NPL Report Qu107

April 1995

Anglo-Russian Agreement in Metrology: Theme 26 The International Temperature Scale of 1990 above 962°C

NPL-VNIIM Intercomparison of Tungsten Ribbon Lamps

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ABSTRACT

During 1993 and 1994 the National Physical Laboratory (NPL), U.K. and the DI Mendeleyev Institute for Metrology (VNIIM), Russia, undertook an intercomparison of the radiance temperature scales maintained on tungsten ribbon lamps held at the two laboratories. Four lamps were involved in the intercomparison, two (one evacuated and one gas-filled) from each laboratory. The intercomparison was carried out over the range 900-2000°C. The results showed that, for three of the four lamps, the temperature scales agreed to well within 1σ of the total combined uncertainties of the measurements across the entire range, and the other lamp agreed within 2σ of the total combined uncertainties.

ISSN DQM 0309-3050

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1. INTRODUCTION

Above the freezing point of silver (961.78 °C) the International Temperature Scale of 1990 (ITS90) is realised using radiation thermometry and Planck's law. Primary Standards Laboratories establish and maintain the scale using the radiance of a blackbody source at the freezing point of silver, gold or copper. High grade tungsten-ribbon lamps may be calibrated against the primary system, and then used as transfer standards for calibrating other tungsten-ribbon lamps, blackbody sources and visual pyrometers [1,2].

Despite the increasing use of blackbody sources as radiance temperature standards, lamps are still widely used. This is due to their stability and their small size, making them suitable for maintaining a scale and as transfer standards, especially for International intercomparisons. Such intercomparisons are essential in order to maintain confidence in the measurements undertaken at different laboratories worldwide. The intercomparison between NPL and VNIIM was carried out under the Anglo-Russian Agreement in Metrology: Theme 26, and was designed to check whether the temperature scales maintained in the two laboratories agreed within a target of 0.1 % of temperature. A multi-lateral intercomparison involving lamps had not been undertaken for some time [3], and, furthermore, such an exercise had not taken place between Russia and Western Europe.

2. LAMP DESCRIPTION

The NPL lamps were of the high-stability type, with a 1.5 mm filament and 80 mm diameter window (Figure 1); number C836 was the vacuum and C841 the gas-filled lamp. The alignment indicators were in the form of a notch in the filament, and a spot on the rear window. They were fitted with water-cooled bases so that the temperature of the lamp pins could be controlled. They were set up with the positive side of the voltage supply connected to the upper end of the lamp filament.

The VNIIM lamps were of the cylindrical envelope type; number N11 being the vacuum and N295 being the gas-filled lamp. They had a 3 mm filament and a 35 mm diameter window in the envelope which was angled at 5-10° to the viewing axis (Figure 2). There were indicators, in the form of a pointer near the filament, and a cross on the rear of the envelope, for the orientation of the lamp during the calibration. The lamp bases were of the Edison screw type and were provided with a special holder designed for temperature control of the lamp pins by water-cooling. The negative side of the voltage supply was connected to the centre contact of the screw base.

Before measurements were made all the lamps were positioned base downwards, with their filaments between the vertical axis of the lamp and the comparator, and aligned vertically from the rear and side using a plumb line.

During the NPL calibration the lamps were compared against the NPL standard high-stability vacuum tungsten ribbon lamp, number C505, using a photoelectric comparator. This lamp had been calibrated between 700°C and 1700°C, against the gold-point black-body furnace, using the NPL Primary Pyrometer and the technique of radiance doubling. Thermocouples were placed in the holes in the water-cooled bases of the lamps to measure the base temperature which was kept at 20 ± 0.5 °C (NPL lamps) and 23 ± 0.5 °C (VNIIM lamps). Base temperature coefficients were measured below 1200 °C.

During the VNIIM calibration the lamps were compared against the VNIIM vacuum and gas-filled standard tungsten ribbon lamps, which had been calibrated from 900-2000°C against the silver-, gold- and copper-point blackbodies, using a spectral comparator and the radiance doubling technique. The temperature of each of the lamp bases was monitored using a thermistor and its variations were no more than 0.3°C, the base temperature being kept at 22 ± 0.5 °C (VNIIM lamps) and 20 ± 0.5 °C (NPL lamps). Base temperature coefficients were measured at and below 1300 °C.

The calibrations of both the NPL and VNIIM lamps were made in terms of radiance temperature and the D.C. current flowing through the filament. The radiance temperature was determined by a comparison of the lamps under test with the standard lamps calibrated at a wavelength near 660 nm. The calibration and calculations are based on the definition of ITS 90 above the freezing point of silver, using the Planck Radiation Law.

3. DESCRIPTION OF THE EQUIPMENT

3.1 THE NPL SYSTEM

The schematic layout of the NPL photoelectric comparator is given in Figure 3. It consists of a system of optics which focuses the thermal radiation from the lamp onto a photomultiplier tube (PMT). The tube has an extended S-20 photocathode, powered by a Hewlett Packard Harrison 6516A D.C. EHT supply. The PMT output is measured using a digital voltmeter.

The comparator has an effective wavelength, in air, of 662.4 nm, and an f/11 aperture ratio. It is constructed in such a way that a mirror can be moved into position so that the radiation is directed into the eyepiece, to enable the source to be viewed and correctly aligned.

When viewing the lamps the comparator is sighted (with its optical axis horizontal) onto a circular area of the filament, 0.75 mm in diameter, centrally positioned either within the filament at the same height as the pointer (VNIIM lamps), or between the tip of the filament notch and the opposite edge of the filament (NPL lamps). The spot/cross marked on the glass, at the rear of the lamp, is positioned behind the partly lit filament in the field of view of the comparator.

