REFLECTION FACTORS OF NICKEL IN THE INFRA-RED AT HIGH TEMPERATURES

By

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INTRODUCTION

The Problem

The temperature coefficient of the reflection factors for metals has been studied by a number of investigators. The reflection factors in the visible spectrum usually increase as the temperature of the mirror is raised; while those in the long wave infra-red region decrease. The transition from the positive to the negative values must occur at a wavelength between the visible and the far infra-red.

The exact location and character of this transition is of considerable theoretical importance, yet only isolated experimental studies have been made of it. Hagen and Rubens (12) measured the temperature coefficients of the reflection factors of nickel through the region, with, however, a comparatively small change in temperature (20 to 300°C). Weniger and Pfund (16) measured those for tungsten for temperatures up to 2067°K. The transition was found by them to take place entirely between about 0.7 and 2.0μ. The actual change from positive to negative coefficients occurred at 1.27μ. McCauley (10) through measurements of

the emissivities of platinum, palladium, and tantalum, computed their reflection factors and found similar results.

It is desirable from theoretical considerations that further data be taken by a direct measurement of the reflection at high and low temperatures so as to establish the transition point for more metals. In this investigation these measurements have been made for polished nickel throughout a temperature range of 20° to 920°C and a wavelength range of 0.8 to 11μ.

Definitions

Before proceeding with the discussion of the theory underlying the reflection of radiant energy by metals, it will be well to define the following terms, some of which have already been introduced.

Reflection factor or reflectivity, R. The fraction of the radiant energy of known character normally incident upon the surface of a body, which is reflected by that surface.

Absorption factor or absorptivity, A. The fraction of the radiant energy, of a known character, incident normally upon the surface of a body, which is absorbed by that body.

Transmission factor or transmissivity, T. The fraction of the radiant energy of a known character, incident

normally upon the surface of a body, which is transmitted by that body.

Coefficient of absorption, k. The ratio of the negative space rate of variation of intensity of a beam of radiant energy passing through a body, to the intensity of the beam. It is expressed by the equation

$$k = \frac{-\frac{dI}{dx}}{I}$$

where x is the thickness of the body already traversed by the beam and I the intensity of the beam at the depth x.

Emissivity, e. The ratio of the total radiant energy emitted per unit area per unit time by a body at a definite temperature to the total radiant energy emitted per unit area per unit time by a blackbody at the same temperature.

Monochromatic emissivity, e_λ. Emissivity confined to the radiation within an infinitesimal wavelength range $d\lambda$.

Temperature coefficient of reflection factor. The numerical change of the reflection factor per unit change of temperature.

Spectral or monochromatic radiant flux per unit area, W_λ. Emission of radiant energy of wavelength λ per unit area per unit time.

Resistivity, ρ. That factor of the resistance of a body which depends upon the material and its physical condition but not its geometric form, and is referred to as the resistance of a specimen in the form of a rod of unit length and unit cross-section when traversed longitudinally by a unidirectional non-varying current.

Theory

At the longer wavelengths the reflection factors and their changes with temperature are closely represented by Drude's (4:349) formula

$$R = 100 - 3650 \sqrt{\rho/\lambda}, \qquad (1)$$

where R is the reflection factor at wavelength λ expressed in microns and ρ is the resistivity of the metal in ohm-cm.

The reflection factor for shorter wavelengths depends upon the molecular properties of the metal as well as the free periods of the free electrons and therefore cannot be expressed by as simple a relation as that just given. Maxwell's theory (4:345) leads to relation

$$R = \frac{(1-n)^2 + k^2}{(1+n)^2 + k^2} \qquad (2)$$

where n and k are the index of refraction and the coefficient of absorption respectively. These constants are well

known for many metals at ordinary temperatures. Their values are usually determined by a measurement of the amount of elliptical polarization caused by the metallic reflection of light which was originally plane polarized at 45° with the plane of incidence. Such a beam may be thought of as consisting of two components, one parallel to and the other perpendicular to the plane of incidence. Since each component suffers a change in phase on reflection, the reflected wave is usually elliptically polarized. This phase difference can be measured by means of a Babinet compensator whereby the beam is restored to a plane polarized wave. The angle of incidence which produces a phase difference of $\pi/2$ and the angle between the original and final planes of polarization determine the index of refraction and the coefficient of absorption. The success of such measurements is naturally affected by the surface condition of the mirror.

As the molecular condition of the surface of a mirror can be expected to change upon heating, the reflection factors at high temperature have either been measured directly or computed from the measured monochromatic emissivity. This computation makes use of Kirchhoff's law (4:485):

$$e_\lambda = W_\lambda / W_{\lambda_b} = 1 - R \qquad (3)$$

In this expression, e_λ is the monochromatic emissivity,

W_λ the monochromatic radiant flux per unit area emitted by the metal, and W_{λ_b} that emitted at the same wavelength and temperature by a blackbody.

There is as yet no accepted theory concerning the relation between the molecular structure of metals and the quantities n, k, and e_λ. Expressions (2) and (3) enable a determination of R as a function of temperature only through experimental value of either n and k or e_λ. Before a complete theory can be formulated, more data must be accumulated. Such data are provided herewith for one more element, nickel.

APPARATUS

Optical Path

In order to measure the reflection factor of a mirror for different wavelengths, the energy of the incident radiation and also that of the reflected radiation must be measured in each wavelength. To avoid troublesome corrections, it is necessary to prepare for these two measurements by having two light paths of identical length, $GM_1M_2S_1$ and $G'M_1'NM_2S_1$ (Fig. 1) before the energy is spectrally dispersed. The source G and the concave mirror M_1 are mounted on a stand so that they can swing as a unit about a vertical conical axis. The rotation is limited by adjustable stops. The device, designed by Weniger (15), enables rapid shifts to be made from one position to the other of the source and mirror. M_2 is a concave mirror, N the plane mirror of nickel and S_1 the entrance slit of the spectrometer.

M_3 and M_5, the collimating and telescope mirrors of the spectrometer, are fixed in position. The Wadsworth mounting consisting of the prism P and the plane mirror M_4 insures that the radiation which leaves the prism parallel to the incident beam has traversed the prism at minimum deviation. The dispersed beam is focused upon the exit

S_2. The nearly monochromatic radiation thus obtained is focused upon the radiometer vane R by the concave mirror M_6.

Spectrometer

The prism table is mounted upon the head of an old U. S. Coast and Geodetic Survey theodolite. The 20 inch circle of the theodolite is provided with measuring microscopes reading to one second of arc.

The spectrometer was set on a large marble slab placed on a heavy table. With the exception of M_1, all of the concave mirrors, the bilateral slits S_1 and S_2 and the radiometer housing were mounted upon heavy cast iron tripods. Each tripod was provided with leveling screws which were set on hole-slot-plane plates waxed to the marble slab. The theodolite and the special tripod upon which the source and M_1 were mounted, also have leveling screws resting on hole-slot-plane plates.

All of the mirrors have front surface silver coatings. The rock salt prism (face 1 3/4" x 2 1/4") was cut from a natural crystal (picked up at the mine of the Detroit Rock Salt Company) to have a refracting angle of approximately 60°. The prism was polished in the usual manner upon a pitch surface with rouge. To obtain optically flat surfaces it was necessary to form a slightly convex surface on the pitch lap to compensate for the tendency of the

