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Transmission Stability and Infrared Windows: "The Effects of Transmissivity on Data Accuracy"

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Abstract

As the saying goes, "garbage in, garbage out." This truism is every bit as applicable in thermography as it is in computer data-mining. The difference is that the inaccurate data which leads a thermographer to a false-negative conclusion could result in a multi-million dollar catastrophic failure of a company's electrical distribution system. In fact, the implications to personnel safety, plant assets and production downtime make the results of transmissivity errors more like toxic waste than mere "garbage."

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When using infrared (IR) windows or sight glasses, it is imperative to understand the accurate transmission rate of the optic used in the infrared window. As this paper will explore, failure to accurately compensate for actual transmission attenuation can lead to significant errors in data. The magnitude of the error is based on the exponential effect that target surface temperature has on radiated infrared energy. In short, temperature differences (**Δ**T) will appear to be minimized if the effects of transmission attenuation are not considered, or if not accurately compensated for. Such errors in **Δ**T may thereby lead thermographers to underestimate the magnitude of many serious electrical faults.

Background

As an instructor, I have noticed that many Calcium Fluoride windows, even in controlled environments, have lost significant transmission rate within just a two to three year timeframe. In 2003 I came across a Calcium Fluoride infrared sight glass (shown in Figure 1) which had lost all transmissivity in the infrared and visual spectrums. It was being used in a motor termination box in an electrical generation plant in Tennessee. This is an extreme case to be sure, but it is not without precedence.

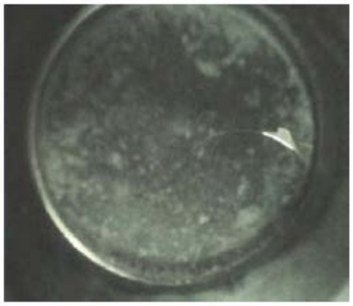


Figure 1 – Calcium Fluoride Sightglass

Recently, upon reflecting on Dr. Robert Madding's original research on infrared window transmissivity (*IR Window Transmittance Temperature Dependence* 1), I became very interested in the practical implications of transmissivity errors (short of complete transmission loss) on real-world inspections. Specifically, what degree of error could one expect to see if the transmission rate of an infrared window optic were to change and if the thermographer failed to accurately compensate for that change?

For the purposes of this paper we will use the following definitions:

Emissivity: Symbol "ε" defined as the efficiency of an object's surface to radiate infrared energy.

Transmissivity: Symbol "τ" defined as the ability of radiation to pass through an object. Although target transmissivity is important and relevant in many thermography applications where radiated energy from sources behind the target might pass through the target and thereby influence temperature calculations, this is generally not a factor in industrial electrical thermography applications where the predomination of targets are opaque (or non-transmissive in the long wave infrared spectrum). Instead, this paper will focus on the use of infrared windows and the implications of IR window transmissivity. We will use the term transmissivity interchangeably with "transmittance," "transmission," and "transmission rate" whereas the rate is discussed as a fraction of being 100% transmissive.

Transmission Degradation: The continued loss in transmission rate across the infrared spectrum resulting from the nature of certain optic materials to lose transmission rate due to inherent properties of that material. (The focus of this paper is on Calcium Fluoride crystal windows, symbolized as "CaF2," which is known to degrade due to its hydroscopic nature, and due to refraction caused by mechanical stresses of vibration and high frequency noise.)

Physics of Thermography & Temperature Calculation

Nothing actually "measures" temperature per se. A thermometer, for example, measures the expansion of mercury against a static background. The amount that the level of the mercury "rises" is then correlated to a temperature. If the amount of mercury in the vial was less than what the lines were calibrated for, then the apparent temperature reading will be lower than the actual temperature. In this case, a mother might send her child to school with a 103° temperature thinking the child was a healthy 98.6°. Similarly, a thermocouple does not measure temperature. The difference in Voltage output from two (2) dissimilar metals due to the thermoelectric effect can be calculated and correlated to known temperatures. If the amount of differential voltage was somehow filtered over a longer cable run, and that attenuating affect was not compensated for, then the resulting temperature calculation will be lower than the actual temperature of the bearing it was measuring. In this case, the PLC (Programmable Logic Controller) might fail to trigger an over temperature alarm until the process seized up.

Non-contact infrared thermography measures the radiated infrared energy from a target. The amount of radiated energy is then calculated and correlated to specific temperatures. To ensure accurate temperatures and accurate temperature comparisons (or differences in temperature, referred to as∆ Delta T and symbolized as “ T”) the thermographer must have detailed knowledge of the science of infrared radiation and must properly control the variables which affect how the imager (camera) interprets and calculates the radiated infrared energy it receives. These variables include (among others) the emissivity of the target, reflection of radiated energy from other sources, and transmissivity of the atmosphere and/or infrared “window” being used.

