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Modern radiation thermometers: calibration and traceability to national standards

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Abstract - Modern trend in radiation thermometry is to substitute the tungsten strip lamp with the silicon photodiode as a secondary temperature standard. Instruments built in this perspective are described. The design of transfer standards of this kind must follow orthodox mechanical, optical and radiometric criteria, presented in this paper. The result is an instrument whose calibration can be either primary, by use of a fixed point and a monochromator, or secondary, by comparison with a primary radiation thermometer kept in a National Laboratory, or with a secondary standard calibrated against a national standard.

1. OLD AND NEW

The history of monochromatic radiation thermometry is divided into three phases by the turnpoints: the invention of the disappearing filament pyrometer (Holburn and Kurlbaum, 1901), the use of photoelectric pyrometers by means of photomultipliers with red light sensitivity (R. Lee, 1966) and the introduction of the silicon photodiode as a detector in photometry (Witherell and Faulhaber, 1970) and in precision radiation thermometry (G. Ruffino, 1971).

The disappearing filament pyrometer (or visual pyrometer) has been for many years, and still partially is, the classical instrument for measuring high temperatures (above ca. 800°C). Its performance is based on the luminance match between the target to be measured and an incandescent tungsten filament within a moderately narrow band in the visible, peaked at ca. 650 nm. The band choice was dictated by the need of observing with the human eye: it was chosen in the red region of the visible spectrum by compromising between eye sensitivity and the luminance level of the sources to be measured. The band limits were set by a cut-off filter, with the edge at ca. 600 nm, and the human visibility curve for photopic vision. The temperature evaluation was based on Planck's law (in earlier times on Wien's approximation), by calculating the luminance integral within the transmission band at different temperatures. As the calculations were being performed before the computer era, they were carried out by using a mathematical device, called the effective wavelength, defined by the following equation:

$$\frac{\int_{\Delta\lambda} V(\lambda)\tau(\lambda)P(\lambda,T)\,d\lambda}{\int_{\Delta\lambda} V(\lambda)\tau(\lambda)P(\lambda,T_o)\,d\lambda} = \frac{\exp(C_2/\lambda_e T_o)-1}{\exp(C_2/\lambda_e T)-1} \qquad (1)$$

in which P(,T) is Planck's function:

$$P(\lambda,T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T)-1]} \qquad (2)$$

and:

$\tau(\lambda)$: filter spectral transmittance
T : kelvin temperature
T_o : reference temperature
λ : wavelength
λ_e : effective wavelenth
C_1 : first Planck's constant
C_2 : second Planck's constant (14388 um K)
$V(\lambda)$: human visibility function for photopic vision.

The effective wavelength depends from the transmittance of the filter and the responsivity of the detector, in the present case, the human eye. It must be noted that it is not a pyrometer constant, but depends on the temperature for which it is calculated.

Visible pyrometers were calibrated at the same time as tunstem strip lamps by means of known steps of radiation fluxes created by sectored discs. In this way pyrometric scales were set up by relating lamp currents to temperatures: the primary scale was the one of the pyrometer lamp. Secondary scales were generated and disseminated by means of tunsten strip lamps. The temperature defined by these scales was a luminance temperature, defined as the one of a black body emitting with the same luminance as the lamp at the stated wavelength. Thus the luminance temperature depends on the wavelength band through which the source is seen. Due to the usual difficulties in evaluating the bands and calculating radiation fluxes within finite bands, the luminance temperature was always related to the effective wavelength.

Here we must point out an inconvenience which has always affected the dissemination of the scales by means of strip lamps: National Laboratories specify the effective wavelength at which they are calibrated but don't supply data on the band shape, not even information on the temperature dependance of the effective wavelength. On the other hand, also the band shape of the pyrometers to be calibrated against the strip lamps is usually ignored, so that most probably the effective wavelengths of the standard and of the instrument under calibration differ. There it follows a disagreement of luminance temperatures which the operator is seldom aware of. Only when the pyrometer band is known, the luminance temperature can be corrected on the basis of published data of tungsten spectral emissivity. In any case the use of the effective wavelenth of 650 nm has been the only practice in keeping and disseminating the pyrometric temperature scales, so that it has been practically considered official.

