

Spectral Emissivities and Optical Constants of
Electromagnetically Levitated Liquid Metals as
Functions of Temperature and Wavelength

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ABSTRACT

The development of a unique, non-contact, temperature measurement device utilizing rotating analyzer ellipsometry is described. The technique circumvents the necessity of spectral emissivity estimation by direct measurement concomitant with radiance brightness. Using this approach, the optical properties of electromagnetically levitated liquid metals Cu, Ag, Au, Ni, Pd, Pt, Zr were measured *in situ* at four wavelengths and up to 600 K superheat in the liquid. The data suggest an increase in the emissivity of the liquid compared with the incandescent solid. The data also show moderate temperature dependence of the spectral emissivity. A few measurements of the optical properties of undercooled liquid metals were also conducted. The data for both solids and liquids show excellent agreement with available values in the literature for the spectral emissivities as well as the optical constants.

1. INTRODUCTION

The behavior of the spectral emissivity of liquid metals at elevated temperatures has not received much attention. However, it assumes fundamental importance when it becomes necessary to carry out radiation thermometry with only an assumed emittance. The questions addressed in this study are; 1) How does the spectral emissivity depend on temperature above the melting point? 2) How do spectral emissivities vary as a function of wavelength? and 3) Is the temperature dependence different at different wavelengths?

The emissivities of liquid metals at elevated temperatures have been measured previously by several methods: 1) comparison of the measured brightness temperature of the liquid at the accepted fusion temperature¹⁻³; 2) comparison of the measured radiances by a two-color pyrometer with a single color pyrometer, and assuming the measurement of the first is independent of emissivity⁴; and, 3) having the sample in thermal contact with a substrate of known temperature, measuring the radiance brightness temperature of the sample and comparing the two temperatures⁵.

There are several difficulties associated with each of these techniques. For example, in the case of melting-point brightness measurements, the question arises as to whether the measured emissivity corresponds to the liquid, solid, or a mixture of both. If the measurement is made precisely at the melting point, equilibrium is established between the liquid and solid, so the measurement corresponds to a mixture. Even assuming one is making the measurement on the liquid, the errors resulting from brightness measurement can be substantial. Bonnell, et. al.,³ have calculated a possible error of 5-6% resulting from a 10K uncertainty in brightness temperature, in estimating a 0.30

value of emissivity at 2000 K. If the temperature being measured is higher, where the brightness-temperature uncertainty is greater, the measured emissivity can be in error by more than 10%. Several workers have pointed out the difficulties associated with two-color pyrometry as a technique for deriving thermodynamic temperatures⁶⁻⁹. The third approach is limited by container contact interactions which can cause uncertainty in temperature. It is also unlikely to provide reliable emissivity estimates due to the chemical reactivity and solubility properties of liquid metals at high temperatures (> 1800 K).

The use of ellipsometry for measurement of the optical properties of metals and alloys is not new¹⁰⁻¹⁸. However, the use of this technique for emissivity measurements on very refractory liquid metals and alloys as a function of temperature above the melting point is certainly novel. In this paper, some results of optical property measurements, including spectral emissivity, as functions of temperature at wavelengths of 488, 514.5, 632.8 and 1064 nm for a number of electromagnetically levitated liquid metals including Cu, Ag, Au, Ni, Pd, Pt, and Zr are presented. The data includes measurements on liquids, solids and undercooled liquids. Perhaps, the most significant outcome of this work is that a technique has been developed to measure accurately the optical constants, and thus temperatures, of levitated liquid materials where sample contact is unnecessary. This is of enormous importance for containerless processing technologies.

1.1. THEORETICAL BACKGROUND

According to Wien's approximation to Planck's law, the flux distribution from a black body per unit solid angle can be written as a function of wavelength, λ , and temperature, T:

$$W(\lambda, T) = C_1 \pi^{-1} \lambda^{-5} \exp\left(-\frac{C_2}{\lambda T}\right), \quad (1a)$$

where C_1 and C_2 are the first and second Planck constants, respectively. Equation 1a has been shown to be accurate⁶ to within 1% for $\lambda T < 2897.8 \mu\text{K}$. A useful form of Wien's approximation is obtained by taking the ratio of the real-body radiation at wavelength, λ , to that of a blackbody at the same wavelength:

$$\frac{1}{T_{\text{TH}}} - \frac{1}{T_{\text{B}}} = \frac{\lambda \ln(E_{\lambda})}{C_2}, \quad (1b)$$

where T_{B} is the measured brightness temperature, T_{TH} the thermodynamic (blackbody) temperature, and E_{λ} is the normal spectral emissivity of the real body at the wavelength, λ .