To properly control for emissivity variations on electrical components, thermographers should standardize the emissivity by amending target surfaces with some type of highly emissive, permanent treatment. Common practices include grill paint, electrical tape or high-emissivity stickers, any of which can give thermographers emissivity values of 95%.

With consistent and high target emissivity, reflection issues are minimized and a trained infrared thermographer will be able to properly calibrate the imager for a target’s emissivity value in most cases. This leaves the IR window’s transmissivity as the key variable to control.

IR window transmission rates can be derived from the manufacturer’s literature; however, this poses several potential problems:

1. Transmission rates are typically variable across the infrared spectrum (as shown in Madding, 20041). Yet the manufacturer’s specified transmission rate is generally relevant for a specific wavelength and is therefore not necessarily accurate for thermography performed using standard infrared thermography cameras which sense a wide band of infrared (for example: 7.5 to 13 µm), rather than a single wavelength. Furthermore, the sensing arrays of different cameras have variable sensitivities along the infrared spectrum. Your camera might be more or less sensitive at the wavelength where a window manufacturer specified transmissivity.
2. If transmission values change over time, then the manufacturer’s specified transmission rate for a new window is irrelevant as it ages.
3. Some optic materials such as CaF_2 have been shown to vary from one window to the next, (as shown in Daugherty, Newberry & Schewe, 20072).

A preferred method of establishing the baseline for transmittance adjustment is to calibrate the imager using an infrared window and a target which has achieved a stable temperature in the range you anticipate your actual target to be operating in (as detailed in Madding, 20041). Doing so will give a thermographer the most accurate baseline transmissivity value. But what if that transmissivity value were to change? What effects will that change have on data accuracy?

Magnitude of Error

One of the most misunderstood concepts in thermography is the degree to which errors in emissivity and window transmissivity calibration will affect temperature and ΔT accuracy. As demonstrated in the Stefan-Boltzmann Law, the radiated infrared energy emitted by a target surface is exponentially related to the absolute temperature of that surface:

> Stefan-Boltzmann Law: **W = εσT4**
> Whereas: W = total radiant Power in Watts/m2
> ε= emissivity (unit less)
> σ= Stefan-Boltzmann constant
> 1.56X10-8W/m2K4
> T4 = temperature (absolute) in Kelvin

Therefore, as the temperature increases, radiant energy increases proportional to the absolute temperature to the 4th power! An infrared camera's built-in calibration helps correlate this fact of nature into accurate temperatures and temperature comparisons. However, incorrect camera settings such as emissivity and infrared window transmission rates will result in errant temperature values.

Furthermore, because the relationship is exponential, this error will worsen as the target gets hotter if transmission rates or emissivity settings are not correct. Consider the effect on ΔT comparisons (whether between historical and current temperatures or real-time comparisons between two or more similar parts) which are by their nature a comparison between different temperatures. The resulting calculations are apt to be radically understated, which could easily lead thermographers to misdiagnose the severity of a fault.

If transmission rates are changing over time, and the thermographer is trending values to determine the health of an application, a steadily decreasing transmission rate could cause temperature values to appear to be stable or decreasing over time while temperatures were actually increasing significantly over the same period. The implications of flawed data to a reliability or predictive maintenance program are obvious.

Test Specifications

For the Test Window, I used a Calcium Fluoride (CaF2) window typical of those offered from various manufacturers. It is a window that I have had in my possession for roughly two years. I use it for training purposes when discussing infrared windows in my training classes. It has mostly been exposed to office and living environments with modest levels of humidity, temperature, vibration and high frequency noise. I utilized a Control Window to provide a basis of comparison. The optic of the Control Window is made of polymer with reinforcing grills on either side of the optic. As with the Test Window, the Control Window is a commonly used infrared window which I have been using for training purposes. As such, it has been kept in the same environmental conditions as the Test Window. One notable difference is that I have demonstrated the impact resistance characteristics of the Control Window many times by hitting the optic with various instruments. Those demonstrations have resulted in several superficial scratches and surface blemishes on the optic and grills.

This window makes a good control sample because the polymer optic has been proven to be stable over time, even when exposed to a variety of environmental conditions. Furthermore, the Polymer Control

Window and the CaF2 Test Window were shown to have nearly identical transmission characteristics when they were new.

For purposes of these tests, I used a FLIR P65 infrared camera, with a standard 24° lens. When taking images through the infrared windows, the camera lens was pressed up to the window optic as is standard practice.

The window temperature and reflected apparent temperature were the same as ambient "room" temperature. The targets were placed approximately 18 inches (46cm) from the window. Care was taken to ensure that targets were properly in focus. The low-temperature target was a standard overhead line clamp. Electrical tape was affixed to the bolt head to serve as the target, and ε was adjusted to 0.95. The target was placed on a hot plate and its temperature was allowed to stabilize at 115.8°F (45.6°C).