In the mid sixties the situation has been improved by the advent of the photoelectric pyrometers using photomultipliers (or photocells) as detectors. Much higher sensitivity allowed the restriction of the pyrometer band, thus ressorting to a better definition of the effective wavelength. This fact, associated to improvements in fabrication and treatment of tungsten strip lamps, resulted in a very satisfactory agreement of the scales of the National Laboratories (of the order of 0.1 K). Now they are equipped with primary standard pyrometers, all using photomultipliers (S 20 extended red cathodes) and interference filters peaked at 650 nm. This wavelength is rooted at the origins of visual pyrometry and has been imposed by the existence in the field of secondary standards calibrated at that wavelength. We omit the description of the national standards to focus our attention onto the transfer standadrs and the precision laboratory instruments.

The temperature measured with a photoelectric pyrometer can be calculated with Planck law in the following form:

$$Q = \frac{\int_{\Delta\lambda} \tau(\lambda)\,\sigma(\lambda)\,P(\lambda,T)\,d\lambda}{\int_{\Delta\lambda} \tau(\lambda)\,\sigma(\lambda)\,P(\lambda,T_0)\,d\lambda} \qquad (3)$$

where: Q is the signal ratio (eventually corrected for non-linearity), T_0 is a reference temperature (a fixed point, e.g. the gold or copper melting point), $\tau(\lambda)$ is the spectral transmittance of the pyrometer (including lenses and interference filter) and $\sigma(\lambda)$ is the detector spectral responsivity. The product of spectral transmittance and responsivity is an istrument characteristic function and can be conveniently called Pyrometer Wavelength Function (PWF, symbol $\phi(\lambda)$. In primary pyrometry work the PWF is measured at finely spaced points and given in numerical form for numerical integration, so that the integral equation (3) can be easily solved by a computer. The effective wavelength turns out to be a useless computational tool: nonetheless it persists to be used to qualify the pyrometer band and to bring corrections into the strip lamp calibrations.

Now, in the practical laboratory use, above a certain precision level, the same uncertainty persists, as in the old visual pyrometry, in defining the radiance temperature by the specification of the effective wavelength of the working instrument. The reason is that the manifacturerers don't forward, and perhaps don't even know, the PWF of their instruments.In any case no doubt that the photoelectric pyrometers put in the

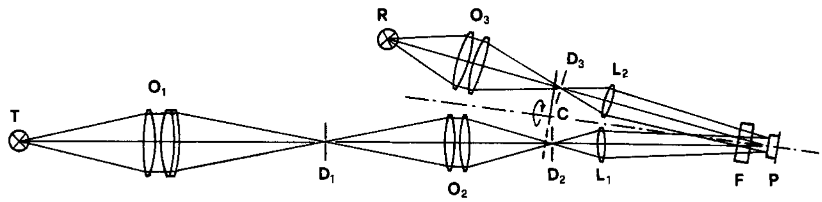

Fig. 1

Schematic diagram of the radiation thermometer of the IMGC

T, target; R, reference lamp; O_1, first objective lens; O_2, second objective lens; O_3, reference objective lens; C, chopper; D_1, field diaphragm; D_2, field stop; D_3, reference field stop; L_1, L_2, field lenses; F, interference filter; P radiation detector.

market greatly increased the precision of laboratory temperature measurements, and, at the same time, provided instruments with electric output for record and control.

