IR Window Transmittance Temperature Dependence

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ABSTRACT

While fluoride-type IR windows are inexpensive and have good transmittance in the mid-wave IR band (3 to 5 micrometers), their transmittance drops rapidly in the long wave IR band (8 to 12 micrometers). We can characterize the graybody approximation of such a window by measuring its IR bandpass transmittance with our IR camera. But as the IR window clearly is not "gray" but a spectral transmitter, the transmittance measured for one target temperature at one window temperature can be different for other target and window temperatures. Does this pose a serious problem for the condition-monitoring thermographer? This paper addresses the issue by modeling the effect of the non-grayness of fluoride-type IR windows in the nominal 8 to 12 micrometer waveband and gives quantitative results. We will show the magnitude of this effect and how to deal with it. If you use low-cost IR windows, you need to know the results of this study.

Keywords: IR window, emissivity, IR window transmittance, condition monitoring

INTRODUCTION

IR windows are being used more and more to enhance safety and increase the IR accessibility to important targets for condition monitoring. We used to remove the cabinet covers from the rear of 4160 volt switchgear to view the connections with our IR cameras. This was a cumbersome, time-consuming, and somewhat dangerous job to remove up to 8 bolts and lift a heavy steel cover away from live equipment. One false move, and an arc flash was the result. Another area we were unable to observe was motor connection boxes. These are but two examples of numerous cases where, with IR windows, we can now look into these areas much more safely and conveniently.

Figure 1 gives an example of viewing motor connections through an IR window. This window has a transmittance of about 50%. Target emissivity is about 0.95. If your IR camera doesn't have IR window transmittance compensation, the best approximation is to find the product of the IR window transmittance times the target emissivity. This is quite accurate, provided the target reflected apparent temperature, IR window temperature, and IR window reflected apparent temperature are all equal.

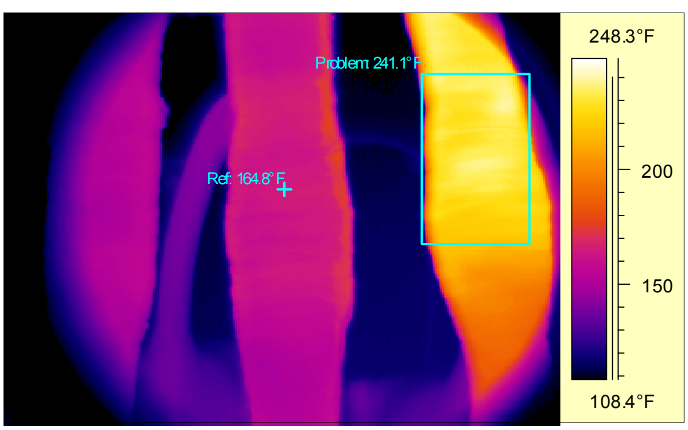

Figure 1. Three phase motor connections viewed through an IR window with a FLIR PM695 with standard 24° lens. Courtesy Chuck Elliott, Southern California Edison.

The connection-to-connection temperature rise, accounting for IR window transmittance and target emissivity, is 78°F (44°C). Compare this to the "apparent" temperature rise of 46°F (26°C). (Apparent temperature is the reading uncorrected for target emissivity and window transmittance.) The corrected temperature rise is almost double the uncorrected rise. If the IR window transmittance were 55% instead of 50%, the calculated temperature rise becomes 74°F (41°C). For an indirect target, such as the insulated connections in Figure 1, this borders on significant, as the internal temperature rise could easily be double or triple the external rise. So, knowledge of IR window transmittance is key to getting good measurements. The more accurately you know IR window transmittance, the more accurately you will know the temperatures and ΔTs.

