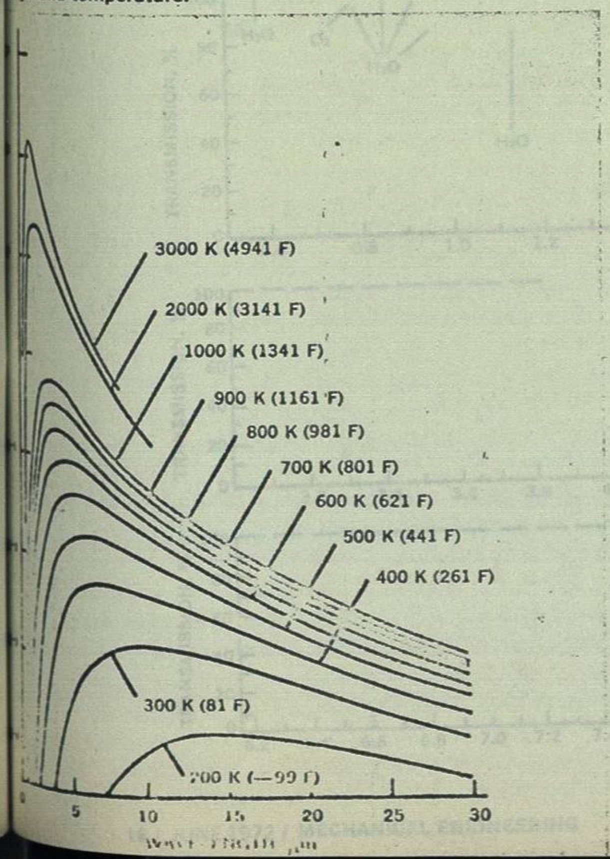
ERMOMETRY

Because it has been, until recently, the most accurate strument with which to measure high temperatures, has been fully developed and exhaustively studied. has been used to realize the International Practical mperature Scale at temperatures above the freezing mperature of gold, and its properties are extensively ported in the literature [3, 4]. Unfortunately the erature has been too little read by the users. Although the instrument will not be elaborated upon re, a brief description will be helpful to those not miliar with its construction and mode of operation, well as helpful in providing a background for what ll follow.

The disappearing-filament optical pyrometer is essentially a low-power terrestrial telescope in which a ngsten-filament vacuum lamp has been placed in e focal plane of the objective lens. A red glass ter is located between the lamp and the eyepiece. hen the telescope is sighted on an object or "target" whose temperature is sufficiently high that it glows visibly—the low-temperature limit on this type of pyrometer is 700 to 800 C, depending on several factors—the image of the target is formed in the same plane as the lamp filament. To the observer, viewing through the eyepiece and red filter, the magnified image of the lamp filament is seen superimposed on the image of the target. By adjusting the current through the lamp filament, the luminance, or brightness, of the lamp filament may be adjusted to match that of the target. Because the image is nearly monochromatic red (nominally 0.65 μm), no color difference is seen between the lamp filament and the target, and the filament seems to "disappear" against the background of the target. Under these conditions, the pyrometer is said to be photometrically "matched." By viewing a blackbody at various known temperatures [3] the pyrometer lamp current can be calibrated as a function of blackbody temperature. For target temperatures above 1300 or 1400 C a neutral "gray" absorbing glass filter is placed between the pyrometer lamp and the objective lens. This has the effect of providing a higher range for the pyrometer. Most such pyrometers are equipped with two or more such filters to extend their range to any desired upper limit.

Fig 1 Spectral radiance of a blackbody as a function of wavength and temperature.



