BY MIKE WOOD

The interconnectedness of all things—A week's connections

I'M CONVINCED that all things are interconnected. We may not yet have a grand unified theory that satisfies all physicists but I'm sure that answer is there somewhere. What's good enough for Albert Einstein and Stephen Hawking is good enough for me. What we do know is that the answer to the ultimate question of life, the universe, and everything is 42, but that doesn't help us here. (*Note: if you don't understand that reference and haven't read* The Hitchhiker's Guide to the Galaxy *by Douglas Adams, drop this journal immediately and go and read it before you do anything else.*)

> **"It doesn't matter whether it's an incandescent lamp, an HID arc source, or LEDs, it all ends up as heat."**

Don't worry, I'm not going to dig into grand unified theories (or Vogon Constructor fleets); my premise is more mundane. It's just that everything we do or think about always seems to end up being connected in some way. What made me start thinking about this was a series of subjects and questions that I was involved with over a single week last month. The topics were efficacy, European ECO regulations, fireflies, air conditioning, the second law of thermodynamics, and followspots. On the face of it, what have all these got to do with each other? Well . . .

Let's start with air conditioning. Hardly a month goes by without someone asking about the amount of cooling they might need for a theatre or other venue. "Yes," they say, "I understand that this luminaire consumes 500 W. But how much of that 500 W ends up in the room as heat for the AC unit to remove? Surely most of it is light that we don't need to worry about? I need to know the ratio between the heat and the light!"

Thus starts the conversation, followed by an explanation that it actually doesn't matter how much is heat and how much is light. At some point that light will hit something and be absorbed. It may bounce around for a while, getting dimmer and dimmer, but it eventually disappears. We know this to be true, if it didn't get absorbed then we could turn a light off and still see by the remaining photons still bouncing around! They don't. When we turn a light off it goes dark. What happens to that light when it's absorbed? Well, it isn't actually absorbed in that the photons don't somehow sink into materials they hit. Instead the energy in the photon gets transferred into the material. Usually into the electrons around atoms, speeding them up. What do we call it when electrons speed up? Heat! Yes, I know this is all very basic physics, but it's surprising how often folks forget it and think that something more complex must be going on. It's really very simple, all the energy that's in the light ends up as heat in the room. (*Note: Yes, some might escape through a window and heat up the garden or help plants to grow, but that's a tiny percentage.*)

The end result is that all of that 500 W the luminaire consumes from the electrical supply ends up as heat in the room for the AC unit to remove. No need to know how much light there is, doesn't matter whether it's an incandescent lamp, an HID arc source, or LEDs, it all ends up as heat. The introduction of LEDs has made this question more common. There's a common misconception that because LEDs are so much more efficient, then somehow less of their power ends up as heat. That's not the case. They consume less power—that's true—but all of that power still ends up as heat. (*Note: This situation is further complicated in the USA by the continued use of archaic units for HVAC systems. HVAC systems here are rated in BTU/hr or tons, rather than watts. Watts and BTU/hr are both units of energy, with 1 W equaling approximately 3.4 BTU/hr. However, if HVAC units in the USA were directly rated in watts, as they are in the rest of the world, it would make it much easier to recognize that electrical power watts = heat energy watts! We don't rate lamps in BTU/hr, although we could.*)

"Everything ends up as heat" should be your mantra in whatever engineering you do. This is entropy, as defined by the second law of thermodynamics. The second law of thermodynamics sounds like it should be tricky, and indeed some of its ramifications are very complex indeed, but in our case it's very simple. Energy flows downhill. In other words, energy, in whatever form, always trends downwards from useful energy to less and less usable forms and, finally, ends up as heat. It can never flow uphill unless you push it. This is equivalent to an increase in entropy. The entropy of a system