But the photomultiplier is a too much delicate device to be mounted into an industrial instrument. So industrial radiometric temperature transducers, always required for record and control, ressorted to the use of the silicon photodiode. In the beginning of the seventies Faulhaber (30) pointed out that this device would be suitable for precise photometric measurements. At the same time, Ruffino (21), on the basis of noise and detectivity data, proved the applicability of the Si-photodiode to high resolution thermometry, provided the radiation band for the instrument should be chosen in the near infrared (NIR), namely around 1000 nm. Soon a precision radiation thermometer with a Si-photodiode was built at the Istituto di Metrologia G. Colonnetti (IMGC, Italy) (22). This instrument is represented in Fig. 1. The radiation of the target under measurement and of a reference strip lamp are sent alternately, through a rotating chopper and an interference filter peaked at 1000 nm, to a radiation detector. The transformation of this instrument into a fast pyrometer for pulse measurements was easily done by substituting the chopper with a shutter (18). Further improvements were brought to the pulse pyrometer, all in the same Insitute, by increasing the electrical bandwidth, thus extending the time resolution to the microsecond region, and extending the optical bandwidth, with the benefit of reducing the target dimension (to the submillimeter order) (8,9,19).

These instruments were simple and precise but could not be calibrated with the available lamps. Their calibration was a primary one and consisted of three steps: measurement of the signal at a reference point (usually the gold freezing point), control of the response linearity and determination of the PWF.

2. SILICON PHOTODIODE AS A DETECTOR AND AS A SECONDARY TEMPERATURE STANDARD

A comprehensive treatment of the Si-photodiode as a radiation detector is presented by W. Budde (5). He writes: "It is the workhorse in many applications in radiometry, photometry and colorimetry because of its ruggedness, simplicity of operation, linearity, and low price".

Si-photodiodes are formed by diffusing a thin layer of p-type impurity (acceptor) into the surface of a n-doped (donor) of a silicon slice. The region located between the p-doped and the n-doped materials is the depletion region, which absorbs the radiation striking it through the transparent p-doped layer. These devices are called PN planar diffused photodiodes. If the depletion region is made with intrinsic material, we get the PIN phtodiodes, in what the larger depletion depth, particularly if associated with reverse bias, causes smaller diode capacitance. As a result its response time is shorter and the linearity is better. Also Schottky photodiodes exist, but nowadays they are less used in radiometry.

Si-photodiodes are sensitive to radiation within a wavelength range of 200-1100 nm. A typical spectral responsivity curve is represented in Fig. 2 (from EG&G data sheets). For this particular type the peak responsivity is located at 900 nm and amounts to 0.5 A/W. In this region the quantum efficiency nearly reaches 100%.

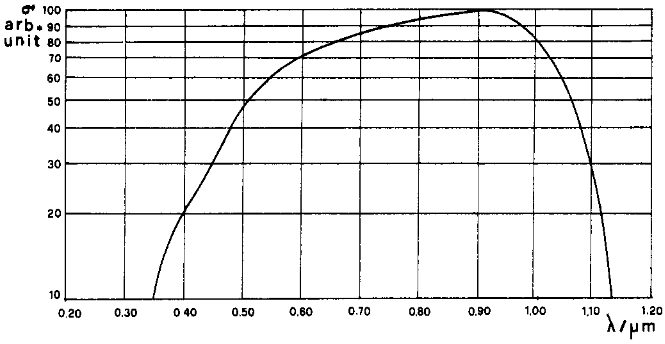

Fig. 2 Spectral response of a Si-photodiode

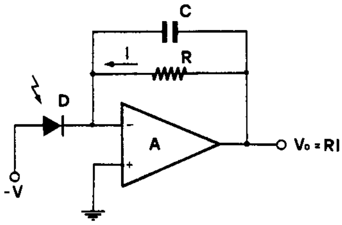

Fig. 3. Photodiode connection with trans-resistance amplifier

D, photodiode; A amplifier; R, load resistor; C, parallel capacitor; I, short circuit current; V , output; -V, bias voltage

Since Geist proposed the use of the Si-photodiode in making an absolute radiometric standard in 1976 (12), this device has been submitted to intensive research to investigate its capability for radiometric measurements so that now it is well accepted in this field (13,14,15,32,33).

For thermometric work, the Si-photodiode possesses two desirable properties: it is linear and it is relatively insensitive to ambient temperature variations.

