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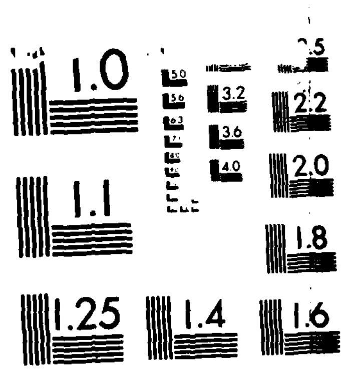

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THE MODIFICATION AND APPLICATION OF A TWO-COLOUR DISAPPEARING-FILAMENT PYROMETER TO PERFORM FLAME TEMPERATURE MEASUREMENTS

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TECHNICAL NOTE 85-27

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25B10

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ABSTRACT

An optical pyrometer of the disappearing-filament type was modified to allow brightness temperature measurements to be made in the green region of the spectrum. The modified instrument was re-calibrated at a wavelength of 547 nm. The manufacturer's calibration of a second pyrometer operating at λ = 645 nm was verified. Sources of error in the calibrations are discussed. The theory and limitations of two-colour pyrometry as a means of obtaining true source temperatures are presented.

1.0 INTRODUCTION

As part of a general investigation of the effects of fuel composition on the performance and durability of military engines, studies are being carried out in the Department of Mechanical Engineering, Laval University on the combustion of tar sands derived fuels in an experimental gas turbine combustor. The measurement of flame temperatures and emissivities is an important component of this work.

In order to utilize the well-known technique of red/green temperature measurements to obtain the true kinetic temperature of a source, it was necessary to modify an optical pyrometer to accept a green filter, which would allow measurements to be made of flame brightness temperatures at a wavelength of approximately 550 nm. A second identical instrument equipped with red filters was used for making measurements of brightness temperatures in the red ($\lambda \sim 645$ nm).

Although two-colour visible and infrared pyrometers are available commercially, preliminary investigations at Laval University showed that these instruments lacked sensitivity and it was decided to buy two disappearing-filament pyrometers and modify one to operate in the green. These flame temperature measurements will supplement the total flame radiation measurements and high-speed colour cinematography work at Laval.

This report describes the basic instrument and the modifications that were carried out, and gives the new calibration of green brightness temperature for the instrument. Limitations on the accuracy of the calibration are discussed in the last section.

2.0 THEORY

The spectral radiance of a blackbody is given by the Planck radiation law:

$$N_\lambda = \frac{C_1}{\lambda^5 \left[\exp (C_2/\lambda T)-1\right]} \qquad [1]$$

where N_λ is the spectral radiance in $W/cm^3/sr$, λ is the wavelength in cm, T is the blackbody temperature in Kelvin, and the radiation constants C_1 and C_2 are equal to 1.1909×10^{-12} $W.cm^2/sr$ and 1.4380 cm.K, respectively. Tables of N_λ for a wide range of temperature and wavelength are given by Pivovonsky and Nagel (Ref. 1).

In the special case where the temperature is low and λ is small, eg. for visible radiation, the term $\exp (C_2/\lambda T)$ in equation 1 is very large compared to 1 and the equation can be simplified to give the Wien radiation law:

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

This latter equation was used in the calculation of lamp brightness temperatures for this report.

The spectral radiance of a tungsten strip filament lamp, as used in the calibration of the pyrometer, is given by:

$$I_\lambda (T) = \varepsilon(\lambda,T)\, N^o_\lambda (T) \qquad [3]$$

where $N^o_\lambda(T)$ is the spectral radiance of a blackbody at temperature T, and the emissivity ε is a function of both λ and the true filament temperature T. The emissivity is also dependent on the viewing angle but this is usually measured normal to the surface.

The emissivity of tungsten for visible wavelengths and temperatures of interest is between 0.4 and 0.5. This emissivity has been measured by Larrabee over the range λ = 0.31 to 0.80 µm and T = 1600 to 2400 K (Ref. 2). By assuming linear dependence of ε on T and λ over a limited wavelength range he provides equations which can be used to calculate ε in three spectral ranges. For the wavelengths of interest to us in this work, the emissivity is given by:

$$E(\lambda,T) = 0.4655 + 0.01558\lambda + 0.00002675T - 0.00007305\lambda T \qquad [4]$$

where T is the temperature in Kelvin and λ is the wavelength in micrometers.

The brightness temperature T_B of a non-black surface may be defined as the temperature of a blackbody which, at a specified wavelength and temperature, would give the same spectral radiance as the surface, ie.

$$N_\lambda(T_B) = I_\lambda(T) = \varepsilon(\lambda,T)\, N_\lambda^{o}(T) \qquad [5]$$

Since ε is always less than unity, the brightness temperature T_B is always less than the true surface temperature T. From equations [2] and [5], we can derive an expression for T_B in terms of the filament temperature T, λ and ε:

$$T_B(\lambda, T) = \frac{T}{1 - \frac{\lambda T}{C_2} \ln \varepsilon(\lambda, T)} \qquad [6]$$

Due to a reflective loss in transmission of approximately 8% at the lamp envelope surfaces, the measured brightness temperature is less than that calculated from equation [6]. However, the lamp calibration provided by NRC includes this transmission factor.