HOW THE SPECTRAL NATURE OF AN IR WINDOW AFFECTS ITS TRANSMITTANCE

Since knowledge of IR window transmittance is crucial for accurate temperature readings, we need to know what may affect transmittance. One key parameter is the spectral transmittance of an IR window. The IR camera does not measure at individual wavelengths. It measures over a "waveband" that varies, depending on the nature of the camera optics and detector. For IR windows whose spectral transmittance is constant over the waveband of the IR camera (graybody), its transmittance will be constant, regardless of its temperature and the temperature of the target, as long as the window doesn't change its physical characteristics. But with an IR window whose spectral transmittance changes within the waveband of the IR camera (realbody), its transmittance will vary with its temperature and the target temperature.

One popular class of IR window is based on fluoride salt crystals. The two IR windows made from these are barium fluoride (BaF_2) and calcium fluoride (CaF_2). BaF_2 is softer than CaF_2. Both have some water solubility, which can be problematic in humid or wet environments. But they are inexpensive, and for large quantities that may be used in condition-monitoring applications, they can be quite economical.

Originally, the fluoride windows were used for mid-wave IR (3 to 5 micrometer waveband), had high transmittance, and were quite gray over this waveband. With the advent of long waveband uncooled IR cameras, these windows are also sold for this purpose. Their transmittance begins to fall off right in the middle of the long waveband as shown in Figure 2.

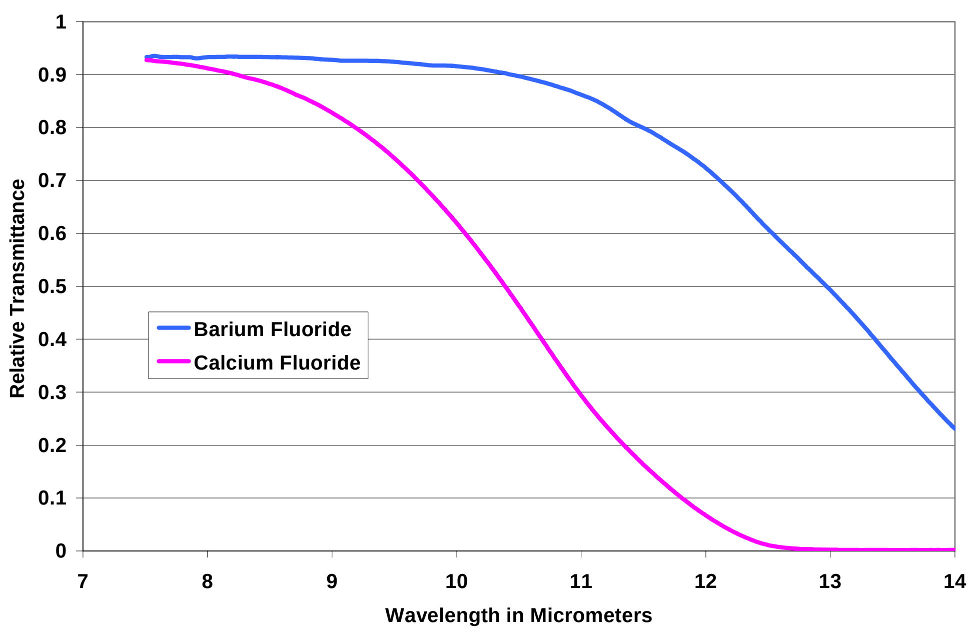

Figure 2. Spectral transmittance of barium and calcium fluoride in the long waveband

Note that BaF_2 begins dropping at a longer wavelength than CaF_2, so it will have a higher graybody transmittance in the long waveband. Figure 3 shows how the Planck function changes with temperature in this waveband. As the temperature increases, the curves increase in magnitude with the peak shifting to shorter wavelengths.

