Lesker Tech "...vacuum science is our business."

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Hot, Hot, Hot! (And Other Merengues)

In previous *Lesker Tech* issues, I've written about infra-red (IR) heating as an outgassing method for vacuum chambers. But suppose you want to:

- degas some bulk material
- melt alloys for casting
- heat-treat or anneal alloys
- assist diffusion (say, after ion implanting)
- alter the morphology of a depositing film
- grow single crystals of elements or compounds
- zone refine elements
- braze metal-to-ceramic joints
- facilitate chemical vapor deposition
- make high temperature reactions happen

or heat anything to high temperature inside a vacuum for any reason that tickles your fancy.

Expecting *convection* to be part of any vacuum heating process is like expecting to win the lottery without buying a ticket. You might think *conduction* has possibilities, but I suspect not. It's the old problem of two planes only touching in three places unless both are atomically flat. No, the major in-vacuum heating mechanism involves *radiation*, or to give the whole process its $3.00 name—*thermal radiation heat transfer.* And there is considerable confusion about radiant heating in high academic and low scuzzy places.

I'll describe the basics in detail so you know what to watch for if there's radiant heating in your future. I'll stop short of practical calculations. For those, you'll need books like *Heat Transfer* by J.P. Holman or *Thermal Radiation Heat Transfer* by R. Siegel and J.R. Howell.

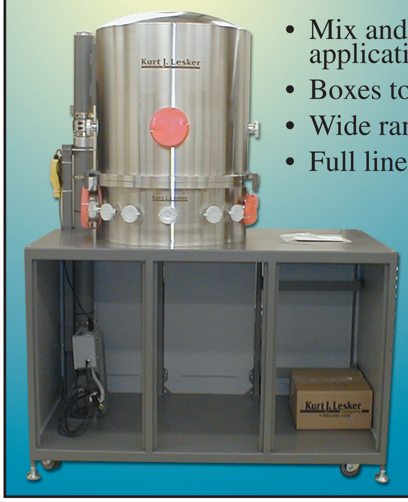
We'll start by looking at factors affecting radiant transfer in airy-fairy 'techie' terms, then we're off to the opera to view those same points in a practical way. We'll end with a rip-roaring, real-life heating example with some strange results.

As always, any wavelength units I use will be nanometers and remember the IR range is ~750nm and longer.

Soupçon of Source Sauce

It doesn't matter whether the radiant source is: a high temperature wire, like your toaster or a light bulb; the sun or other nuclear 'device'; a roaring gush of burning fuel like a jet engine or oil-well fire; or the plasma of a lightning bolt; there are just three criteria governing the transfer of IR energy radiantly from source to object:

1. The object must <u>*absorb*</u> the IR wavelengths emitted by the source.
2. The source <u>*temperature*</u> must be higher than the object's temperature.
3. The <u>*radiation shape factor*</u> between source and object must be high.



And What Does That-all Mean?

Absorbing IR Wavelengths

The total IR energy hitting a surface dissipates in three, and only three, ways. The energy can (A) *reflect,* (B) *absorb,* or (C) *transmit*–nothing else. Initially, I'll split these processes and dig into individual characteristics. But really they're a package and in describing them I'll unconsciously dodge back and forth. Later, in segment (D), I'll take the holistic (even *gestalt*) approach toward all three. You'll see why when we get there.

A. Reflection

It doesn't take much genius to see–what's reflected can't be absorbed. And metals are into reflecting IR photons, big time. We all know what reflection means at visible wavelengths but just to demonstrate it, tear off a piece of that genuine metal—aluminum cooking foil. Look closely at the shiny side and you'll see . . . a pair of eyes staring back at you. That's called *specular reflection* and you really don't need foil to demonstrate metal reflectivity, just look in a mirror. With one exception, all mirrors use aluminum as the reflective surface. The exception is: some astronomical telescopes still use the best light reflector we know, (atomically flat) silver.

