LASER PYROMETRY

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INTRODUCTION

This paper describes a new method of determining the emissivity of a hot target from a laser-based reflectance measurement which is conducted simultaneously with a measurement of the target radiance. Once the correct radiance and emissivity are determined, one calculates the true target temperature from these parameters via the Planck equations.

The earliest published work concerning the determination of emissivity from target reflectivity measurements dates back to 1905 when H. Rubin* employed an arc-lamp reflectometer to determine the emissivity of a (cold) gas lamp wick and then corrected the radiance reading for the hot wick with the emissivity value measured for the cold target. Liebmann** employed more advanced detection methods to determine the reflectivity (and hence the emissivity) of a hot target, i.e. at the temperature of the radiance measurement. The advent of the laser made this technique more attractive and in 1970 Traverse and Foex *** conducted reflectivity measurements with the help of a HeNe laser whose brightness on the target exceeded that of the thermal radiance. A disappearing filament pyrometer operating at the laser wavelength of 6328 Å was used to determine the target's spectral radiance at the laser wavelength with the laser on and off. The difference between the two radiance values is proportional to the target reflectivity. The proportionality constant was determined by replacing the target with a cold sample of known reflectivity.

Quantum Logic Corporation has continued this line of development and introduced a packaged, hand-held commercial instrument in 1985, and recently a fixed-mounted version with a computer interface (see Figs. 1 and 2). Patents for these devices have been awarded.

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*Annalen der Physik   **Z.f. Physik   ***R.G.E. Tome 79,
  Vol 18, p 725 (1905)   Vol 63 p 404   No.10 pp 819-821
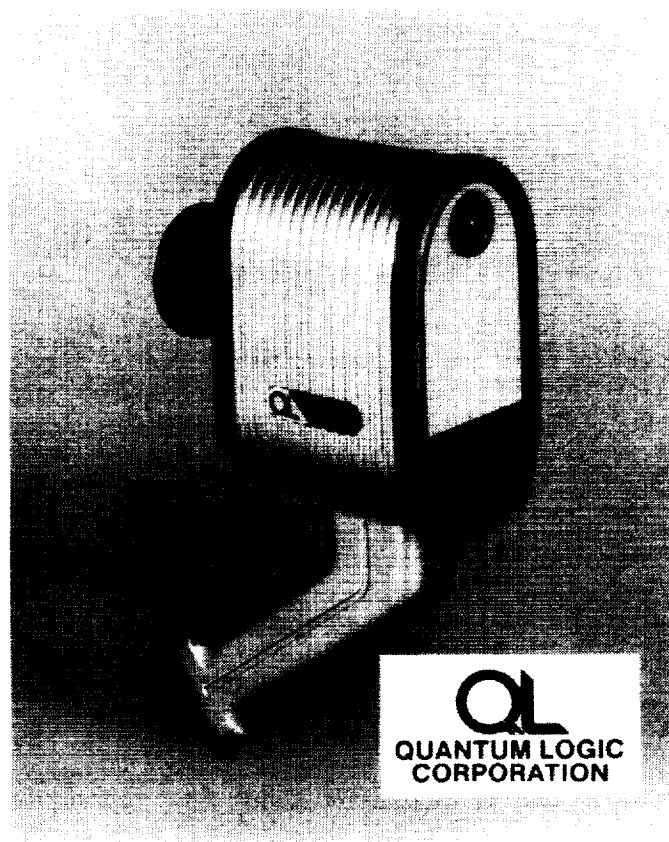
Figure 1.
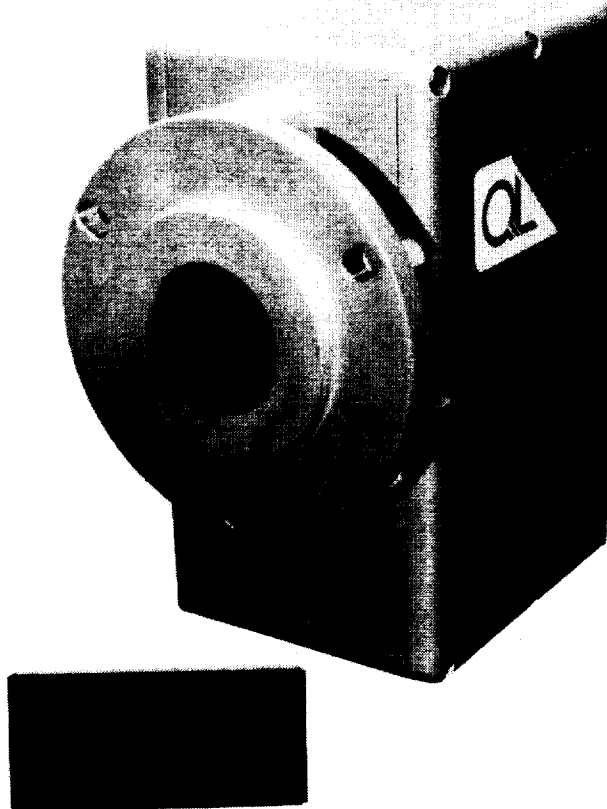
Hand–Held Laser/Microcomputer Pyrometer