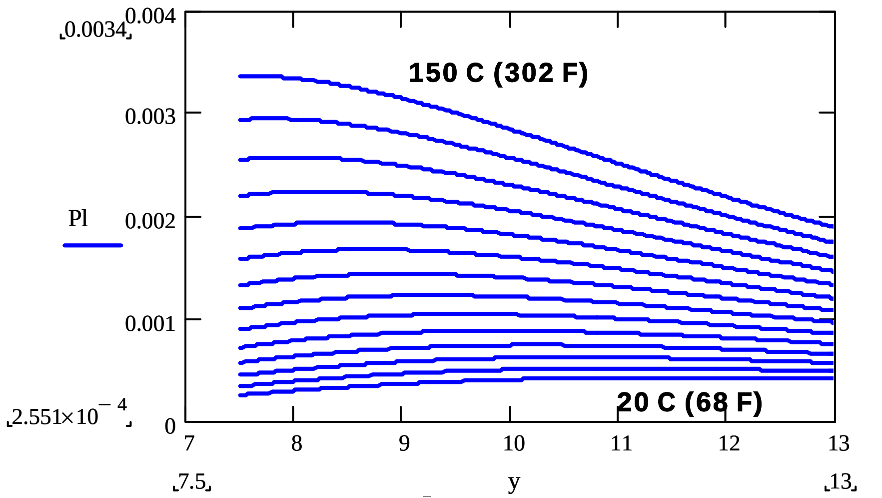

Figure 3. Planck function curves from 7.5 to 13 micrometers for temperatures from 20°C to 150°C

For a blackbody target, the detector will see the end result of these effects multiplied together. That is, when the radiance passes through the IR window, it is spectrally modulated (multiplied) by the window transmittance. Figure 4 is a graphical representation of this effect on the blackbody (Planck function) curves by a CaF_2 window.

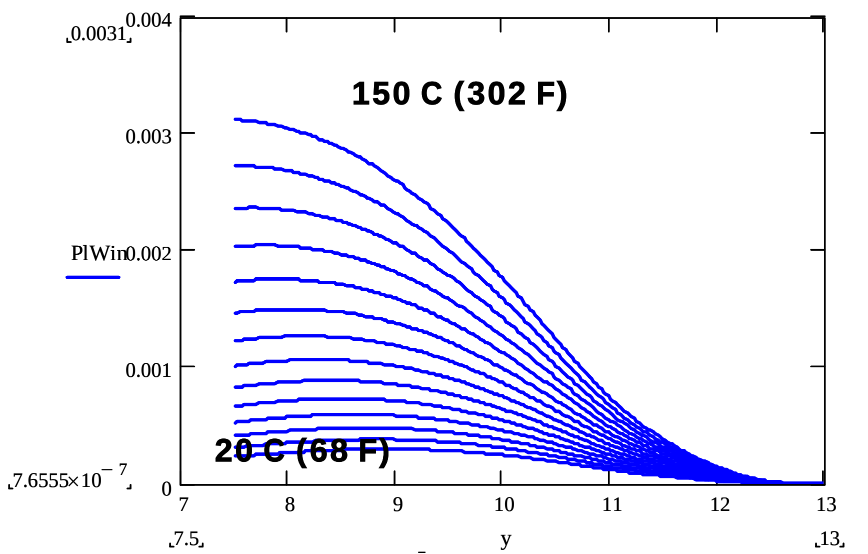

Figure 4. Planck function times CaF2 window spectral transmittance for a range of temperatures from 7.5 to 13 micrometers

The importance of this set of curves is how the magnitude changes with wavelength as the temperature increases. At 9 micrometers the change in magnitude is much greater than at 11 micrometers. This is due to the IR window spectral transmittance being higher at the shorter wavelengths. The CaF_2 IR window weights the Planck function in favor of shorter wavelengths.

A target radiating more energy at shorter wavelengths (hotter) will have relatively more radiant power transmitted through a fluoride window than it would through an IR window whose spectral transmittance was constant with wavelength. The fluoride IR window "likes" hotter targets better in the long waveband. The result is the fluoride IR windows will have a graybody transmittance that increases with target temperature!