Silver's a good IR reflector too, which is how the Laird of Thermos became famous. He silver-plated a glass surface and then made the glass into a re-entrant double-wall vacuum vessel. The poor thermal conduction (of the glass and vacuum) and the poor thermal radiation transfer (of the silver IR reflective coating) reduced the rate at which heat was lost from his hot toddy as he hiked the Scottish highlands. Anyone else need a stiff Dewar's whiskey before accepting that story?

D'you ever see the movie *Goldfinger*? The title character believes aluminum is a good UV reflector too. In an early shot, he's sunning himself in a Miami Beach hotel with an aluminum 'V' resting on his chest to tan the underside of his chin.

As well as *specular reflection* there's another type called *diffuse reflection.* For the physics whizzes out there, *specular reflection* follows Snell's Law and *diffuse reflection* gives Snell the old heave-ho. Perhaps the easiest way we non-physicists can grasp the difference is to think about a corridor which has one wall painted high gloss white and the other eggshell white. If someone down the hall shone a flashlight at us: on the high gloss side we'd see a distorted image of the flash lamp's filament (that's *specular reflection*); while on a true eggshell finish there'd just be, well, a swath of light. The eggshell finish is all about *diffuse reflection* and certainly won't give a discernible reflected image.

There's a non-highfalutin' description of the difference at: gbs.glenbrook.k12.il.us/Academics/gbssci/phys/Class/refln/u13l1d.html. Just be aware it's K–12 stuff. (For non-US readers – it's aimed at kids up to 17 years old.) There's an excellent, more technically profound but highly readable, explanation of diffuse *vs* specular reflection, plus lots of other neat stuff, in Dick Feynman's wonderful little book *QED.*

If you are trying to radiantly heat a highly IR reflective surface, it doesn't matter if the reflection is specular or diffuse, you're in for a long wait. Ideally, for fast, efficient radiant heating, you want the object's reflectance to be so low that the surface appears black. Maybe I should write that ***black***, since here I'm starting to differentiate between the absence of color (black) and the absence of reflection (***blackbody***). . . of which more appears in segment D.

Of course, there is the other side of this coin. If you wish to **not** radiantly heat something, you place several closely-spaced but not touching layers of a highly IR reflective metal between the heater and the object. An aluminum coating on Mylar is used at cryogenic temperatures (so-called *super-insulation*); aluminum cooking foil is a 'cheapie' reflector for <400°C heaters; and for seriously high temperature crucible heaters, polished tantalum is used.

B. Absorption

Metals absorb electromagnetic radiation like there's no tomorrow. Here are two absorption tests for your metal vacuum chamber. First, put your cell phone in it and replace the flanges. (No, don't turn on the pumps, you dingbat, you!) Call the cell phone from your desk phone and wait for the chamber to ring. Nothing, right? Stainless absorbs radio wavelengths from the phone company's nearest transmitter. Second, take a flash-light ('torch' for you Brits) and shine it at the chamber. Can you see your cell phone? Alright already! But remember it's only a daft question because you've witnessed the result every day of your life.

Stainless absorbs electromagnetic radiation with wavelengths from 10s of meters through soft x-ray at ~1 nm. It probably only lightens up and starts transmitting in the hard x-ray region <0.1nm.

Now, here's one of the dodgy bits–the 'tests' don't really tell me if the chamber is absorbing, reflecting, or doing a bit of both. All I'm certain about is, it didn't transmit. Unfortunately, I'd need equipment a bit more sophisticated than my cell phone and a flash light to distinguish between absorption and reflection. But for radiant heating, obviously, the distinction is critical.

C. Transmission

What if you wish to heat a glass tube, or sapphire viewport, or even a polished silicon wafer? These goodies are transparent at wavelengths well into the IR. Already I hear mumbling. . . silicon transparent? What's he talking about? Silicon's as un-transparent as a brick outhouse. Ah yes, in the visible, you're right, it's opaque. But get this, in the IR from 1100nm to 2500nm, silicon is almost perfectly transparent. Like Sgt. Schultz–it sees nnnnothing!

