is to achieve a perfect match with a discontinuous source it becomes apparent why the use of such terms as Color Rendering Index (CRI) and Kelvin Temperature are so hazardous.

Kelvin is only relevant to a black body heated to some temperature until it incandesces

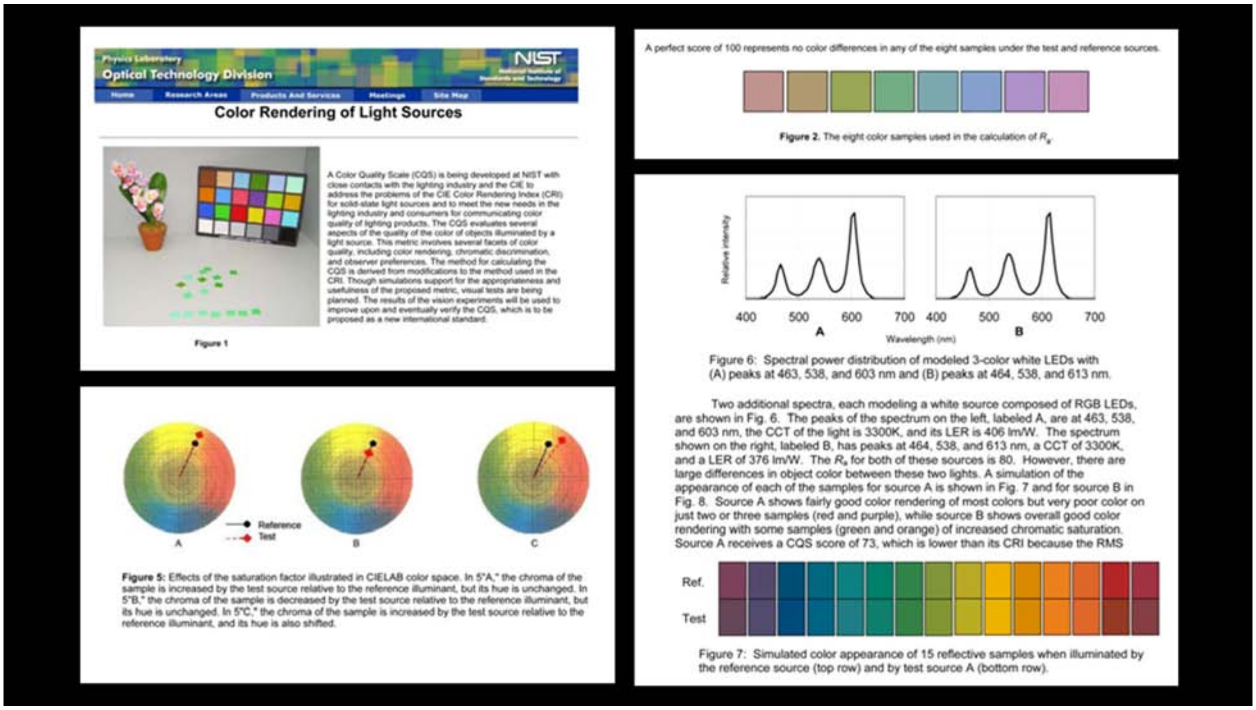
i.e. a tungsten filament heated to 5500 degrees approximates daylight.





But a fluorescent light with a nominal Correlated Color Temperature of 5500 K may well not reproduce colors in the same way due to the uneven, or discontinuous emission. Here we can see that these lines bisecting the Planckian curve represent Correlated Color Temperature and it's obvious there could be significant color differences for the same CCT.

CRI is similarly misleading. When the CIE created the CRI, it used only eight colors of relatively low saturation as the matching criteria, and the viewing instrument was the human eye. There now need to be new metrics and new nomenclature to describe the case that includes discontinuous sources, using not direct human observation, but rather the detectors we use - such as film and digital cameras.