Similarly, if one had an IR window that was a better spectral transmitter at longer wavelengths, the opposite would occur. The graybody transmittance would decrease with increasing target temperature. Figure 5 shows the spectral transmittance of an IR plastic window, material unknown.

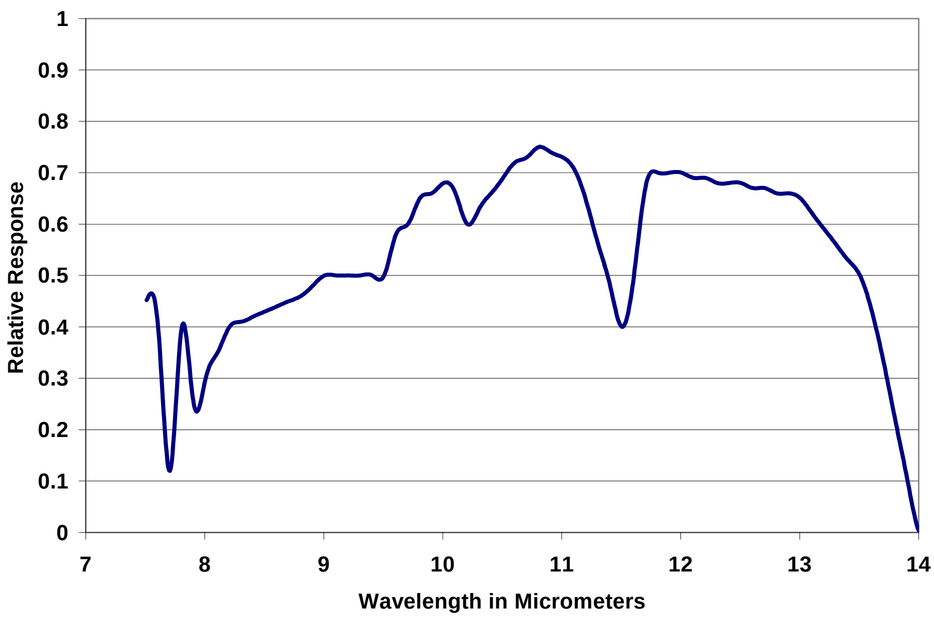

Figure 5. IR plastic window spectral transmittance from 7.5 to 14 micrometers

It has a spectral transmittance that is higher at longer wavelengths. One would expect its graybody transmittance to decrease with increasing temperature.

Finally, if the window changes temperature, we would expect its graybody transmittance to change as well. We had the spectral reflectance of the fluoride windows measured in addition to their spectral transmittance. We found the spectral reflectance to be almost zero. This means a fluoride window has a spectral emissivity that essentially equals one minus its spectral transmittance. What works out mathematically is when we think of the temperature of the target changing, we must think of it relative to the window temperature.

Depending on the magnitude of the graybody transmittance change with target or window temperature, this could be a serious problem for these types of windows. Or, it could be a minor effect, giving us an uncertainty well within our necessary margin of error. The only way to know is to do the calculations.

CALCULATING GRAYBODY TRANSMITTANCE FROM SPECTRAL TRANSMITTANCE DATA

Figure 6 gives the transmittance results for the BaF_2, CaF_2 and IR plastic windows calculated (Eq. 3) using their spectral data and target temperatures from -30°C (-22°F) to 500°C (932°F). IR window temperature was 20°C (68°F).