From 2500nm to ~15,000nm silicon's transparency slowly drops from 100% to around 97% then increases again to ~99.7% transparent and stays that way from 30,000nm to 100,000nm. The only IR region where silicon absorbs significantly is 750nm to 1000nm.

"Holy fading Cheshire cat smiles, Batman! Does this mean if I put a thin, polished silicon wafer on an 800°C heater plate, the wafer's practically invisible to all the heat energy being emitted?"

"Yes, Robin. The Thermal Radiation Riddler has struck again."

Most metals are either good reflectors or good absorbers. Their IR transmission is usually lousy. As a demonstration, put your finger inside a saucepan and touch the bottom. Leaving your finger there, put the saucepan on an electric stove's heater element that's already red-hot. Nothing happens for a second or two and, since IR radiation travels at light speed and your finger tip is only 1-2 mm from an 800°C source, that shows lousy transmission. But eventually absorption, thermal conductivity, and maybe a tad of re-radiation, get into the act and sear off your finger-prints. Oh, you've done that already? And your a.k.a. and last known address are . . .?

My father once told me gold could be hand-beaten so thin it transmitted green light. I always wondered how he knew . . . not much gold around our old shack. But the website www.micronmetals.com/79.htm agrees with him. Also, there's this curious little factoid about the gold-coating on fighter aircraft canopies. Yes, they are coated and don't you wonder why? Wouldn't you expect military pilots to be a little nervous about sunlight reflections from these 'gold mirrors' alerting their adversaries?

According to websites of questionable veracity, a thin gold coating serves as 'flash protection' against bright light or short-wavelength lasers blinding the pilot; or to ensure the whole cockpit doesn't act like a radar-reflecting cavity. But some of us think these explanations are all my eye and Betty Martin. The next time you take a commercial flight, look at the cockpit 'glass'. See how the colors change with angle of reflection? I'm pretty sure they're coated. . . and for reasons unlikely to be connected to exotic laser protection or radar cross-section.

How does charge dissipation grab you? Doesn't the polymethylmethacrylate (Plexiglass) or polycarbonate (Lexan) canopy of a speeding aircraft develop huge electrostatic charges from the friction of air molecules rushing over it? And wouldn't a high voltage plane (what a rotten homonymic pun!) wreak havoc with cockpit electronics?

So, gold coatings thick enough to have the low electrical resistance needed to bleed away charge, transmit visible radiation. What happens in the IR, I don't know. But I'll bet any IR transmission is also metal thickness dependent. In summary then: metals of reasonable thickness (whatever that means) don't transmit in the IR. Non-metals?. . . that's a whole other story.

D. Tout Ensemble or Alle Zusammen

Since IR radiation can only reflect, absorb, or transmit, we can make a statement about the total IR energy reaching an object.

Total Energy =
fraction reflected + fraction absorbed + fraction transmitted

And one value of writing this equation is, we can define an object that is *a perfect absorber of incident radiation*—a ***blackbody.*** Let me re-emphasize the *blackbody's* characteristics in different words–*radiation from any angle and at any wavelength is absorbed with* ***zero*** *reflection and* ***zero*** *transmission*. Of course, if absorption was all a *blackbody* did, its temperature would become infinite and that can't happen. So, while it's a perfect absorber, it is also a perfect emitter. It's a neat concept made even neater because it lets some smart people predict the energy emission spectrum (intensity *vs* wavelength) and show it depends *only* on the body's temperature. (*see figure 1*)