Figure 2.

Fixed-Mounted Laser/Microcomputer Pyrometer

DESCRIPTION OF THE TECHNOLOGY

The method of determining emissivity from reflectivity
relates to Kirchhoff's postulate that at thermal equilibrium
all bodies in a closed environment must emit as much
radiation as they absorb. This postulate leads to the
conclusion that for opaque bodies

$$\mathcal{E}(\lambda, \phi, \theta) = 1 - \mathcal{P}_H(\lambda, \phi, \theta) \tag{1}$$

where:

$\mathcal{E}(\lambda, \phi, \theta)$ is the spectral emissivity at wave-
length λ and for emission in the direction (ϕ, θ).
ϕ is the azimuth angle, and θ the elevation angle.
(See Figure 3.)

$\mathcal{P}_H(\lambda, \phi, \theta)$ is the directional hemispherical re-
flectivity for radiation incident in the direction
(ϕ, θ).

Equation (1) also holds for freely radiating surfaces not in
equilibrium in the thermodynamic sense.* Note that non-
linear scattering processes are neglected here.

Bober and Karow** used an integrating sphere to determine
the directional hemispherical reflectivity (and hence the
directional spectral emissivity) of a laser-illuminated
sample of UO_2 below and above the melting point.

The measurements of Traverse and Foex by contrast, were bi-
directional reflectivity measurements. Implicit in their
method was the assumption that the ratio of bi-directional
to directional, hemispherical reflectivity was the same for
the calibration target and the target of interest. In their
case this was correct, since both targets were uniform diff-
use scatterers, i.e. the apparent brightness of the laser
spot on the target was independent of the viewing angle
(ϕ, θ), see Fig. 4. Note that the radiation intensity in
that case must vary as $\cos\theta$, where θ is the elevation
angle of the emission direction. Each projected unit area
corresponds to a physical area equal to $S/\cos\theta$ on the
target surface. Thus, for the brightness of the laser spot
to appear independent of angle θ, the radiated power per
unit area on the target surface must vary as $\cos\theta$. Hence,
the radiation emitted by the whole spot must follow the $\cos\theta$
polar distribution which is frequently called Lambertian.
The closeness to the $\cos\theta$ polar distribution is indeed the
measure by which one judges the closeness of a scatterer to
the ideal diffuser.

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* "Temperature" by T.J. Quinn. Academic Press, 1983, p.299
** Proc. Symp. on Thermophys. Properties, 7th Series USBS;
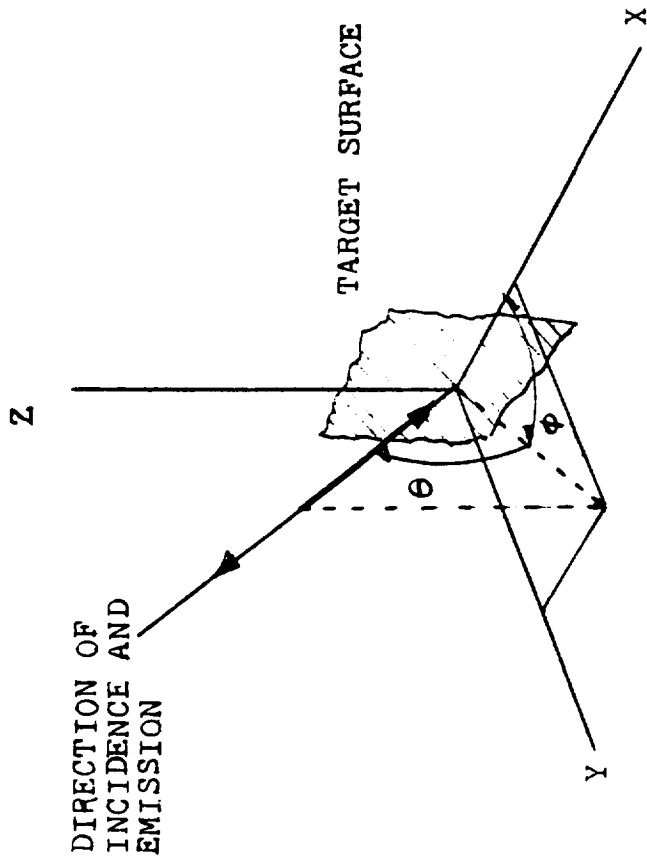   Published by ASME, NYC 1977, pp 344-350