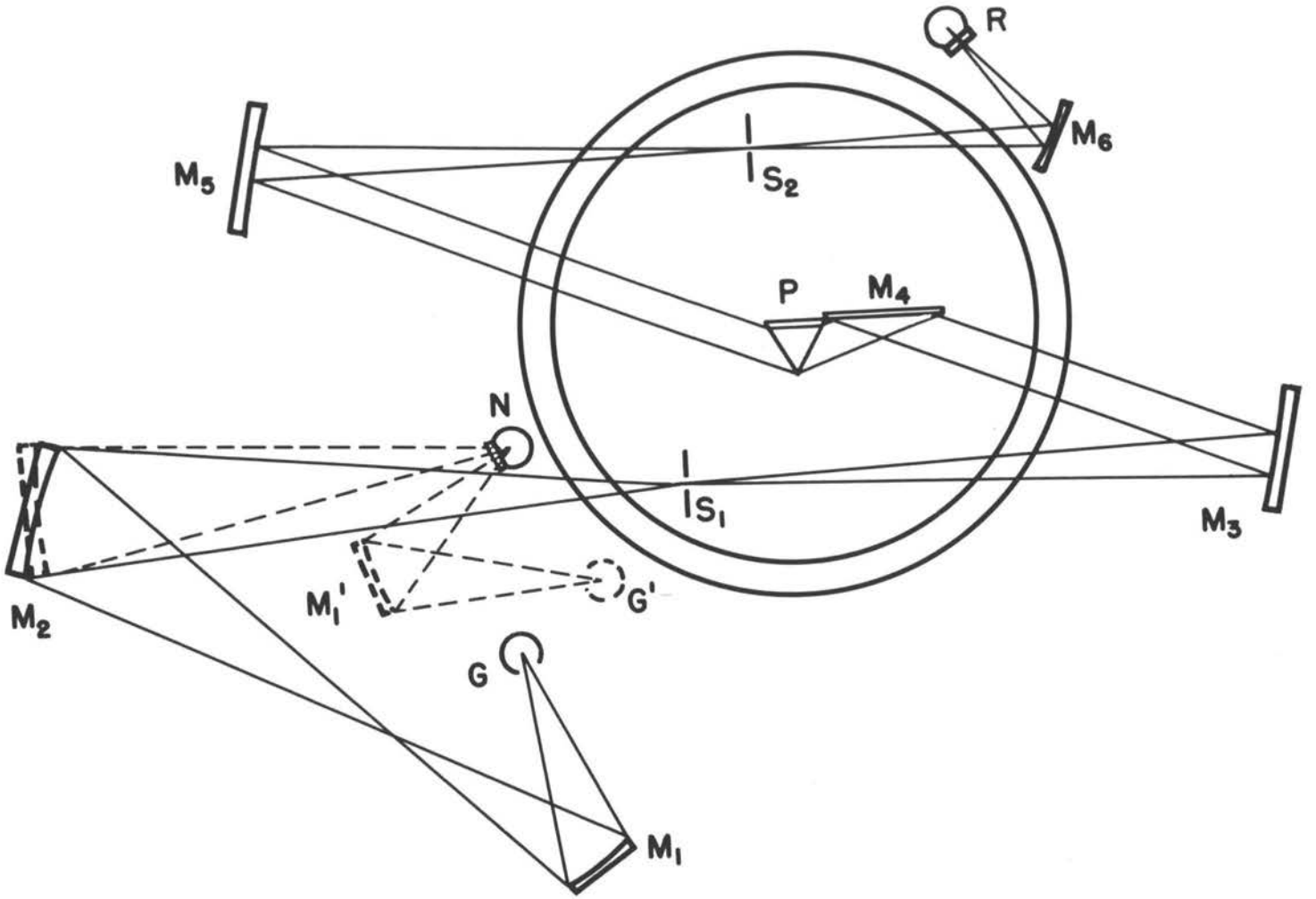

Fig. 1. The Optical System.

crystal to wear irregularly as it was moved to and fro during the polishing. The correct curvature of the lap was found by trial and error, using flat plates of rock salt.

Adjustments of the Wadsworth Mounting

The adjustment of the spectrometer is somewhat intricate. The axis of the theodolite was brought into a vertical line by means of a sensitive level. The prism table was then leveled by means of its three supporting screws. The face of the Wadsworth mirror and the plane bisecting the refracting angle of the prism must both pass through the axis of rotation and must be perpendicular to each other. In preparation for these adjustments a small triangular brass plate was provided with a hole which will ultimately lie at the point of intersection of the bisector of the prism angle and the mirror face. This hole was brought vertically above the axis of rotation by means of a plumb bob whose string passes through the hole. (The end of the spectrometer axis had been brought to a "center" by the manufacturer.) Using a small amount of soft wax, the prism was secured on the triangular plate with the center of its rear edge flush with the center of the small hole.

The simplest method of assuring that the Wadsworth mirror and both prism faces are vertical is to have them, in turn, reflect light into a telescope provided with a

Gaussian eyepiece, the optical axis of the telescope being truly horizontal. As no telescope with a sufficiently large aperture was available, a good reading telescope was mounted on the parallel ways of a sliding microtome so that the telescope could be moved as necessary without disturbing the horizontal direction of its axis. The optical axis of the telescope was made horizontal by taking offset measurements with a surveyor's level set up at the proper height in the room. One offset was measured to the center of the telescope objective, the other to a card on the wall upon which the telescope could be focused. The Wadsworth mirror was held to a vertical brass plate by three special fasteners each of which permits a short horizontal movement. The brass plate carrying the prism was also provided with the necessary means for adjustment.

Circle readings were taken for each of the prism settings and the prism angle thus determined to be 59° 24' 57". Finally, the plane mirror was rotated about a vertical axis until it was at right angles to the plane bisecting the prism angle.

Calibration

As already stated, the wavelength of light refracted in a direction parallel to the undeviated beam from the

collimating mirror has passed through the prism at minimum deviation. At minimum deviation

$$n_\lambda = \frac{\sin \frac{A + D_\lambda}{2}}{\sin (\frac{A}{2})}$$

where n_λ is the index of refraction for wavelength λ, D_λ its angle of minimum deviation and A the prism angle. Solving for D_λ

$$D_\lambda = 2 \sin^{-1} (n_\lambda \sin A/2) - A$$

Values of n_λ for every 0.1μ from 0.5893 to 6.5μ were read from the dispersion curves for rock salt given by Langley and Abbot (7). Values for scattered points between 6.5 and 16μ were taken from the table compiled by Shaefer and Matossi (13). D_λ was computed for each n_λ thus procured, and plotted on a large scale. From the resulting curve, values for D_λ were read and tabulated for every 0.1μ between 0.8 and 16μ.

As the mirrors are not filled by the light passing through the prism, it is possible to obtain the undeviated beam over the top of the prism along with the dispersed beam. The image of S_1 thus formed at S_2 with sodium light was observed through the exit slit with the aid of a telescope set up in the position of M_6. The prism table was rotated until the D lines coincided with the undeviated beam. This circle reading was taken as a fixed point in

the spectrum. Circle readings for any other wavelength λ may be computed from the formula

$$\theta_\lambda = \theta_D + \frac{D_D - D_\lambda}{2}$$

where θ_λ and θ_D are the circle readings for wavelength λ and the D lines respectively, and D_λ and D_D their angles of minimum deviation.

To test the accuracy of the calibration, the absorption bands of water vapor at 1.87 and 2.66μ, the 4.4μ emission band of carbon dioxide, and the absorption band at 13.92μ of the ordinary ray passing through calcite were observed. Each band was found to be accurately in place. The 2.66μ water vapor band provided a sensitive check (see Fig. 4) for the calibration of the instrument and was observed for this purpose before and after every run. The CO_2 radiation was obtained from the flame of a Bunsen burner. A crystal of calcite was cut at right angles to the optic axis and polished with rouge on a soft pitch lap until a plane parallel plate of 0.1 mm thickness was obtained. This was waxed to a plane parallel piece of rock salt about 2.5 mm thick. The compound plate had a sharp band at 13.92μ with a measured absorption of 95 per cent.

Dispersion

The bilateral slits S_1 and S_2 were 8 mm high. As the mirrors M_3 and M_5 were of equal radius of curvature, the

slits were maintained at equal widths except when S_2 was made less than S_1 to reduce the radiometer deflection. From 0.8 to 1.0μ slit S_1 was kept at 1.00 mm and covered a range of 0.05μ at 1μ. The slit widths were reduced to 0.25 mm between 1 and 5μ; this permitted the passage of a wavelength interval of only 0.05μ at 3μ, the region of minimum dispersion of rock salt. Beyond 5μ the slit widths were increased to obtain larger deflections, but in no case was the equivalent width greater than 0.1μ.

The Radiometer

Figure 2 shows the radiometer system and its housing. The frame of the system was made from soda glass rods about 0.05 mm diameter. The crosspieces were welded to the staff in the flame of a gas-compressed air torch directed from below through a small hole (from #72 to #80 jeweler's drill sizes) in a brass plate that served to support the glass rods. The vanes, 1 mm by 4.5 mm, were cut from a sheet of clear celluloid 0.001 inch thick. They were mounted in pairs on opposite sides of the cross-rods (see Fig. 2b) with a solution of celluloid in amyl acetate. The lever arms of the vanes were about 2.5 mm. The concave mirror for observing the deflection was flaked from the surface of a freshly silvered and polished spectacle lens of the proper curvature. A blackened and an