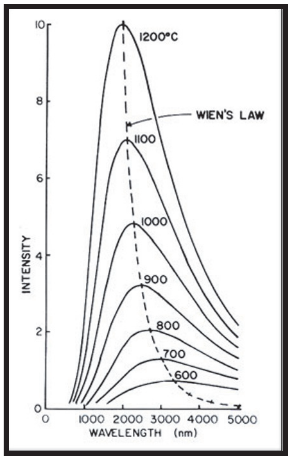


Figure 1.
Blackbody Radiation

But stare at the figure a while and you'll reach a spooky conclusion. There's a curve for the *blackbody* emissions at a temperature of 1200°C. Wouldn't that *blackbody* look (and act) as if it's white hot? Oh yeah! *Blackbody*-ness has nothing to do with appearance. Indeed, the sun is pretty close to a *blackbody*. And on this third rock from that sun, the close-but-no-cigar *blackbody* surfaces include: carbon black, carborundum, 'platinum-black', and 'gold-black'.

The *blackbody* concept lets us talk about, and measure, the degree of a real body's *blackness*. This property is called the body's **emissivity**. A *blackbody* has an total emissivity of 1 but an actual body might have a total emissivity of 0.2. For such a body, of the total IR energy falling on it, 80% is reflected or transmitted and 20% is absorbed.

If you tried heating this body in a hurry, you'd have to push in lots of watts because, there it sits, squandering most of the incident radiant energy in frivolous reflection and transmission.

Let's not quit on emissivity yet. Above I've used the term *total emissivity.* If you're interested–and why isn't your hand raised?–there's lots of stuff on the web about *emissivity,* or *emissivities,* together with modifiers like *total, spectral,* and *hemispherical*. . . some of the information is even true. There's also talk about things called *diffuse gray surfaces* which are real surfaces that give the characteristic *blackbody* spectrum just proportionately lower at every wavelength. Go ahead, search and enjoy!

Source Temperature

If you think about radiant thermal transfer for just a second you'll probably guess: the larger the temperature difference between hot source and cold object, the higher the number of watts transferred. You're right! Actually, you're right to a much higher power than you might think. Radiant energy transfer from a hot surface (at T_{hot} kelvins) to a cold surface (at T_{cold} kelvins) varies as $(T_{hot}^4 - T_{cold}^4)$!

Wow, that's wonderful. Make the source 10ºC hotter than the object and the difference works out to be a number in the ba- or ga-zillion watts, right? Unfortunately, no. This ointment's fly is Stefan-Boltzmann's constant, another multiplier in the calculation, which has an exponent of 10^{-8} even when you're using square meters to measure areas. To transfer beaucoup watts, therefore, you need a substantial temperature difference.

Shape Factor

Shape factor as used in thermal radiation heat transfer has many aliases–*configuration-, view-, angle-factor*. Very roughly, it's a combination of conditions like: the fraction of total 'surface area' into which the hot source radiates that's intersected by the cold object; the 'angles' at which the radiation leaves the hot surface and arrives at the cold surface; and the distance between surfaces. Yeah, maybe examples **are** easier.

(a) If you wanted to heat the flat disc-like bottom of a saucepan, you'd probably choose a flat disc-shaped heater like the 'burner' on your electric stove top. And you'd center the pan directly over the burner (*see figure 2*).

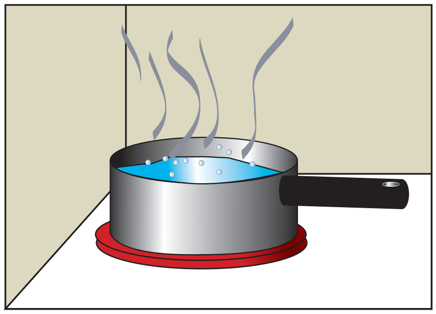


Figure 2

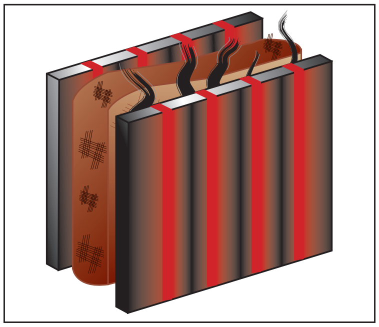


Figure 3

(b) A bread toaster is made with two flat plates, strung with heater wire, that are a little larger than, and closely spaced either side of, the bread slice (*see figure 3*).