Our secondary standard lamp was calibrated by NRC using an optical pyrometer and they provided us with a calibration of lamp current versus brightness temperature at wavelength λ = 654 nm. To obtain a calibration for the standard lamp at the operating wavelengths for the pyrometer, we had to convert this brightness temperature to the equivalent values at λ = 645 nm and 547 nm. Since we do not know the true filament temperature T, and since both the filament emissivity and brightness temperature depend on T, it can only be obtained from equation [6] by iteration (Ref. 3). This is a tedious process and it is much simpler in practice to calculate ε and T_B at discrete values of filament temperature T at the three wavelengths of interest; 654 nm, 645 nm, and 547 nm. These data are shown in Table I for filament temperatures 1000 to 2650 K at 50K intervals. The emissivities were calculated from the formula given in equation [4] and the corresponding brightness temperatures from equation [6]. Linear interpolation was used to obtain T_B values at λ = 645 nm and λ = 547 nm from the 13 calibrated T_B values at λ = 654 nm. Brightness temperatures were also calculated for λ = 630 nm and 557 nm, but these are not shown in the Table.

3.0 EXPERIMENTAL

3.1 Description of Optical Pyrometer

The instrument used in these measurements was the Micro-Optical Pyrometer Model No. 95 manufactured by the Pyrometer Instrument Company of New Jersey. It is of the disappearing filament type and is capable of measuring temperatures of targets as small as 0.001" in diameter. The instrument was supplied with a small table-top tripod but this was found to be rather unstable during operation of the pyrometer. The tripod was replaced with a 0.5 in diameter rod screwed into the base of the instrument and inserted into an optical mount. The instrument can be adjusted in azimuth and elevation with the use of vernier-type worm gears.

The focal distance can be adjusted from 12.5 cm to infinity using a knob on the side of the instrument and with the help of a set of six auxiliary objective lenses. An external lens must always be used with the instrument in order that the factory calibration be valid. In our calibrations a target distance of 1.5 m was used.

A schematic diagram of the instrument is shown in Fig. 1. The optical system includes a Huygens microscope type ocular eye lens which permits a 20x magnification of the object under study. The objective lens system forms an image of the target in the plane of the internal reference lamp. This in turn is focussed by the achromatic lens at the diaphragm stop. The two superimposed images are finally viewed by the eye piece.

Two red filters are used to reduce the intensity of the lamp target source and restrict the wavelength bandpass to a small region around 645 nm. The light red filter cuts on at λ = 600 nm and has a flat transmission of approximately 92% from 630 nm to 750 nm. The relative spectral response of the system to the eye, R_λ is given by the relation $R_\lambda \alpha T_\lambda N_\lambda P_\lambda$, where T_λ is the transmission of the red filter, N_λ is the spectral radiance of the lamp, and P_λ is the photopic eye response. These three parameters, which are all functions of λ, are given in Table IIA together with the relative spectral response. The effective centre wavelength for the system was obtained by plotting R_λ versus λ and was found to be 630 nm. The integrated response curve has equal area above and below the effective centre wavelength. This filter is used for measuring targets at temperatures below 1000°C.

The dark red filter (#2) cuts on at λ = 630 nm and has a constant transmission of 88% from 660 to 750 nm. This filter is used for measuring target temperatures in excess of 1000°C. Table IIB tabulates the corresponding data for the dark red filter. The effective centre wavelength for the system with this filter was 645 nm.

The instrument was supplied with a 4.5V battery and a Model 90 power pack. The power pack was used for all these measurements. The measured temperatures were indicated on a direct-reading meter of the supressed-zero type, which allowed full use of the entire scale for maximum precision. There were three switch-selectable temperature ranges on the meter, viz. 700 - 1400°C, 1300 - 1900°C, and 1800 - 3200°C. Two neutral density (ND) filters were introduced into the beam between the target and the internal filament when operating on scale ranges 2 and 3. The transmission of ND filter #1 was measured and is shown in Table III. We were not able to measure the transmission of the second ND filter as its optical density was too great (>3.0).

3.2 Modifications to Instrument

The filter holder, which contained the two red optical filters, was removed from the instrument and replaced with a spare holder containing a green filter. This filter was cut from a sheet of Rohm & Haas plexiglass #2092. The spectral transmission of this filter was measured from 480 nm to 600 nm and is shown in Fig. 2. It has a peak transmission of 58% at 530 nm and a spectral bandpass (FWHM) of 60 nm.

3.3 Operation of Equipment

The pyrometer was connected in series with the power pack and meter. The appropriate auxiliary objective lens was installed on the instrument for the chosen target distance. Telescope sighting was accomplished by adjusting the horizontal and vertical worm gears, and the target was brought into focus by adjusting the appropriate knob. Finally, the eye piece was adjusted to focus the internal lamp filament. For good precision of temperature measurement, it was most important to keep both the target and the internal filament in sharp focus at all times.

After the instrument is turned on and the lamp brightness allowed to reach equilibrium, the appropriate filters and meter scales are chosen. The filament temperature is adjusted by means of a rheostat. When the filament temperature is too low, the apex of the filament appears darker than the target. When the filament temperature is too high, the filament appears lighter than the target. Correct filament temperature is obtained when the filament blends into the target image.

4.0 RESULTS AND DISCUSSION

4.1 Verification of Calibration with Red Filters

The pyrometer, as delivered by the company, had been calibrated against standards provided by the US National Bureau of Standards. It was decided to verify this calibration before modifying the instrument mainly to check our experimental set-up and technique.