Different authors have measured the Si-photodiode linearity. Budde (3,4), following the multiple aperture method devised by Sanders (27), explored the linearity over 8 decades: for one type it was excelent (non-linearity much lower than 1%) and some types presented "supersensitivity" at higher levels in the NIR. Jung (16) measured linearity characteristics of low-noise Si-detectors for currents between 0.3 nA and 0.1 μA and wavelengths between 600 nm and 1100 nm. He concluded that in radiation thermometry with Si-detectors the temperature error due to detector non-linearity can be kept below 10 mK between gold point and zinc point. Other non-linearity measurements were carried out by Schaefer et al. (28). As a rule, for radiation thermometry in the precision range of 0.1 K within wide temperature range (1000 K - 2000 K), the Si-detector non-linearity may be neglected. For higher precision and wider ranges it should be checked in order to bring appropriate corrections for non-linearities. A fast method for checking linearity has been devised by Coslovi and Righini (10).

The temperature coefficient of responsivity is wavelength dependent: it is negative slightly below 600 nm and it increases strongly above 1000 nm (Jung (16); cfr. Budde (5), p. 243). Finally it must be noted that the Si-detector is exempt from fatigue if it is not grossly overloaded.

The Si-photodiode can operate in the photovoltaic mode - and then it is unbiased - or in the photoconductive mode, with or without reverse bias. The electronic circuit for this mode is represented in Fig. 3 (in the unbiased mode the non-reversing input of the amplifier is simply connected to the anode). The load resistor R is of the order of 1 MΩ, and the capacitor C creates a time constant of integration sufficient to partially suppress the noise at the expenses of the response time of the diode. The diode current I includes the dark current and the output is RI plus the amplifier off-set. Some manifacturers, as EG&G, produce photodiodes with integrated operational amplifier. In any case the resistor R is connected externally for most convenient gain.

We must keep in mind the diagram of Fig. 3 when we speak of the temperature coefficient, which in practice never affects the diode alone. As a matter of fact, ambient temperature bears an influence on photocurent, dark current, amplifier off-set current and voltage and load resistance. Extreme care must be devoted to select a very stable load resistor, with low temperature coefficient (the metal film resistors are the best choice).

All the attractive qualities of the Si-photodiode lead to the conclusion that silicon spectral radiometry may constitute a valid alternative to the tungsten strip lamp as a secondary temperature standard. As a result a radiation thermometer without the enclosed reference lamp can be constructed.

3. DESIGN RULES OF A STANDARD RADIATION THERMOMETER

The correct performance of a high quality radiation thermometer is based on an orthodox optical and mechanical design. The rules of a good optical design can be described on the basis of Fig. 4. An objective lens OL, whose principal planes are represented in the figure, projects the image of the target T to be measured on diaphragm D, which is more a baffle than a proper field stop. A relay lens RL, consisting of

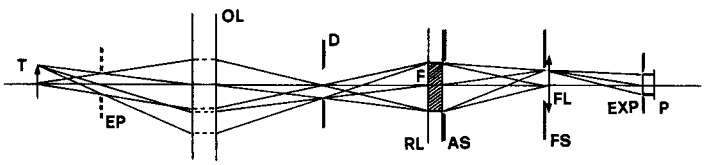

Fig. 4
Schematic diagram of a radiation thermometer
T, target; EP, entrance pupil; OL, objective lens; D, diaphragm; RL, relay lens; F, interference filter; AS, aperture stop; FS, field stop; FL, field lens; EXP, exit pupil; P, radiation detector;

two symmetric doublets and similarly represented by its principal planes, forms the image of the source on the field stop FS. Between the two elements of the ralay, where rays are parallel, a narow-band interference filter F is located, and, on the rear of the relay, there is the aperture stop AS, which delimits the radiation beam. A thin lens, adjacent to the field stop, and therefore called the field lens FL, projects the image of the aperture stop on the sensitive area of the photodiode P, which is the exit pupil EXP of the optical system. The scheme might appear complicated - and it is not realized by all manifacturers - but it is necessary to comply with the following rules.