For the calibration of the gas lamps above 1700°C a neutral density (V/G) filter with a transmission of 1 % is inserted into the optical path when the gas lamp is being viewed. The temperature of the NPL standard (evacuated) lamp is adjusted so that the PMT outputs are as close as possible when viewing each source. The temperature of the gas lamp is then determined directly from the standard lamp, using Planck's law and the value of the filter transmission.

The transmission of the V/G filter is temperature sensitive, and has been calibrated in the range 15-25°C. During the lamp calibration the environmental temperature at a point very close to the filter was measured, so that a correction to the transmission could be applied.

Calibrated temperature-controlled standard resistors and a standard cell were used as references for the absolute measurements of currents and voltages.

3.2 THE VNIIM SYSTEM

The VNIIM spectral comparator is described in [4,5], and shown in Figure 4. It is based on finding the null of the modulated signal at the exit slit of the monochromator, when the spectral radiances of compared sources are equal.

A photomultiplier tube with a multi-alkaline photocathode is used as the detector. The effective wavelength, selected by the monochromator, is 656.3 nm in air. The threshold sensitivity of the comparator is 0.1-0.02°C at this wavelength. The comparator has an f/15 aperture ratio. The target area, in the form of the rectangle of width 0.7 mm and height 1 mm, is centred within the filament near the mouth of the notch or pointer during the calibration. A microscope is used to align the images of the sources.

The comparator has two symmetrical optical channels. The images of each of the sources are focused, using lenses, onto aperture stops. The radiance of each source is directed in turn, using a prism, to the modulating mirror and then to the entrance slit of the double monochromator. The condition of equal radiance of the sources is determined by finding the minimum of the alternating current of the photomultiplier tube at the modulating frequency. The substitution of one radiant flux with another is carried out by the modulator in such a way that the total illumination of the radiation detector remains constant when viewing sources of equal brightness. If the sources are not equal then the total flux contains a variable component having the modulation frequency.

When the radiances of the sources are equal the modulation component of the photocurrent is zero. This is determined by a null-indicator, which is connected via a selective amplifier to a synchronous detector.

Since the comparator channels have a small asymmetry, corresponding to a temperature equivalent of 0.2-0.3°C for sources of a similar type, measurements are usually performed using a substitution method, with one of the channels being exclusively used for viewing a standard tungsten ribbon lamp. The VNIIM or NPL lamp to be calibrated is positioned in the second channel (in the position of the blackbody cavity in Figure 2).

4. MEASUREMENTS

4.1 NPL LAMPS

The NPL lamps (numbers C841 and C836) were originally calibrated at NPL in July 1993 at the following temperatures:

700, 800, 900, 1000, 1100, 1250, 1400, 1500, 1600, 1700 °C - for the vacuum lamp, and

1600, 1700, 1800, 1900, 2000, 2100, 2200 °C - for the gas-filled lamp.

They were taken to VNIIM in August 1993 and four sets of measurements were performed on them during April-May 1994, the lamps being re-aligned before each set of measurements. The measurements were at:

961.78, 1064.18, 1084.62, 900, 1000, 1100, 1200, 1300, 1400, 1500°C - for the vacuum lamp, and

1300, 1400, 1500, 1650, 1800, 1900, 2000°C - for the gas-filled lamp.

The total running time for both C841 and C836 at VNIIM was 16 hours. Measurements were made starting from the highest current value and then lowering the current to each additional setting. The highest rate of current change was 0.2 A/min. The base temperature coefficients were determined for the vacuum lamp at and below 1300 °C, and the results of these are shown in Table 1.

The lamps were returned to NPL in June 1994 and were re-calibrated at NPL during July 1994 over the entire range including the additional temperatures at which they had been calibrated by VNIIM. The two NPL calibrations of the lamps were corrected to a wavelength of 656.3 nm so that the NPL and VNIIM results could be compared directly.

4.2. VNIIM LAMPS

The VNIIM lamps had four sets of measurements performed on them at VNIIM in May-June 1993, with the lamps being re-aligned before each set. The measurements were carried out in the temperature ranges 900-1500 °C and 1300-2000 °C as above. They were taken to NPL in August 1993.

At NPL initial scans were made along and across the filament of each VNIIM lamp. The gas-filled lamp was then run at 24.7 A for approximately one hour before being calibrated at the following temperatures: 1300°C, 1400°C, 1500°C, 1650°C, 1800°C, 1900°C and 2000°C.

The vacuum lamp was run at 14.5A for approximately two hours before being calibrated at the following temperatures: 700°C, 800°C, 900°C, 1000°C, 1150°C, 1300°C, 1400°C and 1500°C. The maximum rate of current change was 0.2 A/sec.

Base temperature coefficients were determined for the vacuum lamp below 1200 °C and the results of these are shown in Table 1.

Extensive measurements of the temperature gradients along and across the filament of each VNIIM lamp were then carried out before they were calibrated a second time at the same temperatures. The calibration was carried out at 662.4 nm and corrected to 656.3 nm, to give a direct comparison with the VNIIM results.

After their return to VNIIM from NPL in June 1994, two further measurement series were performed on the lamps at the same temperatures as for the first set.

UNCERTAINTIES

The uncertainties of the measurements are comprised of the random and non-random uncertainties in the comparison of the lamp with the working standard, and the non-random uncertainty of the calibration of the working standard. They were assessed at VNIIM and NPL and are given in Tables 2 and 3.