A tungsten strip-filament lamp (GE8101) was used as a temperature source for calibration of the pyrometer. This lamp had been previously calibrated by NRC at λ = 654 nm in the temperature range 1173 to 2373 K. The lamp was also checked in our laboratory against a standard lamp obtained from Eppley Laboratories and it was found to agree in brightness temperature with the NRC calibration to within ± 5 K. The DC power supply used with the GE lamp was a precision current source manufactured by Optronics Laboratories Inc. (model No.16/65 DS). The current could be set to 0.01 ampere, which corresponded to a temperature precision of approximately 1 degree at 2000 K.

The pyrometer was mounted 1.5 m from the lamp and the line-of-sight normal to the filament axes. The lighter red filter (#1) was used in the first set of measurements and scale ranges 1 and 2 were chosen according to the lamp temperature. The lamp current was set at the calibrated values and two readings were taken with the pyrometer: one with increasing current to the filament and a second with decreasing current. This technique was used to help reduce systematic errors caused by the human operator. A second set of measurements with this filter was carried out two weeks later. Both sets of measurements are given in Table IV.

The agreement between the two measurement sets (columns 3 and 4) is satisfactory. The second column in the table gives the calibrated brightness temperature in Kelvin computed at 630 nm from equations [4] and [6] and obtained by interpolating the data in Table I. Columns 5 and 6 give the averaged observed temperature values in degrees Celsius and Kelvin, respectively. Finally, column 7 gives the difference ΔT between the observed and calibrated brightness temperatures. The average difference is approximately +9.5 K and appears to decrease somewhat with increasing temperature. Switching from scale range 1 to 2 at 1577 K caused an observed temperature change of +10 K. Measurements at the three highest current settings were not recorded as there was too much scattered light. Agreement between the present brightness temperature calibration and that provided by the company is considered satisfactory. No calibration accuracy was quoted by the company in their literature.

Although red filter #1 is supposed to be used for filament temperatures below 1000°C and red filter #2 for temperatures above 1000°C, the pyrometer was calibrated with both filters over as large a temperature range as possible. The calibration was repeated wth red filter #2 and the results are summarized in Table V. Again, there is good agreement between the present calibration (column 6) and the company calibration (column 2) for the complete temperature range. As before, the calibrated T_B values were obtained at λ = 645 nm by interpolating the data in Table I. The trends discussed above for filter #1 also apply here when switching scale ranges. All three ranges were used in this calibration.

From these two calibrations it is clear that either filter can be used in the temperature range 920 to 1800°C. For temperatures greater than 1800°C, the dark red filter (#2) is required to reduce scattered light. Red filter #1 has an effective centre wavelength of 630 nm (allowing for the change in lamp radiance and photopic eye response with wavelength) whereas red filter #2 has a centre wavelength of 645 nm. This difference in spectral bandpass is not important as both source lamp and internal filament are viewed through the red filters. Also, since the cut-on of the red filters is very sharp, the introduction of neutral density filters during scale range changes does not shift the transmission profile of the instrument.

4.2 Calibration of Instrument at 547 nm

The filter holder containing the two red filters was removed from the instrument and replaced with a spare holder containing the green filter. The calibration procedure was repeated exactly as before and two sets of measurments were made on two different days. The results are summarized in Table VI.

The agreement between the averaged meter readings (column 6) and the calculated lamp brightness temperature T_B at 547 nm (column 2) is good for the five lowest current settings. These were recorded on Range 1 with no neutral density (ND) filter in the system. The good agreement was not unexpected as both the source lamp and internal filament were similarly affected by the green filter. Switching to Range 2 and introducing ND filter #1 caused a large change in meter reading of approximately 30° at a lamp current of 7.97 A. As the current was further increased, the discrepancy ΔT between the meter readings and the lamp brightness temperature T_B increased from 33.5° at 8.63 A to 83° at 12.92 A. Switching to scale Range 3 for the two highest lamp current settings, produced an even greater discrepancy between meter readings and T_B values.

As shown in Fig. 2, the transmission profile of the green filter is broad (HW = 60 nm) and has a maximum at 530 nm. Allowing for the change in lamp spectral radiance and photopic eye response with wavelength, the effective centre wavelength of the system is 547 nm. Table III shows that the transmission of ND filter #1 changes from 0.22% at 500 nm to 3.3% at 600 nm. The result of introducing the ND filter is to shift the effective centre wavelength from 547 nm to 557 nm. Since only the standard lamp was viewed through the ND filter, this caused a slight difference in colour between the two filaments: the standard lamp filament appeared more yellow than the internal lamp. The T_B values given in Table VI for lamp currents greater than 7.97 A were calculated for 557 nm. This correction to the calibration is very small and accounts for only a small part of the large change observed in ΔT in switching from Range 1 to 2. For a wavelength shift of 10 nm, the emissivity of tungsten changes by only 0.25% at 1800 K filament temperature producing a brightness temperature decrease of approximately 2 K.

A much more significant effect of introducing the ND filters can be attributed to the different transmission of the filters in the red and green regions of the spectrum. For simplicity, we will restrict these discussions to Red filter #2, though they will apply equally well to Red filter #1. The measured transmission of ND filter #1 was 4.28% at 645 nm and 1.52% at 547 nm. This large decrease in transmission in the green caused the observed standard lamp radiance to decrease by a factor of 2.8 resulting in a much lower apparent brightness temperature. This explains the large discrepancy between meter readings and lamp brightness temperatures for Scale Ranges 2 and 3 when using the green filter.

