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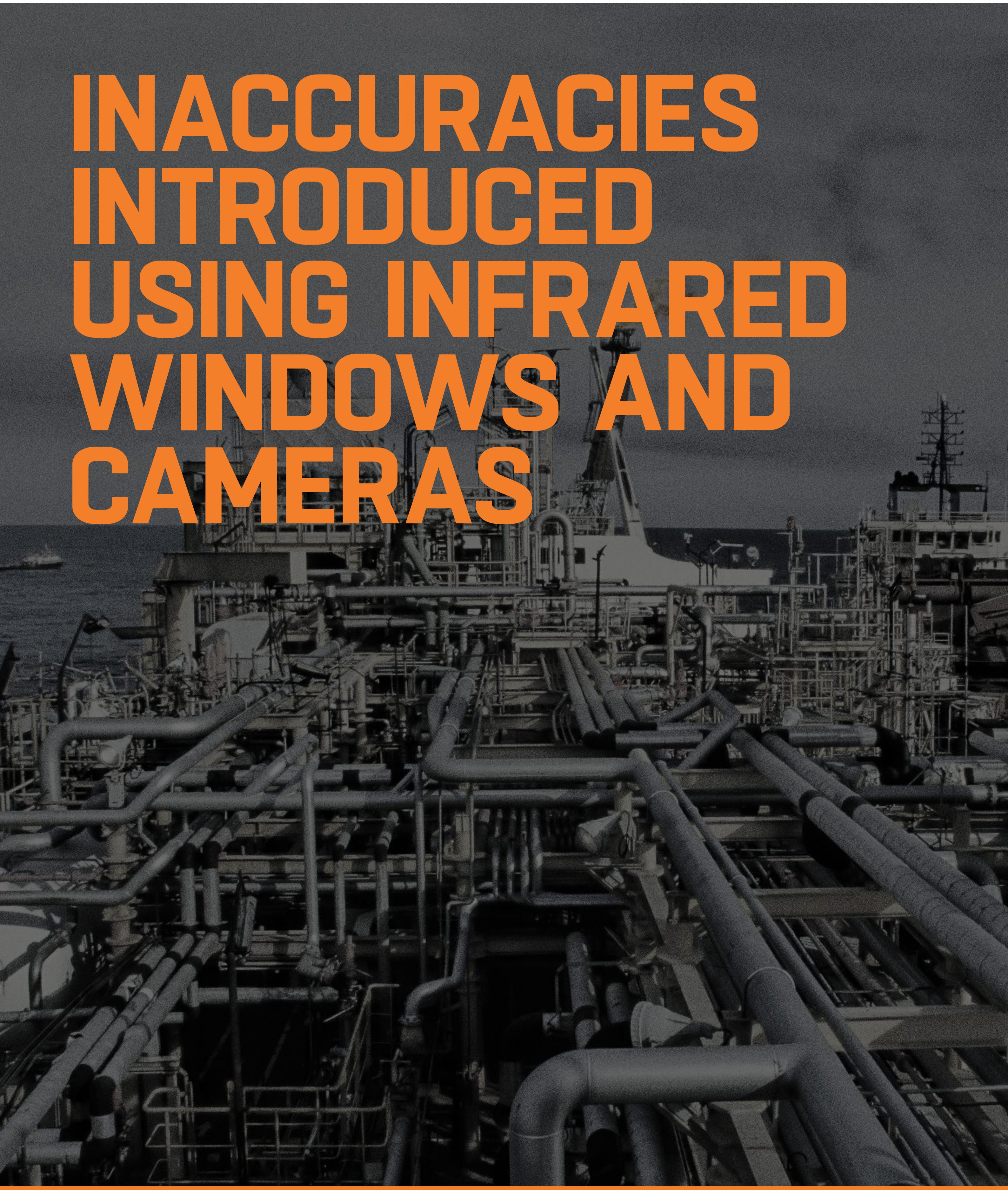
INACCURACIES INTRODUCED USING INFRARED WINDOWS AND CAMERAS



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ABSTRACT

The use of infrared windows in electrical control and distribution equipment has become increasingly more prevalent over recent years.