A) The geometry of the radiation beam which is used to perform th temperature measurement must be well defined and fixed. The radiation flux is the product of the radiance, the field stop area and the solid angle subtended by the aperture stop on the center of the field stop. These geometrical elements must be fixed, whichever the position of the target to be measured. The ojective lens can move along the optical axis to focus the target: as a consequence the entrance pupil EP, namely the image of the aperture stop projected into the object space, moves and the target area is changed so as the flux remains constant. A further requirement is that the beam intercepted by the entrance pupil must not be limited by the objective lens rim. It is apparent that the relay is a need to comply with this rule.

B) The sensitive area of the detector must be placed on the exit pupil of the instrument. (The exit pupil EXP is the image of the aperture stop in the image space). If this condition is met, the radiation beam issued by any point of the source is collected by the whole sensitive area and any inhomogeneity of the detector responsivity doesn't affect any point of the target.

C) The radiation beam must be parallel and normal to the interference filter. The reason is that the wavelength of the light transmitted by the filter depends from the incidence angle and, although the transmitted band is constant when the incidence angle is constant, we have a narrower and better defined band with normal incidence of radiation.

D) The objective lens must be achromatized for the red and the near infrared portion of the spectrum. If the target is aimed at and focused visually, its image is seen through a red glass. On the other hand the optimum peak wavelength of the pyrometer is 900 nm, where the detector has high sensitivity, good linearity and temperature stability. Therefore the doublets composing the objective lens must be calculated for the mid-wavelength line r of the spectrum (706.5 nm) and achromatized for the s and C lines (852.1 nm and 656.3 nm respectively). Moreover the secondary spectrum has to be low. The two relay elements must be doublets if we want good spherical correction and they must be calculated with the same procedure as the ojective lens, especially if more filters of different wavelength in the NIR are to be used.

The color correction doesn't seem to be taken into consideration by the majority of the NIR pyrometers designers, who simply mount the lenses offered by the optical market. As these are color corrected only for the visible, one is almost sure that no infrared image falls on the physical field stop of the pyrometer.

Another rule concerns the mechanical design. The optical axis must be very stable: all optical elements must be centered and normal to it. To give a figure, the excentricity should not exceed 0.01 mm: this is particularly important if we want a very small target dimension or field stop. The best way to do so is to align all elements within a metal tube; if this has to be split in few parts, their coupling must be very precise (the same tolerance as above). Also the detector must be snugly fitted in a cavity which centers its sensitive area on the axis: here centering is not so important, but stability is.

Finally precautions should be taken with regard to ambient influence on the pyrometer signal. The best way to cope with the drifts caused by ambient temperature is to contain all temperature-sensitive elements in a thermostated enclosure. This keeps the detector, the amplifier -including the load resistor - and the interference filter. The latter must be protected against humidity. This is prevented to leak into the coated surface of the filter by a seal on the edges of all glasses packed to form the blocked filter. A further and more drastic precaution may be taken by sandwichig filter and relay lenses into a cartouche sealed at both ends with O-rings, after careful drying of the elements. This set-up is also efficient against dust that can deteriorate the filter transmittance. As a matter of fact, dust is the worst enemy of optical components: the only way to fight it is to make the whole pyrometer dust-proof. Cleaning is a poor remedy, as it never restores transmittances to their initial values, as it is required by high precision measurements.