Assuming the liquid metal surface is specular, Kirchoff's law can be stated as:

$$E_{\lambda} + R_{\lambda} = 1, \quad (2)$$

where R_{λ} is the reflectivity and E_{λ} is the spectral emissivity. The subscript denotes the wavelength dependence of these quantities. Equation 2 holds for any angle of incidence or emission.

ϵ_1 and ϵ_2 , the real and imaginary parts of the dielectric constant, are related to the refractive index, n , and extinction coefficient, k , through the relations:

$$\epsilon_1 = n^2 - k^2, \text{ and} \quad (3a)$$

$$\epsilon_2 = 2nk. \quad (3b)$$

If ϵ_1 and ϵ_2 are experimentally determined, then the remaining optical constants of the material in question can be obtained for the wavelength, λ .

The normal incidence reflectivity is calculated from the Beer equation:

$$R_{\lambda} = \frac{(n-n_0)^2 + k^2}{(n+n_0)^2 + k^2}, \quad (4)$$

where n_0 is the refractive index of the ambient, transparent medium. Using Eq. 2, the spectral emissivity is determined. Simultaneous measurement of radiance brightness at normal incidence provides the thermodynamic temperature from Eqs. 1b, 2 and 4.

When light, plane polarized with an initial azimuth Ψ_0 to the plane of incidence is reflected from a metal surface, the P and the S components of the incident electric vector experience different phase changes and different reflectivities, producing a new azimuth Ψ . If $\Psi_0 = \frac{\pi}{4}$, then the complex reflectance ratio, ρ , is:

$$\rho = \frac{r_p}{r_s} = \tan(\Psi) e^{i\Delta}, \quad (5)$$

where, r_p and r_s are the amplitude reflection coefficients of the P and S components, respectively, Ψ is the restored azimuth and Δ the relative phase difference between the two components of the reflected electric vector ($\Delta = \delta_{rp} - \delta_{rs}$). If the reflected intensity is measured at four azimuths (obtained at two positions of an analyzer) - I_1 (90°), I_2 (0°), I_3 (45°), I_4 (135°), then the fundamental ellipsometric parameters ψ and Δ are given by¹⁴:

$$\tan(\Psi) = \left(\frac{I_2}{I_1}\right)^{1/2}, \text{ and} \quad (6a)$$

$$\cos(\Delta) = \frac{1}{2} \left[\left(\frac{I_2}{I_1}\right)^{1/2} + \left(\frac{I_1}{I_2}\right)^{1/2} \right] \times \left[\frac{(1 - I_4/I_3)}{(1 + I_4/I_3)} \right]. \quad (6b)$$

The real and imaginary parts of the dielectric constant are then calculated from ψ , Δ , and

Θ using³¹:

$$\epsilon_1 = \sin^2\theta \tan^2\theta \frac{\cos^2 2\psi - \sin^2 2\psi \sin^2 \Delta}{(1 + \cos\Delta \sin 2\psi)^2} + \sin^2\theta, \quad (8a)$$

and

$$\epsilon_2 = \frac{2 \sin 2\psi \cos 2\psi \sin \Delta}{(1 + \cos\Delta \sin 2\psi)^2} \sin^2\theta \tan^2\theta, \quad (8b)$$

where Θ is the angle of incidence. Once ϵ_1 and ϵ_2 are obtained, one calculates n and k. Then, the normal incidence reflectivity is obtained from Eq. 4. It is important to note that the entire measurement essentially consists of two ratio measurements ($\frac{I_2}{I_1}$ and $\frac{I_4}{I_3}$).

Thus, systematic errors tend to cancel.