The discrepancy ΔT between lamp brightness temperature T_B and meter reading when ND filters were introduced into the optical system increased from 33.5 K to 83 K when T increased from 1700 K to 2200 K. Two factors could contribute to this effect: a) a shift in system response with lamp filament temperature, and b) the effect of the ND filter transmission on observed lamp radiance and brightness temperature.

a) <u>Shift in System Response Profile</u>

As the lamp brightness temperature is increased from 1700 K to 2200 K, the peak radiation shifts to shorter wavelengths, and the effective centre wavelength of the system response profile shifts from 557 nm to 555 nm. This change in profile with lamp temperature is far too small to account for the large changes in ΔT observed.

b) Effect of ND Filter on Observed Lamp Brightness Temperature

Because ND filter #1 has very different transmission values at 645 nm and 557 nm (4.28% and 1.52%, respectively), the decrease in apparent lamp radiance and brightness temperature T_B caused by introducing the ND filter on Range 2 is different at the two wavelengths. For red filter #2 (λ = 645 nm), this decrease in T_B should be allowed for on the meter scale ranges, but it will cause a discrepancy between lamp T_B and meter readings when operating the pyrometer with the green filter on Ranges 2 and 3.

The effective lamp radiance N_λ and brightness temperature T_B are related by the Wien radiation law:

$$N_\lambda = \frac{C_1}{\lambda^5 \exp (C_2/\lambda T_B)} \qquad [2]$$

Constants C_1 and C_2 were defined earlier in Sect. 2.0.

Considering first the red filter, we can calculate the effective radiance N_λ of the standard lamp at 645 nm corresponding to a brightness temperature T_B of 1575 K with no ND filter in the system (Range 1). This gives N_λ = 759.5 W sr^{-1} cm^{-3}. Multiplying this radiance by the transmission of the ND filter (4.28%) gives the observed lamp radiance on Range 2, N'_λ = 32.5 W sr^{-1} cm^{-3}, and an equivalent brightness temperature T'_B equal to 1288 K. The difference of 287 K between T_B and T'_B is nearly equal to the difference in temperature readings (290 K) between Scale Ranges 1 and 2 on the meter at 1575 K (1302°C). This difference in scale readings, of course, depends on T_B.

We can perform a similar set of calculations for the green filter and ND filter #1. The results are summarized in Table VII. The first column gives the calculated T_B values from Table VI and the corresponding lamp radiances for the six current values used with ND filter #1. Column 3 gives the computed radiances allowing for the transmission of the ND filter. The corresponding T'_B values calculated from Equation [2] are given in Column 4. Column 5 shows the differences $T_B - T'_B$ due to the ND filter. Column 6 gives the differences in the two scale readings on the meter for the six T_B values. Finally, the Δ values shown in Column 7 are temperature scale errors caused by introducing the ND filter which are not corrected for on the meter scales. They are quite similar to the ΔT values shown in Table VI, which are the temperature differences between meter readings and the standard lamp brightness temperatures.

The large ΔT values obtained for the two highest lamp current settings using ND filter #2 could not be verified as we were not able to measure the spectral transmission of this filter.

4.3 Sources of Error in Pyrometer Calibration

Uncertainty in the NRC calibration of the standard lamp at the time of calibration was reported to be ±5°C. Because the lamp has been used for approximately 10 hours since it was calibrated, this uncertainty will be somewhat greater. The NRC calibration included the effect of losses in the lamp envelope.

The manufacturer quotes a reproducibility for temperature measurements of two or three degrees Celsius (Ref. 4). To obtain this degree of precision, care in setting up the system and performing the measurements is required. For example, it is very important to sight the pyrometer on the centre of the lamp filamant as mentioned in the Experimental Section. To determine the precision with which measurements can be made, calibrations were performed on two different days. The average differences between the two sets of measurements were 1.9 ± 4.1 K for red filter #1, 0.2 ± 3.9 K for red filter #2, and 0.5 ± 3.6 K for the green filter.

In the conversion of brightnes temperature from the calibration wavelength to the operating wavelength, we have to assume that the emissivity of the tungsten filament depends on λ and T as described in Larrabee's equation. Actually, the brightness temperature is not a strong function of ε and, as can be seen from Table I, the emissivity of tungsten does not vary greatly with T or λ. The conversion of brightness temperature from λ = 654 nm to λ = 645 nm and 547 nm should not introduce an error greater than 1°.

Taking into account these possible sources of error we conclude that the calibration should be accurate to ±15 K. The data shown in Tables IV and V indicate that our results and the manufacturer's calibration agree within this uncertainty.

4.4 Calculation of True Source Temperature from Brightness Temperatures

From Equation [6] of Sect. 2.0 we can write an expression for brightness temperature T_1 at wavelength λ_1.

$$T_1 = \frac{T}{1-\lambda_1 T/C_2 \ln \varepsilon_1} \qquad [6]$$

and at wavelength λ_2

$$T_2 = \frac{T}{1-\lambda_2 T/C_2 \ln \varepsilon_2} \qquad [7]$$

If we make the assumption that $\varepsilon_1 = \varepsilon_2$, equations [6] and [7] can be combined to give

$$T = T_1 T_2 \frac{(\lambda_1 - \lambda_2)}{T_1 \lambda_1 - T_2 \lambda_2} \qquad [8]$$

where T is the true source temperature. Thus, if we measure T_1 and T_2 and know the effective centre wavelengths λ_1 and λ_2, we can calculate a value for T.