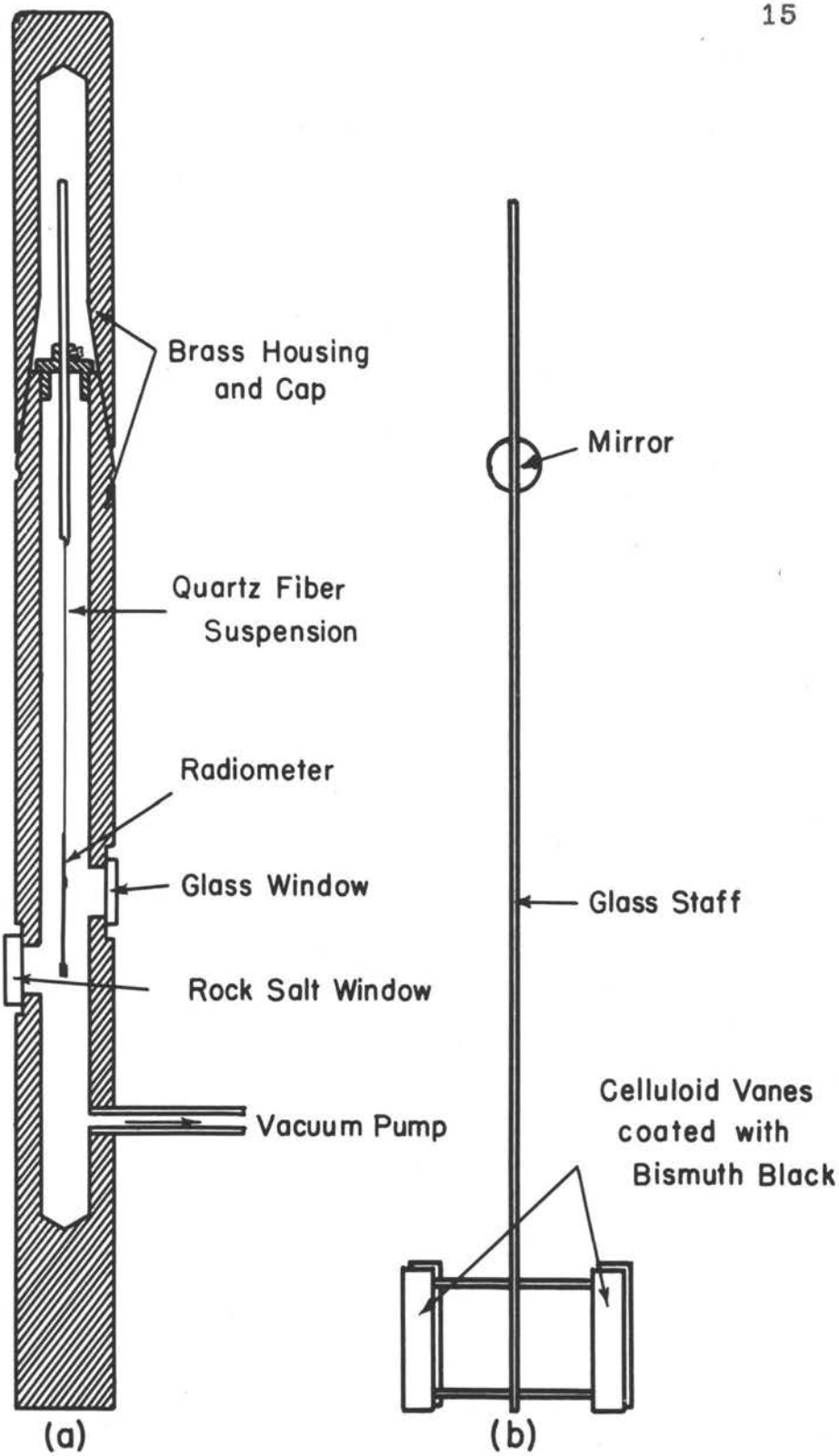

Fig. 2. The Vane Radiometer and Housing.

unblackened system are shown in Figure 3. Two samples of the mirrors are included in the photograph.

The vanes were blackened by the evaporation of bismuth originally supported in a cone of 20 mil tungsten wire in a vacuum of about 0.05 mm of Hg. Upon passing a current of about 20 amperes for from 3 to 4 minutes, the desired deposits were obtained. The optimum thickness or rather the mass per unit area of bismuth black that will absorb all of the radiation in the desired wavelength region, was determined in a preliminary experiment in which the spectral absorption factors for different thicknesses were measured in the wavelength region from 0.8 to 16.0μ. The results for three samples prepared as follows are shown in Figure 4. A plane parallel piece of clear rock salt was polished on both sides; after being cut in half one of the pieces was blackened. The transmission factor of the layer of bismuth black is given by the ratio of the energy transmitted by the blackened plate to that transmitted by the clear plate. The reflection factor is the ratio of the radiation reflected from the black surface to the direct radiation from the source. The absorption factor A, expressed in per cent of incident radiation, is then

$$A = 100 - (T + R)$$

where T and R represent the transmission and reflection factors also expressed in per cent of incident radiation.

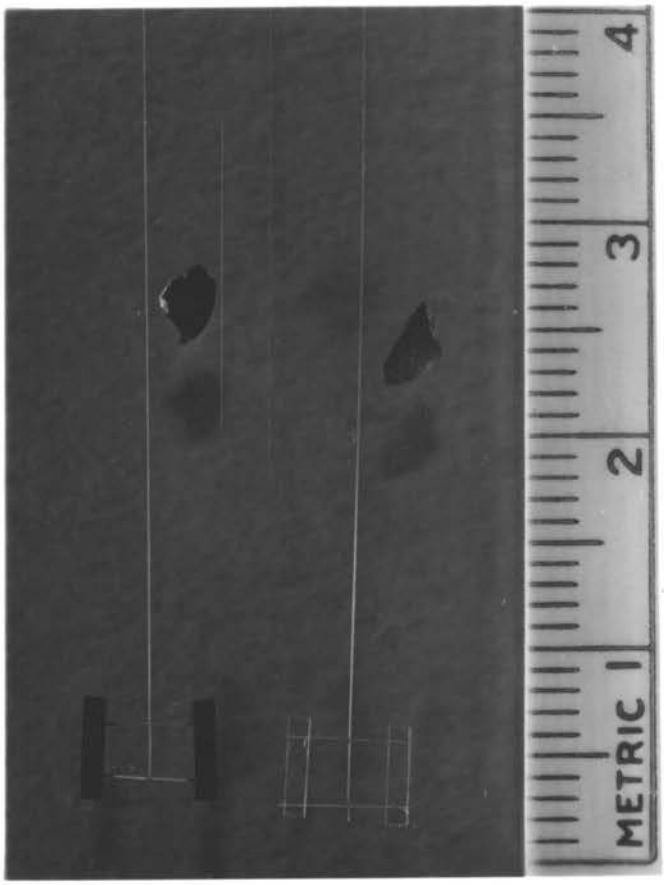

Fig. 3. Radiometer Systems.