5. RESULTS

5.1 SCANS OF THE VNIIM LAMP FILAMENTS AT NPL

Vacuum lamp

The horizontal scan showed that, at 1000 °C, the radiance temperature did not vary by more than 0.1 °C over a distance of ± 0.25 mm from the normal viewing position. The vertical scan showed a significant gradient along the filament, the amount varying depending on the radiance temperature of the filament. The maximum gradient over ± 0.125 mm from the normal viewing position was 0.85 °C at 700 °C.

Gas filled lamp

Both the horizontal and vertical scans showed temperature gradients along the filament over a distance of ± 0.125 mm from the normal viewing position. The magnitude of the gradients varied depending on the radiance temperature of the filament. The maximum horizontal gradient was 0.6 °C, and the vertical 0.30 °C, both at 2000 °C.

Both lamps could be set to within ± 0.125 mm of the correct horizontal and vertical position. The results of the scans were used in the determination of the alignment uncertainties given in Table 3.

5.2 CALIBRATION RESULTS

For both the NPL and VNIIM lamps the results of the second set of calibration measurements, done when the lamps were returned to their originating country, were fitted using a curve fitting procedure and power series polynomial. These results were used as a base line to calculate temperature differences between the first and second sets of measurements carried out in the originating countries and the differences between the VNIIM and NPL calibrations. These differences are given in Figures 5 to 8 and Tables 4 to 7.

Tables 4 - 7 also give values of the Normalised Error Ratio, En, which is a convenient way to represent the results of the intercomparison. En is the difference ΔT(VNIIM-NPL), between the laboratories divided by the RSS (square root of the sum of the squares) of the uncertainties of the laboratories. Thus,

$$En = \Delta T/\text{RSS uncertainty}.$$

The En value will be less than unity where the difference is less than the combined uncertainty and hence it is a useful indicator of the result of the intercomparison. En values are therefore given at each point in the tables, using the 1σ uncertainties for each laboratory from Tables 2 and 3. Values are also given for the differences between the first and second calibrations carried out at VNIIM or NPL.

6. DISCUSSION

The estimates of the measurement uncertainties carried out by both laboratories, in Tables 2 and 3, show similar levels of uncertainty for the reproduction and transfer of the radiance temperature scale over the range 962-2000°C according to the ITS-90 definition.

As can be seen from Tables 4 - 7 the En values are <1 for three out of the four lamps. Hence the differences between the NPL and VNIIM calibrations agree to within 1σ of the total combined uncertainty of the measurements. The results for the fourth lamp, C836, show somewhat larger differences.

One possible cause of the larger differences for C836 is the different designs of the NPL and the VNIIM lamps and comparators, in particular the different widths of the lamp filaments. The lamp alignment system of the VNIIM spectral comparator makes it difficult to ensure the constant alignment of the filament image on the entrance slit of the monochromator. For lamps with a wide filament and a small temperature gradient across the width (which is the case with the VNIIM lamps), the displacement of the centre of the filament by ± 0.5 mm does not lead to a noticeable change in results. However the same displacement of a 1.5 mm width filament (the case with the NPL lamp) viewed with a target area of 0.7 mm width (the case with the VNIIM comparator) gives a large difference in results. Thus, if the lamp filament is displaced due to expansion which often takes place, it is necessary to correct its position relative to the monochromator slit. This is not provided for by the VNIIM spectrocomparator design.

7. CONCLUSION

The results of the intercomparison show very good agreement of the ITS-90 realizations at the NPL and the VNIIM.

This agreement has been achieved in spite of using quite different designs of the photoelectric comparators and lamps in the two laboratories, for the ITS-90 realization over the range 962-2000°C. This gives us confidence in the principles and execution of the ITS-90 realization over this temperature range.

8. REFERENCES

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TABLE 1 : BASE TEMPERATURE COEFFICIENTS

The base temperature coefficients are given in the following table. The coefficient is expressed as the change in radiance temperature per °C change in base temperature.

Radiance temperature °C	Lamp number			
	N11		C836	
	VNIIM	NPL	VNIIM	NPL
700	-	0.52	-	0.38
800	-	0.32	-	0.20
900	0.2	0.18	0.1	0.088
1000	0.1	0.085	0.04	0.033
1100	0.05	0.036	0.02	0.010

TABLE 2 : UNCERTAINTIES OF MEASUREMENTS, VNIIM (in °C)

Source of uncertainty	Vacuum lamps			Gas-filled lamps		
	900 °C	1200 °C	1500 °C	1300 °C	1650 °C	2000 °C
Type A: Reproducibility of comparisons	0.25	0.15	0.20	0.20	0.25	0.30
Type B;						
Calibration of standard lamp (with drift)	0.60	0.70	0.80	0.70	0.90	1.10
Radiance gradient and alignment*	0.25	0.20	0.15	0.25	0.30	0.35
Wavelength correction	0.04	0.06	0.08	0.08	0.11	0.18
Base temperature	0.09	0.02	-	-	-	-
Current measurement	0.05	0.04	0.03	0.04	0.03	0.03
Uncertainty in type B evaluation	0.66	0.73	0.82	0.75	0.96	1.17
A and B combined 1σ	0.71	0.75	0.84	0.78	0.99	1.21
2σ	1.42	1.50	1.68	1.56	1.98	2.41

* typical data

TABLE 3 : UNCERTAINTIES OF MEASUREMENTS, NPL (in °C)

