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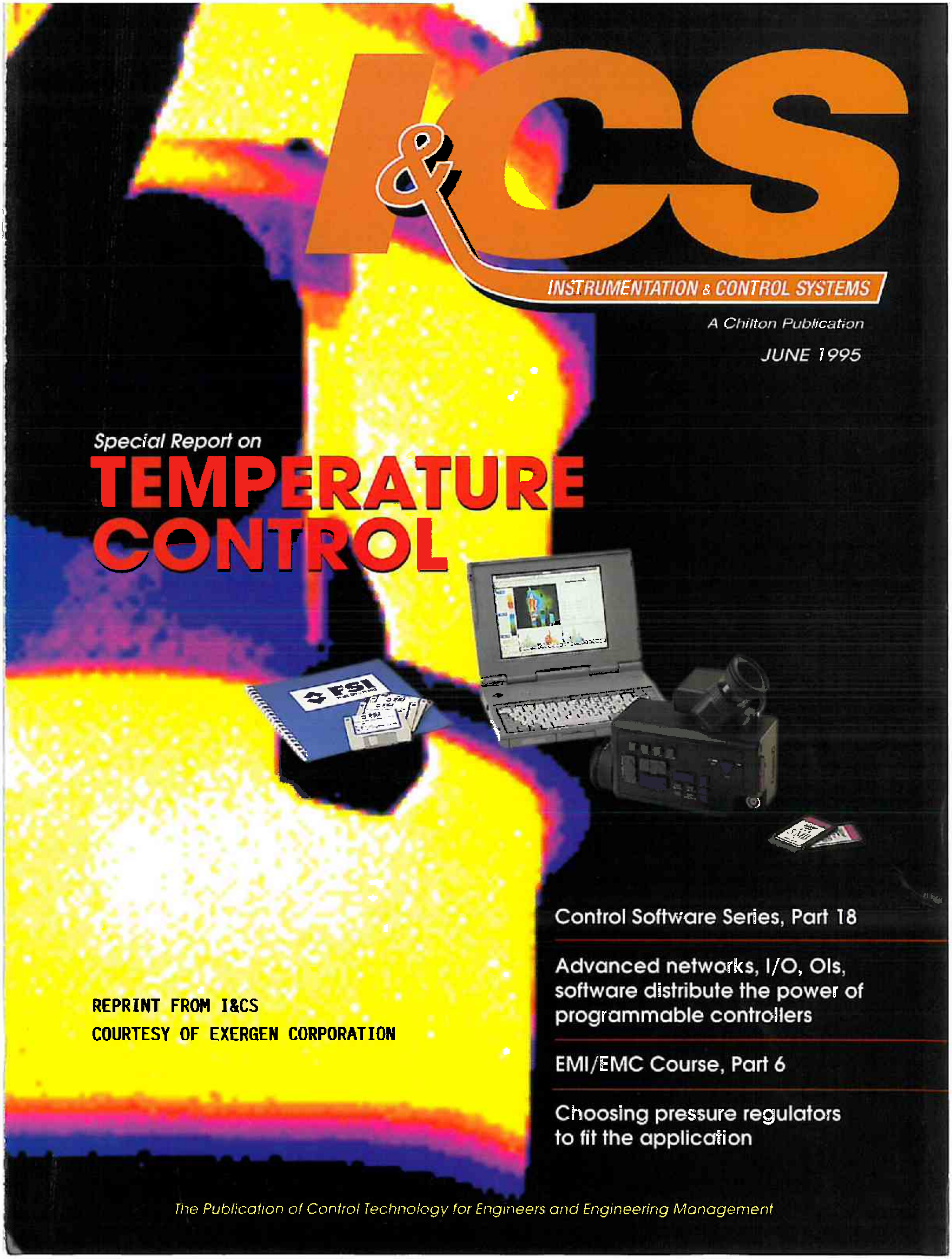

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A case for the unpowered IR thermocouple

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This infrared technology is ideally suited for applications in which temperature swings are less than ±30°C, and high accuracy coupled with precision and repeatability are critical.