4. MONOCHROMATIC PYROMETERS WITH Si-DETECTORS

The first precision monochromatic NIR pyrometer without reference lamp has been described by Sakuma and Hattori (25). It uses a Si-photodiode working with half-bandwidth of 14 nm peaked at 900 nm. The target diameter is 3 mm at a distance of 400 mm and the focusing range goes from this value to infinity. The temperature ranges from 420°C to 2000°C and the temperature resolution is 1°C at 420°C and better than 0.01°C above 600°C. The calibration is made at three points with fixed point black-bodies, to determine the coefficients of the interpolating equation:

$$V(T) = C_2 \exp(-C\ /(AT+B)) \qquad (4)$$

Further advancements were made (26) by building two other pyrometers , one with peak wavelength of 870 nm and the other with 1000 nm, and comparing the three scales after calibration at the same points: they agreed within ±0.5°C between 450°C and 1450°C. Two of these instruments were submitted to primary calibration by taking their signals at the copper point and by measuring the PWF within limits where the signals fell to 10^{-6} of the peak value. The scales based on this calibration agreed with the IPTS within ±0.4°C at the silver, aluminium and zinc points.

Another pyrometer of this type has been made by the author of this note (23). Its optical schematic diagram is represented in Fig. 5. Its construction strictly follows the

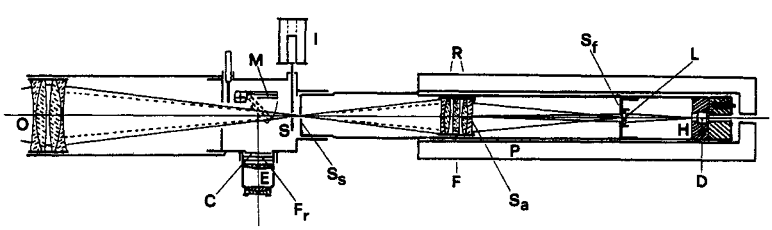

Fig. 5

Diagram of the pyrometer of the National Physical Research Laboratory (S.A.)
A, attenuator; C , cross-hair; D, detector; E, eyepiece; F, filter; F_r , colour filter; H, detector holder; I, solenoid; L, field lens; M, mirror; O, ojective lens; P , heat pipe; R, relay lens; S, shutter; S_a , aperture stop; S_f , field stop; S_s , field selector.

design rules listed in the previous section. Their validity has been proved by a check of the self-consistency of the calibration: by dismantling completely and reassembling the instrument, readings were repeated within 0.1 K at 1700 K. The detector-amplifier-filter assembly is thermostated with a heat pipe of ethil alcohol in aluminium kept at 15°C. This pyrometer has a primary calibration with the reference temperature at the freezing point of copper. The standard deviation over seven plateaux has been 15 mK. The PWF has been taken with an automatic data acquisition system, which is also used for the pyrometer operation. Dark signal, which seems to be reasonably stable with time, is read before and after a set of measurements, by automatically flipping in and out a shutter.

This pyrometer doesn't possess any particular electronic circuit to convert the detector signal into temperature: such circuit will never be accurate enough for a standard or a precision laboratory instrument. The whole conversion is made in software after sending the signal to a computer. There are two ways of performing the calculations. One consists in solving by an iterative process the integral equation (3). Another avenue consists in calculating, with the same equation, the detector signal V(T) corresponding to a number of temperatures and the fitting ln(V(T)) into a polinomial of 1/T:

$$\ln(V(T)) = a + b/T + c/T^2 \qquad (5)$$

which gives an arithmetic accuracy of ca. 0.01 K.

Further investigations have been carried out on this instrument (24): without temperature stabilization a reading drift of ca. 40 mK resulted from ambient temperature variation from 16°C to 21°C. Over a period of 24 days the pyrometer reading at a constant temperature drifted 60 mK. We don't know for the moment the exact origin of this drift, as its responsibility cannot be ascribed exclusively to the detector.

At the same time as the previous one, a similar tansfer standard pyrometer has been built at the IMGC by Rosso and Righini(20). As it appears in the schematic diagram of Fig. 6, it results by suppressing the reference channel in the pyrometer represented in Fig. 1, with all the technological improvements that were brought to that instrument. The target distance varies from 350 to 1100 mm, its size from 0.8 to 3.5 mm respectively. It can work in three bands, peaked at 650, 900 and 1000 nm. The temperature resolution reaches 0.01 K. The pyrometer has a primary calibration. The uncertainty at the gold point is estimated to be less than 0.2 K. Particular care has been taken of the linearity measurement carried out with the system described in ref (10). Non-linearity resulted in temperature errors smaller than 0.03 K, except that in the higher portion of the scale with 1000 nm filter. The total uncertainty of the instrument at 900 nm reaches 0.8 K. At 2000 K and it is somewhat higher with the other wavelengths.