(c) It's picnic time in the land of Oz and you're roasting hot-dogs on your (flat) barbie. If you don't rotate them they become 'half-and-half' dogs–half-burnt and half-raw. If you're handy, you cut a half-pipe from a steel tube and place it over the dog (*see figure 4*). The tube gets hot and re-radiates IR to the dog's backside, to more evenly 'tan' its hide.

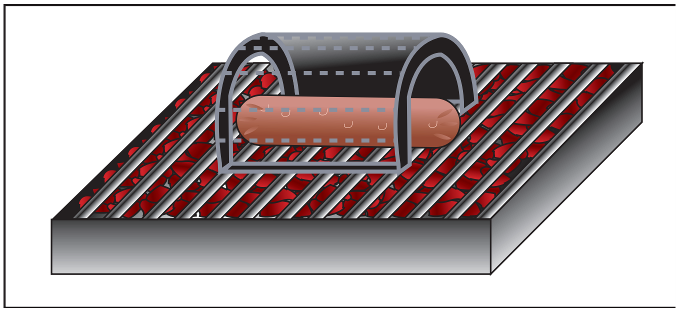


Figure 4

(d) You're at Lords cricket ground watching a test match on a hot summer's day (Ha! now, there's a hidden oxymoron if ever there was one) and you wish to keep your iced brew cool. You'd probably look for some tubular insulating foam to slip over the can (*see figure 5*).

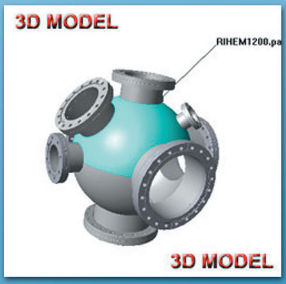
Figure 5

And in making those choices you are instinctively creating (or, as in (d), avoiding) the highest *shape factor* possible between the hot source and a cold object.

New from www.lesker.com

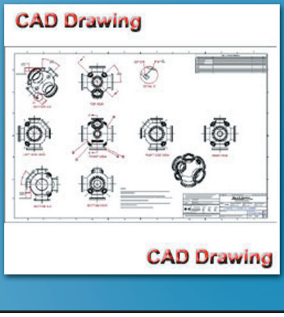
3D Models & Drawings of Vacuum Chambers!

We are now offering 3D CAD Solid Edge models and 2D CAD drawings featuring our three new standard chamber platforms: 12"x12"x24" box, 12" and 18" spherical chambers. Using the free IPA Webview plugin, users can manipulate and interact with the various 3D CAD chamber models. With Adobe Acrobat users can download PDF versions of the 2D CAD chamber drawings.



3D Model Features include:

- Zoom, move, and rotate chamber
- Show or hide specific parts
- Make specific parts transparent to view obscured areas
- Bill of materials listing



More 3D Models of our vacuum chambers and systems will be added to our website soon!

The POTO Effect

Have you seen a stage production of **Phantom of the Opera**? Remember the scene where the actors quickly leave the stage and the darkness is suddenly punctuated for a second by 8-10 huge gas (acetylene?) flames across the footlights? Do you recall seeing those ji-gunda yellow plumes and simultaneously feeling the heat blast your face? You'd just experienced thermal radiation transfer. Let's pick apart that particular spectacle.

Absorption

Sun bathe on the Costa del Sol for a while and your internal temperature regulation kicks in and makes you sweat. It's your good IR absorption that makes you quickly icky. Indeed, according to websites dealing with arcane matters, your body is more *blackbody*-ish than many matte black paints.

Transmission

While your body may be reasonably transparent to red light (prove it by putting your thumb over a small flashlamp and looking at your thumb nail) in the IR your body is a bit like a 'Big-Three' minivan I used to own, mostly transmission-less.