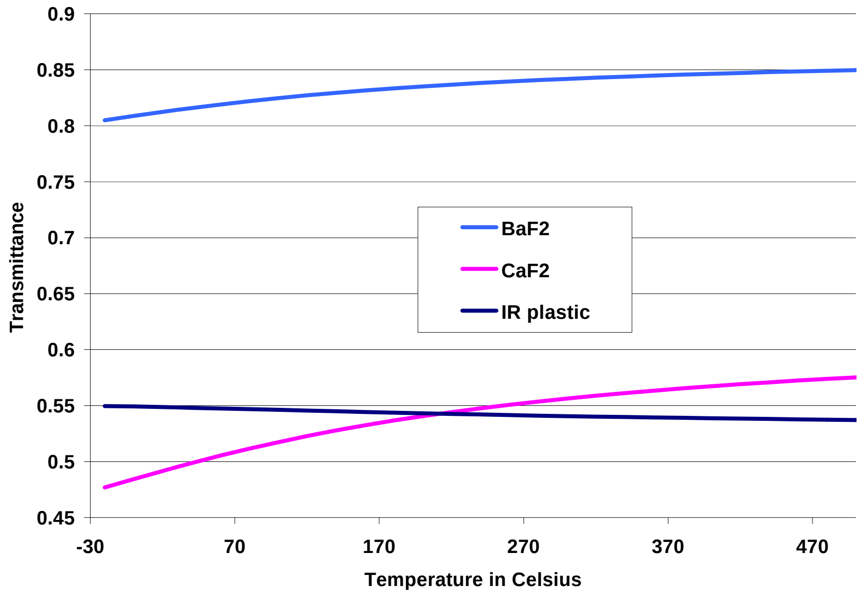

Figure 6. Graybody transmittance of selected IR windows vs. target temperature from -30° to 500° Celsius (-22°F to 932°F)

Both fluoride windows increase in transmittance with BaF_2 ranging from about 80% to 85% and CaF_2 ranging from about 47% to about 57%. The IR plastic window decreases in transmittance from about 55% to about 54%. Our spectral weighting hypothesis was correct.

It is doubtful a condition-monitoring thermographer would view a target as hot as 500°C (900°F) through an IR window, especially during an electrical IR survey! The CM thermographer deals with temperature ranges from about -10°C (14°F) to about 150°C (302°F). We took FLIR Systems ThermaCAM® S60 and E4 IR cameras and measured the transmittance of the BaF_2 and CaF_2 IR windows at various temperatures. (The section below, *Measuring IR Window Transmittance with Your IR Camera*, gives you recipes for doing this.) Figure 7 gives the results of these measurements together with the bandpass transmittance calculated from spectral transmittance measurements.

The IR camera-measured values are in good agreement with the values calculated from spectral measurements. We believe the differences can be attributed to the IR camera spectral response and where it actually cuts off on the long wavelength end. We used a typical curve and somewhat arbitrarily stopped the calculation at 14 micrometers. But if the IR camera is sensitive beyond this wavelength, it will pick up radiance from the window surface, as CaF_2 is opaque and BaF_2 is rapidly becoming so. In this region the windows radiate to the IR camera with high emissivity, as the spectral reflectances of BaF_2 and CaF_2 were measured as low values in this waveband. The IR camera captures the window radiance, which is noise as far as target measurement is concerned. We plan to look into this further with measurements at longer wavelengths. But for now, the agreement between IR camera measurement and spectral measurement is good for the temperatures normally seen by the condition-monitoring thermographer.

