Application Notes – *AN109*
Glass Temperature Measurement

Introduction
The optical properties of soda-lime-silica glass are presented in this application note and are related to the use of infrared thermometers for temperature measurements on glass products. It shows how the thermometer can be selected to conform to the specific application allowing the user to stress surface or interior temperature measurements. Practical rules are provided to enable the user to avoid the common interferences.

Specific data is presented for soda-lime-silica glass because of its preponderant use in common glass products such as sheet, plate and bottles. Other silica gasses, though not identical, behave similarly and the principles illustrated are equally applicable. Further-more, the inclusion of various other constituents in the soda-lime-silica composition in order to color or decolorize the glass does not significantly change the data presented.

Fundamental Background
The Ideal or Blackbody Radiator
A blackbody radiator emits a continuous stream of thermal radiation from its surface. This radiation forms a continuous spectrum though the intensity and varies throughout the spectrum. The radiance (or brightness) at every wavelength throughout the spectrum depends only on the blackbody temperature. The radiance at every wavelength increases with the blackbody temperature. These relationships are quantitatively embodied in Planck's Law of blackbody radiation.

Infrared Thermometer
The infrared thermometer is an optical device which can quantitatively measure the radiance of a blackbody or other radiating object. Various thermometers are available, each responsive to a different band of wavelengths in the spectrum. Planck's relationship shows that each of these thermometers can be employed to determine the true temperature of the blackbody radiator.

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Real Object and the Emittance Factor

The simple relationship involved in employing the infrared thermometer to measure the radiance and thus the temperature of a blackbody is somewhat complicated when applied to a real object. A real object, such as a glass bottle, is generally not a blackbody and is characterized by the fact that its radiance may be lower than that of a blackbody at the same temperature. The ratio of these two radiance values is defined as the emittance (ε) of the real object. Since (ε) can vary with wavelength, we shall refer to the spectral emittance (ε_λ)

$$\varepsilon_\lambda = \frac{\text{Radiance of real object at wavelength } \lambda}{\text{Radiance of blackbody at wavelength } \lambda}$$

as where both are at the same temperature.

Furthermore, $0 \leq \varepsilon \leq 1$

Clearly, the infrared thermometer responsive at wavelength (λ) can measure the true temperature of a real object only if its correct value of (ε_λ) is known.

For objects of many materials, (ε_λ) must be determined experimentally through direct temperature measurements. Certain other materials are available in such forms that the value of (ε_λ) can be readily determined by simpler, indirect means. Glass is one example of the latter.

Kirchoff's Law

This fundamental law relates (ε_λ) for an object to its spectral transmittance (T_λ) and its spectral reflectance (R_λ) as follows:

$$\text{(Eq. 1)} \quad \varepsilon_\lambda = 1 - T_\lambda - R_\lambda$$

Glass is readily available in forms suitable for the direct determination of both (T_λ) and (R_λ) using standard laboratory spectrophotometers. The results of such measurements for soda-lime-silica glass are presented in the following section.

Optical Properties of Soda-Lime-Silica Glass

Spectral Transmission vs. Wavelength

Figure 1 shows spectral transmittance (T_λ) versus wavelength λ for several thicknesses of soda-lime-silica glass. This family of curves clearly shows the strong dependence of (T_λ) on the thickness.

Note the locations of the spectral response regions for various Ircon model series infrared thermometers.