FIG 3 DIRECTIONAL REFLECTIVITY DIAGRAM

TARGET SURFACE

$$\frac{S}{COS\ \theta}$$

S

θ
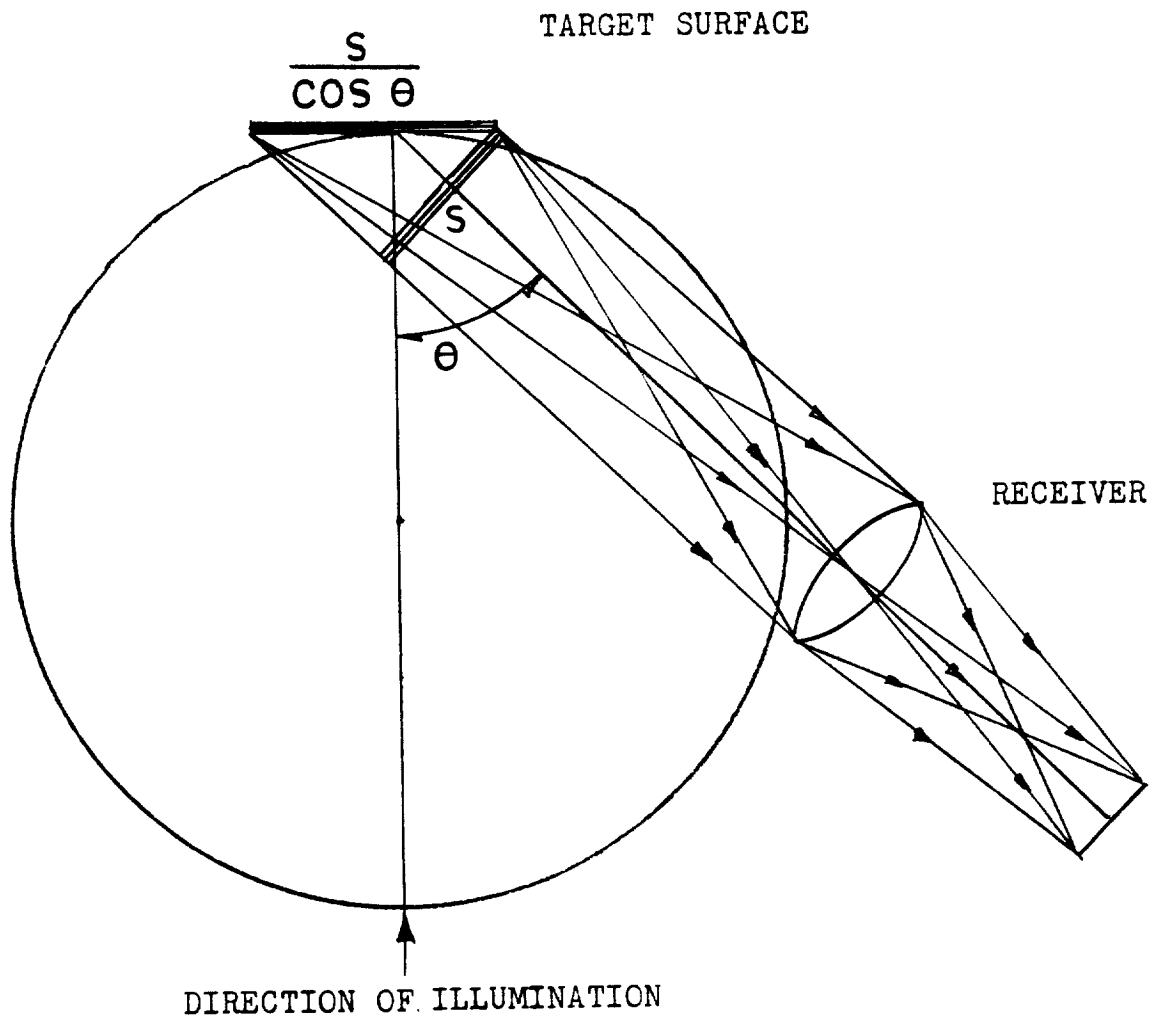
RECEIVER

DIRECTION OF ILLUMINATION

FIG. 4 LAMBERTIAN SCATTERING

Figure 5 shows the polar reflection patterns for metal furnace tubes, firebricks, and a $MgCO_3$ block used as a calibration target. Any variation from the $\cos \theta$ pattern leads to errors in the determination of th emissivity and hence errors and hence errors in the calculated temperature.

It may be shown that the calibration method of Traverse and Foex can be extended to cases where the target of interest and the calibration target are at different distances, as long as the distance ratio is known. One can thus calibrate an instrument in the laboratory at a certain target distance and then correct subsequent measurements for the actual target distance which must be determined separately.

In the hand-held Quantum Logic instrument, the target distance is determined with the help of split-image rangefinder optics. The lens is adjusted by rotation of a focusing ring which converts rotational into translational motion. The rotational motion is encoded. When the target of interest is in focus, an encoded lens position signal is fed to the instrument's micro-computer which calculates the target distance, D, via the Gaussian lens formula. Since the laser output varies with ambient temperature and other factors, it must be monitored. A monitor signal, V_2, is used to normalize the reflected laser signal. By normalizing the reflected laser signal, V_1, with the laser output signal V_2 and the square of the target distance, D, the emissivity is computed as:

$$\varepsilon_\lambda = 1 - C_{23} \; D^2 \; (V_1/V_2).$$
(2)

The target temperature is then obtained from the emissivity and the spectral radiance, L_λ :

$$T = \frac{hc}{\lambda k} \cdot \left\{ \ln \left(\frac{\varepsilon_\lambda}{C_{22} L_\lambda} + 1 \right) \right\}^{-1}$$
(3)

Here:

   h is the Planck constant

   c is the velocity of light

   k is the Boltzmann constant

   T is the target temperature in absolute units

   C_{22} and C_{23} are instrument constants.