Total-Radiation Pyrometer

The "ideal" total-radiation pyrometer would measure the radiance of a target, i.e.,

$$N = \int_0^\infty \epsilon(\lambda) N_b(\lambda, T) d\lambda \qquad (3)$$

where $\epsilon(\lambda)$ is the spectral emissivity of the heated surface, and will be discussed in more detail in a later section. For a blackbody, where $\epsilon = 1$,

$$N_b = \int_0^\infty N_b(\lambda, T) d\lambda = \frac{\sigma}{\pi} T^4 \qquad (4)$$

The signal S from a total-radiation pyrometer is dependent upon the difference between approximately the fourth power of the absolute temperature of the target and approximately the fourth power of the absolute temperature of the detector. Thus the typical lower useful limit for total-radiation pyrometers is approximately 100 C, although some are used below that temperature. Such instruments have been studied in great detail and are well described in the literature [5, 6]. For purposes of the present discussion, it is sufficient to note that the signal depends upon the radiance of the target after it has been attenuated by atmospheric transmittance, $\mathfrak{J}_a(\lambda)$, Fig. 2,[3] and the transmittance of the optical system, $\mathfrak{J}_0(\lambda)$, as well as modified by the responsivity of the thermal detector, $R(\lambda)$.

In virtually all cases the term total-radiation pyrometer is to a considerable extent a misnomer. Energy absorbed by the detector is converted to heat, causing the absorber temperature to rise above that of its surroundings until the rate of radiant heat input to the detector is equal to the rate of heat loss from the detector by means of conduction, convection, and radiation. The signal ultimately depends upon the temperature of the detector, which is therefore classified as a "thermal detector." The signal (after correction for the effect of ambient temperature) will be proportional to the integral of the product of a number of terms that are functions of wavelength, i.e.,

$$S(T) \sim \int_0^\infty \epsilon(\lambda) N_b(\lambda, T) \mathfrak{J}_a(\lambda) \mathfrak{J}_0(\lambda) R(\lambda) d\lambda \qquad (5)$$

$$S(T) = \epsilon_T T^n \qquad (6)$$

The primary application for such pyrometers has been at temperatures below that to which the disappearing-filament optical pyrometer was applicable, or where automatic recording or controlling of temperature was essential. In common practice [7, 8] the value of ϵ_T and the value of n are determined for each instrument and each application in a restricted temperature range. Because of its very broad spectral bandpass, such an instrument cannot be expected to exhibit a high degree of reproducibility if either $\epsilon(\lambda)$ or $\mathfrak{J}_a(\lambda)$ is variable in some portions of the spectrum. Variations in $\mathfrak{J}_a(\lambda)$ are ordinarily minimized by reducing the target distance as much as possible.

New Class of Radiation Thermometers

It should be clear that within the two classes of instruments described, industrial and laboratory applications have not had access to radiation thermometers that can measure temperature with reasonably high accuracy and that are also capable of both measuring and recording over most of the temperature range important in industry. Since the advent of modern photodetectors, that picture has begun to change, with rapid progress having been made in the past 15 years.

The initial change came primarily with the application of photomultipliers in place of the eye [9–11], and in automating [12, 13] the disappearing-filament optical pyrometer. One such instrument developed by the author [14] is described in a previous publication. High resolution is attained with this instrument and an indication of its accuracy [15], together with the accuracy of realization of the IPTS [16], is shown in Table 1.[4]

About half of the uncertainty of the automatic optical pyrometer as indicated in Table 1 is due to instability in the pyrometer lamp [17, 18], and most of the remain-