Source of uncertainty	Vacuum lamps			Gas-filled lamps		
	900 °C	1200 °C	1500 °C	1300 °C	1650 °C	*2000 °C
Type A: Reproducibility of comparisons	0.25	0.15	0.10	0.10	0.10	0.10
Type B;						
Calibration of standard lamp	0.35	0.25	0.38	0.30	0.46	0.29
Drift in standard lamp	0.40	0.33	0.40	0.40	0.48	0.40
Vertical alignment of test lamp	0.32	0.19	0.10	0.20	(0.23)	0.25
Horizontal alignment of test lamp	0.10	0.10	0.10	0.20	(0.30)	0.40
Wavelength correction	0.04	0.06	0.10	0.08	0.12	0.17
Base temperature	0.10	-	-	-	-	-
Current measurement	0.10	0.10	0.10	0.20	0.20	0.30
Transmission of neutral filter	-	-	-	-	-	1.25
Uncertainty in type B evaluation	0.65	0.48	0.59	0.61	0.80	1.47
A and B combined 1σ	0.69	0.50	0.60	0.62	0.81	1.47
2σ	1.38	1.01	1.19	1.24	1.61	2.94

Note:

1.The data in brackets () denotes interpolated values.
2.* measurement taken with the V/G filter, and standard at 1280 °C.

TABLE 4: COMPARISON OF CALIBRATION RESULTS FOR C836, T = 700-1700°C VACUUM LAMP

Radiance temperature °C	ΔT NPL 2nd-1st °C	NPL 2nd-1st En ratio	ΔT VNIIM - NPL °C	VNIIM - NPL En ratio
700	0.30	0.25	-	-
800	0.21	0.20	-	-
900	-0.01	-0.01	-0.59	-0.60
961.78	-	-	-0.31	-0.34
1000	0.04	0.05	0.79	0.90
1064.18	-	-	0.53	0.59
1084.62	-	-	1.03	1.13
1100	0.06	0.10	1.23	1.35
1200	-	-	0.85	0.94
1250	0.06	0.08	-	-
1300	-	-	1.27	1.35
1400	0.04	0.05	1.27	1.28
1500	0.01	0.01	1.21	1.17
1600	0.05	0.05	-	-
1700	0.04	0.04	-	-

TABLE 5: COMPARISON OF CALIBRATION RESULTS FOR N11, T = 900-1500°C VACUUM LAMP

Radiance temperature °C	ΔT VNIIM 2nd-1st °C	VNIIM 2nd-1st En ratio	ΔT VNIIM-NPL °C	VNIIM - NPL En ratio
900	-0.18	-0.18	0.01	0.01
961.78	-0.31	-0.30	-	-
1000	0.12	0.12	0.20	0.23
1064.18	0.24	0.23	-	-
1084.62	0.29	0.28	-	-
1100	0.25	0.24	-	-
1150	-	-	0.11	0.12
1200	0.43	0.41	-	-
1300	0.12	0.11	0.07	0.07
1400	-0.16	-0.14	-0.22	-0.22
1500	-0.19	-0.16	-0.25	-0.24

TABLE 6: COMPARISON OF CALIBRATION RESULTS FOR C841, T = 1300-2200°C GAS-FILLED LAMP

Radiance temperature °C	ΔT NPL 2nd-1st °C	NPL 2nd-1st En ratio	ΔT VNIIM-NPL °C	VNIIM - NPL En ratio
1300	-	-	0.23	0.23
1400	-	-	0.36	0.33
1500	-	-	0.18	0.16
1600	-0.66	-0.69	0.26	0.21
1700	-0.85	-0.72	0.83	0.63
1800	0.28	0.18	0.50	0.30
1900	0.42	0.25	0.47	0.26
2000	0.46	0.26	-0.02	-0.01
2100	0.55	0.30	-	-
2200	0.76	0.40	-	-

TABLE 7: COMPARISON OF CALIBRATION RESULTS FOR N295, T = 1300-2000°C GAS-FILLED LAMP

Radiance temperature °C	ΔT VNIIM 2nd-1st °C	VNIIM 2nd-1st En ratio	ΔT VNIIM-NPL °C	VNIIM - NPL En ratio
1300	0.57	0.51	-0.70	-0.70
1400	0.15	0.13	-0.57	-0.53
1500	0.47	0.37	-0.32	-0.28
1600	0.19	0.14	-	-
1650	-	-	-0.43	-0.34
1700	0.06	0.04	-	-
1800	-0.23	-0.15	-0.33	-0.20
1900	-0.11	-0.07	-0.28	-0.16
2000	0.47	0.27	-0.56	-0.29