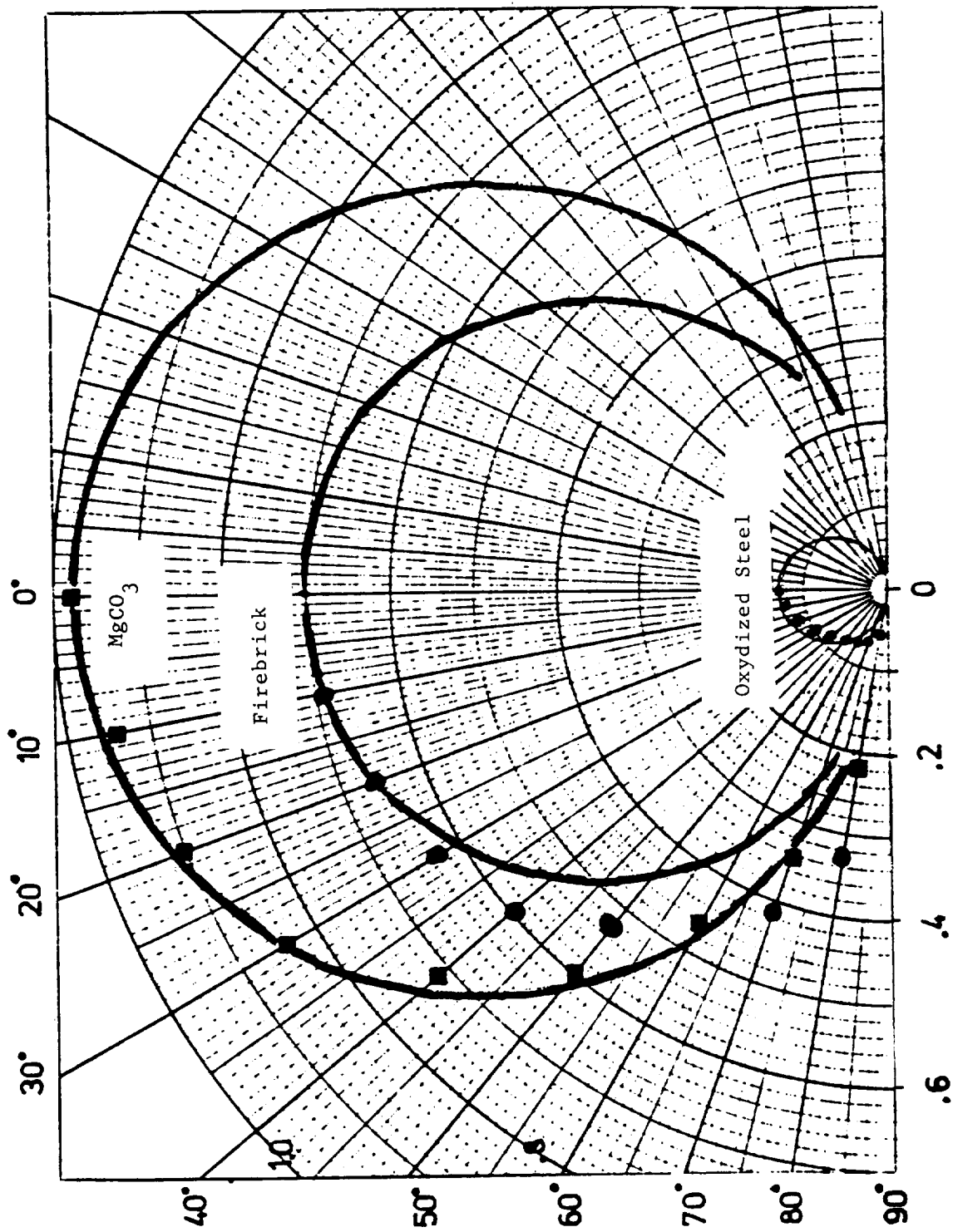Note that the radiance and reflectivity measurements are conducted at the same wavelength.

Fig. 5 Apparent Reflectivity vs. Aspect Angle

In summary, for uniformly diffusing targets, one can determine the emissivity from a bi-directional reflectivity measurement which must be normalized for target distance and laser power. When the target scattering deviates from the Lambertian uniformity, the emissivity determination and hence the calculated temperature values are in error.

ACCURACY ANALYSIS

To consider the effects of emissivity uncertainty or error on temperature accuracy, let us examine the dependence of temperature accuracy on the variances of the radiance and emissivity values.

By differentiating Equ.(3) one obtains the approximate expression:

$$\left|\frac{\Delta T}{T}\right| = \frac{\lambda kT}{hc} \sqrt{\left|\frac{\Delta L}{L}\right|^2 + \left|\frac{\Delta \varepsilon}{\varepsilon}\right|^2} \tag{4}$$

where $\frac{\Delta T}{T}$; $\frac{\Delta L}{L}$; $\frac{\Delta \varepsilon}{\varepsilon}$

represent the relative errors or uncertainties of temperature, radiance and emissivity, respectively.

It is worthwhile to study an example.

Let: $T = 1273^\circ K$ and $\lambda = 0.9$ microns.

In general, $\frac{\Delta L}{L} \ll \frac{\Delta \varepsilon}{\varepsilon}$, hence

$$\left|\frac{\Delta T}{T}\right| = \frac{\lambda kT}{hc} \cdot \left|\frac{\Delta \varepsilon}{\varepsilon}\right|$$

i.e., for our example:

$$\left|\frac{\Delta T}{T}\right| = \frac{1}{12} \cdot \left|\frac{\Delta \varepsilon}{\varepsilon}\right| \tag{5}$$

The 12-to-1 ratio between relative emissivity uncertainty and associated temperature error expressed by Equ.(5) is very helpful in reducing the requirements for emissivity accuracy in pyrometer measurements. However, in many cases of practical interest, the emissivity uncertainty is so large that even with the above leverage, large temperature errors are common if an actual emissivity determination is not made. For example, take the case of iron, where the pure material exhibits an emissivity as low as 35%, whereas the oxidized surface can have an emissivity as high as 95% at high temperatures. Or, the case of aluminum, where the emissivity can vary from 10% to 40% depending upon the degree of oxidation, surface treatment, etc. Other examples of significant changes in emissivity caused by chemical changes or depositions on the surface abound. It is therefore not untypical to find relative emissivity uncertainties of 50% and even 100%. In our example, the associated uncorrected temperature errors would be between 50°C and 100°C. Laser pyrometry yields emissivity determination at least one order of magnitude better, namely: 5% to 10%. The concomitant temperature accuracies would then be -in our example- only 5°C to 10°C.