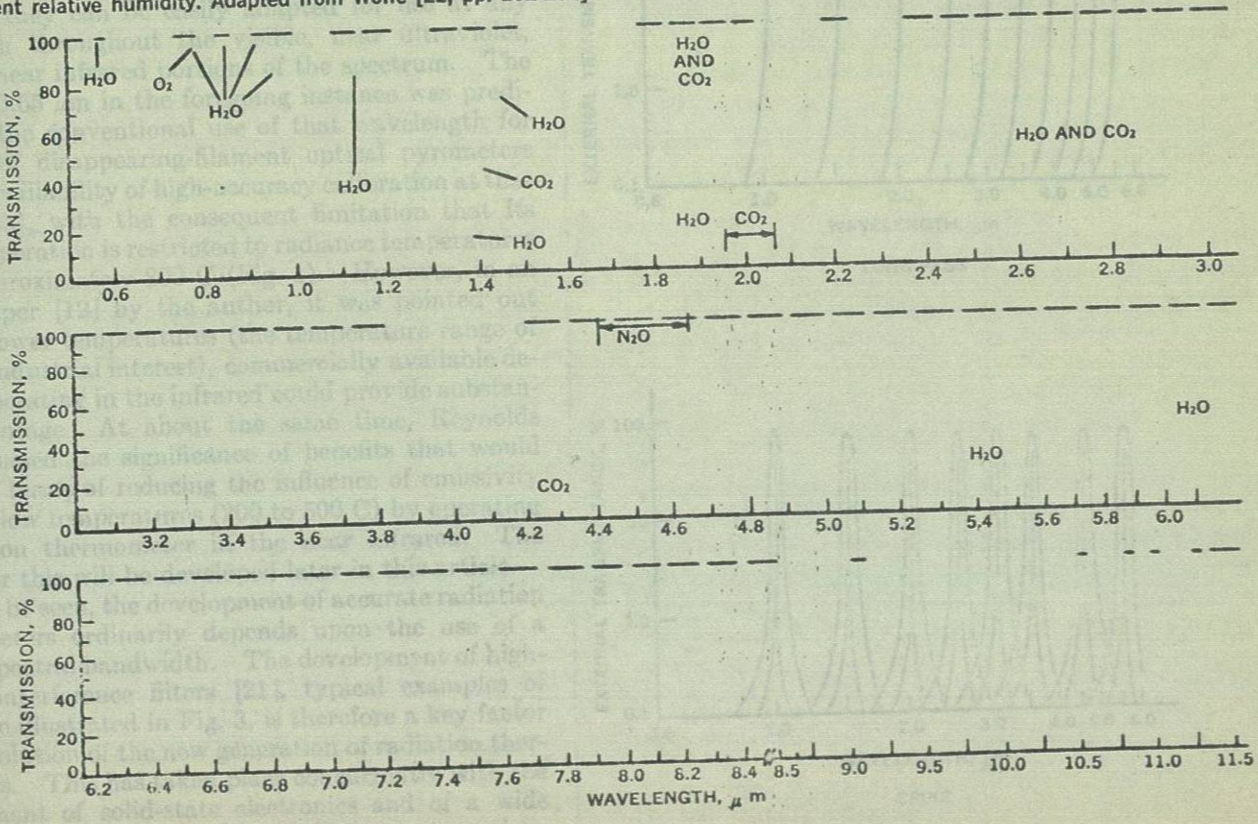


Fig. 2 Atmospheric spectral transmittance at sea level over a 0.3-km path containing 5.7 mm precipitable water at 79 F and 22.5 percent relative humidity. Adapted from Wolfe [22, pp. 252-254].

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[3] Transmittance varies approximately as an exponential function of path length and humidity, and is substantially greater at shorter distances. Nevertheless, the dominant absorption bands are very much apparent even at a distance of 1 m.

[4] Based on a preliminary analysis by Lewis and Kostkowski [15]. Effective wavelength is determined with an uncertainty of 0.2 nm. Calibration drift rate for a typical pyrometer lamp is about 0.01 C/hr, but may vary substantially from one lamp to another. The upper part of the table shows the results of a recent intercomparison of strip-lamp calibrations among four national laboratories, as presented by Lee et al. [16]. Maximum estimated uncertainties at the temperatures tabulated varied among the participating laboratories. The range of the estimated values is given in the table.