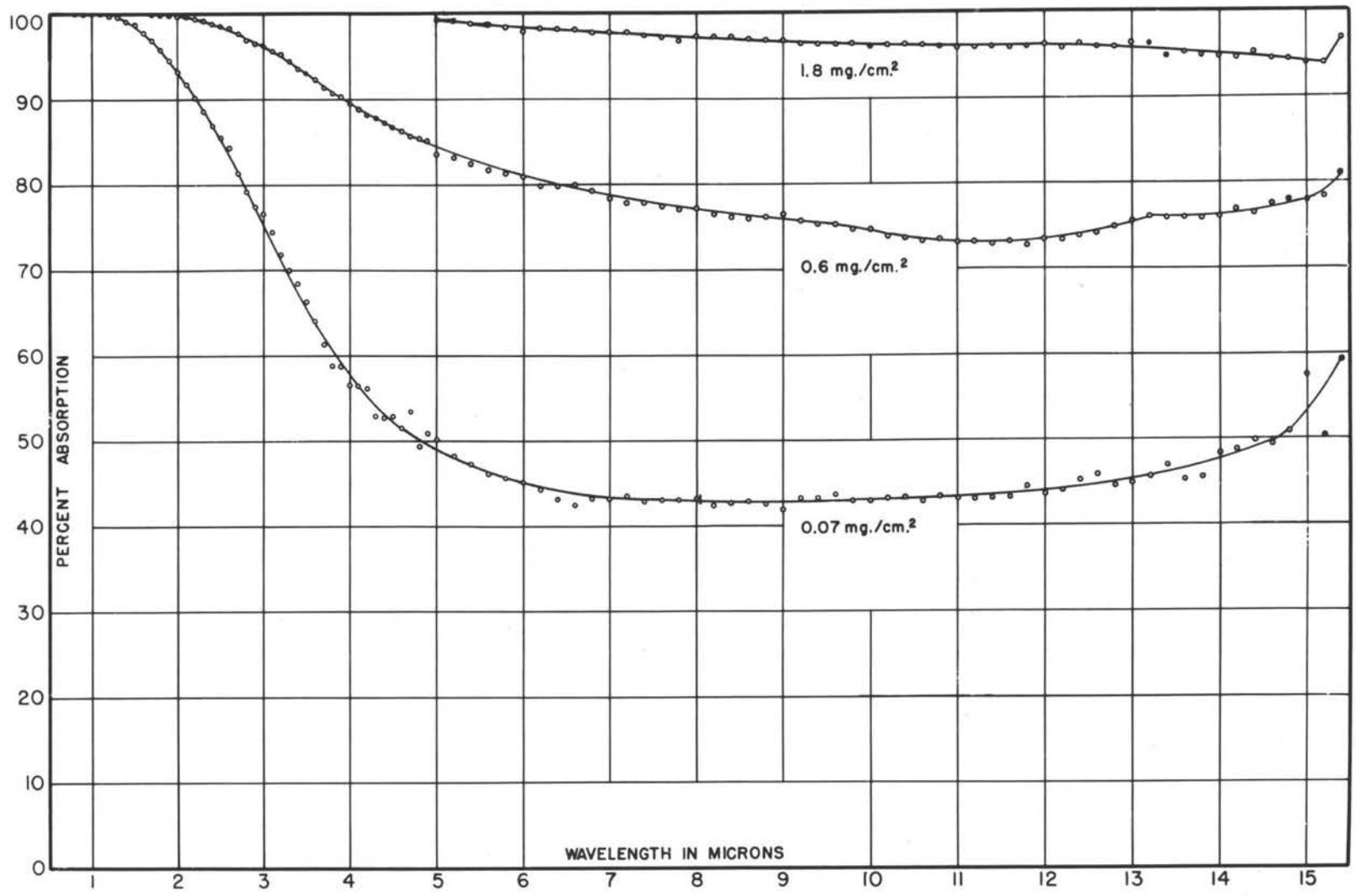

Fig. 4. The Spectral Absorption Factors of Bismuth Black.

Figure 4 indicates clearly that bismuth black should be deposited to the extent of at least 1.8 mg/cm^2 if the instrument is to be used beyond 3μ. The advantage of using this optimum thickness was well demonstrated by comparing a radiometer so coated with the one used in the preliminary experiment. The preliminary instrument was coated, according to standard practice, with acetylene black more than 0.5 mm thick, or approximately 50 mg/cm^2. Even this thickness does not absorb as much radiation as the optimum thickness of bismuth black. The thermal capacity and the period of this radiometer were so large as to slow down the readings very appreciably. In fact the old style instrument had to be used by measuring the deflection produced in 10 sec, whereas the new instrument came to full deflection in less than 6 sec.

The entire system used in the reflection factor measurements weighed 2.5 mg. It was suspended from a drawn quartz fiber of about 1μ diameter. The sensitivity of the fiber was first tested by suspending a small scrap of paper (about 1 mg) from it and slowly twisting the top of the fiber. The fibers used could be twisted through from 50 to 100 turns before the paper began to turn.

The radiometer housing was evacuated to about 0.05 mm of Hg pressure for maximum sensitivity and approximate aperiodic damping (due to gas pressure). A rock salt window

admitted radiation to the radiometer. The glass window allowed observation of the resulting rotation of the mirror (through deflection of a beam of light by the mirror). As the radiometer system was slightly magnetic, the zero-point and period could be controlled by the field of a permanent magnet placed outside the housing. For most of the readings a period of 6 seconds was employed. The zero-point underwent gradual drifts part of the time as a result of the diurnal variations of the earth's field. The effect of drift was minimized by using an average zero-point from readings before and after each deflection. Whenever the drift amounted to more than a millimeter in 6 seconds, readings were suspended.

The Source

The source of radiation for some of the earlier measurements (absorption factors of bismuth black) was a Nernst glower heated by current from a 220 volt A.C. source. The difficulty in maintaining a constant heating current due to irregular variations of the voltage supply amounting to as much as 2 per cent, led to the use of a Globar heater. This has a mass several thousand times that of the Nernst glower, and is therefore less sensitive to voltage fluctuations. It was heated by a current of 11.5 amperes from

a 32 volt D.C. source. This voltage was generated by a synchronous motor-generator set especially built for the purpose. After the generator had come to constant temperature, the heating current varied less than 0.1 per cent.

The Globars used were of a special type, 11 1/4 inches long of which only the central 4 1/4 inches were brought to redness by the current. The relatively long terminals of carborundum of lower resistivity allowed a cool connection to be made with No. 2 Mueller Universal clips. These were clipped to the very ends of the heater, these ends having been wrapped with two or three turns of aluminum foil. There was no tendency to arc at this connection.

The heater was placed in the axis of a thin brass tube 1 3/4 inches in diameter and 4 1/2 inches long. A slot in the cylinder permitted radiation to escape in the direction of the mirror M_1. The brass tube was cooled by tap water flowing through several turns of 1/4 inch copper tubing, surrounding and soldered to each end of the brass tube. No attempt was made to maintain a polish on the interior of the brass tube, as suggested by Levialdi (8) because of the rapid oxidation resulting from the intense heat; Such a polish would be useless anyway, as the glower radiates plenty of energy, and the chief requirement is to have a constant source. With the cooling water flowing at

the constant rate of 5 cc/sec, the brightness temperature of the radiator was constant at 1230°K. The relative energy distribution in mm deflection for a spectrometer slit 8 mm high and 1 mm wide is shown in Figure 5. The principal absorption bands due to water vapor and carbon dioxide are of course present in this curve. Curve (b) is a magnification of the curve (a) between 9 and 16μ.

The Nickel Mirror

To obtain a nickel mirror whose reflection could be measured at both ordinary and incandescent temperatures it was decided to mount a ribbon filament of the metal in vacuum and heat it by passing an electric current through it, this method having been found feasible in the case of tungsten (16).

The samples of nickel used were rolled into ribbons 2 mm wide and about 0.18 mm thick from 40 mil Pure Nickel wire donated by the Wilbur B. Driver Company. This nickel was of the "Grade A" quality which has the composition (5:52):

Ni	98.9%
Fe	0.5
Mn	0.2
Si	0.1
S	0.025
C	0.1
Cu	0.18

Straight portions of the ribbons were selected and mounted side by side upon a flat brass plate with a mixture of half beeswax and half resin. The ribbons were ground flat with a razor hone and polished to a mirror surface with jeweler's rouge. Only the central portions thus obtained were used, to insure a flat surface of constant thickness.

The problem of mounting the strip so as to avoid displacement or rotation of the mirror face during the temperature changes presented some difficulty. The manner finally employed is best explained by reference to Fig. 6. The lower end of the filament, 6, was spotwelded to the crosspiece of 40 mil nickel wire. The upper end was similarly fastened to the stirrup, 5, made of nickel. The lower crosspiece was hooked into notches cut into the back of brass upright, 8. The stirrup was suspended from the coil spring, 1, of 16 mil tungsten wire. With the nickel at room temperature, the tungsten spring was stretched an amount equal to the linear expansion of the strip due to a temperature change from 20°C to 1450°C, the melting point of nickel. This precaution was taken to avoid permanent elongation of the strip after a heating and yet keep it under sufficient tension to prevent bowing. To prevent twisting of the upper end of the strip, the ends of the nickel rocker arms, 3, were pivoted and set into small center punch holes in the back of the stirrup. The oppo-