With increased focus on electrical safety and the widespread adoption by industry of NFPA-70E, infrared systems are increasingly becoming more popular. However, using infrared windows with thermal imaging cameras introduces a serious measurement accuracy problem when it comes to predictive maintenance.

Current thermal imager technologies today can measure, with extreme degrees of accuracy, in the range of ± 5°C or better. However introducing any type of infrared window into a temperature measurement interjects measurement inaccuracies. This paper discusses the effects of various infrared window types on non-contact temperature measurement including the levels of inaccuracies created by alternative infrared window types, how to correct for these inaccuracies with various thermal imagers along with typical before and after accuracy results.

The conclusions will provide methods for successfully using various thermal imagers along with various types of infrared window when combined within a preventive and predictive maintenance program.

“With increased focus on electrical safety and the widespread adoption by industry of NFPA-70E, infrared systems are increasingly becoming more popular. ”

Index Terms — Infrared Windows, IR, Thermal Imagers, Infrared Cameras, NFPA70E, CSA Z462, Arc Flash, Preventive Maintenance, PdM, Predictive Maintenance

INTRODUCTION

A thermal imaging camera, also referred to as an infrared camera or thermal imager, at their most basic level, converts infrared energy into electrical signals that are displayed on a screen for trained human operators to interpret.

A thermal imager is a powerful tool, allowing well trained thermographers to measure temperatures without coming into physical contact with the target. However, the thermographer still must interpret the data being measured.

More advanced thermal imagers, those that measure temperature, are referred to as being “radiometric”. Unlike contact temperature measurement techniques, such as thermocouples or resistance temperature devices (RTD), using a thermal imaging camera to measure temperature, as opposed to simply displaying a thermal image, requires a complex set of algorithms and supplemental sensor inputs to achieve repeatable, accurate readings.

It would be simple to assume that a thermal imager operates in the same way as a digital camera and therefore the “rules” which apply to digital imaging are translatable to infrared imaging. Whilst in some instances this is correct, there are key situations where a thermal imager operates distinctly differently from a digital camera.

The most important difference between the two camera types, in the context of this paper, is what is placed between the camera and the object or heat source being observed, and how the camera responds to the interposing body. A digital camera operates in much the same wavelength as the human eye; what a human sees the digital camera sees. A thermal imaging camera, on the other hand, operates in an infrared “band”. Typically, for today’s thermal imagers, this band is 8-14µm, also known as the longwave part of the infrared spectrum. This means that the thermal imaging camera is looking at a different section of the electromagnetic spectrum than human eyes and therefore the thermal camera distinguishes things the humane eye cannot. Heat is a good example of this. But the thermal imaging camera is also restricted by obstacles our eyes are not, glass or clear plastics for example. A thermal imager cannot “see” through glass, most plastics and many other materials, even though they may be visually transparent.

Unlike a thermal imager, an infrared window is, for the most part, an inert device with an “optic” manufactured from a material transparent in the infrared spectrum (or part of it at least). Infrared windows are permanently installed into electrical equipment cabinets allowing a thermographer to inspect the equipment’s interior without defeating safety interlocks, opening equipment doors and exposing themselves to energized points inside the equipment.

Unfortunately, all infrared window types are also not 100% transparent and therefore they act as a filter with respect to data observed by the thermal imager.

Although the camera image displayed by a thermal imager may be clear, the measurement temperature values displayed will be incorrect.

It is the quantification of this error, along with its causes and potential remedies that this paper intends to explore. The ultimate goal for any equipment user and thermographer is detecting the most accurate temperature measurement, in a cost effective manner.

I. UNDERSTANDING INFRARED WINDOWS

A. Infrared Transmission and Infrared Windows

The term transmission refers to the amount of energy filtered by the infrared window and correspondingly allowed to pass through. No material is 100% transmissive; there will always be an amount of infrared energy that does not pass through the optic from the target and reach the thermal imager. However, this is not the only factor which must be taken into account when explaining infrared window transmission.