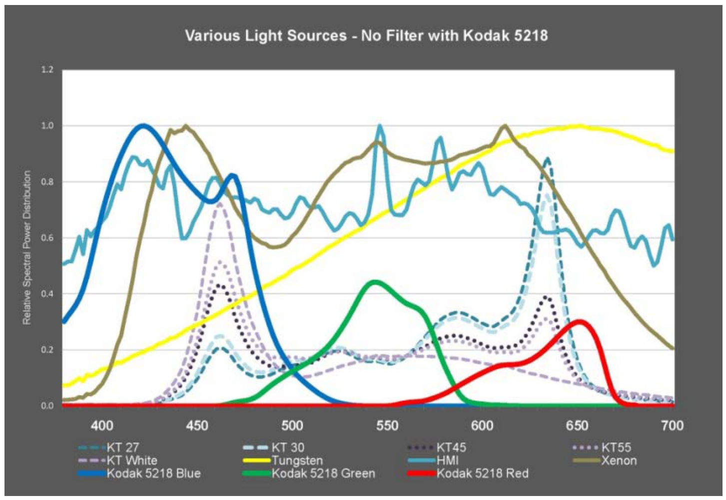


The National Institute of Standards and Technology (NIST) has proposed a "Color Quality Scale" with which they intend to improve the ability to define the color rendering quality, especially for such sources as LED's. But this scale, like the CRI and CCT, is intended only for direct human vision. What is needed in our industry is such a scale intended for the detectors we use, i.e. film and digital cameras. This task will likely be considerably harder and may, in fact, be impossible. At the very least, then, proposed new metrics, like the CQS, should include the disclaimer that they are not relevant to color reproduction by devices such as cameras. We have commenced a dialogue with NIST and are pleased to report that they agree with this proposition and will endeavor to effect it.

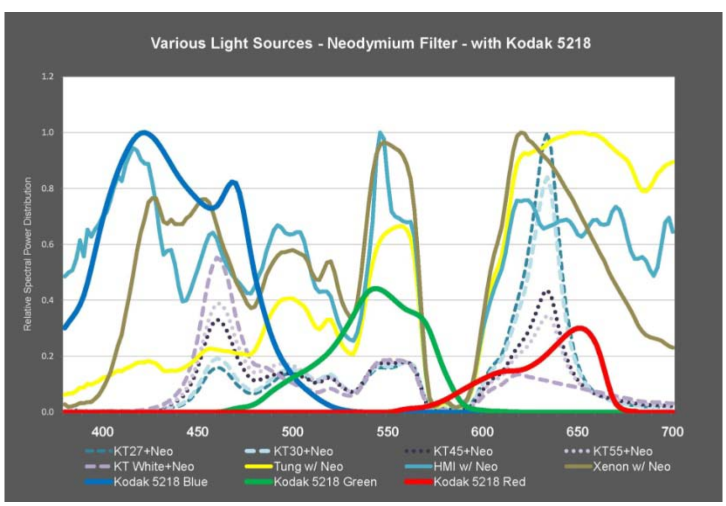
On the bright side (pun very much intended) the incredibly rapid development of this technology offers much hope for the amelioration, even the elimination of the color rendering problems we've discussed here. As we indicated at the beginning of this paper, this will be the first of several reports the Council expects to make to our community on this topic.