2. EXPERIMENTAL

Figure 1 shows the experimental arrangement used to make emissivity measurements by RAE on electromagnetically levitated materials. A chopped (2000 Hz), focussed, plane polarized laser beam impinged on the sample at 67.5° angle of incidence. The laser used at the 488 and 514 nm wavelengths was a Lexel (Model 95) 2 watt Argon-Ion laser that was lasing multi-line. The measurements at 633 nm were carried out using the Aerotech 5 mW He-Ne laser while the measurements at 1064 nm were carried out using an ALC 1064-50P (Amoco Laser Corporation) diode-pumped YAG laser with an output of 50 mW polarized light. The experiments that were performed at the YAG and He-Ne wavelength required the laser to be focussed while no focussing was needed for measurements with the Argon-Ion laser. The plane of polarization of the beam was rotated 45° (clockwise for a viewer looking at the sample from the laser) with respect to the plane of incidence (plane of the figure). Also shown in the figure is a laser shutter

positioned between the chopper and the sample chamber. Closure of this shutter allowed measurements of radiance brightness of the sample without error due to the laser. A Leeds & Northrup, Automatic Optical Pyrometer was used to monitor the brightness temperature of the sample via another port on the chamber situated at 67.5° from the incident laser port. The thermodynamic temperatures of the liquid were calculated using Wien's approximation to Planck's law and using values of spectral emissivity measured at $\lambda = 633\text{nm}$. Additionally, thermodynamic temperatures were also obtained using the radiance detector situated on the ellipsometer based on measured brightness and the optical constants measured by the ellipsometer. This was accomplished by recomputing a spectral emissivity from the measured dielectric constants at this oblique angle and then using Wien's approximation to Planck's law. The second measurement was not feasible in the blue and green regions of the spectrum since samples usually emitted very little light.

Light from the sample (radiated and reflected) was imaged on an aperture by a lens. A second lens and aperture generated parallel light from this image. The f number of the second lens and aperture fixed the maximum solid angle from which light was collected at about 1° . Since the study involved several wavelengths, spectral discrimination was achieved using laser line interference filters obtained from Corion and Ealing. Light that passed through the hole was then analyzed by a beam-splitting Thompson calcite prism that was rotatable around the beam axis.

Shown in Fig. 1 is the flow diagram for the data acquisition system. The outputs of the polarization detectors were monitored individually with separate lock-in amplifiers which were phase-locked with the reference signal from the chopper. The lock-in

amplifiers were obtained from EG&G PARC and had 20 KHz bandwidths. The outputs of the lock-in amplifiers were monitored continuously by the computer, as were the outputs of the radiance detector and the Leeds & Northrup pyrometer.

In a previous paper³⁰, the dynamics of electromagnetically levitated liquid metals and alloys at elevated temperatures were described. These results showed that the levitated liquid metal droplets underwent rotations, shape oscillations, and translations in the coil. This behavior causes oscillations in the intensity of the emitted as well as reflected light from the sample.

It was necessary to minimize the effect of these surface perturbations by carrying out long-time signal averaging. Since the perturbation frequencies from previous studies were established to be on the order of 50-200 Hz, the output time constant on the lock-in amplifiers was set at 0.1 seconds. The outputs of the lock-in amplifiers were monitored for 10-20 seconds, until a reliable mean value could be extracted. The analyzer was then rotated for the second set of measurements and the signal averaging repeated. Finally, the signal intensities were compared for the two analyzer positions and the criterion of validity elucidated by Beattie¹⁵, was verified. Any data not meeting this criterion were rejected. A detailed description of the calibration procedure for the optics and electronics has been presented elsewhere³¹ and will not be presented here.

All samples used had purities in the range 99.9 to 99.999%. The samples were cut from rod or bar stock and had masses in the range 0.5-1.5 gms. After melting in the levitation coil, residual oxide surface contaminants were allowed to vaporize and be removed from the chamber before the measurements were started.

The experiments were performed at pressures on the order of 1 atmosphere and gas flow rates of 10 - 20 cc/min. The gases used were argon and helium with 3% hydrogen added to inhibit surface oxide formation. Temperature control was achieved to a limited extent by regulating the gas mixture and flow rate. Helium, with the higher thermal conductivity, was used to achieve the lower temperatures, including the undercooled state, while argon was used to obtain the higher temperatures. The upper temperature limit for each sample was set by the vaporization rate of the metal. At higher temperatures, vapors near the metal surface scattered the reflected laser light which resulted in much larger measurement errors.