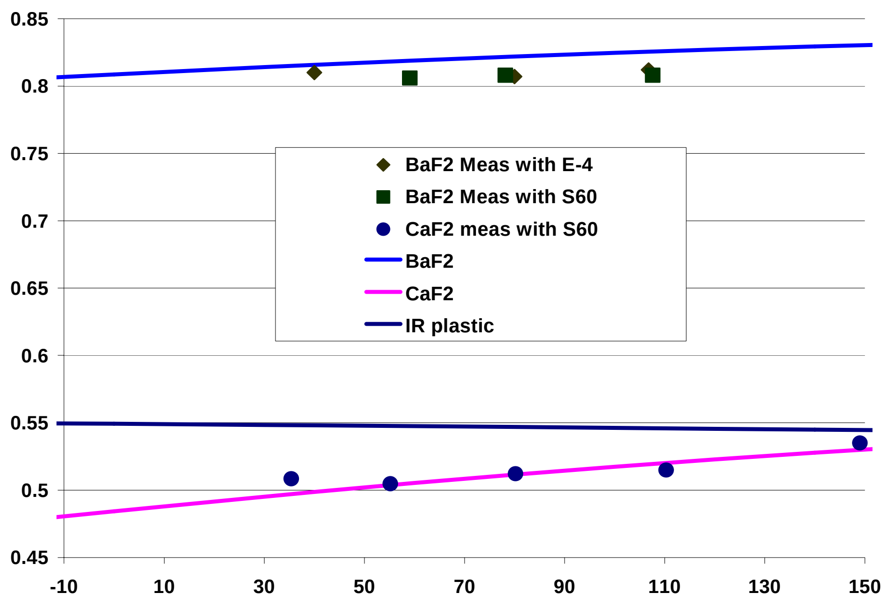

Figure 7. IR window transmittance vs. target temperature for 3 types of IR windows. Solid lines represent calculation from spectral data. Points are values measured using FLIR Systems, Inc. IR cameras as noted.

MEASURING IR WINDOW TRANSMITTANCE WITH YOUR IR CAMERA

There are several methods for measuring IR window transmittance using your IR camera. We will review the two simplest ones here. Measurements made with your IR camera are *graybody approximations,* as the IR camera will spectrally modulate IR energy it receives from an IR window that may spectrally modulate the IR energy transmitted through it, reflected off of it, and emitted by it. Specialized instrumentation is used to measure the spectral transmittance of IR windows and the spectral response of IR cameras. A true graybody has no temperature dependence for either its emissivity or its transmittance. But we have seen the materials shown above are nowhere close to being true graybodies.

Since the IR camera gives only one transmittance number representing a waveband response, this is what we must live with and should know how to measure. For these IR windows, we recommend, for best accuracy, measuring as close to the expected target temperature as possible.

Recipe 1: IR camera has external optics transmittance compensation.

1. Get a target with high emissivity and temperature about 35°C (60°F) hotter than the IR window. Or, get a high emissivity target about the temperature of the target of interest.
2. Set IR camera emissivity to 1.
3. Measure target apparent temperature without window in place.
4. Enter temperature of the IR window.
5. Place window in front of target.
6. Adjust window transmittance until same apparent target temperature without window is found.
7. When measuring through the IR window, set appropriate values in your camera for IR window transmittance and temperature.

Recipe 2: IR camera does not have external optics transmittance compensation.

1. Get a target with high emissivity and temperature about 35°C (60°F) hotter than the IR window. Or, get a high emissivity target about the temperature of the target of interest.
2. Set IR camera emissivity to 1.
3. Measure target apparent temperature without window in place.
4. Place window in front of target.
5. Adjust target emissivity until same apparent target temperature without window is found.
6. When using IR windows in this mode, enter the product of the target emissivity times the window transmittance for emissivity in your IR camera.
7. The major caveat here is that the target reflected apparent temperature, the window reflected apparent temperature, and the window temperature must all be equal.

CALCULATING IR WINDOW BANDPASS TRANSMITTANCE USING SPECTRAL TRANSMITTANCE VALUES

IR windows that are realbody radiators, not graybodies, exhibit a bandpass transmittance that depends on the waveband response of the IR camera, the spectral response of the IR window, and the temperatures of the IR window and the target of interest. There can also be reflected apparent temperature dependence, depending on the IR window. For fluoride windows the spectral reflectance is low enough to be ignored.