Conventional infrared (IR) temperature sensors offer a good measurement solution for industrial applications in which high accuracy is not absolutely critical, and wide temperature swings (more than ±50°C) are the norm. However, for processes in which temperature swings are not so great (less than ±30°C), and high accuracy coupled with precision and repeatability are needed, IR thermocouple (T/C) technology can be the best way to go.

Conventional powered IR devices that produce a simulated T/C signal are also classified as IR T/Cs, but the type we will discuss is unpowered, developing its signal from the Seebek effect. This sensor produces a signal proportional to the difference between hot junction (target) and cold junction temperatures, using standard T/C extension wire and T/C readout devices.

In this article we'll begin with a look at the effects of variable emissivity and variable ambient temperatures on both conventional IR techniques and IR thermocouple sensors. We'll then describe a few of the applications for which the latter technology is best suited.

Black body vs gray body vs real body

Emissivity is a measure of what proportion of an object's surface emits (rather than reflects) radiation. For example, a perfect mirror would reflect all light and infrared radiation that reached it and emit none; thus, it would have an emissivity of zero. Of course, the fact that we can see a "real" mirror tells us that it isn't perfectly reflective. If 90% of the mirror's surface reflected light, the remaining 10% would emit light; thus, the mirror would have an emissivity of 0.1. For any nontransparent material, emissivity (ε) plus reflectivity (ρ) always equals one:

$$\varepsilon + \rho = 1$$

A *black body* is an object that reflects no radiation ($\rho = 0$) and has an emissivity of 1. The concept of a black body is a highly useful and essential mathematical construction in the application of infrared radiation physics, and has had firm theoretical support from the time of Max Planck.

However, in real-world temperature control applications, IR devices do not measure black bodies. They measure objects with an emissivity of less than 1, and reflectivity of greater than 0. For example, shiny metals that act like mirrors have emissivities in the 0.05 to 0.2 range, and are more difficult to measure with IR technology. Nonmetals, coated metals, and organic materials, on the other hand, have emissivities in the 0.8 to 0.95 range and can be measured with IR devices with much greater precision.

A useful first approximation of real-world targets is the *gray body*–that is, an object with an emissivity of less than 1.0. *Gray bodies* also have the additional characteristic that their emissivity is constant at all wavelengths of interest and, therefore, is constant at all temperatures of interest. Accordingly, for gray bodies:

$$q_{gb} = q_{bb}\varepsilon$$

at all wavelengths, where q_{gb} and q_{bb} are radiated energy from a gray body and black

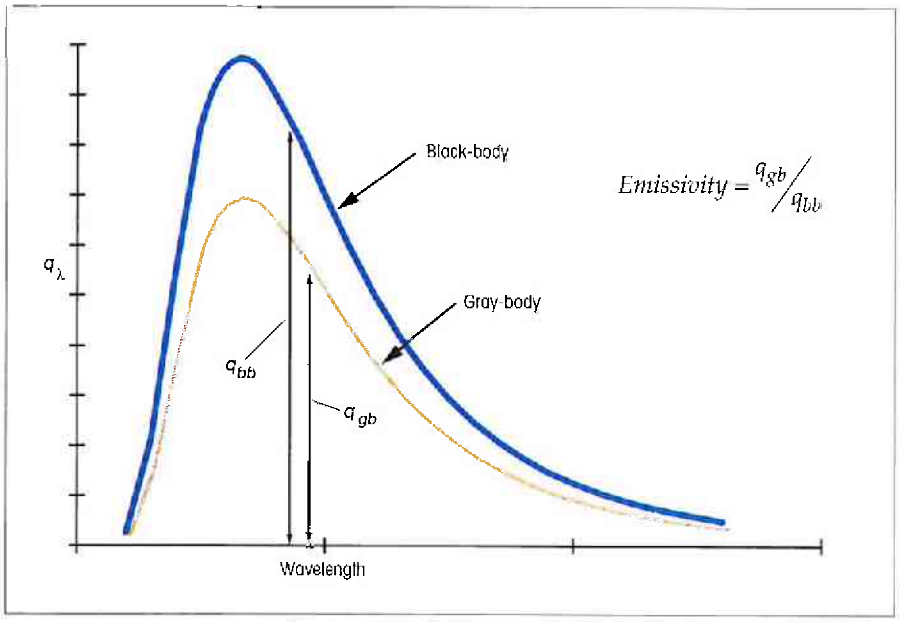
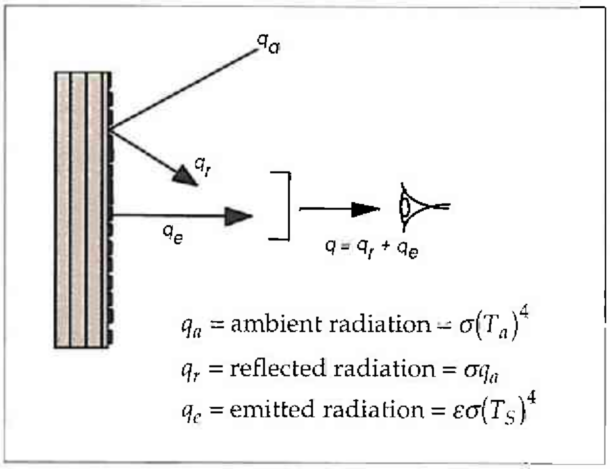