3. RESULTS

Tables 1 to 4 give a summary of some of the results of the experiments reported here. In these values are given of the dielectric constants, and spectral emissivities of Cu, Ag, Au, Ni, Pd, Pt, and Zr over wide ranges of superheat of the liquid at the four wavelengths respectively. Since much of the data reported here showed moderate to strong temperature dependence, an interpolated value based on a linear regression to the data is provided. For each element, a common temperature was chosen to interpolate towards. A value of the confidence interval is listed in the parenthesis below each of the tabulated values. These intervals correspond to a confidence level of 95% for the data listed in the table. Also listed parenthetically below the temperature range is the number of determinations of the optical properties over the range. The temperatures for the interpolation (in some cases, extrapolation) were chosen on the basis of the temperature range over which most of the data were acquired. The interpolation temperatures were: Copper at 1400 K, Silver at 1300 K, Gold at 1400 K, Nickel at 1800 K, Palladium at 1925 K and

Platinum at 2250 K. The data for liquid zirconium represents an average of the optical properties as is the case with the data for solid palladium. Correspondingly, the values in those parenthesis represents a standard deviation and not a standard error of estimate. In a few cases, extrapolation of the data to the chosen temperature was necessary, and consequently the error bars were slightly higher.

Since the chosen temperatures were at least 100 degrees or more above the melting point, some disagreement with available literature data is expected. Each of these four tables corresponds to measurements at a single wavelength. The three noble metals Cu, Ag, and Au, and the three transition metals Ni, Pd, and Pt were studied at all four wavelengths while Zr was studied only at the He-Ne wavelength. A salient feature of the data listed in Tables 1 - 4 is that almost all spectral emissivities were measured with an error of ± 0.01 corresponding to the 95% precision limits of the data.

Table 5 is a compilation of emissivity data found in the literature, together with the data obtained in this study, to illustrate the changes in emissivity as a function of temperature. In this table we list emissivity data for these metals at room temperature (RT), incandescent temperatures (IT) and in the liquid regime. The spectral emissivities calculated from the data reported by Miller²¹ and our study have been obtained at a photon energy of 1.97 eV ($\lambda = 0.63 \mu\text{m}$) while the other emissivity data pertaining to the elevated temperatures were measured at $\lambda = 0.65 - 0.665 \mu\text{m}$ (1.91 - 1.87 eV). The room temperature emissivity data were obtained at 1.97 eV. It can be seen that the agreement of the present results with data found in the literature is excellent in all cases except perhaps in the case of liquid zirconium where there appears to be a large discrepancy in the literature data. The lack of spectral emissivity data in the literature at the other

wavelengths made a similar compilation at other wavelengths impossible.

To illustrate the overall wavelength dependence of the spectral emissivity, the spectral emissivities of the copper and nickel groups are plotted in Figs. 2 and 3 respectively. The spectral emissivity data used for these plots are the same data that are listed in Tables 1 - 4. The error bars in Figs. 2 and 3 correspond to a 95% confidence interval. The spectral emissivities correspond to the previously listed interpolation temperatures. In these two plots, it is seen quite clearly that the spectral emissivity increases gradually as the wavelength decreases, until the blue region where a sharp rise is seen. The behavior of Cu and Au are similar while silver does not show such a dramatic rise. The corresponding plot in Fig. 3 for the nickel group has two points of interest. Firstly, all three metals behave identically in the visible region of the spectrum. Secondly, they seem to show very little dependence between the red and green regions of the spectrum and then show a rise in the blue. They also converge to almost the same value of spectral emissivity in the blue.

In order to illustrate the temperature dependence of the spectral emissivity, we have selected the results for liquid gold, nickel and platinum as examples.

The optical constants of liquid gold were measured in the temperature range 1270-1980 K ($0.98 - 1.48 T_m$), where T_m is the melting point. Measurements of spectral emissivity and optical properties at the four wavelengths were conducted in this temperature range. These data include three measurements on the undercooled liquid (He-Ne wavelength).

Figure 4 is a plot of the spectral emissivity of liquid gold in the above temperature range at the 4 wavelengths. The solid lines in the figure represent the results of a least

squares fit to the data at each of the wavelengths. The results of the least squares fit, $a + bT$, are also shown in the figure. Since raw data are directly plotted and fitted in the plots shown, the least squares fit tends to be weighted somewhat to those regions where a large numbers of data are present. In many cases, several data points overlapped since the temperature was not constantly varied. A small increase in spectral emissivity is seen in the blue while there is a very large decrease in the green. The spectral emissivity in the green close to the melting point is 0.47 while at 1900 K it decreases to about 0.40. This corresponds to about 12.5% decrease in spectral emissivity. The spectral emissivity is constant in the red and has a small positive slope in the infra-red.