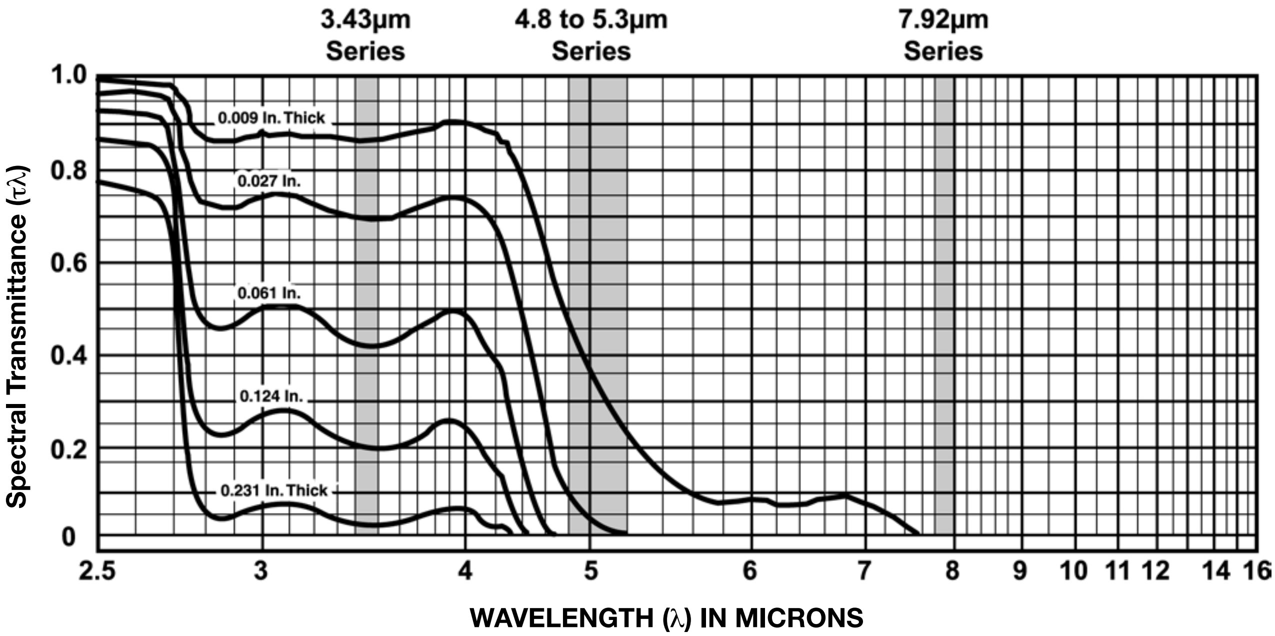


Figure 1–Effects of Thickness on Spectral Transmittance Curves for Soda-Lime-Silica Glass

Spectral Transmittance vs. Thickness

Figure 2 is a semi-log plot of spectral transmittance (T_λ) versus thickness (x) evaluated for the spectral regions of the model series operating at 7.92 µm, 4.8 to 5.3 µm and 3.43 µm. The data for the latter two series are taken directly from Figure 1, using the center wavelength of the spectral responses.

Note: The curve for the 7.92 µm series has been estimated from other experimental data not presented here.

All three curves are straight lines on this plot as predicted by Beer's Law, which states:

$$\text{(Eq. 2)}\ T_\lambda = \varepsilon - \kappa_\lambda x$$

where (κ_λ) is the spectral absorption coefficient. Clearly, (κ_λ) varies markedly with (λ) for glass.