TABLE 1a International Comparison of Strip-Lamp Calibrations on IPTS-68

Temperature	(°C)	1064	1100	1200	1300	1400	1500	1600	1700	2200
Estimated Uncertainty	(°C)	.09-.12	.11-.15	.12-.17	.16-.20	.19-.22	.22-.25	.25-.29	.29-.43	.54-1.8

TABLE 1b Typical Uncertainty of Initial Calibration of Automatic Optical Pyrometers on IPTS-68 at the 95 Percent Confidence Level

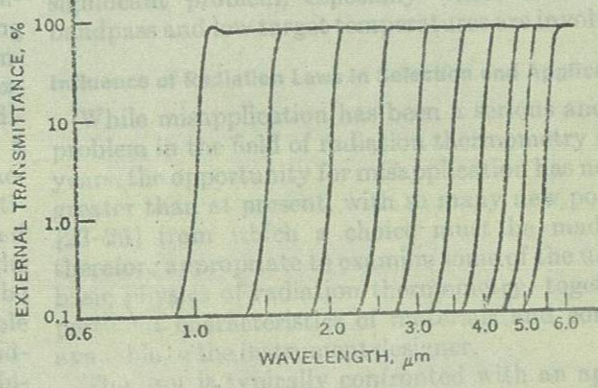
Range		Range 1			Range 2			Range 3			Range 4		
Temperature	(°C)	800	1064	1235	1100	1400	1750	1500	2300	2725	2500	2725	3524
IPTS uncertainty (NBS)	(°C)	.5	.12	.15				.32	1.5	2.4			
Pyrometer instability	(°C)	.5	.4	.4				1.3	1.4	1.6			
Transfer error	(°C)	.2	.2	.21				.4	.5	.5			
Maximum error	(°C)	1.2	.7	.8	1.2	1.2	1.6	2.0	3.4	4.5	5.8	5.7	8.7

ing uncertainty is associated with the IPTS. Quinn and Lee [19] have recently developed vacuum tungsten-strip lamps having long-term calibration instability not greater than 0.1 C/1000 hr, about a factor of a hundred improvement over presently used pyrometer lamps. The extent to which this improvement can be incorporated into pyrometer lamps is yet to be determined.

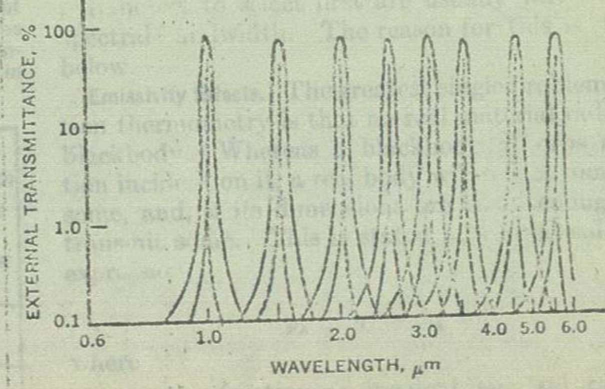
Automatic optical pyrometers of the type described operate at the conventional wavelength of 0.65 μm. However, they can be easily adapted for use at any wavelength throughout the visible, near ultraviolet, and very near infrared portions of the spectrum. The choice of 0.65 μm in the foregoing instance was predicated on the conventional use of that wavelength for purposes of disappearing-filament optical pyrometers (and the availability of high-accuracy calibration at that wavelength), with the consequent limitation that its range of operation is restricted to radiance temperatures above approximately 800 C (Fig. 1). However, in an earlier paper [12] by the author, it was pointed out that for lower temperatures (the temperature range of greatest industrial interest), commercially available detectors operating in the infrared could provide substantial advantage. At about the same time, Reynolds [20] discussed the significance of benefits that would accrue in terms of reducing the influence of emissivity errors at low temperatures (200 to 500 C) by operating a radiation thermometer in the near infrared. The reason for this will be developed later in this article.

As will be seen, the development of accurate radiation thermometers ordinarily depends upon the use of a narrow spectral bandwidth. The development of high-quality interference filters [21], typical examples of which are illustrated in Fig. 3, is therefore a key factor in the evolution of the new generation of radiation thermometers. This has taken place concurrently with the development of solid-state electronics and of a wide range of photodetectors [22] suitable for use in various

Fig. 3 Typical examples of commercially available interference filters. Adapted from Wolfe [22, pp. 299-306].



LONG PASS



SPIKE