The spectral emissivity (at 1400 K) in the blue is 0.52 and compares well with that calculated from the data of Miller²¹ (0.52). The spectral emissivity is 0.40 in the green and is a little lower than that of Miller. The emissivity of liquid gold in this range for the He-Ne wavelength was determined to be 0.30. This value is in agreement with that computed from the data of Miller²¹, but is higher than that reported by Burgess and Waltenburg⁴⁹. There appear to be no data available in the infra-red for liquid gold and the value reported here is 0.12.

The optical constants and spectral emissivities of liquid nickel were measured in the temperature range 1776-2143 K ($1.03 - 1.24 T_m$) at $\lambda = 488, 514.5, 632.8,$ and 1064 nm. Figure 5 is a plot of the spectral emissivities of liquid nickel as a function of temperature at the four wavelengths. There is non-linear but monotonic increase in emissivity with decreasing wavelength. That is, there is an initial rapid increase in emissivity from 1064 to 632.8 nm. The values at 632.8 and 514.5 nm are close, but the difference between 514.5 and 488 nm is again substantial.

The mean values of spectral emissivity (at 1800 K) for liquid nickel agree reasonably well with literature. The value of spectral emissivity in the blue is 0.49 and is 0.41 in the green. The values calculated from the data of Miller⁶ are lower in the blue and higher in the green than the values measured in this study. The agreement at the He-Ne wavelength with the literature data is good as can be seen in Table 5. The spectral emissivity in the infra-red is 0.31.

The optical properties and spectral emissivities of liquid platinum were measured in the temperature range 2000-2650 K ($0.98-1.30 T_m$). The data obtained in this range included 6 measurements on the undercooled liquid (for the He-Ne wavelength). Figure 6 is a plot of the spectral emissivity of liquid platinum as a function of temperature at the four wavelengths together with the results of a least squares fit to the data at each of the wavelengths. It is seen quite clearly that the spectral emissivity decreases with increasing temperature in the blue, green and in the infra-red while it appears to increase in the red. It must be pointed out that the data in the green would probably fit better with a curve rather than a straight line although no such fit was attempted. An unusual feature of the data in the green was the dramatic change in the values of the dielectric constants in the neighborhood of 2550 K.

Since most of the data for liquid platinum were measured at temperatures substantially higher than the melting point, extrapolation of the data to temperatures close to the melting point would result in larger errors. Therefore, the temperature of interpolation was chosen as 2250 K which is about 200 K above the melting point. The spectral emissivity in the red was determined as 0.38 and compares very well with the data in the literature (see Table 5). The spectral emissivity of undercooled platinum in the red was

measured as 0.36. The mean values in the blue, green and infra-red were determined as 0.48, 0.45, and 0.30 respectively. It was not possible to assess the agreement with literature data since such data were not available at these wavelengths.

4. DISCUSSION

One of the goals of this work was the development of a pyrometric technique by which one could measure both spectral emissivities and true temperatures of liquid metals *in situ*, since an error is introduced in temperature measurement of incandescent solids or liquids when spectral emissivities are only estimated. Also, the paucity of emissivity data for liquid metals at temperatures above the melting point has made reliable temperature measurement in that regime difficult. As a result, thermophysical property data such as specific heats, expansion coefficients, etc., have always been subject to this uncertainty. In order to measure accurately the thermodynamic temperature of these high temperature liquids, it is necessary to know the surface spectral emissivity as a function of temperature and independent of radiance brightness measurements.

Two important results reported here are the observations that the spectral emissivities at the four wavelengths of the metals in the Ni and Cu groups show a moderate temperature dependence in the liquid over the temperature ranges studied and that the spectral emissivities of the liquids are *higher* than those of the corresponding solids. Furthermore, in those liquid metals where moderate supercooling was observed, the measured spectral emissivities of the supercooled liquid were essentially the same as the those of the liquid above the melting point. Corrections may need to be made to thermophysical data obtained previously which have made the assumption of constant emissivity. For instance, Bonnell³⁶ observed an anomaly in measurements of the specific heat, $C_p(l)$, of

liquid zirconium at elevated temperatures. He attributed the behavior to either a real change in C_p (l) or a monotonic decrease in emissivity. The latter would compensate for the non-linear rise in total enthalpy, $H(T) - H(298)$, making C_p (l) constant. The few measurements on liquid zirconium suggested a constant spectral emissivity at $\lambda = 633\text{nm}$. At the present time it appears that the data of Bonnell³⁶ may not need to be corrected therefore suggesting that C_p (l) does increase but only further work can confirm this observation.