High quality infrared windows are typically manufactured from a crystal type of material. This material could be calcium fluoride, sapphire or even germanium. Although more exotic materials, such as barium fluoride may sometimes be suggested, care must be taken as to the potential toxicity levels. These materials are selected primarily due to the clarity of the image they allow. Traditionally, crystal infrared windows were generally expensive to manufacture. These high costs led to the introduction of lower cost opaque plastic/polymer optics infrared windows.

Unfortunately, plastic/polymer optics that are infrared transmissive are extremely thin and delicate. As such, the use of plastic/polymer optics often requires a metal or thick plastic mesh reinforcement grid on the front and/or back of the optics to prevent the optic from easily being pushed out of the window's frame. Fig. 1 illustrates a typical plastic/polymer optic with a protective mesh. When exposed to high or low ambient temperatures certain plastic/polymer can also warp or become very brittle.

Crystal type infrared windows are not affected by either of these problems. Early generation crystal infrared optics were not well sealed and became disabled due to moisture degradation. The current generations of crystal infrared optics now include optic coatings making them totally impervious to moisture.

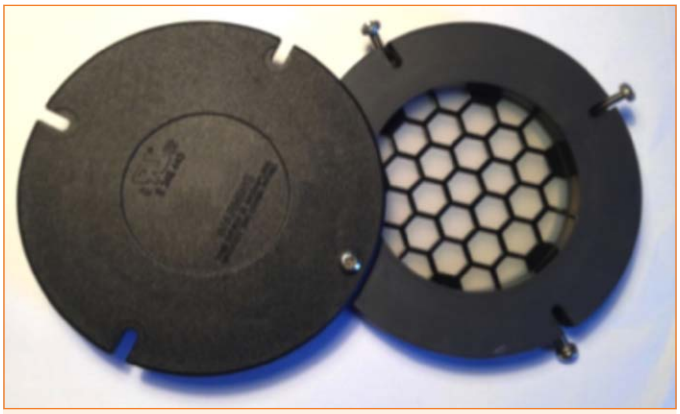

Fig. 1 Plastic/Polymer Type Infrared Window with Reinforcement Mesh/Grid

The inclusion of an opaque metal or thick plastic grid, on one or both sides of the plastic/polymer optic, introduces significant measurement degradation which prevents accurate correction for transmission loss. Recent developments in crystal infrared window manufacturing technologies have dramatically reduced the cost of crystal optics to the extent that this high quality, high accuracy construction is now available at costs generally lower than that of even the polymer/plastic solution.

A. Clarifying the Issue

When initially considering infrared transmission, it would seem logical to simply divide the reading noted by the infrared camera when taking a measurement through the infrared window, by the reading noted by the infrared camera without the infrared window in place. This should provide the "transmission" of the infrared window as a percentage. But this is not the case.

Example:

A thermal camera is aimed directly at a cup of coffee, with no infrared window between the camera and the target and the camera reads 50°C. A crystal infrared window is then placed between the camera and the coffee target and the reading drops to 35°C. By dividing the new reading by the initial reading, the apparent "transmission" of the infrared window will be obtained.

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$$\text{Transmission} = 35°\text{C}/50°\text{C} = 0.7 \qquad (1)$$

So the apparent "transmission" of this infrared window is 70%. Unfortunately, this is not correct.

When considering a quantitative approach to non-contact temperature measurement, an infrared camera has three "signal" inputs which must be resolved in order to obtain an accurate reading. The total infrared energy an imager "sees" is made up of three components: reflected, absorbed and transmitted energy.

The summation of these three signals equates to the total incident energy on the infrared camera detector array, and in turn, an actual temperature reading can be calculated. For a basic understanding, these three signals can be combined into this formula.

$$R + A + T = 1 \qquad (2)$$

R= Reflected energy
A= Absorbed energy
T= Transmitted energy

When attempting to correct the transmission loss caused by an infrared window, the effects of not only the transmitted energy through the window must be considered, but also the effect of the reflected energy from the surface of the infrared window and the absorbed energy of the infrared window's own "optic" temperature.

