Why Paint Your Box Pink?

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WHY PAINT YOUR BOX PINK?

Heat flows from a hot source to a cooler source by three distinct mechanisms of thermal transfer: conduction, convection and radiation.

Conduction – the transfer of energy between adjacent matter by direct contact and a passing of thermal energy – and Convection – the transfer of energy between a solid and a fluid phase – are widely utilised by the electronics community as primary mechanisms of heat removal from a device. For example, many off-the-shelf electronics cooling manufacturers will sell small finned heatsinks to stick directly on components. In the rugged embedded computing community for example, the VITA 48.x specification range identify various methods of extracting heat from a module, either by passing air over a module or providing a solid path for heat to travel down.

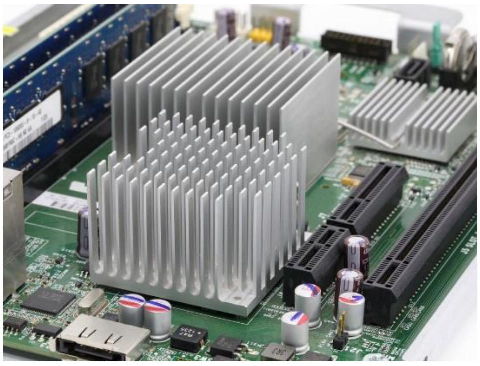

FIGURE 1 - A TYPICAL "STICK-ON" HEATSINK FOR ELECTRONICS APPLICATIONS

Radiation however is a slightly different beast and not one that can be turned on or off by state of the system. Simply put, it is the transfer of energy from one medium to another through energised waves (photons) and is incident across the entire electromagnetic spectrum. It is commonly understood that white is a good colour for reflecting heat, and black is good for absorbing it, but across the entire spectrum, does colour that really matter? This paper will evaluate the impact of radiative heat transfer in a typical heat frame, and how important coating colours and other surface factors are to true performance.

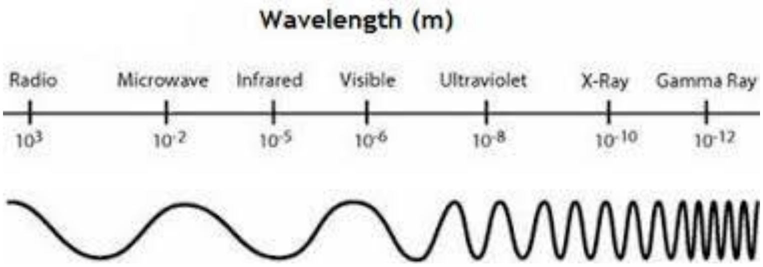

FIGURE 2 - THE ELECTRO MAGNETIC SPECTRUM [1]

WHAT IS RADIATION EXACTLY?

Radiation is a measure of the conversion of thermal energy within a body into electromagnetic energy. As thermal energy travels through a medium it causes charged particles to oscillate and change acceleration, resulting in generation of electric and magnetic fields. As these particles oscillate, they emit photons of differing energy levels, producing a continuous spectrum of frequencies. These photons require no medium or matter to carry the thermal energy, and so are independent of the intermediate properties between the source and sink surfaces.

In radiation theory, a perfect emitter of radiation is called a “black body” and is given an emissivity, ε, value of 1. This value is used to characterise the radiative performance of all real bodies:

$$\varepsilon = \frac{emergy\ emitted\ by\ a\ surface}{energy\ emitted\ by\ a\ surface\ of\ an\ ideal\ emitter, a\ black\ body}$$

And a simple formula for radiative heat transfer, known as the Stefan-Boltzmann Law, is given as

$$Q_R = \varepsilon\sigma A\left({T_s}^4 - {T_\infty}^4\right)$$

Where A is the heat transfer surface area, T_s is the heatsink temperature, T_∞ is the ambient temperature and σ is the Stefan-Boltzmann constant.

It should be noted that, determined by the conservation of energy and not explored further within this paper, a good emitter of radiation is an equally good absorber, ε=α. For further reading on this subject see [2].