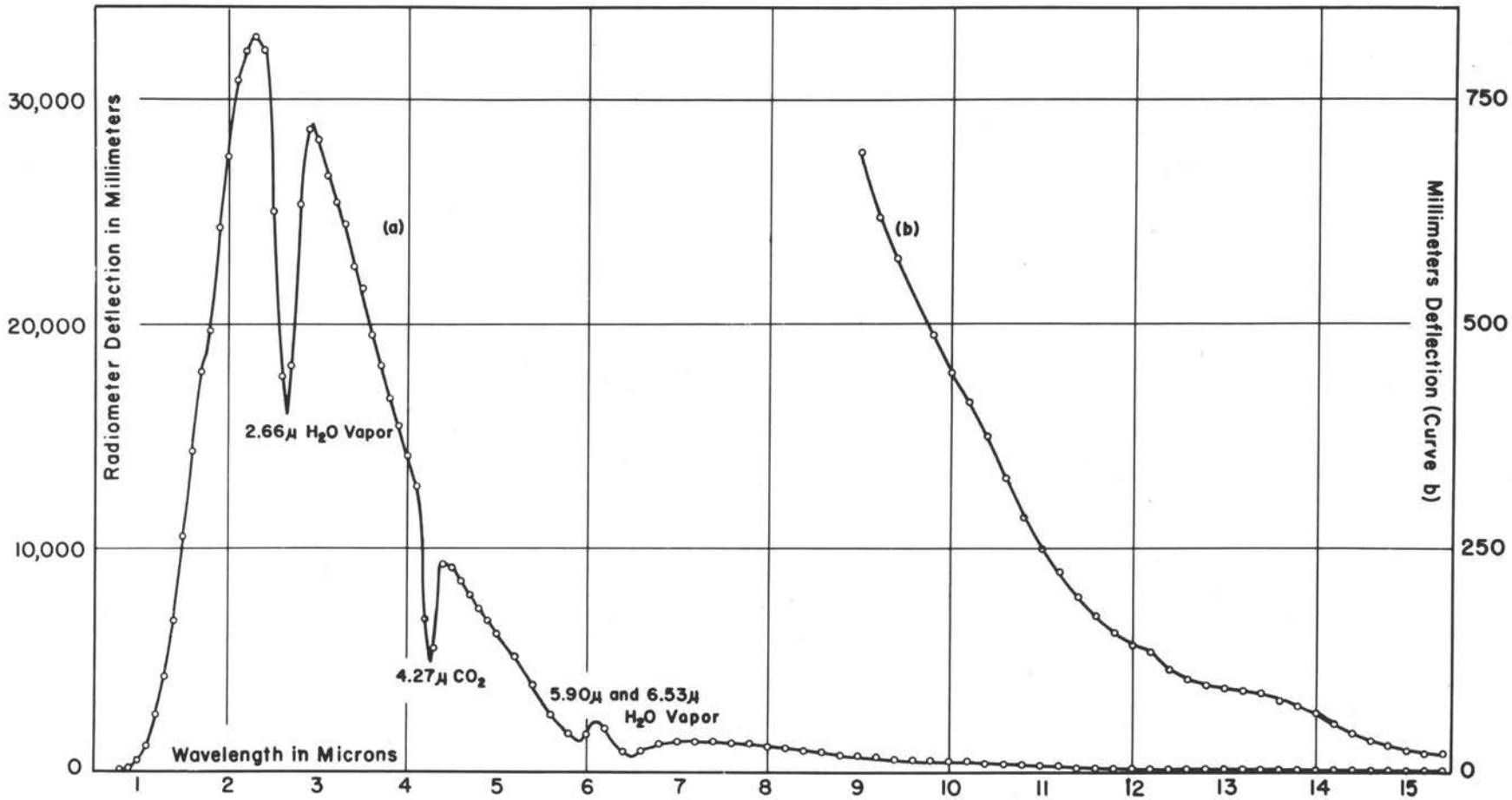

Fig. 5. Relative Energy Distribution of Globar Heater at 1230° K, Showing Principal Absorption Bands of Atmospheric Water Vapor and Carbon Dioxide.

site ends of these arms were similarly supported by set-screws (size 1-72) in the U-shaped brass piece, 4. As the tungsten spring would have been heated excessively by the heavy heating current, the stranded copper pigtail, 2, was used to shunt the current from the nickel stirrup to the brass upright, 7. In order to avoid having the pivot points spoiled by the current, the brass support, 4, was insulated from the uprights, 7, by thin strips of mica.

The rods, 8, were screwed into the base plate, 11, which acted as one terminal. The rods, 7, were mounted on the machine bolt, 9. This bolt passed through the base plate and was insulated from it by a mica bushing. A coating of wax over the head of the bolt on the outside made a vacuum tight seal. To aid in removing air from the bushing, the bolt was drilled along its axis and also radially in several places.

Fig. 7 shows the housing in place but without the rock salt window. At 1 is the exhaust tube; 2, shows the water jacket and 3, the heavy flange screwed onto the housing to enable the use of a fuse wire gasket in the vacuum seal. A ring gasket is shown still in place at, 10, Fig. 6.

With the lamp in place in the spectrometer, a test was made to see whether the plane of the mirror moved during heating. Two telescopes were sighted upon opposite

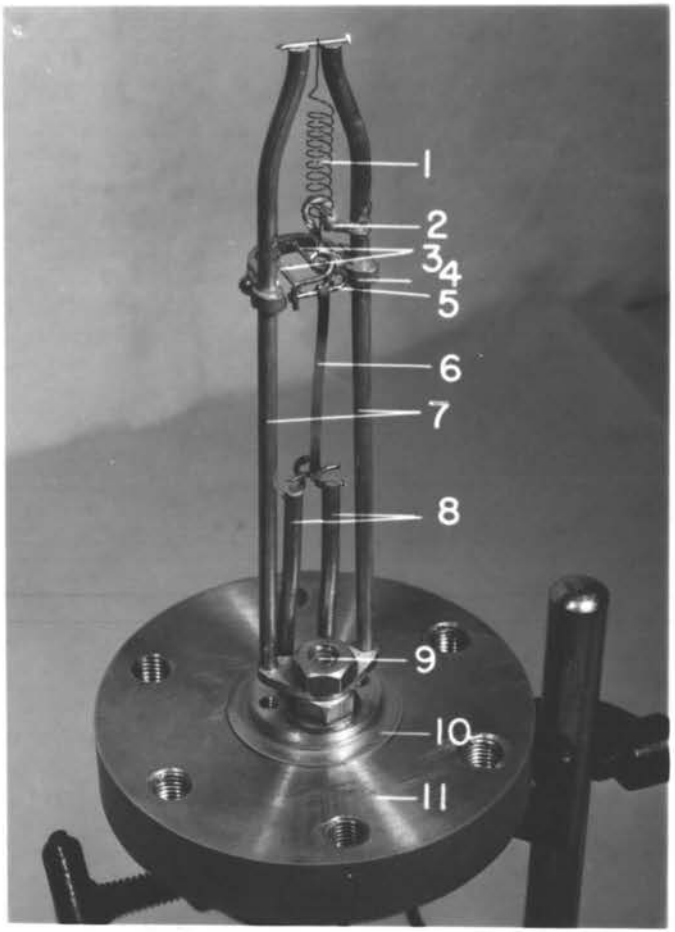

Fig. 6. Support for the Nickel Mirror.

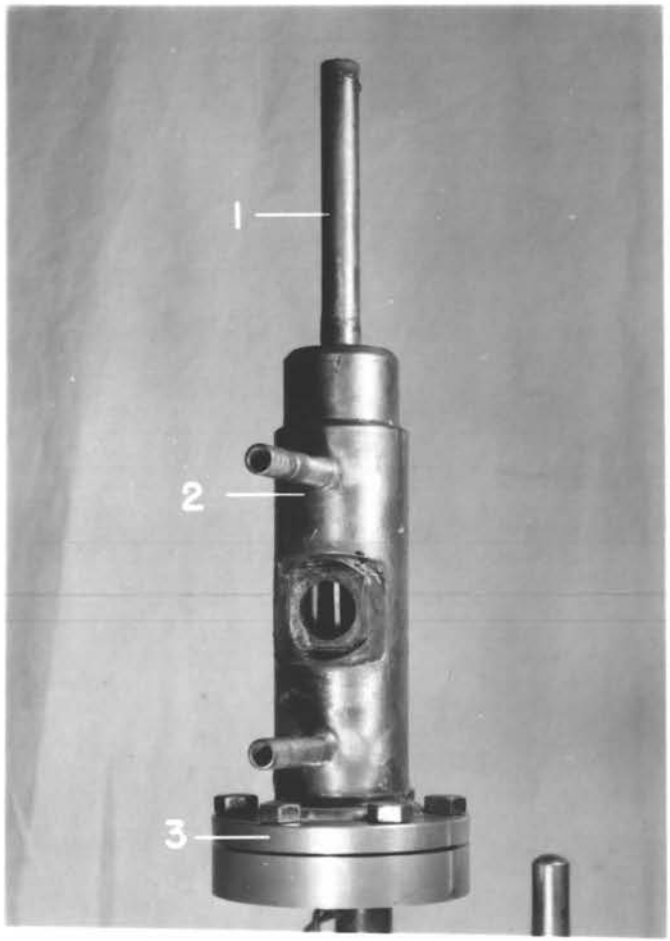

Fig. 7. Nickel Mirror with Housing.

edges of the strip through the rock salt window, their lines of sight being oriented approximately perpendicular to each other. No motion whatever was observed during the heating and the subsequent cooling.

The vacuum system consisted of a mercury diffusion pump backed by a Cenco Megavac mechanical pump. Mercury vapor was frozen out in a trap surrounded by a slush of dry ice and acetone. The vacuum was measured with an ionization gauge constructed from an old 5 watt transmitting tube. A pressure of less than 5×10^{-6} mm of Hg was maintained throughout the experiment.

The Optical Pyrometer

To measure the temperature of the nickel mirror, a disappearing filament optical pyrometer was constructed (Fig. 8). The telescope, the pyrometer lamp, and the lens, L, and their mounts were borrowed from the Holborn-Kurlbaum pyrometer built by Dr. W. R. Varner, of this department. These parts were mounted upon a 2x6" fir plank which was in turn mounted upon an old barber chair pedestal. The plank could be rotated about a vertical axis, and by means of the hydraulic lift, could be raised to any desired height.