One final addition to the reflected, absorbed and transmitted energy signals is the addition of the reflected quotient from the target itself.

This seemingly complex relationship can be simplified diagrammatically as shown in Fig. 2. The total sum of the signals associated with the energy incident on the infrared camera, with respect to an infrared window, is called the total radiance.

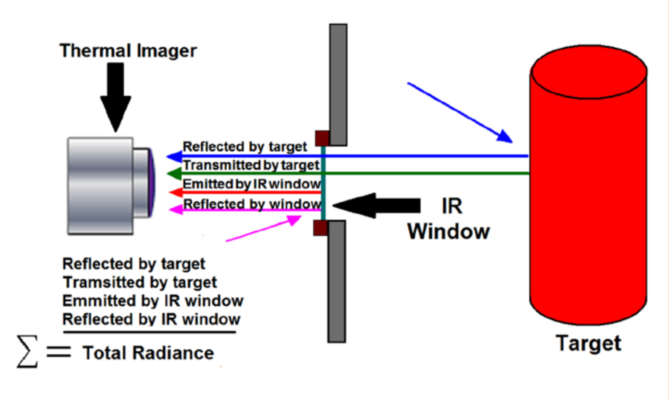

Fig. 2 Simplified crystal IR Window signal diagram

It can be seen from Fig. 2 that two of the signals are modulated (multiplied) by the infrared window as they are transmitted through the optic. The "intensity" of these signals are bound by the same R+A+T = 1 relationship, but since general electrical targets have zero transmission, this equation can be reduced to R+A = 1. If we accept for the moment that the combination of reflected and absorbed energy from the target is modulated by the infrared window optic and the subsequent modulated energy must be accounted for to correct for loss, then we can take the next step.

Which energy signal should actually be resolved to get the most accurate reading and how can it be accomplished?

Examining Fig. 2, it can be seen that the thermal imager will detect various pieces of thermal information, only one signal denoting the actual temperature emitted by the target. It is this signal which must be isolated and resolved in order to obtain an accurate temperature reading of a target behind any infrared window.

As with most infrared techniques, this is not straight forward. As outlined earlier, infrared cameras operate within a spectral band, usually 8-14μm and it is the total energy across this band that is quantified by the camera as total radiance. Most infrared windows modulate the target signal as a function of wavelength, which means a simple multiplication correction will not be sufficient. This phenomenon is known as spectral transmission.

B. Spectral Transmission and How it Affects Accuracy of the Readings

Most, if not all, infrared windows used in electrical inspection are referred to as Spectral Transmitters. To understand the effect of spectral transmission and how it affects infrared window readings, one must first appreciate how a target-body emits its infrared radiation across the infrared spectrum.

Planck's Law describes the electromagnetic radiation emitted by a black body, in thermal equilibrium, at a definite temperature [1]. Fig. 3 illustrates this effect as explained by Planck's Law. As can be seen, the energy emitted from an object, which is representative of its surface temperature, changes both with wavelength and with target temperature itself. In effect, it can be said that the curve "moves" along the wavelength depending upon the target temperature.

The area under this curve, between 8-14μm is the data used by infrared cameras. The area under this curve, is the amount of energy an infrared camera would record assuming that the target was a perfect radiator, also referred to as a Blackbody.

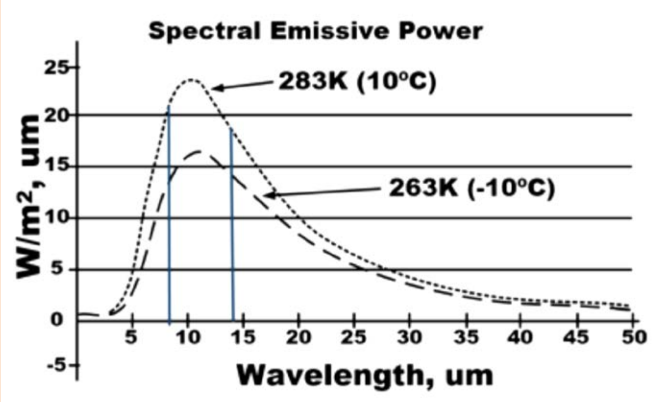

Fig. 3 Spectral Emissive Power versus Wavelength for a Black Body at Different Temperatures (Plank's Curve)