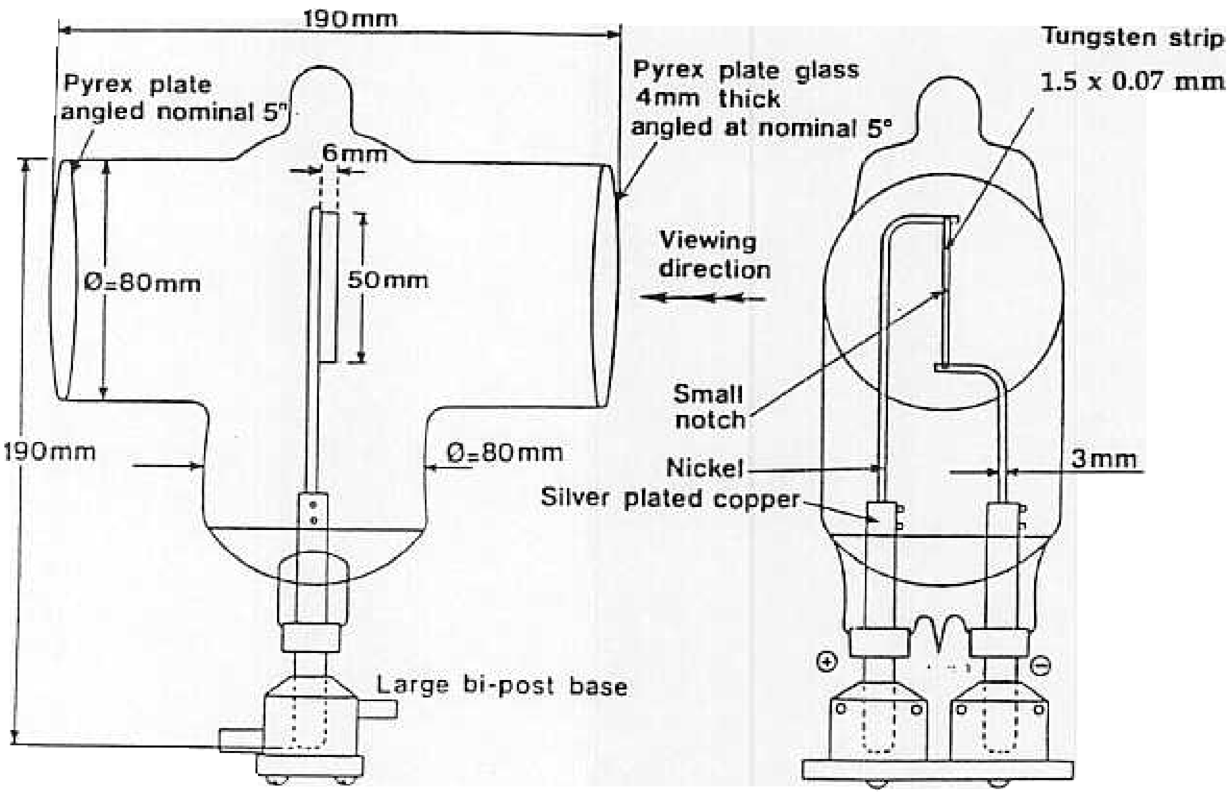
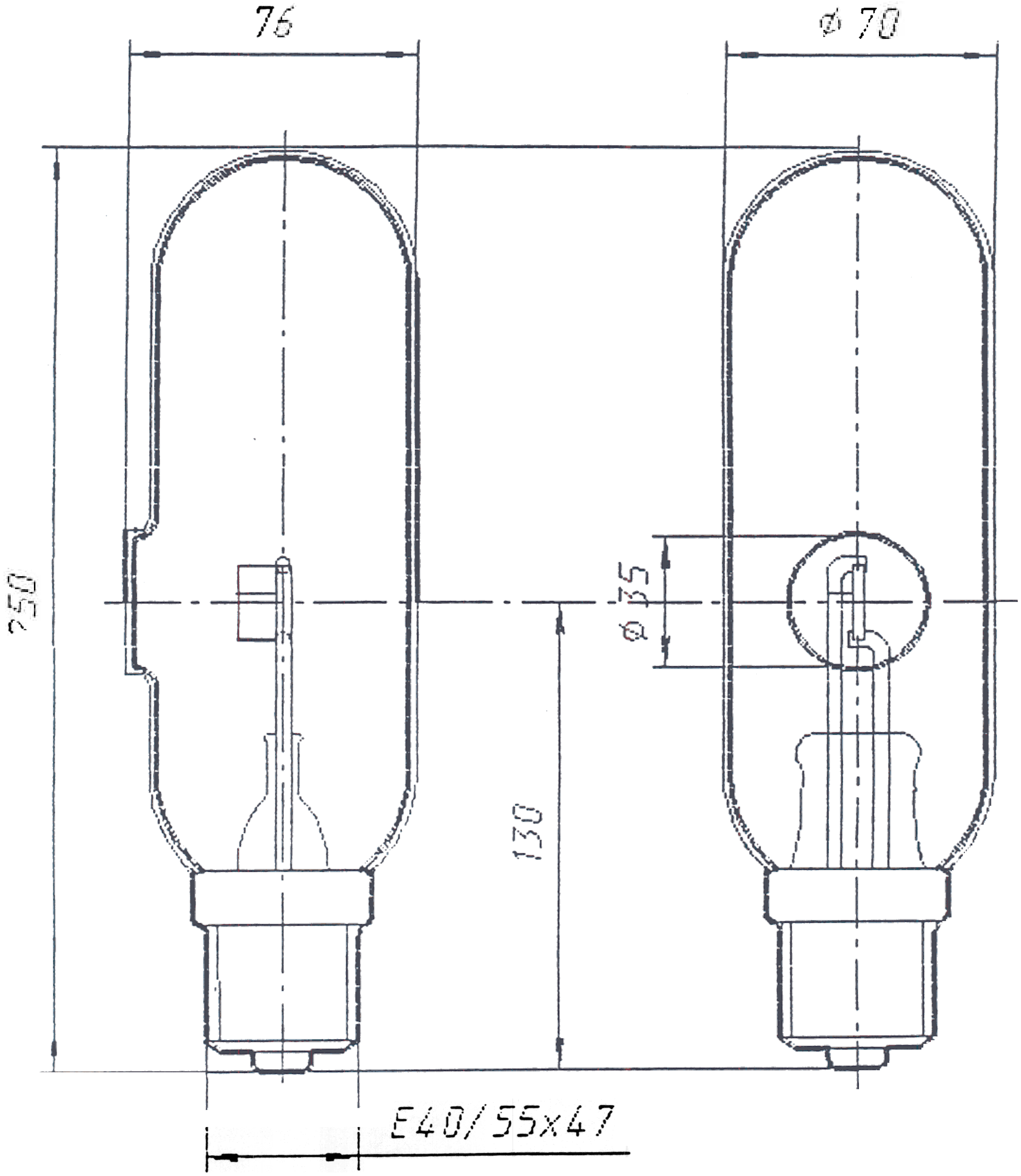