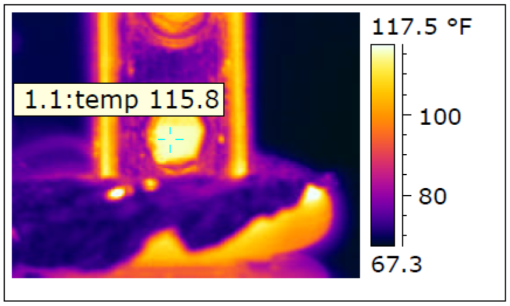
The high-temperature target was a soldering iron tip. Emissivity of the iron's tip was known to be 0.95 from an earlier test. The imager was adjusted to compensate for emissivity, and the soldering iron was left running until its temperatures stabilized at 661.3°F (349.6°C).

Test: Effects of Transmission Degradation

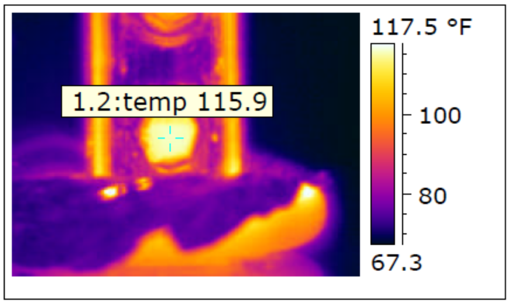
When the Control Window and Test Window were new, they were both shown to have a transmission rate of 49%. Therefore, a thermographer using either window would expect to receive accurate data if they were to adjust their imager to compensate for the attenuating effect of the secondary optic. However, this was not the case for the CaF2 Test Window. (For details on how to test for and adjust for transmission attenuation, please refer to Madding, 2004[1].)

Test 1 – Low Temperature:

Thermogram 1.1 shows the thermal image of the overhead line clamp with no infrared window. The target temperature is shown to be 115.8°F (45.6°C). We will call this the true temperature.



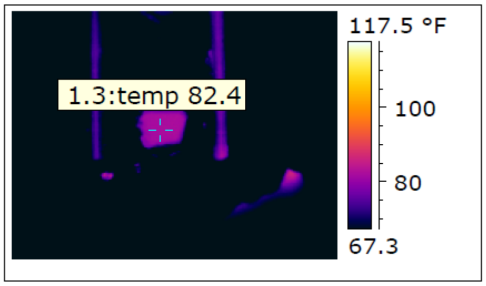
Thermogram 1.1



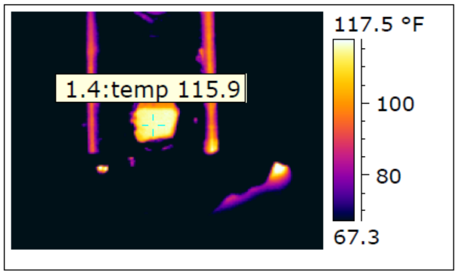
Thermogram 1.2

Thermogram 1.2 shows the same target through the Polymer Control Window, with the τ set to 0.49 per the baseline established when it was new. The target temperature is shown to be 115.9°F (45.6°C): a statistically insignificant 0.09% error between apparent and true temperatures, which is well within the +/-2% accuracy ratings for the camera used in the tests.

Thermogram 1.3 shows the same target through the CaF2 Test Window, with the τ set to 0.49 per the baseline established when it was new. However, in this case the apparent temperature registers as 82.4°F (28°C), resulting in a 33.5°F (17.6°C) or 28.84% error between apparent and true temperatures.



Thermogram 1.3

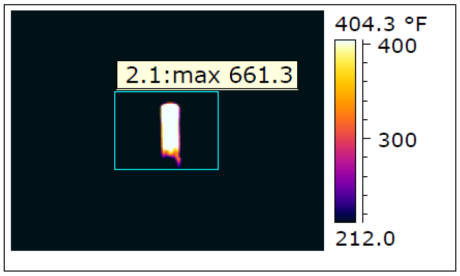


Thermogram 1.4

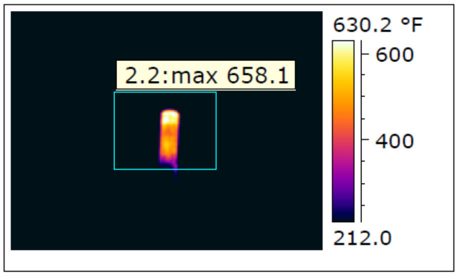
Thermogram 1.4 shows the target after recalibration of the imager to the degraded τ value of the CaF2 Test Window. Transmittance was adjusted to 15% to bring the apparent temperature in line with the true temperature. This represents a 69.4% degradation in transmission of the CaF2 Test Window over a two (2) year period.