It is useful to determine how the value of T depends on the precision of measurement of T_1 and T_2. From equation [8], a 1% eror in measuring T_1 or T_2 will result in a 6% error in the calculated source temperature. Clearly, to obtain an accurate value for T, it is necessary to measure T_1 and T_2 with the greatest possible precision. As an example, the ±15 K uncertainty in the instrument calibration would produce a source temperature uncertainty of ±90 K.

If we do not assume that $\varepsilon_1 = \varepsilon_2$, we can write a more general expression for T:

$$T = T_1 T_2 \frac{\lambda_1 \ln \varepsilon_1 - \lambda_2 \ln \varepsilon_2}{T_1 \lambda_1 \ln \varepsilon_1 - T_2 \lambda_2 \ln \varepsilon_2} \qquad [9]$$

This expression cannot be simplified even if we make some assumption about the emissivities ε_1 and ε_2. Fortunately, the calculated temperature T is not a strong function of ε. Using the data given in Table I, a 2% change in emissivity with wavelength gives a 12 K change in calculated source temperature at a temperature of 1500 K. This dependence of T on emissivity changes with λ is an order of magnitude less than the dependence on brightness temperature errors.

Since we do not know the emissivities of many sources, eg. flames, we have to make the assumption that the emissivity does not change with wavelength over the spectral region of interest.

5.0 CONCLUSIONS AND RECOMMENDATIONS

An optical pyrometer was modified to operate in the green region of the spectrum and a new calibration of the instrument was carried out. The manufacturer's calibration of the pyrometer in the red spectral region was verified and our results and theirs agreed within an uncertainty of ±15 K. Possible sources of error in the calibrations are discussed.

The theory behind the two-colour brightness technique for obtaining flame temperatures is presented. The relationship between lamp radiance, brightness temperature, and emissivity, and their dependence on wavelength and filament temperature are also discussed.

The dependence of the true source temperature T on brightness temperature indicates that to obtain an accurate value for T, it is necessary to measure the brightness temperatures at the two wavelengths with the greatest precision. It is also shown that small changes in emissivity ε do not produce unacceptably large errors in T and the assumption that ε does not vary with wavelength over the spectral region of interest is valid.

It is recommended that the two pyrometers be further modified so that each contains both red and green filters. This will allow a single instrument to be used to measure red and green brightness temperatures and will provide maximum precision.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. D.R. Snelling and Dr. D. Kretschmer for helpful discussions during the progress of this work. I am also grateful to Mr. Weiss of the Pyrometer Instrument Company for permission to use the schematic diagram of the instrument.

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TABLE I

CALCULATION OF ε and T_B AT 654, 645 and 547 nm

FOR TEMPERATURE RANGE 1000-2650 K

	654 nm		645 nm		547 nm	
T(K)	ε	T_B	ε	T_B	ε	T_B
1000	0.4547	965.4	.4552	965.9	0.4608	971.4
1050	0.4536	1011.8	.4542	1012.4	0.4602	1018.4
1100	0.4526	1058.0	.4531	1058.7	0.4595	1065.3
1150	0.4515	1104.1	.4521	1104.8	0.4588	1112.1
1200	0.4505	1150.0	.4511	1150.7	0.4582	1158.7
1250	0.4494	1195.6	.4501	1196.5	0.4575	1205.2
1300	0.4484	1241.1	.4491	1242.0	0.4569	1251.5
1350	0.4473	1286.5	.4481	1287.4	0.4562	1297.8
1400	0.4463	1331.6	.4470	1332.6	0.4555	1343.7
1450	0.4452	1376.5	.4460	1377.7	0.4549	1389.6
1500	0.4442	1421.4	.4450	1422.5	0.4542	1435.4
1550	0.4431	1465.9	.4440	1467.2	0.4535	1481.0
1600	0.4421	1510.3	.4430	1511.7	0.4529	1526.4
1650	0.4410	1554.5	.4419	1556.0	0.4522	1571.7
1700	0.4399	1598.6	.4409	1600.1	0.4516	1616.9
1750	0.4389	1642.4	.4399	1644.0	0.4509	1661.9
1800	0.4378	1686.1	.4389	1687.8	0.4502	1706.7
1850	0.4368	1729.5	.4379	1731.4	0.4496	1751.5
1900	0.4357	1772.8	.4369	1774.8	0.4489	1796.0
1950	0.4347	1815.8	.4358	1817.9	0.4483	1840.5
2000	0.4336	1858.7	.4348	1861.0	0.4476	1884.7
2050	0.4326	1901.4	.4338	1903.8	0.4469	1928.9
2100	0.4315	1944.0	.4328	1946.5	0.4463	1972.9
2150	0.4305	1986.3	.4318	1988.9	0.4456	2016.7
2200	0.4294	2028.4	.4307	2031.2	0.4450	2060.4
2250	0.4284	2070.4	.4297	2073.3	0.4443	2103.9
2300	0.4273	2112.1	.4287	2115.2	0.4436	2147.3
2350	0.4263	2153.7	.4277	2156.9	0.4430	2190.6
2400	0.4252	2195.1	.4267	2198.5	0.4423	2233.7
2450	0.4242	2236.3	.4256	2239.8	0.4417	2276.6
2500	0.4231	2277.3	.4246	2280.9	0.4410	2319.4
2550	0.4221	2318.1	.4236	2321.9	0.4403	2362.1
2600	0.4210	2358.7	.4226	2362.7	0.4397	2404.6
2650	0.4200	2399.3	.4216	2403.3	0.4390	2446.9