Planck's curve shows that the higher the target temperature, the more energy is emitted and that the peak of the curve tends to be towards the shorter wavelength as the target temperature increases. At 10°C, Fig. 3 shows a much higher peak than at -10°C and this peak is further to the left of the X-axis which represents the shorter infrared wavelengths.

In practical terms, this explains why humans can see something becoming hot. As an item begins to glow red the energy moves into the extreme shortwave and into the visible spectrum.

So, the energy emitted by a target changes not only in overall intensity as the temperature rises, but the peak of this energy also changes in conjunction with temperature. For an infrared camera operating within the 8-14μm band it is immaterial where within that band the radiation comes from; just the total radiance incident upon its detector array. This total radiance forms part of the infrared camera's calibration routine where the camera is taught to recognize that a specific total radiance equates to a known target temperature.

Fig. 4 shows a typical infrared window transmission curve. The X-axis shows wavelength while the Y-axis shows transmittance.

Also, illustrated by Fig. 4 is the fact that the transmission percentage of this infrared window material is in excess of 90% until approximately 8µm. At that point, the transmission percentage rapidly falls off to 0 at between 10.5 and 11µm. This change in transmission, as a function of wavelength, is referred to as spectral and this is the ultimate cause of the target signal modulation and corresponding error when using an infrared window.

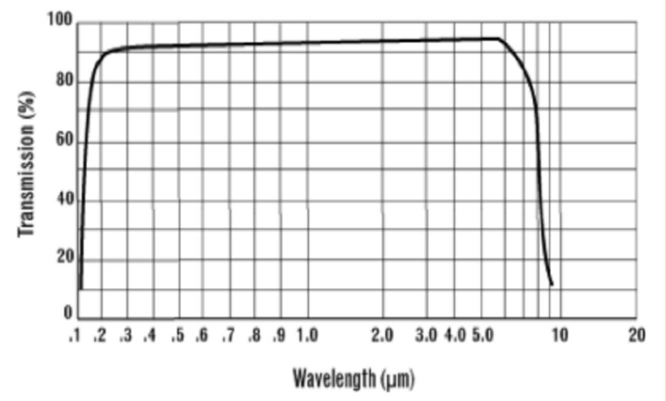

Fig. 4 Typical Infrared Window Transmission Curve

The Planck's curve, shown in Fig. 3 shows a changing emitted energy profile as a function of wavelength. In order to correct for the infrared window signal modulation, you must overlay Planck's curve with the corresponding infrared window transmission curve and determine the apparent transmission at differing target temperatures in order to take into account the movement of infrared energy.

To summarize this section, the following key points have been determined:

1. The signal required to obtain accurate target temperature is the emitted signal from the target
2. Infrared windows are spectral transmitters by nature; therefore they modulate the emitted target signal differently depending upon wavelength and corresponding target temperature
3. The infrared radiation emitted from a target changes intensity and wavelength as a function of the target temperature

II. OBTAINING ACCURATE READINGS WITH INFRARED CAMERAS

A. Basic Temperature Measurement Requirements

In order for an infrared camera to obtain accurate readings, human intervention is required to provide the camera the following parameters: target emissivity, reflected target temperature and, if applicable, infrared window transmission. If the latter is indeed applicable, then the infrared window optic temperature is also required as it has an effect on the total radiance upon the detector array, refer to Fig. 2.

If the target has high absorption/emissivity, then by using the R+A+T=1 equation, the reflected component will be low. The higher the emissivity, the more accurate the reading will be. Generally accepted industry principles agree that for an emissivity of 0.5 or less, it is not possible to obtain an accurate ±2° temperature reading using an infrared camera. The effect on total radiance by the reflected component is too great and too changeable to be reliably compensated for by the camera.