FIG. 1: Radiated energy vs wavelength for black bodies and gray bodies.



$$q_a = \text{ambient radiation} = \sigma(T_a)^4$$

$$q_r = \text{reflected radiation} = \sigma q_a$$

$$q_e = \text{emitted radiation} = \varepsilon\sigma(T_S)^4$$

FIG. 2: Equations for gray bodies. T_a = ambient temperature; T_S = surface temperature

body respectively. Figures 1 and 2 illustrate gray body properties.

A *real body* includes the additional property that its emissivity is not constant as temperature changes. Mathematically, the gray-body approximation proves useful in dealing with reflective errors, and the real-body property must be used to deal with target temperature variations.

Conventional IR vs IR thermocouples

Because conventional IR devices are designed and calibrated to theoretical black body conditions at single ambient temperature points, it's more difficult for them to cope with emissivity shifts. However, IR thermocouple devices are calibrated with multiple ambient temperatures, and are constructed to minimize ambient reflective errors and the effect of emissivity shift errors.

Mathematically, the signal output of an IR thermocouple is a complex function of target temperature, ambient temperature, target emissivity, reflected energy, thermocouple type, and so on. To clarify the specifications, we can represent the change in signal with respect to a variable of interest, while holding all other variables constant, as a partial derivative.

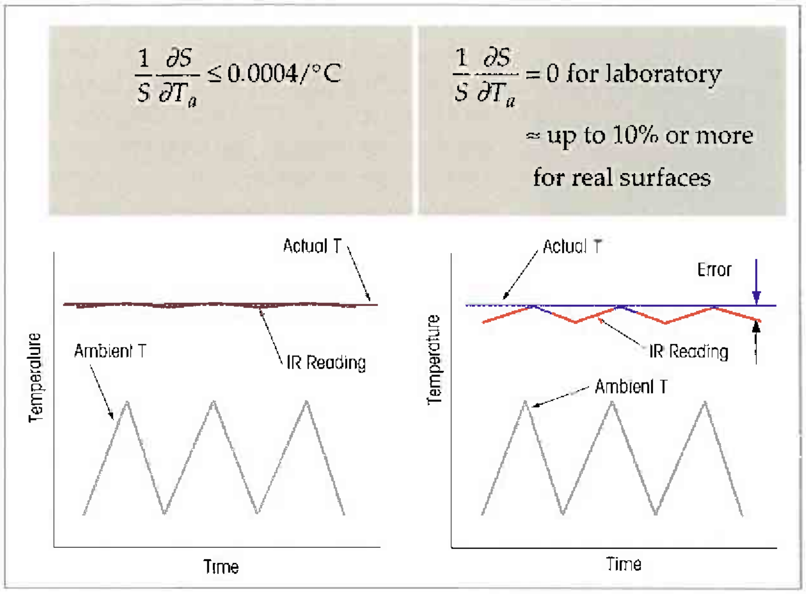
Ambient temperature coefficient specification

The output signal of an IR device varies according to its ambient temperature coefficient. Figure 3 shows this effect, and the resulting error for IR thermocouple devices and conventional IR sensors.