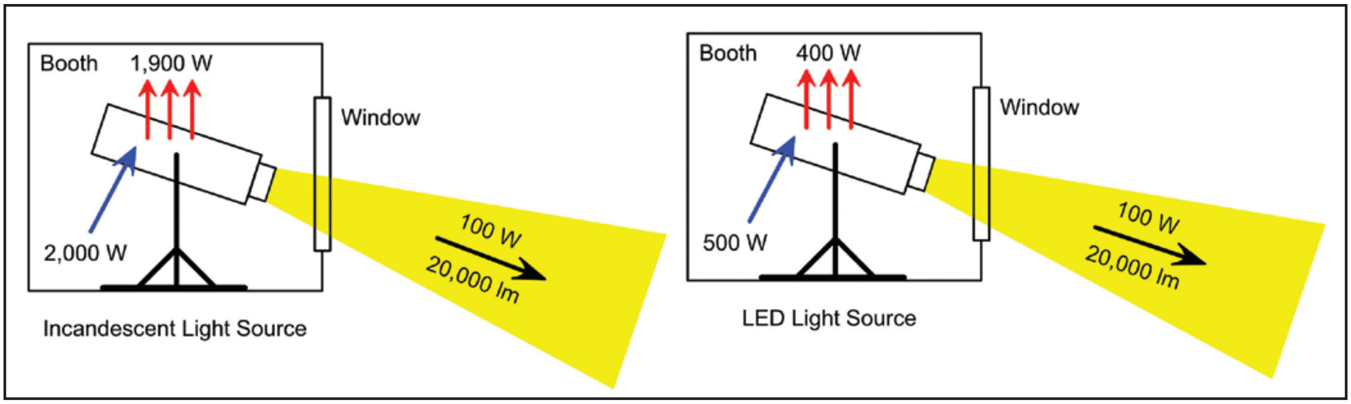

Figure 1 – Followspot in booth

always increases and can never decrease unless energy external to the system is used. It applies to every system, no matter how large or small. In its largest sense it applies to the universe itself. One possible end to the universe is a point long, long in the future when all energy sources have been consumed, all the energy has flowed downhill, and everything has settled out at the same temperature. With complete thermal equilibrium energy (heat) cannot flow anymore and everything stops. The temperature at that point would be just above absolute zero.

Now we get the connection to followspots. An exception to the "all the energy consumed by the luminaire ends up as heat in the room" mantra could be a followspot. If that followspot was run in a separate room or booth with a window onto the performance space then we do need to know how much energy is in the light beam as that energy will end up as heat in the performance space, not in the followspot booth. How much heat is that?

I'm sure you are familiar with the concept of the efficacy of a light fixture expressed in lumens per watt, (lm/W). This tell us how many lumens of light we get for each watt of power consumed. However, you might not be so familiar with the reverse, luminous efficacy of radiation, LER. (*Note: Confusingly NEMA also has an LER metric, however in their case it stands for Luminaire Efficacy Rating, that's not what I'm talking about here.*)

The luminous efficacy of radiation tells us how much energy is in a particular spectrum of visible light. The problem is that lumens, which is what we see and what we measure with a light meter, are weighted towards the human eye response. This response is a maximum at green and drops off into the reds and blues. UV and Infrared have zero lumens; light doesn't exist if we can't see it! However, energy is not limited in this way, just because we don't see blue light as well as green doesn't mean that there isn't just as much energy there. This means that we need to convert back from lumens to watts using the reverse of that same human eye response curve. That's what LER tells us. If we know that a light source has an LER of 250 lm/W then we know that 1 W of heat will be generated for every 250 lm of light. To go back to our followspot example, if that followspot consumes 400 W of power and produces 20,000 lm then it has an efficacy of 50 lm/W. If then the light spectrum of that 20,000 lm in the beam has an LER of 200 lm/W then there will be 20,000/200 = 100 W of energy in the beam. So, of that total 500 W of power input, 100W ends up on the stage, while 400 W remains to be dissipated in the followspot booth.

A less efficient light source, such as an incandescent lamp, might have an efficacy of only 10 lm/W instead of 50. In that case, assuming the light output and spectrum remain the same, there will still be 100 W in the output beam, but the luminaire will consume 2,000 W to produce that same 20,000 lm!

The take-away here is that the energy in the light beam, assuming the light output remains the same, doesn't change much. It's the energy consumed by the luminaire that changes. Returning to our followspot example, changing the followspot light source from incandescent to LED won't make much difference to the heat on stage, all the heat savings will be seen in the followspot booth. (*Note: I know I'm oversimplifying here. For example, I'm ignoring infra-red and UV and whether they pass through glass windows or not, but the principle remains sound.*)

> **"Sometimes a slavish demand for efficacy isn't always the right answer to achieving efficiency."**

This all leads on to the European ECO regulations. As you likely have heard, there are new light source regulations being proposed by the EU which could have significant ramifications for entertainment lighting products. There's a lot being written about this topic elsewhere, so I won't delve in here. (See the Summer 2018 *Protocol* for an EU lighting regulations update.) However, one important point which is still unclear is what the definition of a "light source" is. The proposal sets out minimum efficacies for light sources, but what is a light source in a theatrical luminaire? If it was a removable incandescent lamp then