When the parts were assembled, the pyrometer was focused upon the nickel filament, Ni, shown in Fig. 8.

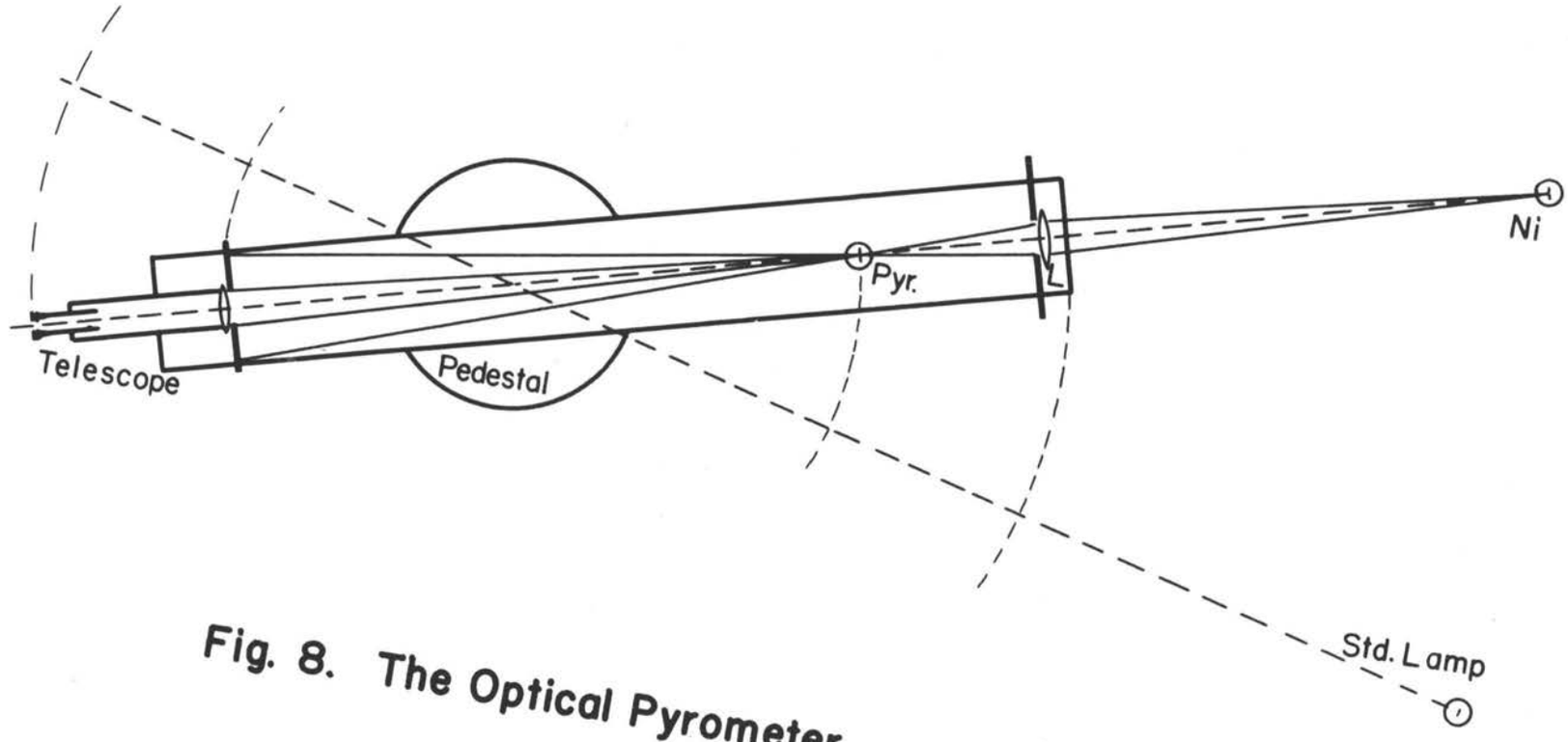

Fig. 8. The Optical Pyrometer.

Then, without changing any of the adjustments, the pyrometer was rotated to the dotted line position so as to view the filament of the standard lamp. With this set-up, it was easy to calibrate the pyrometer without moving the nickel mirror housing.

The pyrometer current was measured by means of a standard ohm and a Leeds and Northrup Student potentiometer. The current through the standard lamp was measured with a calibrated Weston Model 45 ammeter. The heating currents through the nickel mirror were adjusted to fixed values on a Weston Model 280 ammeter. By careful matching, it was possible to repeat pyrometer readings within 0.1 per cent.

Summary

The photograph, Fig. 9, shows a general survey of the apparatus. The table in the foreground contains the current measuring apparatus for the pyrometer located directly behind the table at the left of the picture. The spectrometer assembly is in the background at the right. At (a) lie the remote control and reading devices for operating and observing the spectrometer positions. The vacuum system is at (b). The special tripod carrying the source G and the mirror M_1 of Fig. 1 is at (c). The chamber for the nickel filament can be seen just behind the

tripod. The top of the radiometer housing is at (d). The scale (e) was used to read the radiometer deflection.

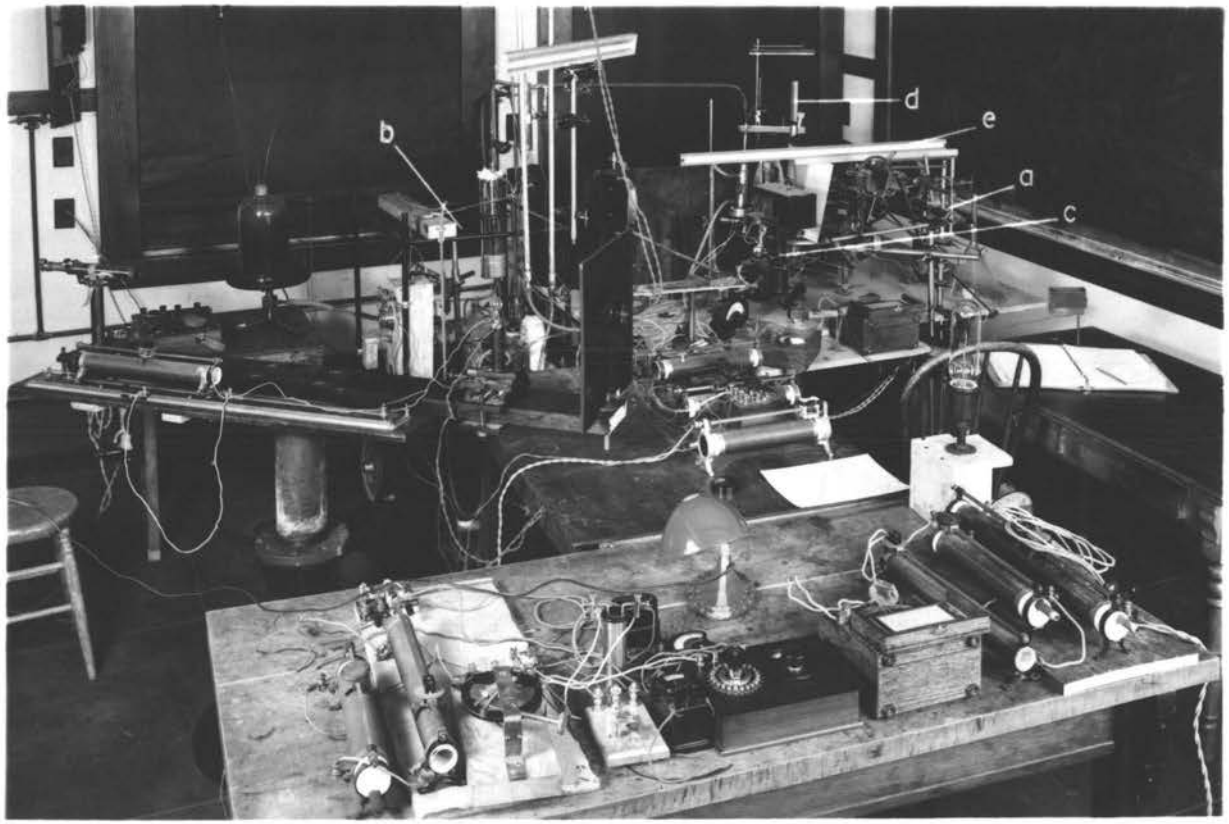

Fig. 9. General View of the Spectrometer and Accessories.

METHOD OF OBSERVATION

At each setting of the spectrometer, successive deflections were observed for the direct radiation from the Globar (position G and M, Fig. 1) and for the radiation reflected from the nickel (position G' and M', Fig. 1) Without changing the spectrometer setting, the same readings were taken with the nickel at high temperature.