There are additional inputs a thermographer can manipulate to further increase measurement accuracy such as relative humidity and distance to target. But, in general practice, the effect of these parameters is minimum compared to target emissivity and reflected temperatures.

B. Infrared Camera Detector Arrays

The current generation of infrared camera technology is much more advanced than that of even a decade ago. Most of this paper so far has focused on the 8-14µm band, also referred to as the longwave band or spectrum. However, there are infrared cameras that operate in both the shortwave (0.5 -3µm) and the midwave (3 - 5.5µm) bands. These short and midwave cameras often required the use of special coolers which reduced the detector operating temperature to such an extent so that the detector was not affected by changes in its own temperature. Mechanical coolers themselves have had a negative effect on the camera's overall operating performance, when compared to uncooled systems by virtue of the increased power requirements associated with the coolers themselves. This has resulted in lower camera runtimes and relatively high battery drain compared to uncooled systems. On the positive side, these cameras were generally extremely sensitive and capable of specific tasks such as viewing through flames to view boiler tube integrity. This type of infrared measurement is particularly suited to midwave cameras, since the boiler flames are transparent within the camera's operating band. So by using a filter, it is possible to make the flames transparent to the camera.

Longwave cameras do not require coolers and are referred to as Uncooled Thermal Imaging Cameras, (UTIC). As outlined earlier, these cameras operate within the 8-14µm longwave band and are available with differing array densities from low resolution 100x100 arrays to higher resolution 640 x 480 array options. The greater the resolution, the better the image quality obtained by the camera.

The use of the term "8-14µm" is actually used rather loosely and refers more to the industry accepted definition of the longwave rather than the detector response. If all infrared cameras quoting an 8-14µm response band actually operated within that band, then the act of correcting for infrared window transmission would be relatively straightforward. In this case, the correlation between target temperatures and apparent transmission would simply be a curve which is applied to any 8-14µm camera.

In reality, each detector array operates slightly differently from the next. Specifically, the spectral responses of the detectors vary, as does their output at specified target temperatures. This means that even though manufacturers may quote a nominal 8-14µm longwave infrared camera, in actual fact, the detector array incorporated into the camera, may actually respond at 7.9-14.1µm, the next array at 8.2-13.8µm and so on. Thus, every imaging camera will have an array with a different response scale within the range of the 8-14µm longwave band.

In normal everyday use this is not an issue as the camera is calibrated to understand that the total radiance it sees, at a particular time, equates to a specific temperature. However, when looking at transmission loss associated with an infrared window, the spectral transmission of the window "chops" the signal in an irregular manner which is target temperature dependent. When coupled with infrared detector arrays that have different spectral responses, one must take into account that the effect of an infrared window on one specific infrared camera is different to that of another, even though they may both operate in the same 8-14µm nominal longwave band.

Table I illustrates the difference in apparent readings between two well-known infrared camera manufacturers' models, with and without viewing the target through a crystal infrared window.

Target Temperature Without Infrared Window (C°)	Measured Target Temperature Through Crystal Infrared Window			
	Camera "A" (C°)	Error	Camera "B" (C°)	Error
30	26	13%	25	17%
45	32	29%	32	29%
60	40	33%	40	33%
75	44	41%	48	36%
90	59	34%	56	38%
105	63	40%	64	39%
120	72	40%	72	40%
135	86	36%	81	40%
150	92	39%	90	40%

TABLE I - COMPARISON OF TWO DIFFERENT INFRARED CAMERA READINGS AFFECTED BY INFRARED WINDOW

The "Target Temperature Without infrared Window" reading, in Table I, is from a calibrated blackbody with which both cameras agreed. Take note of the increasing error as the target temperature itself increases. Were you to simply look at a straight percentage calculation as postulated at the beginning of this paper, it is clear that this method would not work across a range with the error being a massive 40% at the high end compared to 13% at the low end of the scale.