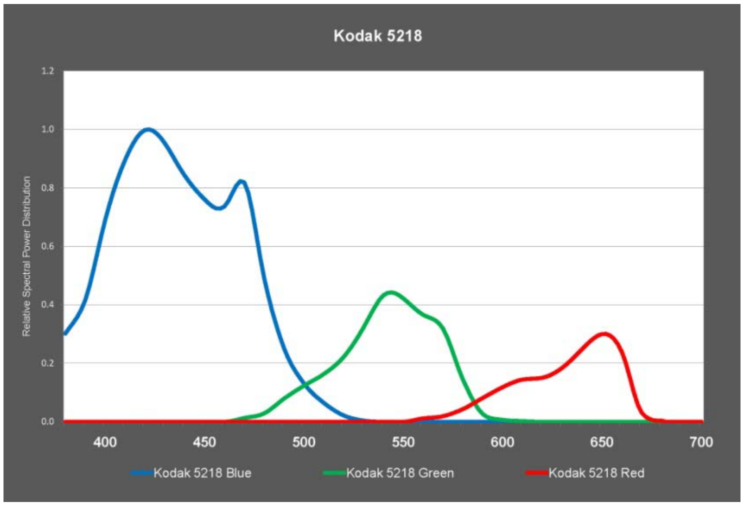
Moreover, in keeping with the Academy tradition we mentioned at the beginning of this paper, it's a mission of the Council to be pro-active in facilitating the development of new technology, as we can bring to bear the insight of the Council's formidable brains trust to both identify problems and possibly point the way to solutions.

In the present instance, we have conjectured that there just may be, and we stress - "may be" - some potential in the notion of "fighting fire, with fire," in that the problems posed by a discontinuous source, may be addressed by the deft application of a discontinuous filter. Thus we're exploring the effect of applying a discrete amount of "rare earth" materials, e.g. the neodymium we discussed earlier, along with other elements, to a "filter" that may be applied either at the light, or even at the camera, or indeed, in the camera.



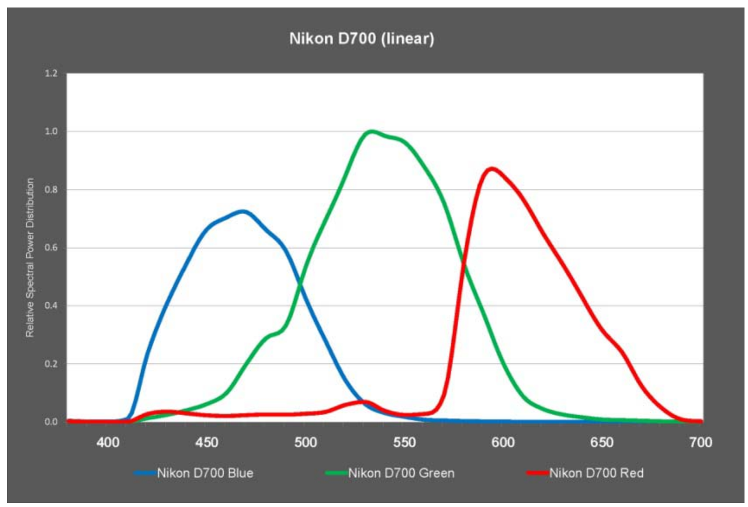
A filter with a particular transmission spectra, when "superimposed" over the diverse sources we're now encountering, such as Tungsten, Fluorescent and Solid State, just may bring all of them into sufficient accord as to make the differences acceptable. One of the more serious quandaries here is that, while any one of these disparate sources may be individually amenable to color correction, correcting such divergences in multiple directions at once is impractical.

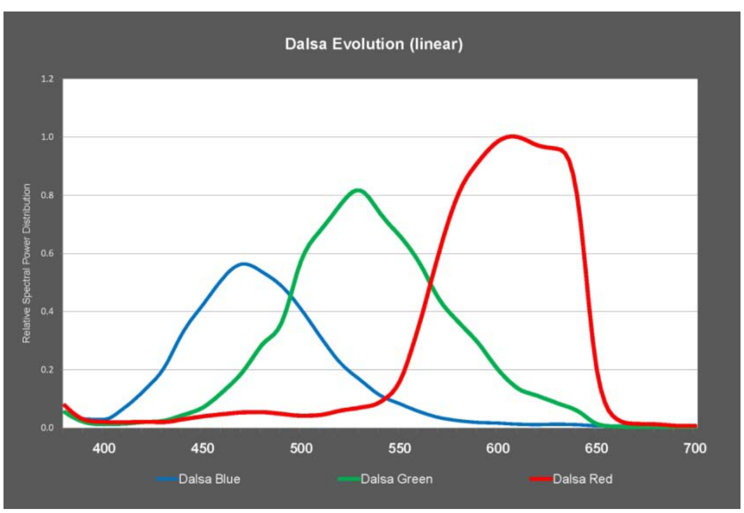




Further, the situation becomes exponentially more complicated if one includes the condition where more than one type of camera is employed.