TABLE IIA

MEASURED TRANSMISSION OF RED FILTER NO. 1 AND RELATIVE SYSTEM SPECTRAL RESPONSE

Wavelength (nm)	Transmission	N_λ	P_λ	Relative Response
600	0.083	2527	0.61	128
610	0.611	2894	0.50	884
620	0.851	3295	0.37	1038
630	0.900	3732	0.27	907
640	0.904	4206	0.18	684
650	0.916	4716	0.10	432
660	0.916	5264	0.055	265
670	0.916	5849	0.030	161
680	0.916	6473	0.016	95
690	0.916	7134	0.0072	47
700	0.916	7833	0.0036	26
710	0.916	8569	0.0018	14
720	0.916	9342	0.0009	8
730	0.916	10150	0.00045	4
740	0.916	10994	0.00023	2
750	0.916	11872	0.00012	1

Notes:

1) Spectral radiance N_λ was calculated for a 1800 K blackbody source.

2) P_λ is the photopic eye response.

3) Neutral density filter #1 does not alter significantly the relative response profile of the system.

TABLE IIB

MEASURED TRANSMISSION OF RED FILTER NO. 2 AND RELATIVE SYSTEM SPECTRAL RESPONSE

Wavelength (nm)	Transmission	N_λ	P_λ	Relative Response
600	<0.002	2527	0.61	< 3
610	<0.002	2894	0.50	< 3
620	<0.002	3295	0.37	< 2
630	0.0436	3732	0.27	44
640	0.407	4206	0.18	308
650	0.813	4716	0.10	383
660	0.879	5264	0.055	254
670	0.879	5849	0.030	154
680	0.879	6473	0.016	91
690	0.879	7134	0.0072	45
700	0.879	7833	0.0036	25
710	0.879	8569	0.0018	14
720	0.879	9342	0.0009	7
730	0.879	10150	0.00045	4
740	0.879	10994	0.00023	2
750	0.879	11872	0.00012	1

Notes:
1) Spectral radiance N_λ was calculated for a 1800 K blackbody source.
2) P_λ is the photopic eye response.
3) Neutral density filter #1 does not alter significantly the relative response profile of the system as its transmission is almost flat over this wavelength region.

TABLE III

TRANSMISSION OF ND FILTER #1

Wavelength nm	Absorbance	Transmission
500	2.66	.00219
510	2.38	.00417
520	2.19	.00646
530	2.03	.00933
540	1.89	.0129
550	1.79	.0162
560	1.71	.0195
570	1.63	.0234
580	1.57	.0269
590	1.52	.0302
600	1.48	.0331
610	1.44	.0363
620	1.413	.0386
630	1.393	.0405
640	1.378	.0419
650	1.361	.0436
660	1.347	.0450
670	1.337	.0460
680	1.328	.0470
690	1.323	.0475
700	1.321	.0478
710	1.322	.0476
720	1.326	.0472
730	1.331	.0467
740	1.343	.0454
750	1.355	.0442
760	1.370	.0427
770	1.400	.0398
780	1.41	.0389
790	1.43	.0372
800	1.46	.0347

TABLE IV

CALIBRATION OF PYROMETER AT 630 nm (RED FILTER #1)

LAMP CURRENT A	T_B K	METER READINGS °C	METER READINGS °C	AVERAGE °C	AVERAGE K	ΔT K	RANGE
6.17	1175	920	918	919	1192	+17	1
6.51	1275	1016	1013	1014.5	1287.5	+12.5	1
6.91	1376	1110	1111	1110.5	1383.5	+ 7.5	1
7.39	1476	1207	1204	1205.5	1478.5	+ 2.5	1
7.97	1577	1309	1308	1308.5	1581.5	+ 4.5	1
			1318	1318	1591	+14	2
8.63	1677	1418	1420	1419	1692	+15	2
9.36	1778	1515	1520	1517.5	1790.5	+12.5	2
10.16	1879	1611	1619	1615	1888	+ 9	2
11.01	1980	1709	1716	1712.5	1985.5	+ 5.5	2
11.94	2081	1810	1815	1812.5	2085.5	+ 4.5	2
12.92	2182						
13.95	2282	TOO MUCH SCATTERED LIGHT FOR THE HIGHEST 3 SETTINGS					
14.98	2383						

NOTES: 1) Switching from Range 1 to Range 2 (i.e. adding ND Filter) gives a 10 degree increase in indicated temperature.