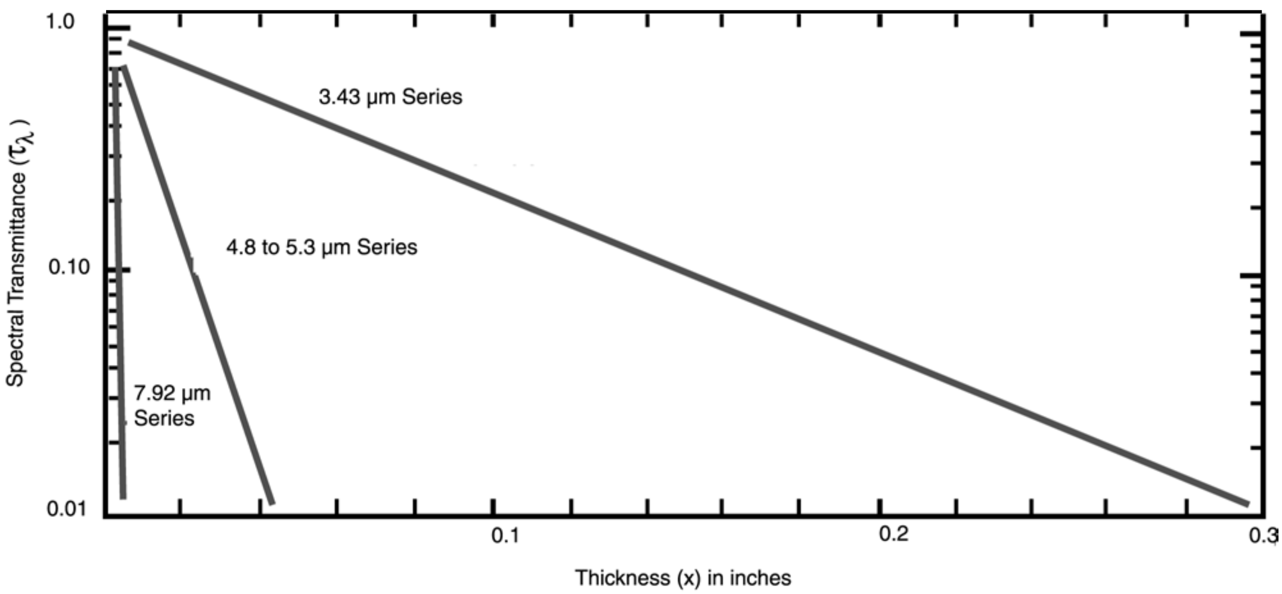
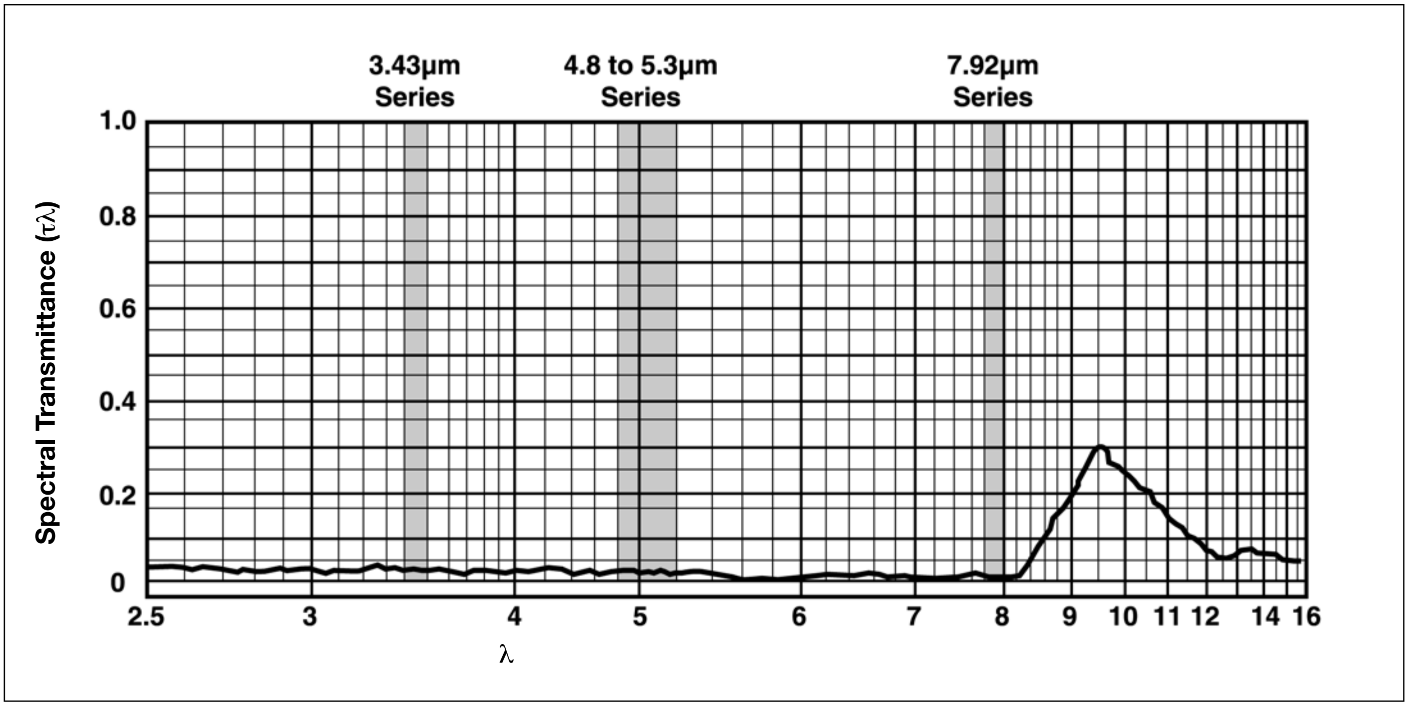


Figure 2–Transmittance Variation with Thickness for Soda-Lime-Silica Glass

Spectral Reflectance vs. Wavelength

Figure 3 plots spectral reflectance (R_λ) versus wavelength (λ). This data is for a smooth surface of glass taken at normal incidence. Only a single curve appears here because (R_λ) is independent of glass thickness. The shape of the curve is typical of all silica glasses. The reflectance starts out low at 2.5 microns and slowly drops to zero near 8 microns before soaring to peak at about 9.5 microns. This reflectance peak is caused by the silica in the glass and is associated with the very strong silica absorption band in this region.