HOW IMPACTFUL IS RADIATION?

It is difficult to readily determine the relative effectiveness of radiative heat transfer in relation to the other two methods, since each is highly dependent on the environment and needs of the system. For example, conductive thermal loss is dependent on the distance between a heat source and the heat sink, while the convective loss is dependent on the speed and properties of the fluid medium. These parameters are not interchangeable between methods.

A more plausible example is to bound the heat transfer methods to a typical use case and evaluate the proportion of power transfer in each. The study described below shows the impact to temperature of a simple uniform heat load which is to be cooled in a bounded volume. In this example, to simply evaluate the comparative effects of all three heat transfer mechanisms a slightly unusual heatsink design and thermal path has been used, however this is intended to showcase the relative strengths of each method in this specific situation only. For this study, the heatsink is assumed to have a black anodised coating applied with corresponding surface emissivity.

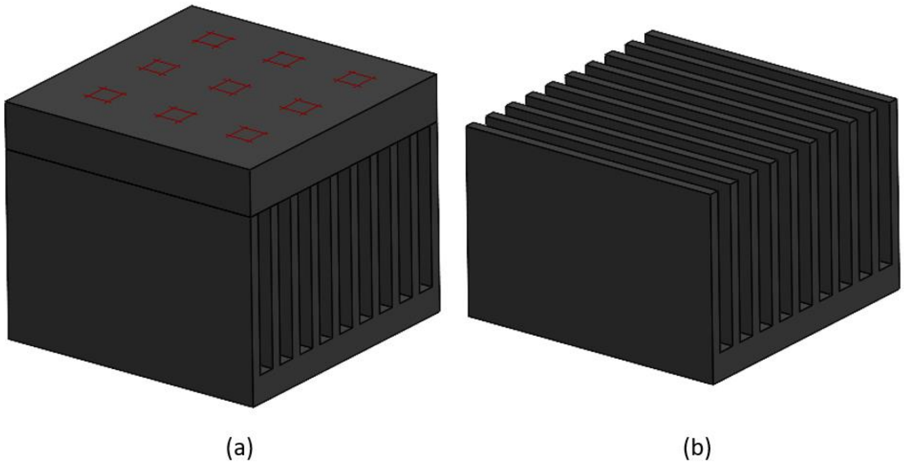

FIGURE 3 - A SIMPLE FINNED HEATSINK MODEL USED TO SHOWCASE STRENGTH OF THERMAL TRANSFER METHODS

Figure 3 shows two simple finned heatsink models. Version (a) implements a solid block on the top held to an infinite cold wall intended to allow a path for conduction energy to flow, while in version (b) there is no allowance for conduction as a cooling path from the heatsink to environment. For both versions, a 3W load is applied uniformly to the bottom surface.

Using a CFD solver, these models were both run in two air flow configurations: one with perfectly static air (0m/s), and one with low moving air speed (1.5m/s) parallel to the fins.

TABLE 1 - SIMULATION RESULTS FOR HEAT TRANSFER EXPERIMENT

Test version	Airflow (m/s)	Power Dissipation Contribution		
		Conduction	Convection	Radiation
(a)	0	99%	1%	0%
(a)	1.5	94%	6%	0%
(b)	0	0%	67%	33%
(b)	1.5	0%	93%	7%

Table 1 shows a severely dominant effect that conduction cooling has over a general thermal transfer scenario, to the extent that in a perfectly ambient cooled environment there need be almost no consideration for other transfer methods whatsoever.

For systems which cannot utilise conduction cooling however, the impact of radiation becomes more prevalent. In a forced convection environment radiation is no longer negligible, although its impact is low enough that performance gains made in improving surface emissivity and view factor may be outweighed by focussing on gains in the convective transfer region. Such is the dependency for convection cooling on moving air, however, that in a still environment radiation now plays a significant role (33%). It is in these conditions that engineers should be most considerate of surface treatment decisions.