The possibility that spectral emissivities change appreciably with temperature has been suggested by Nordine³⁷ and Margrave³⁸, but never really established. However, indirect support for such an observation can be found in the literature. For instance, the contributions to C_p (l) in the range 3000-5000 K due to expansion coefficients, compressibility factors, and electronic parameters have been studied using exploding wires by Cezariliyan³⁹ and by Gathers, et. al.,⁴⁰ and significant deviations from the classical 3R value have been observed. Similar variations in spectral emissivities can be expected, especially at temperatures of 3000 K and higher.

The second point concerns the increase in emissivity on melting of the metal. In these experiments, measurements of the spectral emissivities of solid copper and palladium were performed just below their melting point by allowing them to freeze within the levitation coil. The emissivity measured for solid copper was 0.10, while for palladium the value was 0.32 (for the He-Ne wavelength). These are 15-20 % lower than the emissivity of the corresponding liquids. A similar increase of about 13% was observed in the green for palladium. This increase in emissivity on melting was observed previously for these metals by others^{3,5}, but no explanations have been forthcoming. Intuitively,

one expects the smoother, liquid surface, to have a lower emissivity than the solid. This would be the case if factors affecting emissivity were the macroscopic physical and chemical structure of the surface; however, the optical properties are also governed by the electronic properties of the material. Factors which affect the electronic properties will play a role in determining the spectral emissivity of the material. For example, significant destruction of the long range order of the lattice occurs on melting. This will significantly modify the band structure and may provide at least part of the basis for the changes observed in the optical properties upon melting of these metals.

Further, some measurements of the optical properties of undercooled liquids were carried out in this study (palladium, platinum, gold). These data reveal that the spectral emissivities of the undercooled liquids are virtually the same as that of the liquid above the melting point, although they are just slightly lower. Since large undercoolings were not attained, the extension of this behavior to larger undercoolings must be performed with caution.

5. CONCLUSIONS

Rotating analyzer ellipsometry has been used successfully to measure the optical constants of Cu, Ag, Au, Ni, Pd, Pt and Zr and extract normal incidence spectral emissivities at 488, 514.5, 632.8, and 1064 nm over a large range of superheat in the liquid state. The technique was adapted as a non-contact diagnostic method to our electromagnetic levitation system, and it was possible to extract the dielectric functions and complex indices of refraction data for liquid metals at elevated temperatures.

The spectral emissivities at 633 nm of the liquid metals obtained in this study agreed well with most of the data available in the literature. In the cases of palladium and copper, the emissivities were also measured in the solid state with the sample levitated. The data for all metals studied showed that the spectral emissivities of the liquids were higher than those of the solids. Additionally, the spectral emissivities of all the metals studied here showed moderate to strong temperature dependence in the liquid over large temperature ranges. This fact therefore suggests that corrections may need to be made to thermophysical property measurements that have been based on the assumption of constant emissivity.

Comparisons of the dielectric functions and complex index of refraction data with those available in the literature showed excellent agreement. Since only data for the low melting materials were available, it was not possible to compare the results for liquid Pd, Pt, and Zr.

6. ACKNOWLEDGEMENTS

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TABLE 1
Optical Constants of Liquid Metals at 488 nm

METAL	TEMP. RANGE(K)**	ϵ_1	ϵ_2	E_λ
Copper	1499-1877 (13)	-4.92 (0.13)	7.63 (0.12)	0.45 (0.01)
Silver	1398-1552 (17)	-9.28 (0.38)	1.78 (0.31)	0.11 (0.01)
Gold	1420-1907 (16)	-2.77 (0.28)	7.57 (0.62)	0.522 (0.018)
Nickel	1789-2109 (24)	-2.66 (0.35)	13.17 (0.30)	0.486 (0.007)
Palladium (s)	1424-1699 (11)	-5.66 (0.24)	12.23 (0.31)	0.43 (0.01)
Palladium (l)	1911-2120 (27)	-3.47 (0.39)	13.51 (0.65)	0.468 (0.004)
Platinum	2266-2646 (33)	-1.86 (0.66)	15.72 (0.90)	0.48 (0.01)

* Confidence interval for 95% limits of the data is listed parenthetically below each value.