Spectral Reflectance vs. Angle of Incidence

Figure 4 (on following page) represents the variation of spectral reflectivity (R_λ) versus angle of incidence ϕ evaluated at 5 microns. The important consideration here is that (R_λ) is quite constant out to 45° and reasonably constant out to about 50°. However, as the angle increases beyond here (R_λ) increases rapidly and approaches 1.00 as ϕ approaches 90°.

Spectral Emittance vs. Thickness

The glass optical properties presented to this point permit the evaluation of spectral emittance (ε_λ) versus thickness (x). Kirchoff's Law (Eq. 1) can be solved using the data of Figure 2 and 3. As an example, consider a sheet of glass 0.125 inch thick. The value for (ε_λ) for each of the three thermometers shown can be evaluated as follows:

$$\varepsilon_\lambda = 1 - T_\lambda - R_\lambda$$

$$\varepsilon\ 78 = 1 - .00 - .01 = 0.99$$

$$\varepsilon\ 77 = 1 - .00 - .02 = 0.98$$

$$\varepsilon\ 43 = 1 - .16 - .03 = 0.81$$

Here, the values for (T_λ) and (R_λ) are estimated to the closest ± 0.01 units which is more than adequately close for practical infrared thermometry. Figure 5 (on following page) shows the derived curves of (ε_λ) versus thickness for various thermometer series. In each case, (ε_λ) increases rapidly with thickness and levels off at the limiting value of $1–R_\lambda$. Note the limiting emittances for the three thermometer series range from 0.97 to 0.99. These unusually high values of (ε) are particularly advantageous in helping to cope with various measurement interferences that can arise in practical applications.