In Fig. 3, S is the output signal and T_a is the ambient temperature. The equation describes the change in output of the IR thermocouple with respect to ambient temperature, assuming that emissivity = 0.9 (gray body assumption), and that the sensor itself is at the same temperature as the environment.

The practical implication of this is that an IR thermocouple, once installed and calibrated in place, tends to change temperature with the ambient background, and internally applies the correction required to reduce errors. Lacking multiple ambient temperature calibration, a conventional IR device usually will produce a greater error, which, in turn, will cause unwanted shifts in process control temperatures, *even though its black body calibration may be perfect.*

For example, in waterless printing processes, the temperature of the ink application roll must be controlled to maintain high-quality output (Fig. 4). If the temperature is to be maintained at 80°F (26.7°C) and temperatures inside the press enclosure can range from 70 to 100°F (21.1 to 37.8°C)–because of warm-up, weather, building air ventilation, and other factors–a conventional IR device can produce an error of about 3°F (1.7°C). Under the same conditions, an IR



$$\frac{1}{S}\frac{\partial S}{\partial T_a} \le 0.0004/°\text{C}$$

$$\frac{1}{S}\frac{\partial S}{\partial T_a} = 0 \text{ for laboratory}$$

$$\approx \text{up to } 10\% \text{ or more for real surfaces}$$

FIG. 3: (top left) Comparison of errors caused by shifts in ambient temperature coefficient between IR T/Cs (left) and conventional IR systems (right).

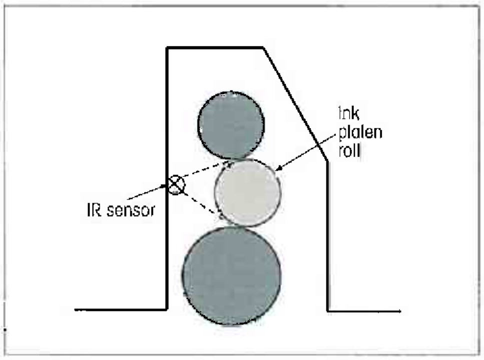
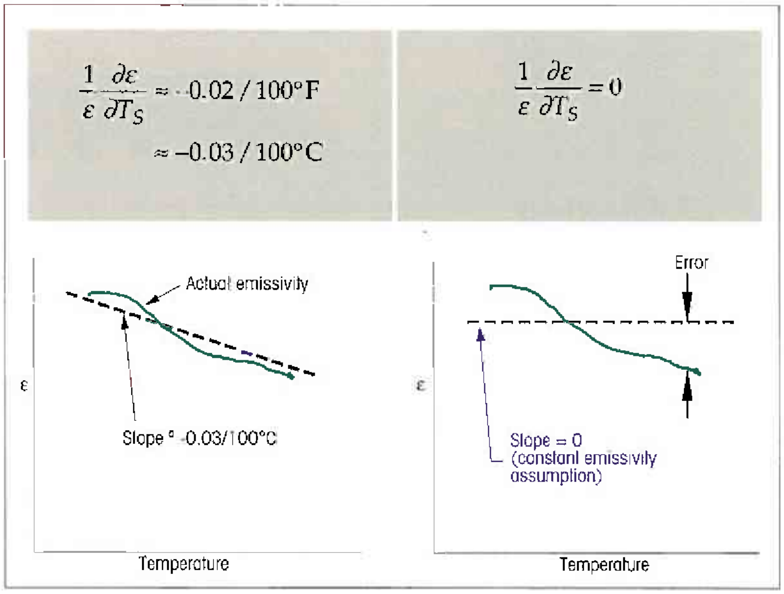


FIG. 4: (top right) In waterless printing, an IR sensor is used to monitor the temperature of the ink platen roll. Conventional IR error is 3°F (1.7°C); IR T/C error is 0.2°F (0.1°C) in this example.



$$\frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial T_S} \approx -0.02/100°\text{F}$$

$$\approx -0.03/100°\text{C}$$

$$\frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial T_S} = 0$$

FIG. 5: (bottom) Comparison of errors caused by emissivity variations between IR T/C (left) and conventional IR devices (right).

thermocouple should produce an error of about only 0.2°F (0.1°C).