The radiance received by an IR camera from a graybody IR window is the sum of the emitted reflected and transmitted components as given by Equation 1.

$$S_{gray} = \varepsilon \int_{\lambda} R_{\det} \cdot L_{window} + \rho \int_{\lambda} R_{\det} \cdot L_{winrat} + \tau \int_{\lambda} R_{\det} \cdot \left(\varepsilon_{t\arg et} L_{t\arg et} + \left(1 - \varepsilon_{t\arg et}\right) \cdot L_{tgtrat} \right) \qquad \text{Eq. 1}$$

Spectral and temperature dependences are omitted here for the sake of simplicity. S_{gray} is the signal measured by the IR camera, L_{window} the window radiance, L_{winrat} the window reflected radiance, L_{target} the target radiance through the IR window, and L_{tgtrat} the radiance reflected off the target through the IR window. ε is the window emissivity, ρ the window reflectance, τ the window transmittance and ε_{target} the opaque target emissivity. The radiance impinging on the IR camera is modulated by the IR camera's optical system and detector response, R_{det}, which is spectral in nature. The integrals are technically from 0 to infinity, but they can be written as the limits of the IR camera response short and long wavelengths. (We use emissivity and emittance interchangeably as it has become an industry standard to do so. Technically, in this case, it's emittance.) Values of L are calculated using the Planck function for their appropriate temperatures. (Note for a blackbody in place of the IR window, the equation reduces to the first term with $\varepsilon = 1$. S equals the integral of the IR camera response times the blackbody radiance. The manufacturer calibrates the IR camera to account for this response.)

If the IR window is not gray, we must leave the emissivity, reflectance, and transmittance inside the integral as shown in Equation 2.

$$S_{real} = \int_{\lambda} \varepsilon \cdot R_{\det} \cdot L_{window} + \int_{\lambda} \rho \cdot R_{\det} \cdot L_{winrat} + \int_{\lambda} \tau \cdot R_{\det} \cdot \left(\varepsilon_{t\arg et} L_{t\arg et} + \left(1 - \varepsilon_{t\arg et}\right) \cdot L_{tgtrat} \right) \qquad \text{Eq. 2}$$

We want to find the window transmittance the IR camera would "see" using the measured spectral values of the IR window and IR camera response function. That is, we want the graybody approximation value of realbody IR transmittance. This means $S_{gray} = S_{real}$. Assuming the target is a graybody and that the window radiance is the same as the target reflected radiance, the solution is given in Equation 3. This latter assumption is probably reasonable, as the region where the window is mounted is most likely the source of reflected energy off the target. The spectral and temperature dependences have been inserted for completeness.

$$\tau = \frac{\int_{\lambda} \tau(\lambda) \cdot R_{\det}(\lambda) \cdot \left(L_{target}(\lambda, T_{target}) - L_{window}(\lambda, T_{window})\right) \cdot d\lambda}{\int_{\lambda} R_{\det}(\lambda) \cdot \left(L_{target}(\lambda, T_{target}) - L_{window}(\lambda, T_{window})\right) \cdot d\lambda} \qquad \text{Eq. 3}$$

A similar derivation can be made by taking the signal difference between two targets of different temperatures transmitting through the IR window that both have the same reflected apparent temperature (background radiance), a reasonable assumption for targets inside cabinets. Equation 4 gives the results. The only difference is that we are comparing two targets (target and target2) in Equation 4, whereas we are comparing the target to the window in Equation 3.

$$\tau = \frac{\int_{\lambda} \tau(\lambda) \cdot R_{\det}(\lambda) \cdot \left(L_{target}(\lambda, T_{target}) - L_{target2}(\lambda, T_{target2})\right) \cdot d\lambda}{\int_{\lambda} R_{\det}(\lambda) \cdot \left(L_{target}(\lambda, T_{target}) - L_{target2}(\lambda, T_{target2})\right) \cdot d\lambda} \qquad \text{Eq. 4}$$

Note that in Equations 3 and 4 the numerator and denominator differ only by the window spectral transmittance. If the window is gray, the transmittance can come out of the integral, and we get $\tau = \tau$. Spectral radiance L values in Watts/(μmcm^{2}sr) are given by the Planck function as shown in Equation 5.

$$L\ (T, \lambda) = \frac{c_1}{\lambda^5 \left[\exp\left(\frac{c_2}{\lambda \cdot T}\right) - 1\right]} \qquad \text{Eq. 5}$$

The wavelength, λ, is in micrometers; temperature, T, in Kelvins. C_1=1.19X10^4 Wμm^4/(cm^{2}sr) and C_2 = 1.44X10^4 μmK. The IR camera response is measured. A typical uncooled bolometer spectral response, R_{det}, is shown in Figure 8.