Test 2 – High Temperature:

Thermogram 2.1 shows the thermal image of the soldering iron tip with no infrared window. The target temperature is shown to be 661.3°F (349.6°C). We will define this as the true temperature of the target.



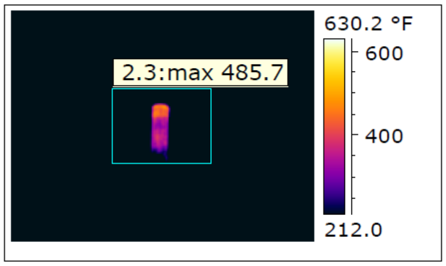
Thermogram 2.1



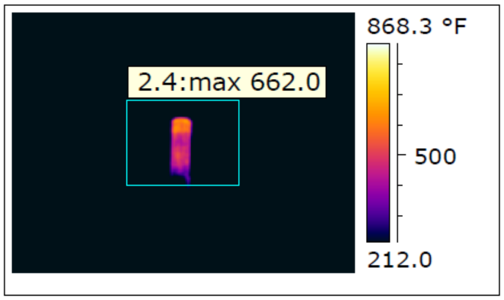
Thermogram 2.2

Thermogram 2.2 shows the same target through the Polymer Control Window, with the τ set to 0.49 per the baseline established when it was new. The target temperature is shown to be 658.1°F (347.8°C): a 0.49% error between apparent and true temperatures. Again this margin of error is not significant since it is well within the cameras +/- 2% accuracy specifications.

Thermogram 2.3 shows the same target through the CaF2 Test Window, with the τ set to 0.49 per the baseline established when it was new. However, in this case the apparent temperature registers as 485.7°F (252.1°C), resulting in a 175.6°F (97.5°C) or 26.55% error between apparent and true temperatures.



Thermogram 2.3



Thermogram 2.4

Thermogram 2.4 shows the target after recalibration of the imager to the degraded τ value of the CaF2 Test Window. Transmittance was adjusted to 30% to bring the apparent temperature in line with the known true temperature. Notice that this differs from the 15% transmittance at the lower temperature, confirming Dr. Madding's findings with regard to the variability of Calcium Fluoride's transmittance across the long wave infrared spectrum.

Conclusion:

It is of critical importance to choose an infrared window made with materials that are designed for the environment in which you will be using them. As stated in 1.3 of the UL 50V standard for Infrared Viewports, "The acceptability of an Infrared Viewport in any particular application depends upon its suitability for continued use under the conditions that prevail in actual service." In other words, it is incumbent on the purchaser of the window to understand whether or not a window will suffer effects of degradation due to exposure to the environment in which it will be used.

When IR windows were properly compensated for as in the Polymer Control Window used in these tests, it was easy to obtain accurate data which could be trusted.

The Control Window used in this paper is made of a polymer which has been proven to maintain a stable transmission rate in a variety of conditions. In this test it proved to maintain a stable transmission rate over a two (2) year period even when subjected to abusive impact resistance demonstrations. I am confident that the data taken through this type of window will be accurate when a qualified thermographer controls for relevant variables.

Conversely, after just two (2) years in relatively controlled environments, my CaF2 window has shown considerable transmission degradation and is not yielding accurate results. In both tests the temperature error using the CaF2 Test Window was in excess of 25%. To make matters worse, the error resulted in apparent temperatures which were lower than the true temperature, which means that the error is likely to produce a false negative result for the thermographer. Furthermore, there was no visible evidence of the change in transmission rate, so the thermographer would likely have no obvious cues to check for transmissivity changes.

In the event that a thermographer is using an IR window material which is known or suspected to degrade over time, accuracy dictates periodic recalibration of the camera to the changing transmission rate of the window optic so that the new transmission rate can be known and compensated for. The recalibration requires the thermographer to test each window with a target of a known temperature. Therefore, the panel cover holding each window must either be removed or opened for window calibration. In industrial applications this is best done during a shutdown for time and safety reasons. It may not seem practical, but it is absolutely necessary if data from a degrading optic is to be accurate and trusted.

Just as an infrared imager will periodically calibrate itself to compensate for drift caused by the effects of temperature on the camera's Germanium lens and internal components, a thermographer must calibrate his imager to account for attenuation through an infrared window. If the thermographer chooses a window with an optic that remains stable over time in their environment, this calibration can be based on a one-time transmission test when the window is new. Otherwise, periodic recalibration will be required to ensure accuracy.

Resources:

1. Madding, Dr. Robert. "IR Window Transmittance Temperature Dependence." Infrared Training Center, FLIR Systems, Inc. 2004
2. Daugherty, Newberry & Schewe, "Opening the Windows." UpTime Magazine. Nov 2007: p. 22.

"10 Things You Need to Know About Infrared Windows" contains more information on the benefits of IR windows. To get your free digital copy, Click Here.

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