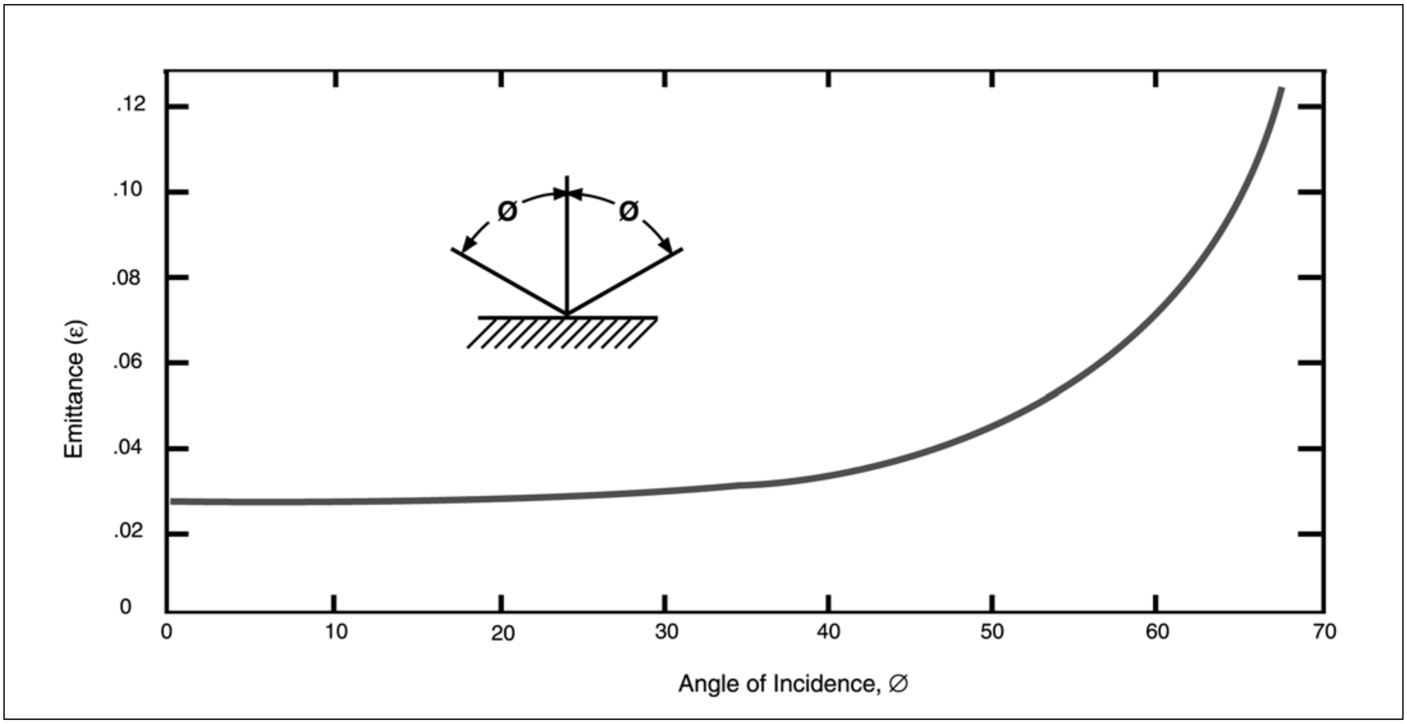


Figure 4–Variation of Reflectivity with Angle of Incidence for Soda-Lime-Silica Glass in the region of 5 microns

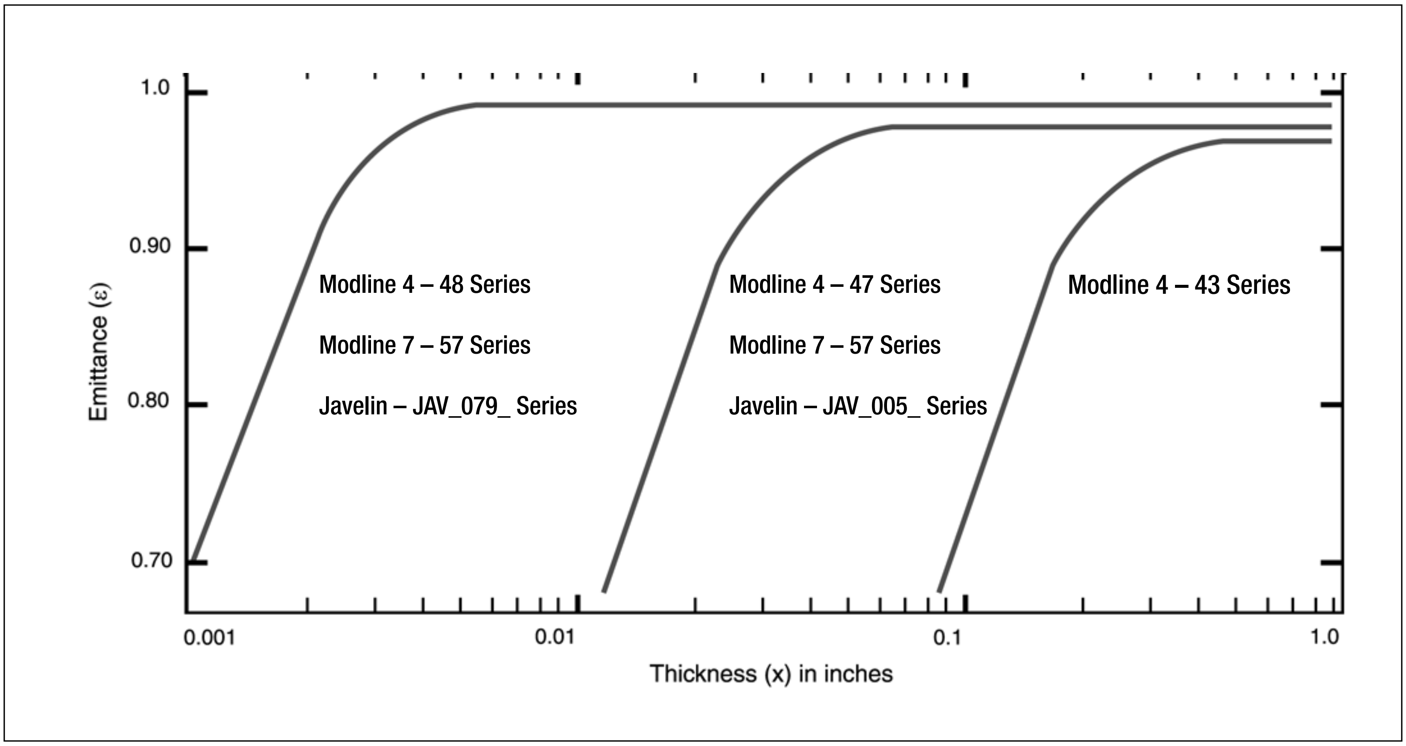


Figure 5–Emittance Variation with Thickness for Soda-Lime-Silica Glass for Ircon Instruments