When this pyrometer works at 900 nm, the output signal changes very weakly with sensor temperature (less than 0.2% for ambient temperature change between 15°C and 30°C). For other wavelengths, especially for 1000 nm, the temperature coefficient is substantially higher; but, in any case, the detector temperature is monitored by a sensor placed in thermal contact with it.

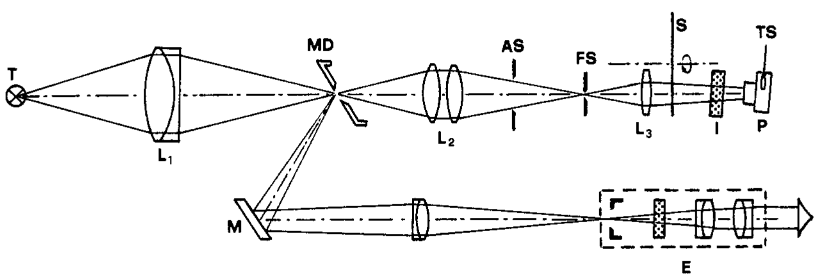

Fig. 6

Diagram of the pyrometer of the IMGC without reference lamp

T, target; L_1, movable objective lens; L_2, relay; L_3, field lens; MD, mirror-diaphragm; AS, aperture stop; FS, field stop; S, shutter; I, interference filter; P, Si-photodetector; TS, detector temperature sensor; M, mirror; E, eyepiece of the viewing microscope.

This pyrometer has been compared during a year with a set of high stability lamps by Bussolino et al. (6). The results of monthly comparisons showed that the high temperature scale kept on the transfer standard pyrometer and that kept on the high stability lamps are equivalent within the reproducibilty of the scale on the lamps (±0.3 K band in the temperature range 1000-2000 K). This instrument has been calibrated at the gold point three times before the comparison and two times afterwards: a difference in the reference signal has been detected which, for the 900 nm operation, corresponded to 0.87 K. The behaviour of this drift has been checked with another set of periodical comparisons carried out during the same time span at fixed temperature against a high stability lamp.

Two more instruments should be mentioned, although they are not completely related with the previous ones. The first has been made by Woerner (31) in the Insitut fuer Kernenergetik (IKE, west Germany): it is based on the linearity of a photoemissive cell and operates in the 650 nm band. It has resolution of 0.02 K at 1337 K. Extended tests at the PTB showed agreement with the standard pyrometer within a few 0.1 K on strip lamps up to 2500 K and to within 0.1 K on a black radiator up to 1700 K.

Another optical pyrometer has been made by Szilagyi (29) in the National Office of Measures (Hungary): it uses a Si-photodiode, but it operates in the 650 nm band. It has been copared with a strip lamp, showing a discrepancy of not more than 0.25 K.

5. CALIBRATION AND TRACEABILITY OF MONOCHROMATIC PYROMETERS OPERATING IN THE NIR

The temperature scale above the gold freezing point (1337.58 K) is kept by National Laboratories by their standard pyrometers and sets of high precision strip lamps, all calibrated for the radiance temperature in the vicinity of 650 nm. These scales are disseminated by strip lamps calibrated at the same effective wavelength.

This situation has been quite satisfactory when all precision pyrometers in use for research worked at the same wavelength of 650 nm. The introduction of the Si-detector has changed the wavelength band of the new pyrometers and therefore has created problems to their calibration. At the present moment there are four types of calibration.