FIGURE 1 : The NPL high-stability tungsten-ribbon lamp

FIGURE The VNIIM tungsten-ribbon amp



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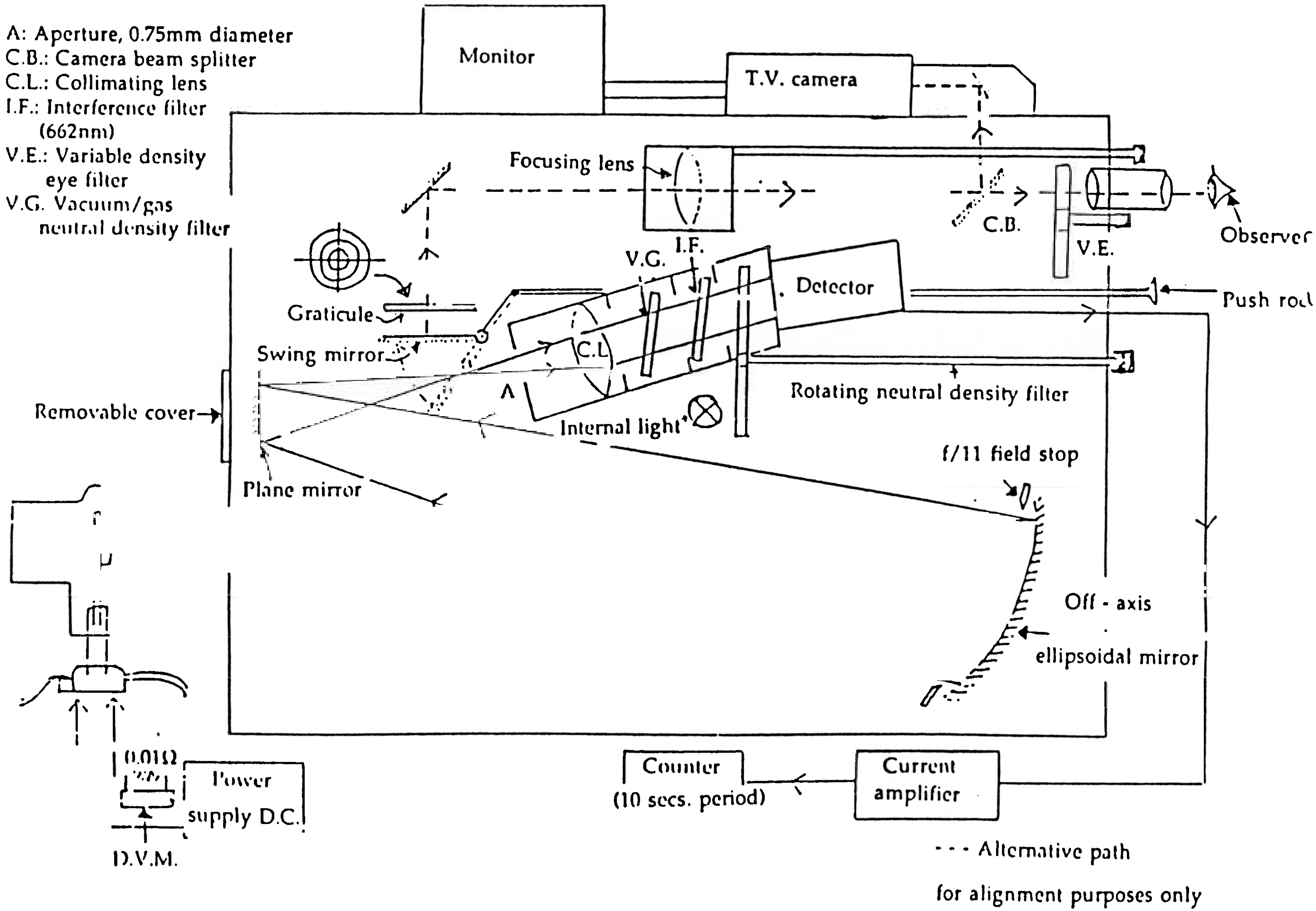