Factors Affecting Thermometer Selection and Use

Depth of Temperature Measurement

Glass has a relatively poor thermal conductivity. Consequently, during many phases of processing into finished parts, there exist high temperature gradients extending from the surface into the interior. This fact often prompts the thermometer user to ask questions similar to the following:

"How far under the surface am I measuring?"

"The thermometer indicates 500°C (932ºF). Is this the surface or the interior temperature?"

For qualitative answers to these questions, we can refer to Figure 2. A thin layer of glass located at a depth (x) below the surface is radiating thermal energy toward the surface at a rate governed by its temperature and its thickness. The portion of this energy reaching the surface is proportional to the transmittance to the surface or $\varepsilon - \kappa_\lambda x$. The closer this thin layer is to the surface, the greater the transmittance to the surface, and the greater contribution it makes to the radiance of the surface as "seen" by the thermometer. Using the example of the 3.43 µm spectrum, we see that for the layer lying right at the surface, 100% of its radiance arrives at the surface; for the equivalent layer lying 0.15 inch under the surface, 10% of its radiance is transmitted to the surface; for the layer at 0.3 inch from the surface, only 1 % of its radiance reaches the surface; and so on.

The radiance of the surface as viewed by the thermometer is the sum of the radiance values of all the thin radiating elements extending from the surface on down into the depths of the interior. The measured radiance and thus the measured temperature, is an integrated average of all the values extending in from the surface. Clearly, the surface layers always contribute more to the measurement than deeper layers.

Again, with reference to Figure 2, let it suffice to say that 90% of the "weight" of the radiance values measured by the 7.92 µm, 4.8 to 5.3 µm and 3.43 µm series thermometers arise from the first .002, .022, and .153" thick layers at the surface, respectively.

If the glass temperature is at a constant 500°C from the surface on down, all three thermometers will indicate 500°C! If the temperature is 500°C at the surface and it increases with depth into the interior, each thermometer will indicate above 500°C with the 3.43 micron series indicating the highest temperature, followed by the 4.8 to 5.3 micron, and 7.92 micron series in stated order.

Product Thickness Variations

The effect of the thermometer indicated temperature caused by product thickness variations depends on the thickness and the thermometer series. If the minimum product thickness is thicker than the value required to provide the limiting value of (ε_λ) no error will result. This is because the thermometer does not "see" all the way to the back surface. If the product thickness is below this value, variations in its thickness represent variations in emittance -temperature errors will result unless the emittance settings are properly adjusted.

For example, consider a process where a continuous strip of sheet glass of thickness 0.10 ±.01 inch is passing a thermometer temperature station. Figure 5 shows that the emittance for the 7.92 µm and 4.8 to 5.3 µm series are completely unaffected, and consequently both the 7.92 µm and 4.8 to 5.3 µm series will indicate the proper temperatures independent of thickness. However, the emittance for the 3.43 µm series will vary from 0.71 to 0.77 for the extreme thicknesses. Consequently, with the 3.43 µm series and with a sheet temperature of 900°F, these uncompensated thickness variations will cause "apparent" temperature swings of ±10°F.

The message here is to select the infrared thermometer which is not influenced by the expected thickness variations.

Interfering Sources

Interfering sources behind the product and hotter than the product can cause high temperature readings if the glass is thin enough to transmit the background radiation. Select the longer wavelength thermometer, if necessary, to avoid this.

Interfering hot sources can also reflect off the glass surface viewed by the thermometer. Best to aim the thermometer at a different angle to avoid the bad reflection and/or interpose a cool shield in front of the interference to block it at the source. If these solutions are not available, switch thermometers in the sequence 3.43; 4.8 to 5.3; and 7.92 micron series as the reflectance values decrease in that order. The reflectance values for all three thermometers are quite low and reflection problems are seldom a problem.