Laser pyrometry is therefore particularly successful in cases where large and unpredictable emissivity variations are present. Here, improvements in the temperature accuracy by one order of magnitude are not uncommon. Even more dramatic improvements in temperature accuracy are achievable in furnace applications as discussed in the next section. Quantum Logic Corporation's laser pyrometers are in use in industrial and laboratory applications where the substantial improvements in temperature accuracy as described above are now being realized.

The above discussion applies for materials whose polar scattering patterns are uniformly diffuse. However, the polar scattering patterns of many physical surfaces actually fall between uniformly diffuse (Lambertian) and specular (mirror-like). One can therefore not make a general calibration of the above kind in such cases, since the relationship between the bi-directional and the hemispherical reflectivities is undetermined. For such cases, Quantum Logic Corporation has designed a modification of the above described technique. An instrument of this kind is being developed. The technical details cannot be disclosed at this time, since the patent application is still in review by the U.S. Patent Office.

The general design concept adopted by Quantum Logic Corporation in each of its instruments is that of a co-axial arrangement between laser transmitter, infra-red receiver and optical viewer. This eliminates all parallax problems, but calls for a high degree of optical and electrical isolation between the transmitting and receiving systems. Of course there are many other difficulties and complications which must be overcome in producing a practical and accurate system, and this has required many years of effort.

AMBIENT RADIANCE EFFECT

Until now we have considered only free-radiating targets. In many cases of interest, however, such as inside a furnace, the target is placed in an environment where other sources of intense radiation are present. This radiation is reflected off the target of interest adding itself to the target's self-emission and leading to false temperature readings. One such case to which Quantum Logic Corporation has given particular attention is the measurement of surface temperatures for steel tubes inside pyrolysis furnaces where radiation from the furnace walls is reflected off the tubes. The range of emissivity values which we have measured for furnace tubes varies between 60% and 95% depending upon the tube alloy, the tube age and the type of fuel employed.

Let us consider one particular example where the tube temperature $T = 1273^{\circ}K$ and the hemispherically averaged ambient radiance is equal to that of a black body at $1473^{\circ}K$. At the measuring wavelength $\lambda = 0.9$ micron, the measured apparent temperature is $20^{\circ}C$ higher than the true temperature where the tube emissivity is 95%. However, where it is 60%, the apparent measured temperature is $110^{\circ}C$ higher than the true temperature. Therefore, without a knowledge of the actual tube emissivity and a correction for the reflected ambient radiance, a large uncertainty in the temperature measurement results.

The Quantum Logic Corporation Model QL1300 series of instruments are specifically designed for the measurement of tube metal temperatures in furnaces. These instruments have provision for the measurement of the ambient radiance as well as the target emissivity and radiance. By exploiting the above relationship between reflectivity and emissivity, the instrument's computer compensates each target measurement first for the ambient component and then for the (measured) target emissivity to yield the true target temperature. With the QL1300 system customers have achieved accuracies of $\pm 3^{\circ}C$ for tube metal temperatures in the $800^{\circ}C$ to $1100^{\circ}C$ range, where conventional, uncorrected instruments gave errors of between $50^{\circ}C$ to $100^{\circ}C$.

CONCLUSION

For uniformly diffuse scattering (Lambertian) targets, such as are typically encountered in furnaces, the Quantum Logic Corporation laser pyrometer technology currently in production is capable of reducing by more than one order of magnitude the non-contacting temperature measurement errors which frequently result from emissivity uncertainties and reflected ambient radiation when using conventional (passive) technology.

For non-contacting temperature measurement of general surface types, including specular (mirror-like), Lambertian, and surfaces in between, Quantum Logic Corporation is presently developing extensions of its laser technology which are expected to provide performances equivalent to, or superior to, that which has been achieved with its current technology.