TABLE V

CALIBRATION OF PYROMETER AT 645 nm (RED FILTER #2)

LAMP CURRENT A	T_B K	METER READINGS °C	METER READINGS °C	AVERAGE °C	AVERAGE K	ΔT K	RANGE
6.17	1174	920	917	918.5	1191.5	+17.5	1
6.51	1274	1017	1011	1014	1287	+13	1
6.91	1374	1113	1107	1110	1383	+ 9	1
7.39	1474	1208	1207	1207.5	1480.5	+ 6.5	1
7.97	1575	1308	1305	1306.5	1579.5	+ 4.5	1
		1311	1310	1310.5	1583.5	+ 8.5	2
8.63	1675	1412	1411	1411.5	1684.5	+ 9.5	2
9.36	1775	1509	1512	1510.5	1783.5	+ 8.5	2
10.16	1875	1603	1607	1605	1878	+ 3	2
11.01	1976	1700	1707	1703.5	1976.5	+ 0.5	2
11.94	2076	1796	1800	1798	2071	- 5	2
			1813	1813	2086	+ 10	3
12.92	2176	1921	1920	1920.5	2193.5	+ 17.5	3
13.95	2277	2022	2018	2020	2293	+ 16	3
14.98	2377	2116	2116	2116	2389	+ 12	3

TABLE VI

CALIBRATION OF PYROMETER FOR GREEN FILTER (λ = 547 nm)

LAMP CURRENT A	T_B K	METER READINGS °C	°C	AVERAGE °C	K	ΔT K	RANGE
6.17	1182	918	915	916.5	1189.5	+ 7.5	1
6.51	1284	1015	1013	1014	1287	+ 3	1
6.91	1386	1116	1112	1114	1387	+ 1	1
7.39	1488	1216	1211	1213.5	1486.5	- 1.5	1
7.97	1591	1315	1314	1314.5	1587.5	- 3.5	1
8.63	1692	1385	1386	1385.5	1658.5	-33.5	2
9.36	1794	1481	1481	1481	1754	-40	2
10.16	1897	1573	1572	1572.5	1845.5	-51.5	2
11.01	2000	1664	1667	1665.5	1938.5	-61.5	2
11.94	2104	1754	1760	1757	2030	-74	2
12.92	2207	1850	1852	1851	2124	-83	2
13.95	2311	1865	1870	1867.5	2140.5	-170.5	3
14.98	2415	1945	1950	1947.5	2220.5	-194.5	3

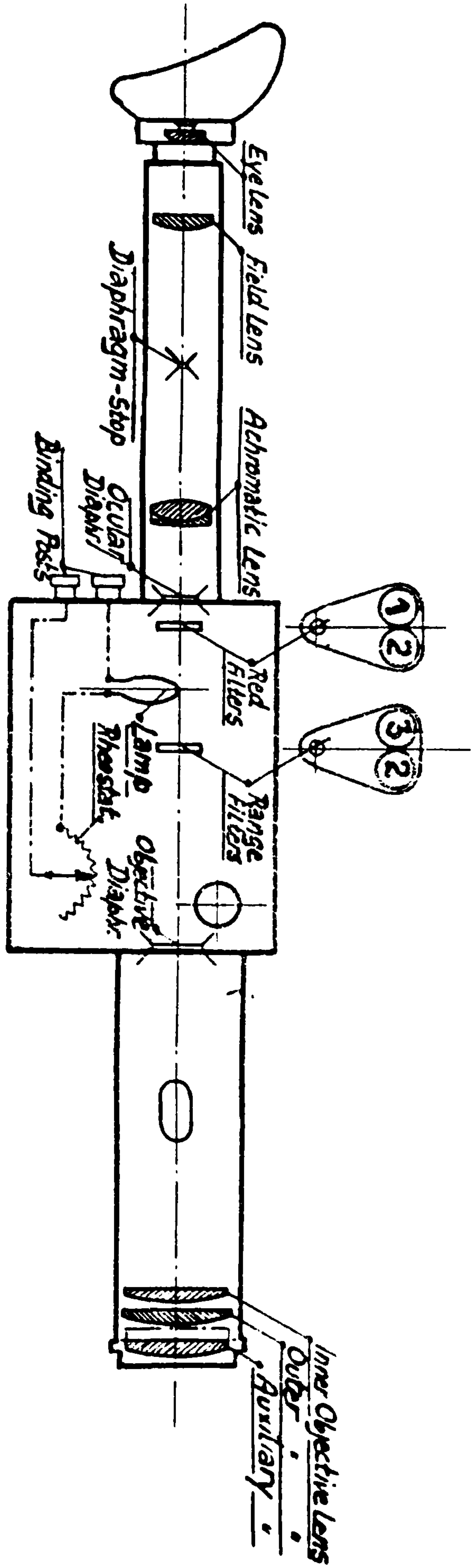
T_B calculated for 557 nm for measurements made on Ranges 2 and 3

ΔT is the difference between meter readings (K) and calculated lamp brightness temperatures T_B.