Because it was found impossible to completely outgas the nickel mirror housing without danger to the rock salt window seal, much difficulty was experienced with oxidation of the mirror. To minimize this, the time of heating of the filament was reduced to that just necessary to bring it to constant temperature, to take a deflection due to the radiation from the hot mirror and another due to the combined radiation of the hot mirror and that emitted by the Globar and reflected from the hot mirror. The nickel was allowed to cool after each pair of deflections, the pumping being continued to remove gases liberated from the walls by the heat of the mirror. Readings were taken with filament currents of 0, 8.6, 9.0, 9.4 and 10 amperes. The corresponding temperatures were 20°C, 740°C, 800°C, 840°C, 920°C, due corrections having been made for the window and the emissivity of nickel at 0.65μ.

At least two such pairs of readings were taken at 0.8μ, 1μ and at 1.0μ intervals to 11μ. The whole process was immediately repeated in the reverse direction starting at 11μ. Within reasonable limits the time allowed for the heating of the mirror was kept constant. By this procedure not only were two values obtained for each spectrometer setting for the purpose of averaging, but also an automatic check was provided as to the reliability of the values, because a change in the surface condition of the mirror due to oxidation produced a systematic trend in the readings. When this occurred to a marked extent, the mirror was re-polished or replaced by another. Even with these precautions, the loss in polish showed a reduction in the reflection factor of about 10 per cent at 1μ, 4 per cent at 2μ, and 0.5 per cent at 3μ, becoming too small to measure at longer wavelengths. The temperature coefficient of reflection factor at a particular wavelength was the same for both sets of readings, within the limit of experimental error.

Temperature measurements of the hot mirror were made both before and after the above readings were taken. The calibration of the pyrometer lamp was checked against the standard lamp both before and after the measurements.

To correct for losses at the rock salt window, the reflection factors as measured through the window for the mirror at room temperature were measured for every 0.1μ from 0.8μ to 5.0μ and for every 0.2μ from 5.0μ to 12.0μ. After the window was removed, taking care not to disturb the position of the mirror, the measurements were repeated. From the two sets of reflection factors the loss due to a single transmission of the radiation through the window was computed. Deflections due to radiation emitted by the mirror were corrected for a single transit; those due to reflected radiation for two transits.

RESULTS AND DISCUSSION

The observed reflection factors at 20° and 920°C are recorded in Table I. The table also contains the values found by Hagen and Rubens (6) for 20°C and the values predicted by Drude's formula for the two temperatures indicated. For the computations the value of the resistivity of this particular grade of nickel and also its temperature coefficient were obtained from the manufacturer, the Wilbur B. Driver Company.

The agreement between the observed values and the calculated values is fair between 5 and 11μ. For wavelengths shorter than this, however, the discrepancy becomes large. The values for the intermediate temperatures are not included in the table as they differ very little from those of the higher temperature. The observed values of the reflection factors at the lowest and highest temperatures are plotted in Figure 10.

Table II contains the ratio of the observed values of the reflection factors at 920°C and at 20°C for different wavelengths; those predicted by Drude's formula $R = 100 - 3650\sqrt{\rho/\lambda}$ for the same temperatures; and those observed by Hagen and Rubens (12) for 300°C and 20°C. Figure 11 is a plot of Table II. The change from positive to negative temperature coefficients for the reflection

TABLE I

REFLECTION FACTORS OF NICKEL

λ in microns	$R_{20°C}$		$R_{920°C}$		$R_{20°C}$
	Calc	Obs	Calc	Obs	H and R
0.65					67.2
0.78					70.0
0.8		74.8		79.5	
1.0		58.7		61.8	73.0
2.0		78.3		78.8	83.5
3.0	93.8	86.4	84.5	84.3	88.1
4.0	94.0	90.2	86.8	87.6	92.5
5.0	94.6	95.5	88.0	91.7	94.7
6.0	95.1	96.1	89.0	92.3	
7.0	95.5	96.3	89.9	92.3	94.8
8.0	95.8	96.1	90.5	91.8	95.0
9.0	96.0	95.1	91.0	90.8	95.6
10.0	96.2	96.1	91.5	92.5	95.4
11.0	96.4	96.4	91.9	93.0	95.9

Legend: $R_{20°C}$ Reflection factor at 20°C in per cent of incident radiation

$R_{920°C}$ Reflection factor at 920° in per cent of incident radiation

H and R Hagen and Rubens (6)

TABLE II

RATIO OF THE REFLECTION FACTORS OF NICKEL
AT HIGH TEMPERATURES TO THOSE AT LOW TEMPERATURES

λ in microns	$\frac{R_{920°C}}{R_{20°C}}$		$\frac{R_{300°C}}{R_{20°C}}$
	Obs	Calc	Hagen and Rubens (12)
0.78			1.000
0.8	1.062		
1.0	1.051		1.001
2.0	1.007		0.999
3.0	0.976	0.901	0.989
4.0	0.973	0.924	0.982
5.0	0.961	0.930	0.966
6.0	0.961	0.937	
7.0	0.958	0.941	
8.0	0.955	0.944	
9.0	0.955	0.948	
10.0	0.962	0.951	
11.0	0.961	0.955	

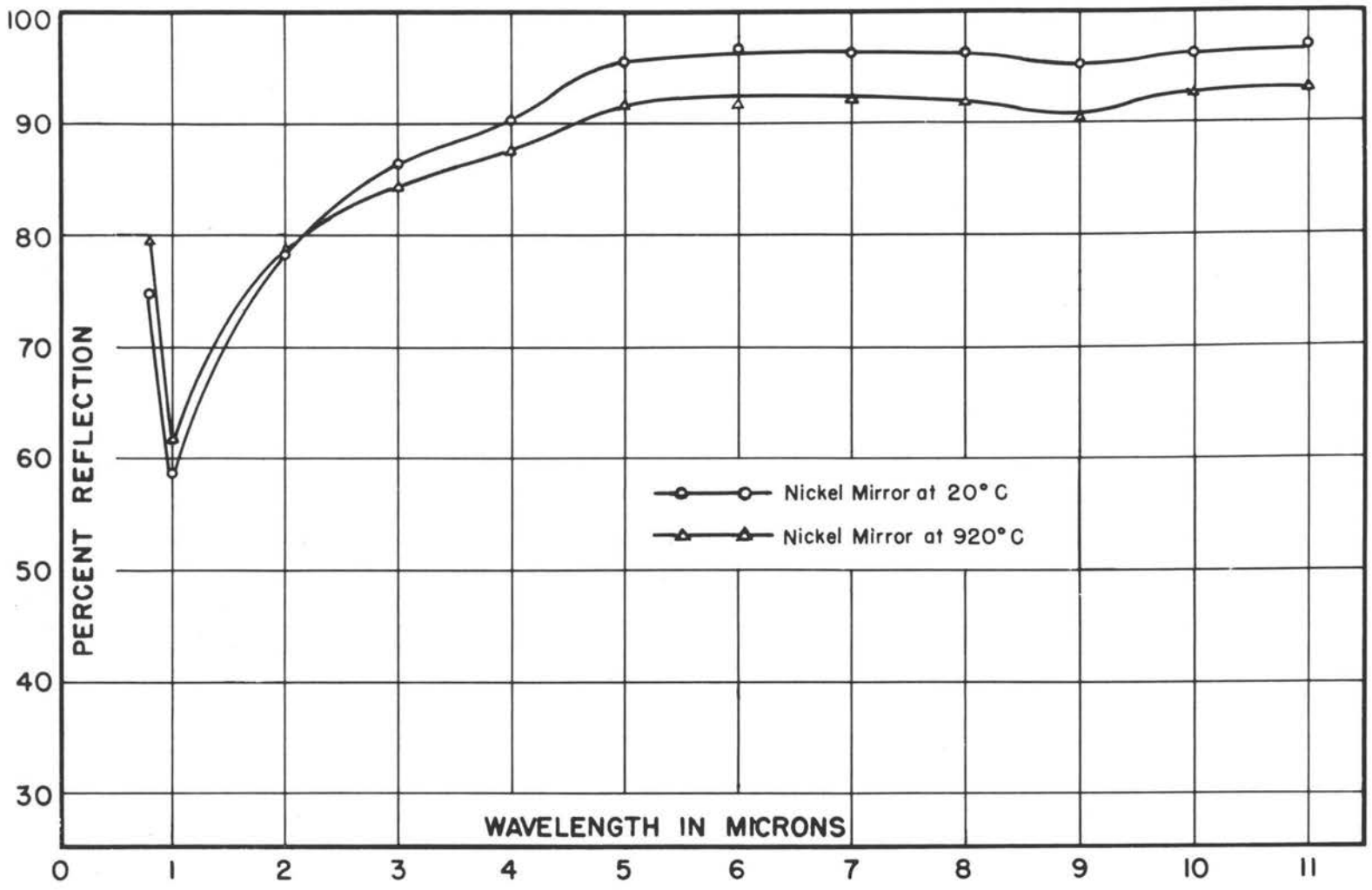

Fig. 10. The Reflection Factors of Nickel at 20°C and 920°C.