Just look at the disparities evident in these sensitivity curves and then contemplate what happens when these are cascaded with the variety of lighting sources we've been discussing. We suspect nothing could then resolve the resulting chromatic confusion.

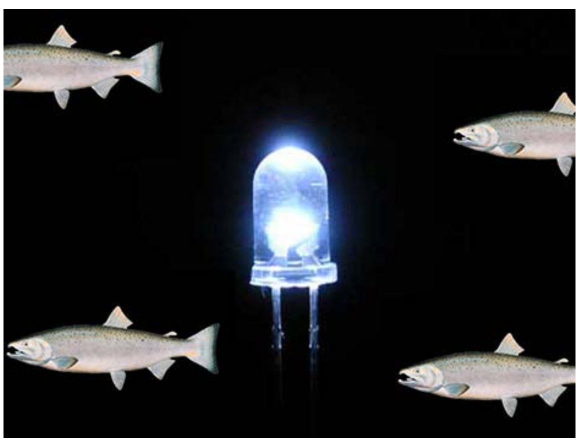




We'll report in the future as we proceed with this line of enquiry.

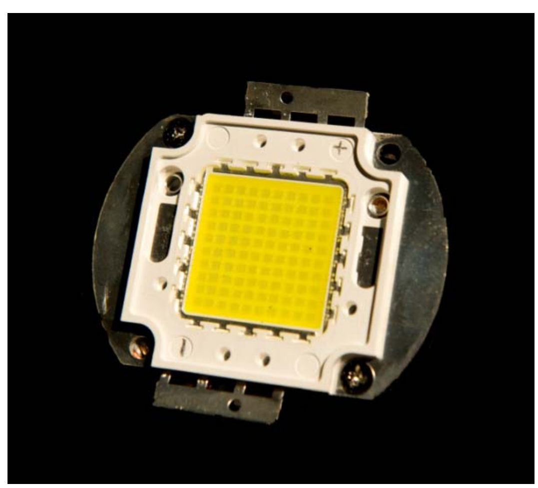
Meanwhile, our survey of the developing trends of Solid State Lighting devices has yielded interesting results. Let's take a quick look at some.

A Korea Advanced Institute of Science and Technology (KAIST) research team led by Prof. Kyung-Cheol Choi of the School of Electrical Engineering & Computer Science discovered the surface plasmon-enhanced spontaneous emission based on an organic light-emitting device (OLED), a finding expected to improve OLED's emission efficiency. For surface plasmon localization, silver nanoparticles were thermally deposited in a high vacuum on cathode. Since plasmons provide a strong oscillator decay channel, time-resolved photoluminescene (PL) results displayed a 1.75-fold increased emission rate, and continuous wave PL results showed a twofold enhanced intensity.



Meanwhile, researchers led by Gregory Sotzing at the University of Connecticut have experimented with adding fluorescent dyes to Salmon DNA, then spinning the strands into nanofibres. When excited by an ultraviolet LED, - it produces light. The spectral emission curve of this light can be adjusted by modifying the proportions of different fluorescent dyes.

This is a close up look at a high power LED. It's a 100 Watt LED array, which operates on 36 Volts at about 3 Amps., producing over 6000 lumens.