To estimate the improvement in control accuracy produced by the IR thermocouple for a specific application, the following approximation can be applied:

Error with conventional IR

$$\approx (1-\varepsilon)(\Delta T_a)(T_s - T_a)$$

Error with IR t / c

$$\approx (0.9-\varepsilon)\left(\frac{\Delta T_a}{10}\right)(T_s - T_a)$$

Compensating for emissivity variations

The standard assumption for conventional IR thermometry is that emissivity is constant with changes in target surface temperature. Real target materials, however, do not have this characteristic. The average value for nonmetals, for which the change in emissivity with respect to surface temperature has been reported, is about -2% per 100°F target temperature change (-3% per 100°C).[1] For some materials, emissivity can vary by much more.

Figure 5 shows the emissivity variation for IR T/Cs and conventional IR devices when the partial derivative mathematical formulation is applied. Conventional IR devices miss this effect by not taking into consideration that emissivity variations can be caused by temperature changes, and the resulting error can cause process control errors.

The signal produced is proportional to the radiation emitted by the surface:

$$S = \varepsilon q_{bb}$$

The change in signal with respect to target surface temperature is shown in Figure 6. Note that the conventional IR device loses one term of the signal change with respect to surface temperature.

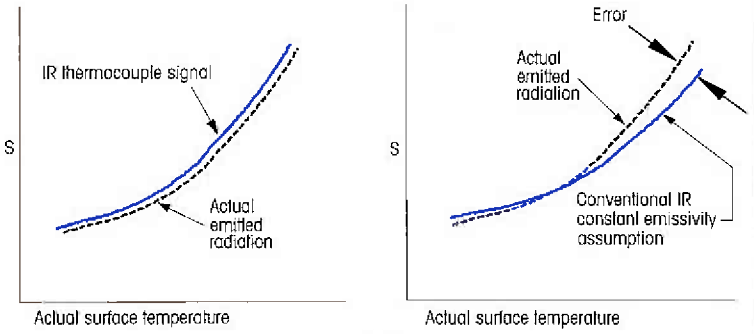
Since real-world emissivity for most nonmetal materials decreases with temperature, the constant emissivity assumption of conventional IR devices produces errors in readings over wide temperature excursions that are not obvious to the typical IR user. Over a wide temperature range, these errors can cause inaccurate process control. However, over a narrow range, these devices can be used with reasonable assur-

$$\frac{\partial S}{\partial T_S} = \frac{\partial S}{\partial \varepsilon}\frac{\partial \varepsilon}{\partial T_S} + \frac{\partial S}{\partial q_{bb}}\frac{\partial q_{bb}}{\partial T_S}$$

$$= q_{bb}\frac{\partial \varepsilon}{\partial T_S} + \varepsilon\frac{\partial q_{bb}}{\partial T_S}$$

$$\frac{\partial S}{\partial T_S} = \frac{\partial S}{\partial \varepsilon}\frac{\partial \varepsilon}{\partial T_S} + \frac{\partial S}{\partial q_{bb}}\frac{\partial q_{bb}}{\partial T_S}$$

$$= 0 + \varepsilon\frac{\partial q_{bb}}{\partial T_S}$$



$$\frac{\partial S}{\partial T_S} = \frac{\partial S}{\partial T_a}\frac{\partial T_a}{\partial T_S}$$

$$\frac{\partial T_a}{\partial T_S} = c$$

$$\frac{\partial S}{\partial T_a} = S(1-\varepsilon)$$

$$\frac{\partial S}{\partial T_S} = S(1-\varepsilon)c$$

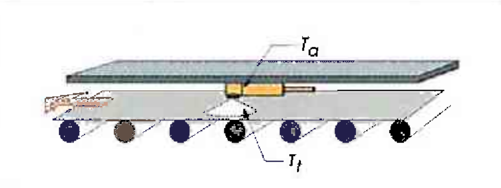
$$c \approx 0.25 \text{ by test}$$

$$\frac{1}{S}\frac{\partial S}{\partial T_S} = 0.25(1-\varepsilon)$$

For a typical case of ε = 0.9, the change in signal is ≈ 2.5%, which is accounted for in the ambient compensation system over the linear range.

$$\frac{\partial T_a}{\partial T_S} = 0$$

The 2.5% error is present, but not accounted for in the design or calibration, thus resulting in potential process control error



(clockwise from top)
FIG. 6: Change in signal with respect to target surface temperature for IR T/C (left) and conventional IR (right).