FACTORS AFFECTING EMISSIVITY

Clearly then surface emissivity is a significant driver in the performance of a free convection system, and so a design engineer should be aware of the material properties that impact this tendency. There are a number of factors that drive the emissivity of a surface above that of the material properties itself, such as: temperature, surface roughness, emission angle and colour. Some of these are described in more detail below.

MATERIAL PROPERTIES

As discussed previously, the photon energy incident on the surface of a material can be absorbed entirely or partially by surface electrons. Some energy of the incident photon is required to free the electron from the surface and the remaining energy is reflected back as a photoelectron.

In a metallic lattice, these electrons are not strongly attached to the atoms and so both require low excitation energy, and are not able to transfer their energy to the atomic lattice, thus reflected energy is high. Similarly, thermal energy in the lattice has a poor relationship with the free electrons, and so cannot transfer enough energy to cause the electrons to oscillate [3].

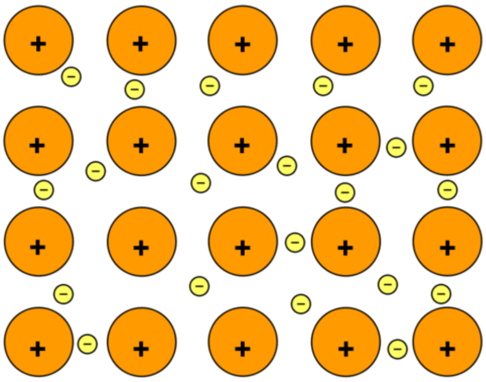

Figure 4 - Metallic bonds and surrounding electrons [4]

In a non-metal structure – such as a polymer or an oxidising layer – the bond between shell electrons and the atoms is strong and energy transfer between the two is much more efficient allowing more radiative energy transfer between objects.

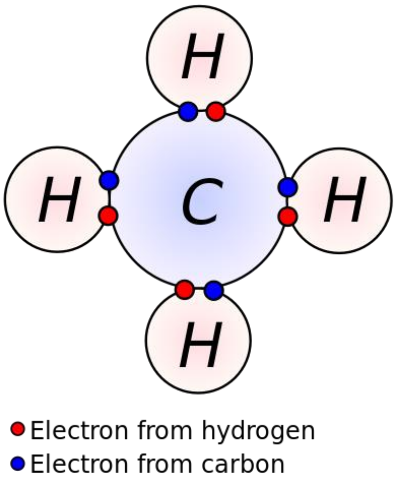

Figure 5 - Electrons in an organic covalent bond [5]

The general trend of emissivity values therefore sees metals as a very poor emitter of radiation energy, while dull chemical layers are significantly more effective. Some typical emissivity values are given in Table 2 below where it can clearly be shown the presence of a metallic structure is impeding the transfer of thermal energy.

Table 2 - Table of typical emissivity values [6]

Material	Bonding Class	Emissivity
Aluminium (Polished)	Metallic	0.05-0.1
Aluminium (Rough)	Metallic	0.1-0.3
Aluminium (Oxidised)	Covalent	0.1-0.4
Enamel	Covalent	0.9
Gold	Metallic	0.05
Plastic	Covalent	0.95-1.0
Polyester	Covalent	0.75-0.85
Wood (Planed)	Covalent	0.8-0.95

Surface Roughness and Emission Angle

For reference, Table 2 shows the emissivity of Aluminium can be improved by increasing the roughness of the exposed surface. As explained above, when an excited photon interacts with a surface, enough energy will be imparted to raise the state of the electron while instantaneously reflecting away from the surface as a photoelectron with the remaining energy. If this reflection is against a parallel surface that energy is lost to the atmosphere. On a rough surface, there is a much higher chance that the reflected photoelectron will have a second opportunity to interact with the material surface. Figure 6 shows this event visually.