Reflection

No matter how shiny your Yul Brynner coiffure, apparently the only reason your pate glistens is sweat. Towel off and your skin isn't very reflective. Indeed, to comply with the rules, if your body doesn't transmit and has good IR absorption then its reflection must be quite dinky.

Temperature

I'm guessing the flame's temperature was ~1000K (727°C) and I'm fairly sure my body temperature is 310K (37°C). Taking 4th powers and subtracting gives 9.9×10^{11}. Compared to that, Boltzmann's constant with its 10^{-8} exponent looks a bit puny. So the temperature difference was quite enough to transfer beaucoup watts.

Shape Factor

The flames rose vertically and the plane of my face was vertical. I happened to be sitting about ¾ back in a large auditorium, so the height and width of my face intersected only a <u>very</u> small fraction of the total surface area (dissipating as expanding cylinders around each flame?). But, obviously, since I felt a strong heat 'wave', either the power/temperature conditions where just dandy, or my embedded thermal sensors are pretty darned good.

Before leaving POTO, let's think about what I could have done to avoid feeling the heat. Well, if I'd held some of that aluminum foil in front of my face, I'm pretty certain I'd have felt very little. Oh, perhaps a dope-slap from the person behind me, but no heat blast.

What's the Final Temperature?

Think about two isolated bodies.

What determines if energy is transferred between them and in which direction the energy flows? Their relative temperatures, right? And the higher the source's temperature, the more energy it radiates.

Emissivities simply determine how quickly energy is transferred. The higher an object's emissivity, the quicker it reaches its equilibrium temperature and the higher that temperature will be.

Unless the body has a shape factor of 1 to a uniform temperature source, it will never reach the source's temperature. And it's really easy to get a low equilibrium temperature, place the object miles from the source and turn it sideways.

There I go again. I've twice tossed out *equilibrium temperature* without telling you what I'm talking about. With a shape factor <1 and emissivity <1, the object's temperature equilibrates where its energy absorption rate exactly balances its energy re-radiation rate *at that temperature*.

Practical Example

What happens in the real world? Well, here's one example from some work we did.

Ignoring some nifty engineering details, we have a square heater (100 x 100mm) that reaches a fairly uniform 600ºC across its surface. The heater's edges extend up 10mm and terminate in a tiny lip intended to clamp a substrate in place (*see figure 6*). As an aside, you should understand in typical heating experiments, *edge-effects* cause the substrate's perimeter to be at a lower temperature than its center.

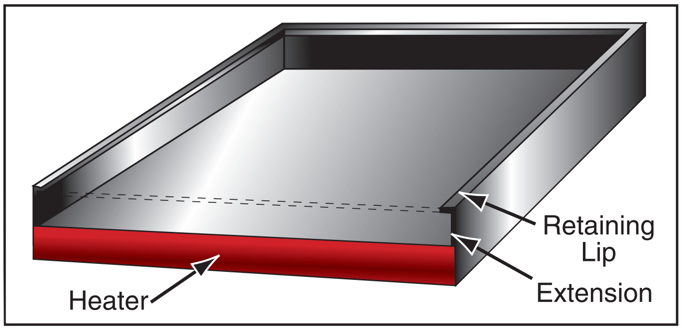


Figure 6

The substrate was a glass plate (100 x 100 x 10mm thick) drilled with 9 small-diameter holes each about 7mm deep from one surface. Thermocouples were pushed to the bottom of each hole and the substrate placed on the heater (with the T/C leads pointing away–*see figure 7*).