FIG. 7: A laminating process with several temperature control settings.

FIG. 8: Error caused by the effect of target temperature on background temperature for IR T/C (top) and conventional IR (bottom).

ance that measurements will be precise, repeatable, and accurate.

To get the measurement benefits from IR thermocouples, engineers should specify these devices for a specific useable temperature range, in which the effect of emissivity change is accounted for in the optimum range specification of the device *(See "IR thermocouple accuracy table," next page)*. The user can then be confident that process control will be accurate over the temperature range. Note that testing an IR thermocouple with a black body will not give the same result as a test with a real body.

A second effect on useable temperature range is that of target surface temperature on ambient temperature and, therefore, on the reflected component of radiation to the sensor. As target temperature increases within a process, the increased radiation heat transfer to the surroundings will cause the target ambient radiant background to also increase in temperature.

As an example, consider a laminating process that has several temperature control settings–each of which depends upon the material and feed speeds *(Fig. 7)*. These target operating temperatures may vary by as much as 100°F (56°C). As the temperature of the material changes, the temperature of the background radiation in the vicinity of the measurement will also change, and influence the IR reading.

In this case, the variation in signal with target temperature has an additional component, as shown in Fig. 8.

High degree of accuracy is possible

Earlier we mentioned that the calibration of IR thermocouples is set up over various temperature ranges. When we do the numbers on the combined effects of emissivity variations and ambient reflection variations, we can predict the optimum temperature ranges for specific thermocouple models *(Fig. 9)*. This assures a high degree of accuracy for a specific device over its rated temperature range.

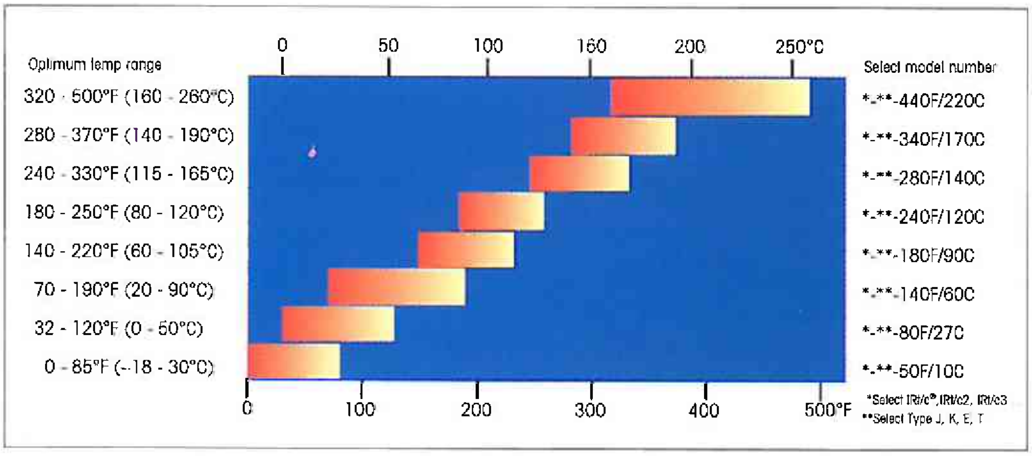
Accuracy depends on the width of the temperature span to be measured. For example, if the requirement is to measure and control a target temperature at 200°F (90°C), the error is 0.0% after initial calibration at that point.

As the target temperature varies from the 200°F (90°C) calibration point, the error increases gradually, as shown in the accuracy table. For a temperature span of 190 to 210°F (87 to 99°C), the error at the temperature extremes would be ±0.4% or 1.0°F (0.6°C); this is shown in the table as the error for a span of ±10°F (±6°C) from the calibration point.

OEM's and users of programmable controllers and computers who require greater accuracy over wider temperature ranges, should remember that multiple point calibration will reduce errors caused by changing emissivities, changing reflections, etc.