FIGURE 3 : Optics of the NPL Photoelectric Comparator

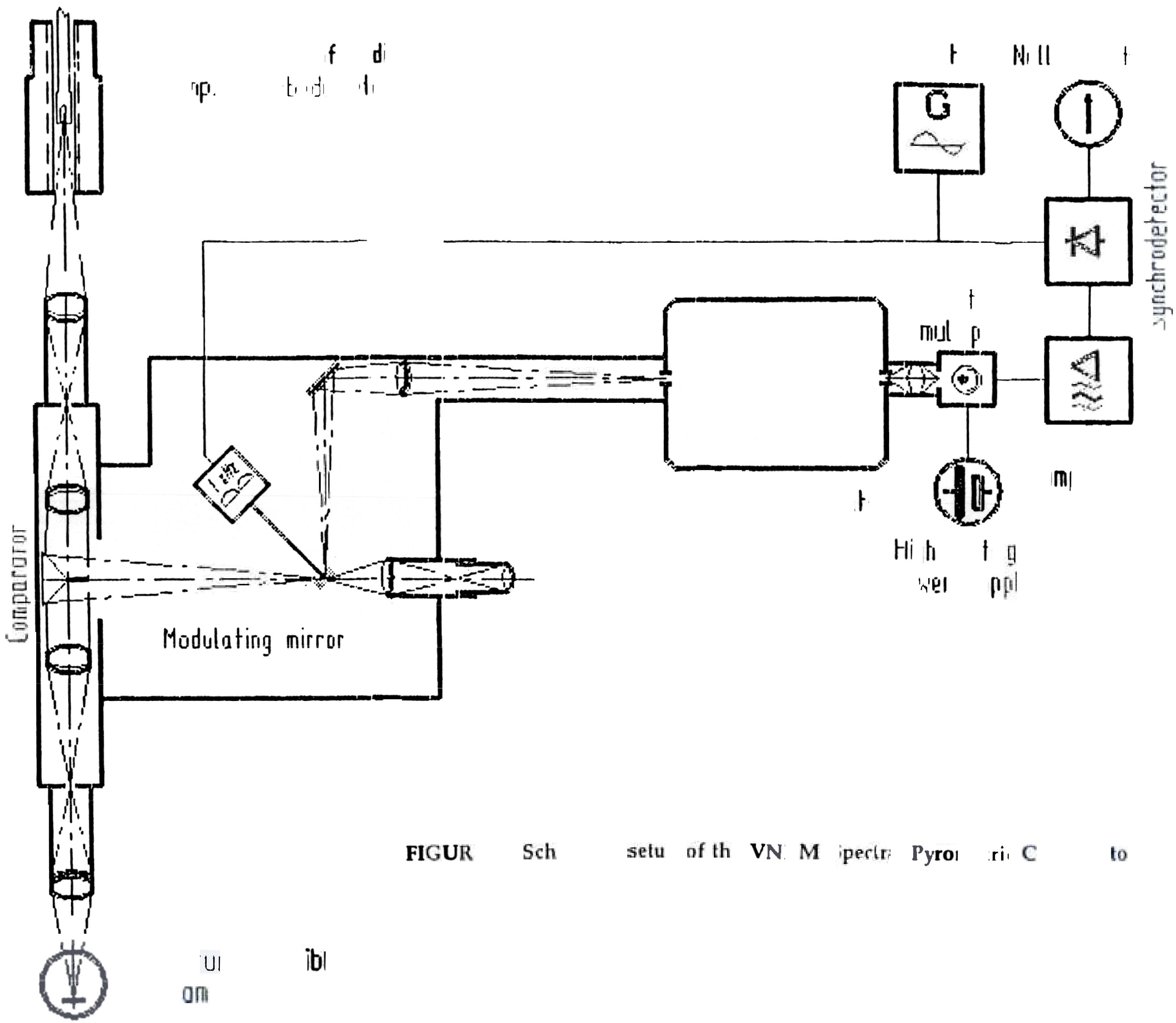

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Figure 