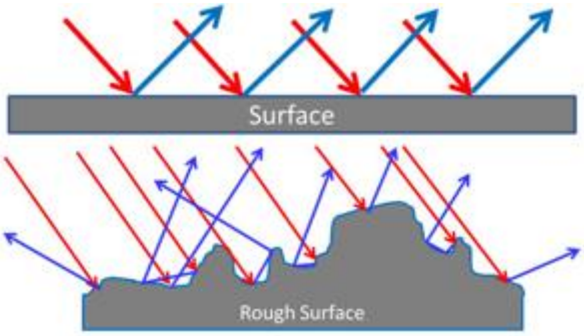

FIGURE 6 - HOW DIFFERENT SURFACE ROUGHNESS CAN IMPACT THE REFLECTION OF ELECTROMAGNETIC WAVES [7]

An engineer should therefore look to avoid mirrorlike finishes when designing radiative surfaces.

COLOUR

When considering the impact of colour, it is important to remember that visible light is only a small portion of the electromagnetic spectrum, while radiative emissions can occur over a much wider bandwidth.

For reference, the image below is taken from a NASA study evaluated the emissivity effects of black and white paint. The visible spectrum has been superimposed onto the chart and only accounts for a small portion of the full energy band that these paints see.

As white reflects a high proportion of colours (wavelengths in the visible light spectrum) it has a low absorptance in this band, while black has a high absorptance. In the far infrared region (2um and above) colour is not associated with thermal dissipation and both the white and black coatings are excellent emitters (a good absorber is a good emitter, remember).

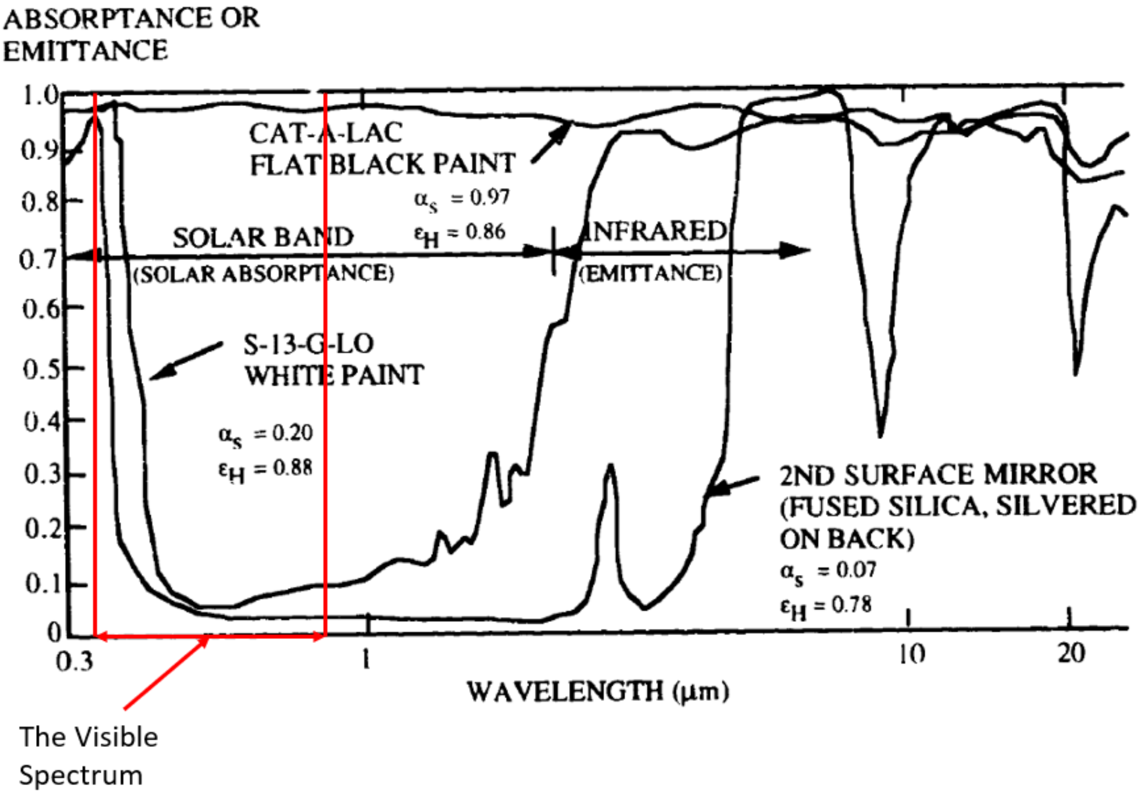

Figure 7 - Emissivity of white and black paints over a wider frequency range [8]

It is clear then that the colour of a coating only affects the thermal performance in a narrow bandwidth pertaining to the wavelength of the energy released from the surface.