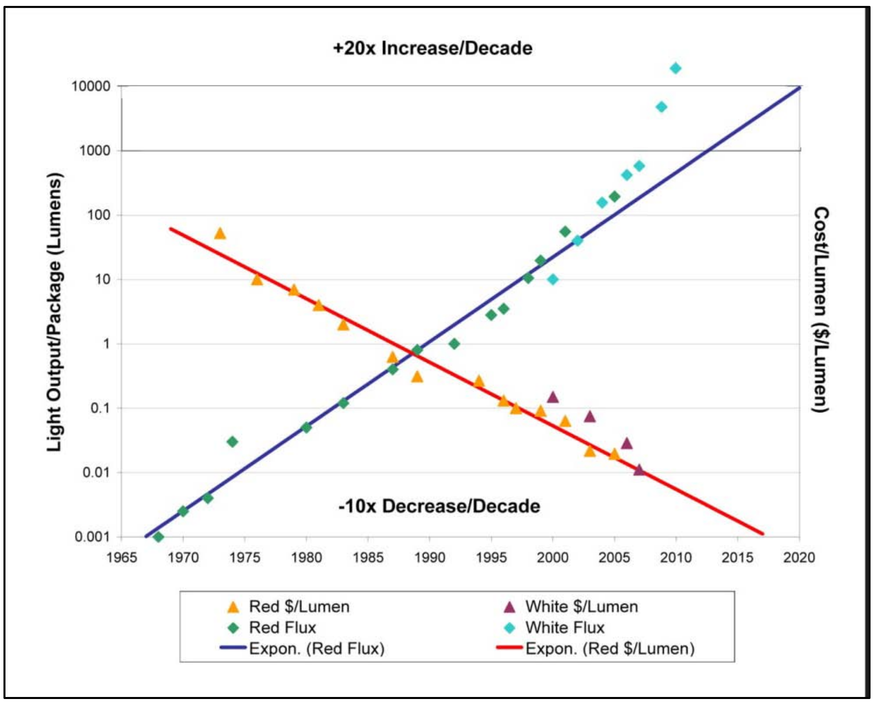
Let's take a look at what results when we install such a device into a conventional motion picture luminaire.

Visual: 43. Live demo of high brightness LED in Arri lamphead.

Joe Di Gennaro here, a member of the Council staff, has brought in a 5K lamphouse which is normally equipped with a quartz halogen source. He's swapped that out for one of these diminutive little devices (hold up sample) like this. In a further testament to the efficiency of such devices, you'll notice there's no power cable attached to the lamp. The LED is running on a small battery-pack tucked into the lamphouse.

We'll just fire up our back-up unit here to show this is all on the level. There's no funny business going on inside the lamphouse.

As we said earlier, these new devices may require an update of Haitz law, at least on the Light Output side of the equation. We're engaged in a dialogue with Mr. Haitz on this matter. Note, the scale is log. If this trend is real the mind boggles.



Obviously, the advances we've just cited may be a long way from commercialization, and may never live up their initial promise. But bear in mind that some of these advances were announced within just a few days of each other in July of this year. Just part of a steady stream of such announcements occurring practically weekly. With $75 million in DOE research grants plus a huge investment from the private sector, it should be possible to address our color rendering concerns expeditiously, provided those concerns are clearly defined and annunciated. And then provided that the Solid State Lighting industry regards the interests of the motion picture community and the rest of the color reproduction community as warranting the effort and investment.

What's needed is that the manufacturers, presently intent on rushing product to our market, pay attention to the concerns we're raising lest the shortcomings of these early products poison the well and cause our industry to reject a promising new technology.

Summary.

In conclusion, then, we have shown that we have the advent of an extremely attractive lighting technology. One that offers great economy, flexibility and versatility, but one that is also fraught with peril, in that, absent a proper understanding of the color rendering issues attendant on this new lighting instrument, serious unintended and exceedingly expensive consequences can ensue from their use. We have further demonstrated that existing metrics for quantifying light source color rendering are inadequate when applied to motion picture imaging devices, be they film or digital, and these will need to replaced with more meaningful and useful metrics if, indeed, that's possible.

Thank you, Mr. Chairman.