A) Primary calibration. It consists of three steps:
1) Reading of the detector signal at a reference temperature, which is usually the freezing point of copper, namely at 1358.02 K (the gold point is used to define the IPTS, but it is too expensive for ordinary laboratory work). This calibration requires a blackbody cavity in a crucible containing the pure (99.999%) metal, placed in a tubular furnace.
2) Determination of the PWF, a function which is given at points acquired automatically by focusing the pyrometer on the exit slit of a monochromator whose wavelength shaft is actuated by a computer via a stepping motor: at each wavelenth step the pyrometer reading is taken and stored. Each reading is corrected for the monochromator transmittance and the source radiance and emittance. The function, in tabular form, is used to calculate the temperature.
3) Non-linearity determination of the sensor, which is performed by reading the signal at a number of steps of radiation flux. These steps are created by the addition flux method, i.e. by summing up two fluxes on a beam combiner, or with use of a neutral optical attenuator.

B) Calibration at fixed points. This procedure is followed by Sakuma et al. (26), who use three black-bodies at the freezing points of Al, Ag and Cu. The scale is created by interpolating the signals and temperatures with the formula (4). The problem of this calibration procedure is to find the interpolating formula which gives the best conformity of the pyrometer readings with the IPTS.

C) Calibration conversion of strip lamps. The radiance temperatures of the same source at different wavelengths are related by the following equation:

$$1/T_r = 1/T_{r1} + (\lambda_1 \ln(\tau(\lambda_1)\varepsilon(\lambda_1)) - \lambda_2 \ln(\tau(\lambda_2)\varepsilon(\lambda_2))/c_2 \qquad (6)$$

in which the symbols have the usual meanings and indexes 1 and 2 are referred to the two wavelengths. To take into account the finite band of the pyrometer an effective wavelength should be introduced into this equation.

The calibration conversion requires the knowledge of the emissivity ε which is given by the littarature, and of the transmittance of the lamp window, which shoul be, but never is given by the manifacturers. This problem has been investigated by Ricolfi and Lanza (17), by Battuello and Ricolfi (1,2) and Dumitrescu et al. (11). A general conclusion is that, if transmittance data are available, either by measurements in situ or on window samples, the calibration conversion is affected by an error not much higher than the orginal uncertainty of the calibration at 650 nm. Ricolfi gives useful formulas for this conversion. But three objections can be made against the use of the strip lamps for calibration:

1) strip lamps are less and less available on the market;
2) Their window transmittance in the NIR is not adequately known;
3) the manifacturers of radiation thermometers with silicon detectors use a wide variety of wavelength bands on which they don't forward any information to deduce their effective wavelength and, above all, the temperature dependance of the latter. This difficulty would hardly be removed even if provision is made by the National Laboratories to supply lamp calibrations in the NIR.

D) Calibration by comparison with a transfer standard pyrometer. This procedure consists in focussing the pyrometer to be calibrated and the standard on the aperture of a black-body at different controlled temperatures. Excellent cavities at uniform temperature and with high emissivity can be done with heat pipes, but, with the present technology, their operating temperature has an upper limit of 1100°C. Higher temperatures can be reached by using refractory materials to make the cavities; but then emissivity and temperature problems may arise. This subject is discussed by Battuello and Ricolfi (2). Despite the aforementioned difficulties, this method seems to be the most accurate for working pyrometers calibration.

In any case a common basis of temperature measurement for thermophysical properties must be established with the traceability of the working instruments to the national standards, by means of a relyable chain of sub-standards, and by the intercomparison of the scales of the National Laboratories.

Let us conclude with a personal remark. Modern experimentation is made by automatic data acquisition and process systems. The metrological core of these systems is the digital voltmeter multiplexed to all sensors of the experimental system. With this arrangement the radiation thermometer only needs a reliable sensor with the simplest pre-amplifier whose output is measured by the digital voltmeter and the reading is processed in software to yield the temperature. A relatively small addition to the experimental system, consisting of a monochromator and a fixed point black-body, could provide a calibration facility in the same research laboratory. The cost of these additions is largely compensated by the higher precision attainable, by better reliability and by independance from sophisticated and expensive electronics for the processing in hardware of the temperature signal.

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