5 - Lamp C836

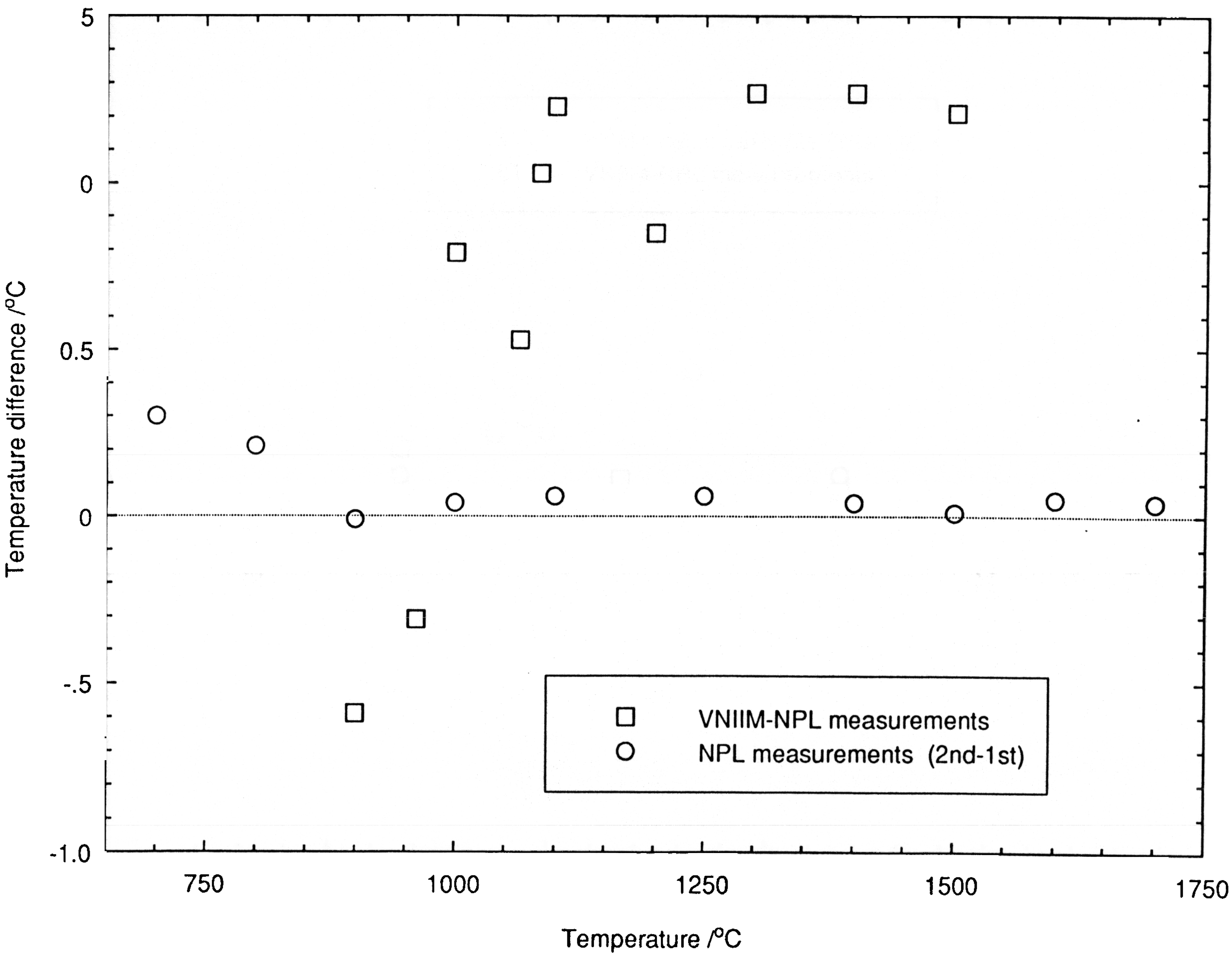

Figure 7 Lamp C841

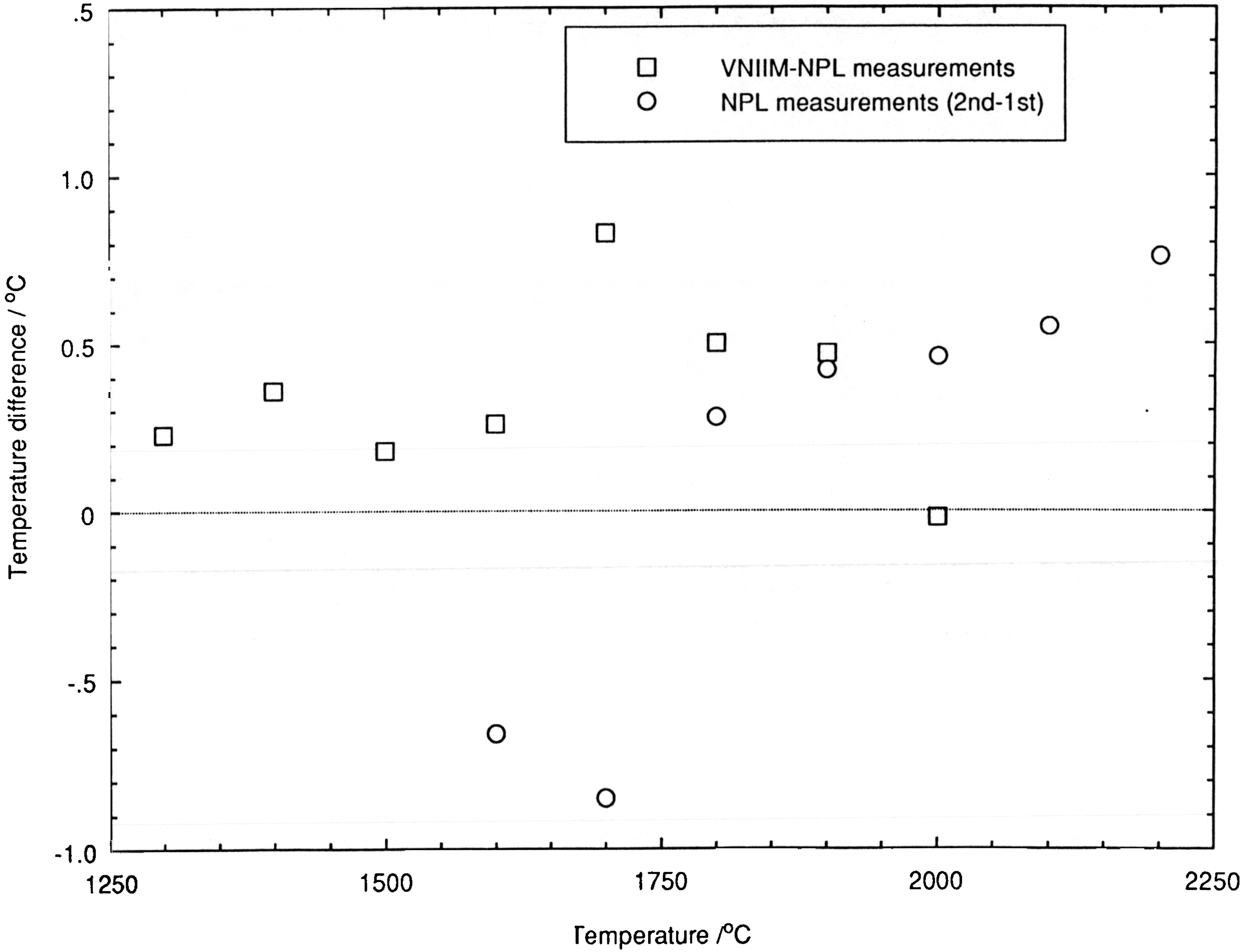

Figure 8 - Lamp N295