Repeatability and Interchangeability

The IR thermocouple's repeatability error, defined as the ability to reproduce a reading under identical conditions, is very small. There are no active electronics that can shift, and no source of spurious signals until the resolution limit–which is 0.0001°C (due to Johnson noise)–is reached. The result



is a repeatability error of less than 0.02°F (0.01°C).

Interchangeability error, which is defined as the difference in reading between any two IR thermocouples of the same model making identical measurements, is less than or equal to 1% or 0.5°C (1°F). This is of particular importance when a temperature sensor must be replaced.

IR thermocouple pluses

Here are the key points to remember about IR thermocouple technology:

1. In-place device calibration is always recommended, due to uncertainties in emissivities and ambient temperature.
2. Once an initial system has been qualified and calibrated, IR thermocouples of the same model can be substituted without the need for recalibration
3. An added benefit of the IR thermocouple is its specified optimum range per model. A user is not misled into believing that the measurement is accurate over a wide temperature range.
4. The performance of an IR thermocouple can't be accurately checked with a black body. Standard laboratory black bodies can be used for pass-fail or reproducibility testing only.
5. The performance of an IR thermocouple can't be accurately checked by using a conventional handheld portable IR device, because the emissivity and reflected component are almost never known with any precision. IR instruments that are certifiably accurate with unknown emissivities should be used to accurately check IR thermocouple installation and performance.

IR thermocouple devices, like conventional IR sensors, are manufactured for use in many different process control, factory automation, and OEM applications. Prices for these devices range from $99 to $699.

Where wide temperature ranges need to be measured, and tight accuracy is not that important, regular IR devices will serve you well. For applications with more narrow temperature swings that also call for a high degree of accuracy and repeatability, the IR thermocouple *(Fig. 10)* may be the solution of choice. ▌

IR thermocouple accuracy table

Target temp. span	Accuracy (greater of)
0°F (0°C)	0% or 0.02°F (0.01°C)
±5°F (±3°C)	± 0.2% or 0.5°F (0.3°C)
±10°F (±6°C)	± 0.4% or 1.0°F (0.6°C)
±20°F (±12°C)	± 1.0% or 2°F (1°C)
±40°F (±24°C)	± 2.0% or 4°F (2°C)
±75°C (±42°C)	± 5% or 8°F (5°C) approx

Reference

[1] MQ Brewster ed., *Thermal Radiative Transfer and Properties*, John Wiley & Sons, 1992.

About the author

Francesco Pompei is president and founder of Exergen Corp., developer and manufacturer of IR thermocouples. He holds undergraduate and graduate degrees from MIT, and continues as an active scientist in human thermoregulation physics in a special Ph.D program at Harvard. Pompei has more than 20 patents in thermoregulation technology for use in industrial instrumentation and medical applications.

For more information...

The author, Frank Pompei, will be available to answer any questions you may have about this article. He can be reached at (800) 422-3006 during normal business hours.

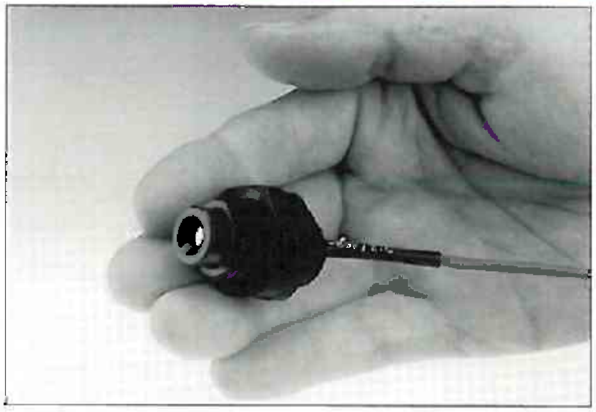


FIG. 9: (top and center) Infrared thermocouple selection chart shows company's various model IR thermocouples as they are optimized for specific temperature ranges. In the accuracy table, error is shown for various target temperature spans.

FIG. 10: (bottom) Infrared thermocouples, such as the IRt/c® from Exergen, can provide a high accuracy temperature measurement system where relatively narrow temperature ranges are involved.