Figure 2 – Firefly

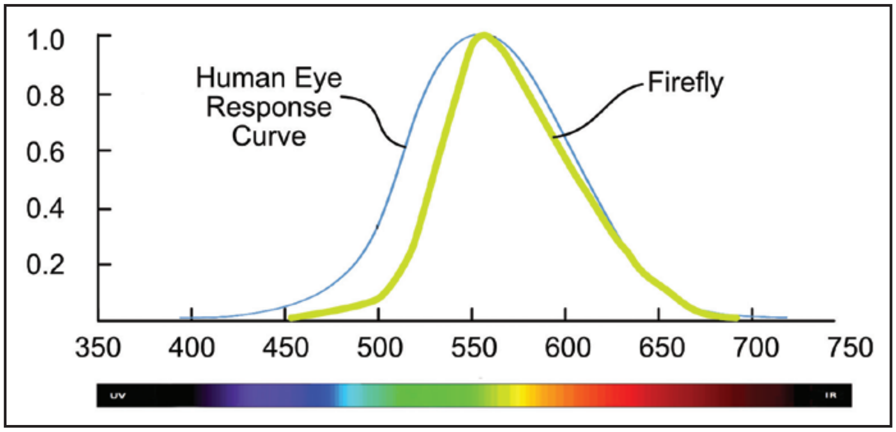

Figure 3 – Firefly spectrum compared with human eye sensitivity curve

it's easy: you remove the lamp and point to that as the light source. But what about an LED light engine? Is it the whole light engine, along with its collection optics, homogenizers, and lenses that is measured? How about the electronics? Is it just the LEDs? How do we measure the efficacy of a moving light? What about the energy consumed by motors, fans, and other electronics? Yes, it all ends up as heat, and it's all energy consumed which we are trying to minimize, but is it reasonable to use the same rules for an A lamp and a theatrical automated light? The discussion continues, and we have obtained some modifications to recognize our product types, but I don't expect full resolution of all our concerns. Sometimes a slavish demand for efficacy isn't always the right answer to achieving efficiency. A large COB LED source may be many times more efficacious than an HID lamp with a tiny arc gap, but all that efficiency goes out the window when you try and squeeze that light through a tiny hole to create a beam projector.

Finally fireflies, where did they come into my week? Well, I've written articles and given seminars where I say that, if LEDs continue on the improvement path we've seen, we'll reach a point where they approach 100% efficiency. At that point, where every electron coming in is emitted as a photon, there can never be a new light source invented that stomps all over LEDs in the way LEDs have to incandescent lamps. New lamp inventions could match LEDs in efficiency, and have other advantages, but they could never beat them. Someone who'd seen one of my seminars where I had said this, pointed me to an article on fireflies where the author had said that firefly light emission was the most efficient on the planet, and was many times better than LEDs. So wasn't I wrong in my assertion? Well, yes and no. It's true that, today, fireflies beat LEDs, but I don't think it will be for long. The very best LEDs in labs are approaching 80% absolute efficiency. A firefly beats this with over 95%, but it cheats! While it's true that the chemical reaction that results in the light output from a firefly is incredibly efficient, the entire process when you include the internal synthesis of the chemicals by the firefly's body, isn't quite as good.

Fireflies also emit energy in a limited wavelength band, not white light. In fact, very interestingly, although fireflies around the world radiate in many different colors, the ones we see here in North America tend to primarily emit light in a lime color (at least the ones I've seen). Coincidentally that lime color is exactly where the human eye sees color best! That means their flashes have the most lumens they can. Of course, this just applies to human eyes, which fireflies don't care about. Fireflies care about firefly eyes, and I have no idea what color wavelengths their eyes see most clearly! You could come up with a metric of firefly lumens, which would be different from the normal human lumens, but life's too short. However, I still find it fascinating that, by some strange evolutionary quirk, the color of the light from a North American firefly is precisely the best color it could be for humans to see it.

Everything is interconnected, one thing

leads to another, one idea leads to a better one, and the world moves on. If this kind of thing interests you, then I highly recommend an old BBC TV documentary series from the late 1970s called *Connections*. In it, James Burke explores the interconnectedness of all things through some fascinating historical examples, and he does it all wearing a white leisure suit! It was 1978 after all. Don't watch the 1990s remakes, watch the original 1978 BBC series. All ten episodes are available on YouTube, go and watch them. ■

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