Interfering sources (continued)

However, one special case where reflections can be a serious problem involves the use of high intensity tungsten filament quartz lamps in radiant heating applications. The extreme temperatures of the filaments of these lamps provide radiation levels that can cause severe interference with thermometers operating at wavelengths shorter than about 4.7 microns (See Figure 6). Above this wavelength the quartz envelope becomes opaque, eliminating the source of interference. The 3.43 µm series can suffer interference here while the 4.8 to 5.3 µm and 7.92 µm series will be completely immune.

Angle of View

Figure 4 shows the variation of reflectivity with ϕ at 5 microns. Qualitatively, this behavior also applies to the other spectral regions, too. Best to avoid the higher values of (R_λ) and the consequent lower values of (ε_λ) by viewing the target surface at any angle below about 50° from the normal.

Atmospheric Absorption

Figure 7 shows the spectral regions covered by atmospheric absorption bands. Atmospheric water vapor and carbon dioxide absorb strongly in these regions and can cause serious errors for thermometers operating therein. The Ircon thermometers series do not operate in any of these regions and do not encounter atmospheric transmission problems.

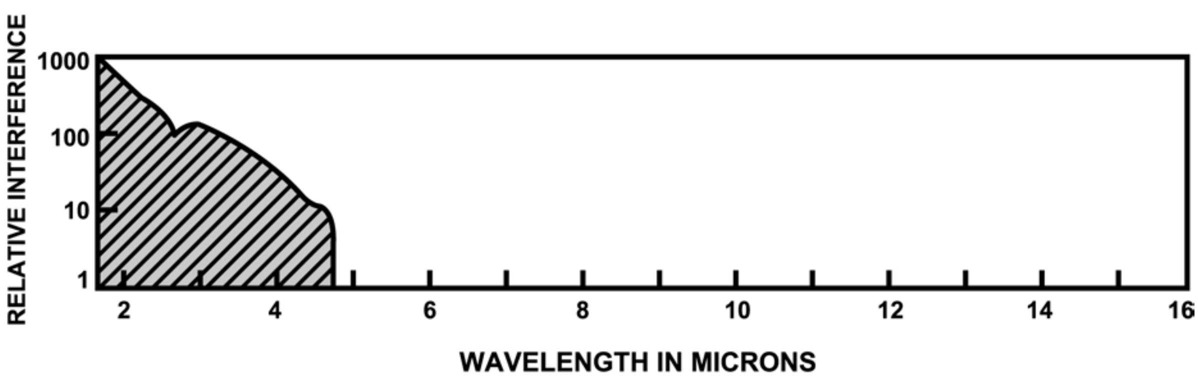


Figure 6–Relative Interference Caused by Quartz Lamp Infrared Heaters

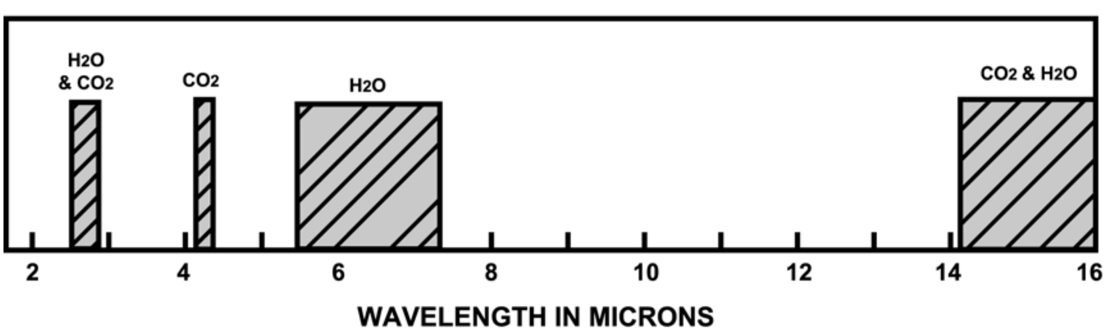


Figure 7–Areas of Significant Atmospheric Absorption over a Path Length of 10 feet

Summary

We have described the basic evaluation criteria for selecting the correct infrared thermometer for various glass applications.

We will confidentially and without charge, run an evaluation of your specific glass temperature measurement application. This will include an infrared spectrophoto meter analysis of your glass samples. Just send us a brief letter telling us the approximate range of temperatures, method of heating, minimum and maximum thicknesses and include 2 or 3 samples of the glass. If possible, the samples should include the thinnest and thickest glass to be used.

We will send you infrared transmission curves and our recommendation of the correct instrument.

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