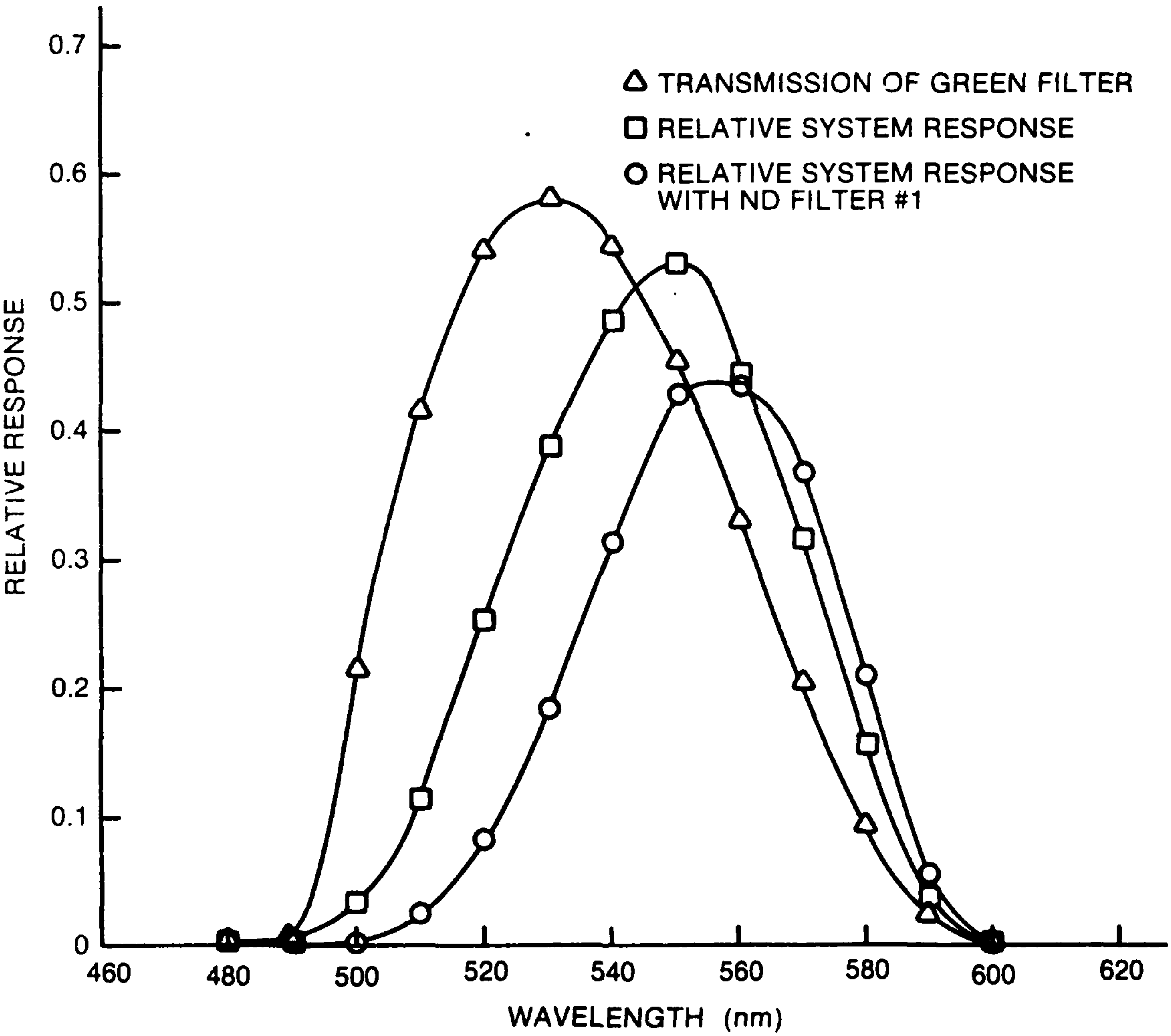
TABLE VII

EFFECT OF ND FILTER #1 ON LAMP RADIANCES AND BRIGHTNESS TEMPERATURES AT 557 nm WAVELENGTH

T_B (K)	N_λ (557 nm)	N_λ'	T_B' (K)	T_B-T_B' (K)	SCALE DIFFERENCES (K)	Δ (K)
1692	524.9	7.979	1328	364	324	-40
1794	1249.7	18.995	1390	404	358	-46
1897	2729.9	41.494	1451	441	391	-55
2000	5502.2	83.633	1510	490	424	-66
2104	10414	158.29	1569	535	460	-75
2207	18465	280.67	1625	582	499	-83



Eye Lens
Field Lens
Diaphragm-Stop
Achromatic Lens
Ocular Diaphr
Binding Posts
1
2
Red Filters
3
2
Range Filters
Lamp
Rheostat
Objective Diaphr.
Inner Objective Lens
Outer " "
Auxiliary "


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
RELATIVE RESPONSE
TRANSMISSION OF GREEN FILTER
RELATIVE SYSTEM RESPONSE
RELATIVE SYSTEM RESPONSE WITH ND FILTER #1
460
480
500
520
540
560
580
600
620
WAVELENGTH (nm)

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1 ORIGINATING ACTIVITY Defence Research Establishment Ottawa Department of National Defence, Ottawa, Ontario K1A 0Z4 Canada	2a DOCUMENT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP

3 DOCUMENT TITLE

The Modification and Application of a Two-Colour Disappearing-Filament Pyrometer to Perform Flame Temperature Measurements.

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Note

5 AUTHOR(S) (Last name, first name, middle initial)

Findlay, Frank D.

6 DOCUMENT DATE	7a TOTAL NO OF PAGES	7b NO OF REFS 4

8a. PROJECT OR GRANT NO 25B10	9a. ORIGINATOR'S DOCUMENT NUMBER(S) DREO TN -
8b CONTRACT NO	9b. OTHER DOCUMENT NO.(S) (Any other numbers that may be assigned this document)

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13 ABSTRACT

An optical pyrometer of the disappearing-filament type was modified to allow brightness temperature measurements to be made in the green region of the spectrum. The modified instrument was re-calibrated at a wavelength of 547 nm. The manufacturer's calibration of a second pyrometer operating at $\lambda = 645$ nm was verified. Sources of error in the calibrations are discussed. The theory and limitations of two-colour pyrometry as a means of obtaining true source temperatures are presented.

DSIS
77-065

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Brightness temperatures
Flame temperatures
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