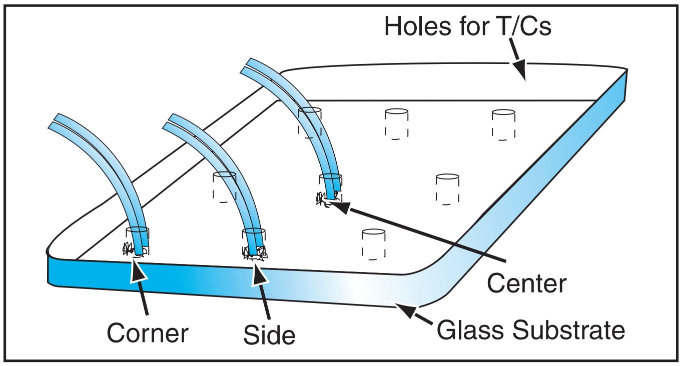


Figure 7

The intent was to measure the uniformity of heating the substrate under vacuum. What we found was:

T/C Position	Temperature
Corner	Highest
Side	Lower than corner
Center	100°C less then corner

Since that can hardly be called a rip-roaring temperature uniformity success, I was asked to try and explain the results. (I'll refer to shape factor so often I've shortened it to 'SF'.)

- The SF '*glass-heater*' is only so-so. One side of the glass faces a cool chamber wall.
- Don't know the glass-type but all glasses transmit some IR. Fused silica, for example, is still transmitting out near 4000nm. Wien's law (*see figure 1*) shows much of the energy from a 600ºC heater is emitted at wavelengths shorter than 4000nm and, therefore, slips right through silica without a backward glance.
- So far, then, it's safe to predict the substrate's equilibrium temperature is not even close to 600ºC. But uniformity could still be OK.
- The pretty good SF '*hole-to-T/C*' means the T/Cs could be close to the glass' temperature, once we've taken the emissivities of glass and T/C metals into account.
- However, there's the SF '*heater-to-T/C*' too. The initially large temperature difference between heater and T/C, plus the glass' transmission and the T/C's lack of transmission,

mean the T/C's might easily be hotter than the glass.

- But how do the corner T/Cs get hotter than the rest? Well, remember those 'extensions?' As integral parts of the heater, they have a good thermal conduction path and will reach a high temperature. And this leads to two effects:
  - The extensions are radiating into the edge of the glass. Since the glass' IR transmission is inversely related to its thickness and, since the glass is obviously 'thicker' viewed from the edge, more thermal energy is absorbed in the corner glass sections. Not only that, at each corner there are, of course, two extensions radiating into the glass.
  - But what about the effect of the two SF 'extensions-to-corner T/C'? Yes, the distance between extensions and T/C is a bit far, but the lead wires to the T/C joint are parallel to the extensions' surfaces. If the wires absorb thermal radiation, they'll heat up. That means thermal losses from the T/C joint–by conduction along the leads–will be less. Hence, the corner T/C's equilibrium temperature will be high.
- By contrast, a side T/C only has one SF *'extension-to-side T/C'* that will have much effect. Its equilibrium temperature will be lower than a corner T/C.
- And finally, the extensions will have little influence on the center T/C's temperature. The distance between this T/C and any extension is much greater, lowering the SF. Plus the glass is much thicker between edge and center, providing more opportunity for the glass to absorb all the energy from the extensions.

Yeah, it's hindsight-able all right, but wouldn't you just love to predict these situations without calling in Jeane Dixon or Nostradamus?

Happy holiday heating.

Lesker Tech started just about two years ago. Even though we've kept our promise about not spamming our contacts, readership has grown to almost three times its initial size. That suggests 'word of mouth' is alive and well and for that, a big thank you to those who spread the word. A few readers have commented on the content and, apart from one academic who wanted no jokes but more partial differential equations, they've been positive. Again, thank you!

But in two years I've only had one suggestion on what subjects I should discuss. I realize you have other things to do, but feedback always helps. If you can take a few minutes to write to **techinfo@lesker.com** letting me know what you think about subject matter, style, depth, future articles, etc., it will help enormously. Of course, if you ask for "no jokes" I'll just ignore you too.

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Mar. 8-9	Florida AVS & FL Soc. for Microscopy	Orlando, FL	
Mar. 8-11	PITTCON 2004	Chicago, IL	4316
Mar. 8-11	SAE World Congress	Detroit, MI	1164
Mar. 8-10	OLEDs Asia	Taipei, Taiwan	