These differences are caused by the difference in detector spectral response when combined with the infrared window at different target temperatures. The detector spectral response is not something that is generally recorded by the infrared camera manufacturer and therefore not a parameter which can be retroactively applied to the infrared window correction. For truly accurate infrared window correction, each individual infrared camera's spectral response should be mapped against the infrared window optic transmission curve across a typical predictive maintenance (PdM) range of 30-150C as shown in Table I.

The upper level limit of 150C is a practical limitation. Attempting to increase the range of calibration can induce further errors and in reality, any part of an electrical enclosure exceeding 150C is already at a critical level

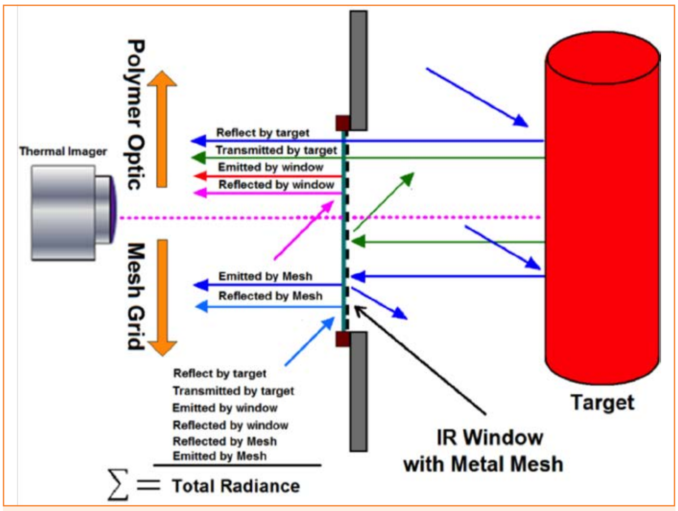

Fig. 5 Polymer/Mesh Infrared Window Signal Schematic

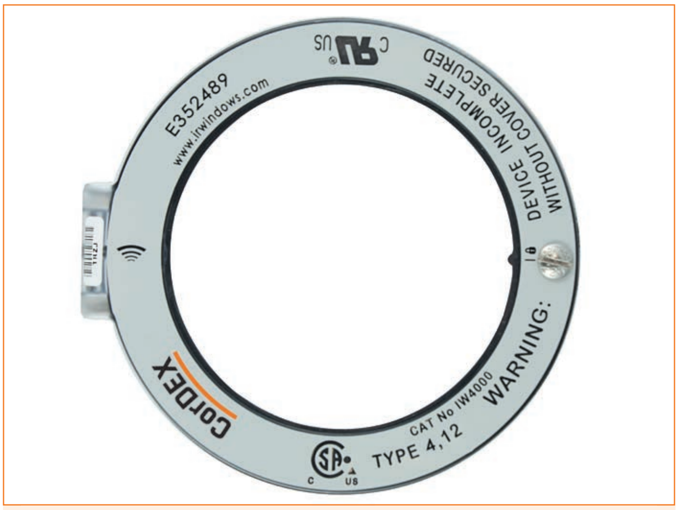

Fig. 6 Crystal Type Infrared Window

III. MEASUREMENT ERROR CORRECTION METHODS

A. Infrared Window Errors

From Table I it can be seen that the error rate for this test ranged from 13% up to 40%, compared to the specified accuracy of most infrared cameras of ±2%. Clearly an error of even 13% is unacceptable, but rising to 40% creates an issue of either misdetection of real problems or misdiagnosis of early warnings.

By overlaying Planck's curve with the known infrared window optic over a specified range and then mapping those overlays against each individual infrared detector array, it should be possible to achieve a measurement of nearly the ±2% accuracy of the infrared camera, even when viewing through an infrared window. However, the only way to achieve accuracy measurements requires that the window's optic material, which the infrared imager is looking through, have consistent transmission, reflection and absorption characteristics across its entire surface area. Only high quality crystal type infrared windows can provide the needed consistent transmission, reflection and absorption characteristics to achieve high measurement accuracy.