This variable effect is present in all materials although is typically represented by a single emissivity value covering the entire frequency range, hence similar materials with very different colours will have comparatively similar emissivity values despite possessing opposing traits in the visible spectrum. Table 3 compares the emissivity of white and black paint as these should have polar opposite performance in the visible spectrum. All other colours – provided they are of similar material – will fall between these two outliers.

Table 3 - Emissivity values for similar paint of oposing colours [9]

Colour	Emissivity
Paint; black	0.95
Paint; white	0.84

Even comparing directly opposing colours, the difference between these two paints only contributes to an emissivity difference of around 10%. The bulk of the surface performance is outside the visible spectrum.

To estimate further what wavelength a surface will give emit at temperature we can use Wien's Law. Wien's Law determines at what wavelength the intensity radiation of a blackbody reaches its peak, and is determined by the following formula [10]:

$$\lambda_{max} \times T = 2.8978 \times 10^{-3}\ m \cdot K$$

As the absolute temperature of the body increases, the peak wavelength emitted moves further toward the ultraviolet portion of the spectrum and the dominant colour changes to suit. This is most observable when measuring superhot objects, such as stars.

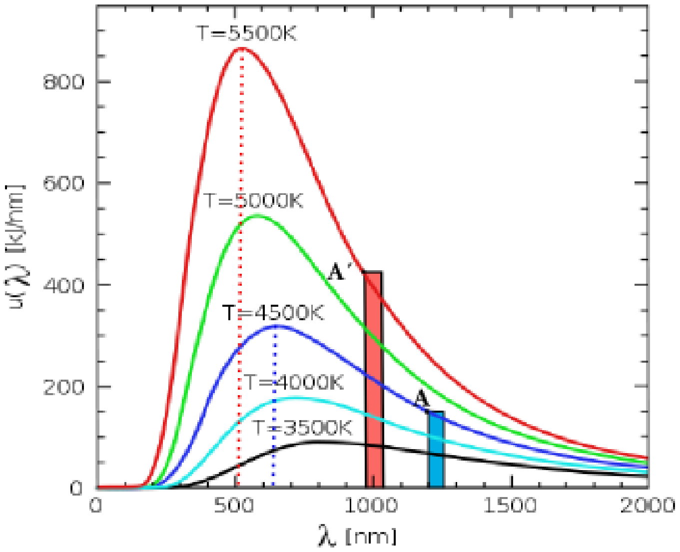

FIGURE 8 - WIENS LAW DISTRIBUTION CURVES FOR DIFFERING TEMPERATURES

Considering again a typical embedded application use case, where the surface temperature will be slightly above +71°C, we can estimate what the peak wavelength of the radiated energy will be.

Assuming for this example our heatsink is a perfect radiator, and that the outer skin of the heatsink is uniform at +80°C (353.15K):

$$\lambda_{max} = \frac{2.8978 \times 10^{-3}}{353.15} = 8.2\mu m$$

The peak emitted wavelength of 8.2um is greater than that of waves in the visible spectrum (you cannot see the item glowing under heating). As in Figure 8, this calculation gives the peak value of a frequency bandwidth, with a high likelihood that for this heatsink some higher energy level emittance does fall just within the range of the visible spectrum.

While it is difficult to calculate the power of the energy that falls in this range, it is clear that colour only impacts a small portion of the total energy released at the surface.