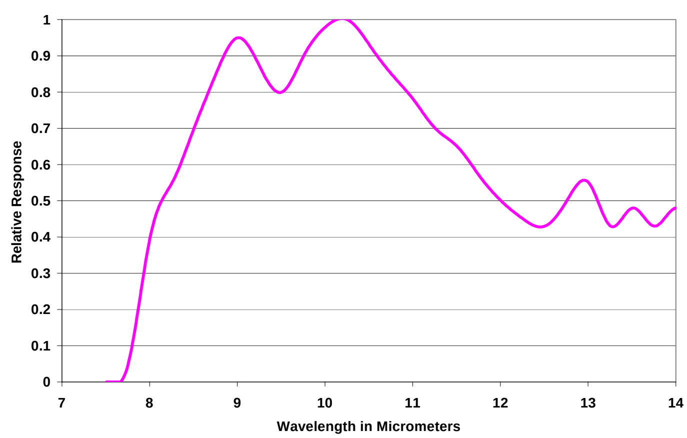

Figure 8. Typical uncooled microbolometer IR camera spectral response

Equations 3 and 4 show the IR window bandpass transmittance for a realbody depends on the window temperature and the target temperature. If the window temperature equals the target temperature, Equation 3 becomes zero divided by zero. This means you can put anything you want for transmittance and get the correct answer—the window is emitting at the same level it is transmitting. Since its reflectance is low, it will look like a blackbody! But target temperature equaling window temperature is not what interests us.

Also, we see from Equation 3 that we could interpret Figure 6 as being varying IR window temperature, with target temperature fixed at 20°C (68°F), instead of varying target temperature, with window temperature fixed at 20°C (68°F). But for most applications, the IR window will be close to ambient temperature and the target will be hot.

SUMMARY

Realbody IR windows will have a bandpass transmittance that varies with target temperature and window temperature. The magnitude of this variation depends on the IR window and the IR camera spectral responses. Spectral measurements of fluoride IR windows in the long waveband show a higher transmittance at shorter wavelength, with spectral transmittance falling significantly through the long waveband. Their spectral reflectance in this region was quite low. Published data for an IR plastic shown for comparison has increasing spectral transmittance through the long waveband. Its spectral reflectance was not found for this work.

The barium fluoride window had the highest bandpass transmittance, over 80%, and varied by about 3% over a "condition-monitoring temperature range" of -10°C (14°F) to 150°C (302°F). Calcium fluoride varied from about 48% to 53%. This represents a 10% overall change in value. The IR plastic dropped from about 55% to 54%, a 2% overall change. These transmittance values are for a given window thickness. You cannot assume these values in general, as transmittance depends strongly on window thickness. Assuming an IR window transmittance of 50% instead of 55% causes an error in a 74°F (41°C) ΔT of about 4°F, a 5% change. In most condition-monitoring cases for high emissivity targets, this shouldn't be a problem. For lower emissivity targets caution is advised, as the low emissivity could leverage the error. We will continue to investigate these possibilities. For now, we recommend the product of target emissivity times window transmittance be about 50% or greater.

The bandpass transmittance of a realbody IR window depends on your IR camera spectral response, target temperature, window temperature, window material, and window thickness. Your best bet for good measurements is to measure the transmittance of your IR window type with your camera and use those values. For careful measurements, do this measurement for several target temperatures. If you purchase a significant quantity of IR windows, get the supplier to ensure they are all of the same material and thickness. Then you need only measure one window.

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