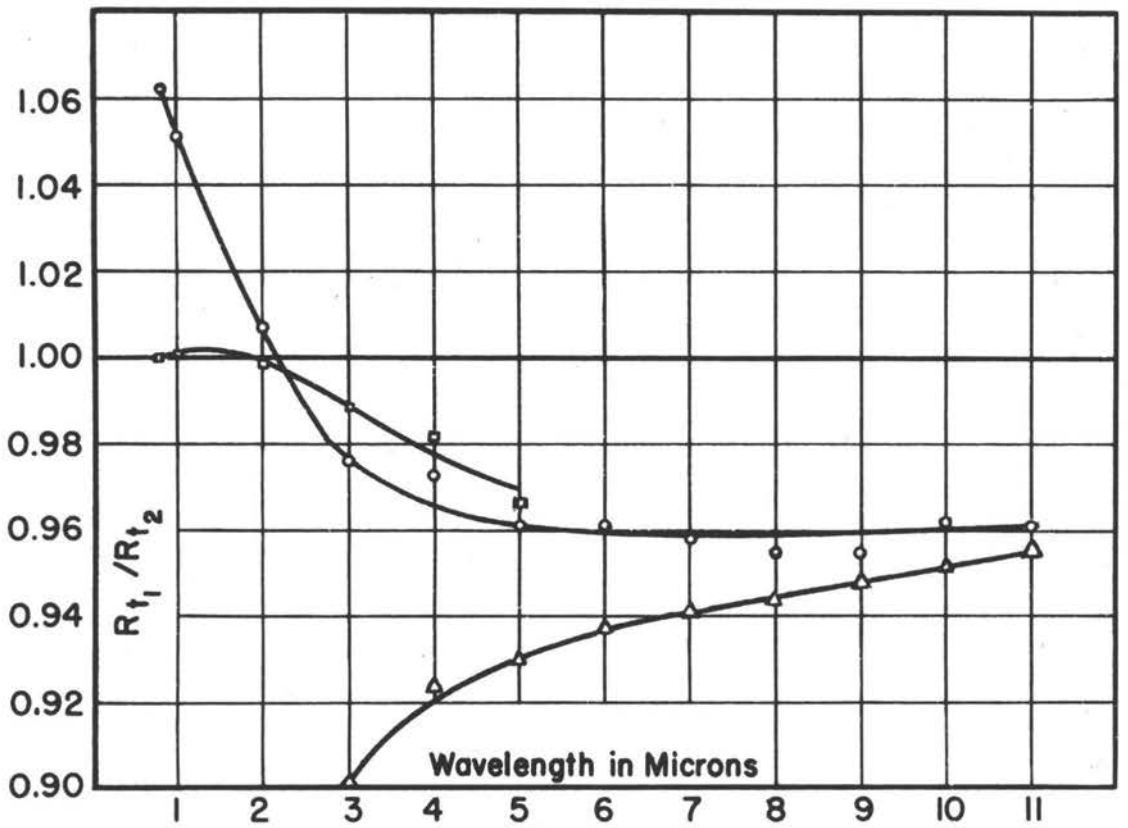

Fig. II. Ratios of the Reflection Factors at High Temperatures to the Reflection Factors at Room Temperature.

o——o t_1= 920° C, t_2= 20° C, Observed

Δ——Δ t_1 = 920° C, t_2= 20° C, Computed

□——□ t_1= 300° C, t_2= 20° C, Observed by Hagen and Rubens

factors occurred at 2.15μ. Hagen and Rubens found the change slightly below 2.0μ.

The largest difference between the present results and those of Hagen and Rubens lies in the large positive temperature coefficient found at 0.8 and 1.0μ. Hagen and Rubens show no change with temperature at 0.78μ and only a small positive coefficient at 1.0μ. It seems at first sight that their results are confirmed by the measurements of Worthing (17) on the emissivity of nickel at incandescent temperatures. He found no change with temperature from about 900°C to 1400°C and states that the average of his values is about the same as that found by other investigators at room temperature. On the other hand, Bidwell (1) found a negative temperature coefficient of emissivity (positive coefficient of reflectivity) for the same range of temperatures at 0.660μ. As neither of these observers measured the emissivity at room temperature, quantitative comparisons with the present results are not possible. The present measurements agree with those of others (9, 10, 11) in giving a small temperature coefficient of the reflection factors for high temperatures. In all probability an average temperature coefficient computed between incandescent and room temperatures does not mean much because nickel passes through the Curie point at 350°C. Lowe (9)

studied the monochromatic emissivity of nickel in the neighborhood of the Curie point and found that the monochromatic emissivity at long wavelengths shows the same anomolies as the electrical resistivity. In particular, the temperature coefficient of monochromatic emissivity in the neighborhood of the Curie point is much larger than it is at either higher or lower temperatures. The measurements of Ornstein and van der Veen (11) on the reflectivities of iron as a function of temperature near its Curie point (760°C) show the same effect to an even greater degree.

Other metals showing positive temperature coefficients of the reflection factors in the visible region are tungsten, molybdenum, palladium, tantalum, and iron. Copper, gold, and platinum show negative coefficients in the same region. Worthing has suggested that in the case of gold the transition may occur in the blue end of the visible spectrum.

An interesting datum obtained in this investigation is the discovery of the sharp reflection minimum at 1.0μ (see Fig. 10). The position of this minimum does not vary with increasing temperature. This minimum was not reported by Hagen and Rubens (6). Among other metals, the only ones showing corresponding minima in the infra-

red at ordinary temperature are zinc and its alloy with aluminum, Al_2Zn_3 (14) and tungsten (3). The minimum for zinc also lies accurately at 1.0μ. However, the minimum for the alloy of aluminum and zinc was found at 0.9μ and is not so sharp. The minimum for tungsten lies at 0.8μ.

McCauley (10) found minima for platinum, palladium, and tantalum at high temperatures only. The minima, all between 0.8 and 1.25μ, became more pronounced with increasing temperature.

To determine the true origin of the minimum here reported, further studies must be undertaken using samples of nickel containing varying amounts of the impurities present in the Grade A sample which was used.

SUMMARY AND CONCLUSIONS

A study of the reflection factors of metals at different temperatures in the region between the visible spectrum and 10μ is of particular interest because it is in this region that the reflection factors and their temperature coefficients pass through a fundamental change in the nature of their dependence on the properties of the metal. At long wavelengths the dependence is simply on electrical resistivity; at short wavelengths the molecular properties of the metals must be considered as well as resistivity. How the molecular properties enter, is not known. To aid in establishing a relation, data on reflection factors are necessary. It is proposed to make such studies on a number of metals. Data on one metal, nickel, are presented herewith. More metals were not studied because of the time consumed in building the spectrometer and overcoming experimental difficulties.

The problem has some bearing on the use of incandescent substances in lamps and radio tubes.

The measurements were made with the aid of a Wadsworth fixed arm infra-red spectrometer. The radiation was obtained from a Globar heater and measured by the deflections of a linear radiometer. A preliminary experiment was conducted to determine the optimum thickness of

bismuth black with which to coat the radiometer vanes for maximum sensitivity. The thickness necessary to absorb not less than 95 per cent of the radiation at any wavelength between 0.8 and 16μ was found to be 1.8 mg/cm^2.

The nickel mirror used was in the form of a plane ribbon filament, mounted in a vacuum so that it could be heated to incandescence by an electrical current.

The reflection factors at both high and low temperatures were found to agree fairly well with Drude's formula for wavelengths greater than 5μ. For wavelengths shorter than this the observed values were considerably less than the theoretical.

The temperature coefficients of the reflection factors are nearly constant between 5 and 11μ. Proceeding toward shorter wavelengths, however, the coefficient, which has a negative value at 5μ, steadily decreases in absolute value to zero at 2.15μ. Below 2μ the coefficient rapidly increases with positive values.

The transition just described is similar to that of palladium and tantalum (10), and tungsten (16). Platinum shows a similar decrease in the negative temperature coefficient but does not become zero in this region (10).

Tungsten, at ordinary temperatures (3), and platinum, palladium, and tantalum at elevated temperatures (10) show

reflection minima in the region lying between 0.8 and 1.25μ. The present results for nickel show a sharp minimum at 1.00μ. With the exception of platinum, these minima lie within the transition region of the temperature coefficients of reflection factors. As this may be only a coincidence, generalizations must await data for other metals.

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