COATING PERFORMANCE IMPACT

In order to change the colour of a surface, or alter its material composition, the most typical approach is to coat the surface of the metal. While a treatment such as anodising greatly improves the radiative properties of a metal, it creates an oxide barrier which will resist conductive heat flow through the boundary to the surface itself. The magnitude of this impact must be considered when determining where this process is applied, however its impact can often be neglected due to low bondline thicknesses of the coating.

Table 4 below shows a comparison between 3 typical surface treatments used for an embedded electronic chassis: powdered polymer paint, black anodisation and nickel plating. Please note all figures are given for an aluminium frame, however should not vary significantly with the underlying metal.

TABLE 4 - STANDARD HEATSINK COATINGS AND THEIR THICKNESS'

Material Coating	Coating Thickness (mm)	Thermal Conductivity (W/mK)	Emissivity

Polyester Powder Coat	0.06 [11]	0.52[1]	0.85[2]
Anodisation	0.05[3]	0.53-1.62[4]	0.88 [12]
Nickel Plating	0.026[5]	4.39 [13]	0.37[6]

It should be noted that while these thickness values can be varied, often layered thinner than given in this table, these values are intended only to show the representative low thermal impact across this boundary.

The size of this thermal loss can be shown clearly by evaluating the Fourier's law of conduction and making some realistic assumptions for order of magnitude of the heatsink.

$$Q = kA\frac{\Delta T}{\Delta x}$$

As an example, values have been chosen which are in line with anodisation data in Table 2, and the given surface area and power loading of a typical Small Form Factor air cooled chassis:

$Q=10^1$ W
$A=10^{-1}$ m^2
$k=10^{-1}$ W/mK
$\Delta x=10^{-5}$ m

Rearranging Fourier's equation for temperature gives,

$$\Delta \mathrm{T} = \frac{\mathrm{Q}}{\mathrm{A}} \cdot \frac{\Delta \mathrm{x}}{\mathrm{k}} = \frac{10^1}{10^{-1}} \cdot \frac{10^{-5}}{10^{-1}} = 10^{-2}\ {}^\circ\mathrm{C}$$

It can be seen from this example that using the magnitudes from Table 4 gives an almost negligible temperature drop across the coating boundary despite relatively poor conductors being used. Using high conductivity doping [14] or reducing the coating thickness will therefore have diminished returns. The impact should be evaluated for systems with far higher power requirements, however typically as the power scales so do does the requirement for surface area for convective transfer.

A design engineer should however continue to bear in mind that this impact is at the external of the unit, where air cooled fins dramatically increase the surface area. When coating a surface closer to a critical component, values for Q, k and Δx will remain almost consistent while surface area, A, could reduce by as much as a factor of at least 100 ($A=10^{-3}$ m^2). Applying these thermal boundaries close to die therefore may see a temperature rise in the order of 10^0 °C or greater and must be considered in design.

CONCLUSION

While this article cannot accurately advise the impact of adjusting the colour of a heatsink, it highlights the many facets to consider on thermal design when selecting surface preparations and materials.

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[1] This value is heavily dependent on material content, application process and other factors and may vary from below 0.5W/mK [13] to 5W/mK [10].

[2] No data for the emissivity of a polyester powder coat was found, the emissivity for solid polyester has been used in its place. It is accepted that this will differ slightly from the true value, however this deviation should be significantly less than an order of magnitude (10^{-1})

[3] Nominal coating thickness as per MIL-A-8265F

[4] Thermal conductivities [12] incorporating all process types as defined in MIL-A-8265F

[5] Grade A used for aluminium alloys within MIL-C-26074E

[6] No data for nickel plating of aluminium was found, with given information for nickel plated copper. It is expected that the true value for aluminium will be similar.

The colour of a coating impacts the thermal energy transfer in the visible spectrum only, which is a small part of the radiation energy bandwidth released at typical cooling temperatures, which in turn can be a small part of the total thermal transfer of your system – depending on what your cooling options are. If every last degree is critical to functionality in a static air environment, a non-reflective black coating is probably the best choice. However, if some thermal margin is available, or your system is conduction/convection dominant, then why not: pain your box pink.

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