B. Quantitative versus Qualitative Readings

If the intent of using an infrared camera is only to gauge what's referred to as an "apparent" temperature; the measured temperature is strictly only used for a general conclusion like "the connection may be hot", then the quantitatively measurements and the associated accuracy is not important or not that relevant. Making assumptions on bad data can lead to serious consequences.

However, if one is using the infrared imager's measured temperatures as a "Go", "No-Go" indication of equipment performance or an indication of a poor connection, junction or union, with the intent of conclusively stating the measured point is over the design maximums, one must use accurate data in making these conclusions.

Comparing one electrical connection with adjacent connections only indicates a general delta in temperature between two or more points. This delta may not be an issue at all if one considers the actual temperature of the measured point and the designed maximums for that point in a piece of equipment. Using inaccurate temperature readings could result in erroneous conclusions resulting in unnecessary process downtime, unnecessary equipment or component replacement and unscheduled maintenance.

C. Getting the Most Accurate Temperature Readings

How then does a thermographer obtain sufficiently accurate readings through an infrared window to ensure that the health of the system is true?

The various types of infrared windows available, including those which use a combination of opaque mesh, metal mesh and semi-transparent polymer materials, all having differing transmission characteristics across their "optic" surface. This makes the ability of obtaining accurate temperature data increasingly difficult. The number of data signals the infrared camera receives will increases to six or more. The addition of so many independently fluctuating signals across the infrared window optic on both sides of the optic, plus the issue of focus and vignette effect, means that it is not possible to reliably correct and obtain accurate, repeatable measurements through any mesh type infrared window.

The only reliable method is to obtain a transmission "map" of each infrared window. As outlined earlier, a crystal type infrared window has the most uniform transmission across both its front and rear surface. This translates to a much simpler and hence repeatable correction algorithm for the thermal imager.

"Since every infrared window is slightly different, it is important to make certain each infrared window falls within a set transmission tolerance. This transmission map must then be inserted into the thermal camera's temperature measurement algorithm, also known as the "radiometric chain". This must be done when the camera is calibrated at the factory, and a particular type of infrared window transmission map is applied to the individual detector spectral response."

Once the camera understands how it is specifically affected by a particular type of infrared window, it can now accurately and repeatedly correct for that particular type of infrared window.

Some thermal cameras can perform this entire function automatically for the thermographer, a process called "Dynamic Optics Correction" or DOC. To perform a DOC, the thermal camera communicates with the infrared window installed in the field and retrieves information about the infrared window itself. This then enables the camera to access and enable the specific correction algorithm relating to this specific infrared window and the camera detector response with its radiometric chain. The result is very accurate temperature readings through a specific infrared window, across a range of temperatures with no human intervention or error. This "complex" DOC process takes less than 500ms on some thermal imagers.

CONCLUSIONS

The paper has outlined the facts regarding measurement inaccuracies surrounding the use of various infrared window media and, constructions along with infrared cameras variances.

Illustrated is a fundamental and common misconception that all infrared windows utilize optics with uniform transmission characteristics. Infrared windows, which use a combination of opaque mesh, metal mesh and semi-transparent polymer materials, make the ability of obtaining accurate temperature data increasingly more difficult.

As well, every infrared camera will have an imaging array with a different response scale within the range of the 8-14µm longwave band. The combined error rate between various infrared cameras and infrared windows could result in incorrect temperature readings easily reaching or exceeding a ± 40% error range. As a result, the use of inaccurate temperature readings could result in erroneous conclusions resulting in unnecessary process downtime, unnecessary equipment or component replacement and unscheduled maintenance.

The fundamental aspects of obtaining accurate infrared temperature scans, especially those obtained using infrared windows, is to insure consistency of the infrared camera and the error data injected by the infrared window the camera is viewing through. New advancements in both infrared camera and crystal infrared window technologies, now facilitate nearly instant calibration or mapping between the window and the infrared camera. This resultant configuration permits the camera to automatically compensate for any crystal infrared windows reducing the error rates to a ± 2% error range.

With accurate temperature data, traditional quantitative predictive maintenance of electrical equipment can be converted into highly accurate qualitative predictive maintenance of electrical equipment.