The number of determinations is listed parenthetically below the temperature range.

**Temperatures chosen for interpolation of optical constant values are: Cu (1400 K), Ag (1300 K), Au (1400 K), Ni (1800 K), Pd (1925 K), and Pt (2250 K). Pd (s) and Zr values represent mean values.

TABLE 2
Optical Constants of Liquid Metals at 514.5

METAL	TEMP. RANGE(K)**	ϵ_1	ϵ_2	E_λ
Copper	1361-1903 (19)	-8.81 (0.16)	7.11 (0.42)	0.30 (0.01)
Silver	1452-1541 (17)	-10.86 (0.52)	0.84 (0.14)	0.05 (0.01)
Gold	1449-1903 (20)	-6.34 (1.08)	8.07 (0.47)	0.47 (0.02)
Nickel	1776-2063 (31)	-6.35 (0.39)	15.42 (1.20)	0.412 (0.008)
Palladium (s)	1486-1810 (11)	-11.63 (0.37)	13.68 (0.26)	0.32 (0.005)
Palladium (l)	1869-2134 (25)	-7.83 (0.42)	16.95 (0.83)	0.381 (0.006)
Platinum	2307-2649 (19)	-2.46 (0.37)	25.44 (0.60)	0.45 (0.01)

* Confidence interval for 95% limits of the data is listed parenthetically below each value.

The number of determinations is listed parenthetically below the temperature range.

**Temperatures chosen for interpolation of optical constant values are: Cu (1400 K), Ag (1300 K), Au (1400 K), Ni (1800 K), Pd (1925 K), and Pt (2250 K). Pd (s) and Zr values represent mean values.

TABLE 3
Optical Constants of Liquid Metals at 633 nm

METAL	TEMP. RANGE(K)**	ϵ_1	ϵ_2	E_λ
Copper	1315-1727 (27)	-14.11 (0.45)	3.83 (0.39)	0.13 (0.01)
Silver	1291-1481 (41)	-16.31 (0.36)	3.34 (0.44)	0.086 (0.01)
Gold	1270-1932 (37)	-9.58 (0.79)	8.20 (1.36)	0.30 (0.01)
Nickel	1822-2143 (21)	-6.60 (0.90)	18.55 (1.24)	0.40 (0.01)
Palladium (s)	1297-1577 (11)	-12.12 (0.43)	19.35 (0.39)	0.32 (0.005)
Palladium (l)	1807-2126 (23)	-7.32 (0.72)	18.93 (0.73)	0.38 (0.01)
Platinum	2006-2475 (33)	-6.04 (1.38)	25.20 (1.63)	0.38 (0.01)
Zirconium	2175-2402 (3)	-4.81 (0.87)	21.7 (2.46)	0.41 (0.005)

* Confidence interval for 95% limits of the data is listed parenthetically below each value.

The number of determinations is listed parenthetically below the temperature range.

**Temperatures chosen for interpolation of optical constant values are: Cu (1400 K), Ag (1300 K), Au (1400 K), Ni (1800 K), Pd (1925 K), and Pt (2250 K). Pd (s) and Zr values represent mean values.

TABLE 4
Optical Constants of Liquid Metals at 1064 nm

METAL	TEMP. RANGE(K)**	ϵ_1	ϵ_2	E_λ
Copper	1434-1729 (11)	-33.19 (1.25)	11.18 (1.02)	0.085 (0.008)
Silver	1236-1489 (12)	-38.13 (1.60)	7.68 (0.44)	0.06 (0.005)
Gold	1417-1976 (10)	-34.82 (1.88)	14.25 (1.02)	0.12 (0.01)
Nickel	1888-2031 (9)	-12.71 (1.33)	15.31 (0.92)	0.31 (0.016)
Palladium	1947-2073 (5)	-15.21 (2.05)	7.91 (1.08)	0.23 (0.01)
Platinum	2106-2386 (10)	-12.05 (1.62)	13.44 (2.80)	0.298 (0.006)

* Confidence interval for 95% limits of the data is listed parenthetically below each value.

The number of determinations is listed parenthetically below the temperature range.

**Temperatures chosen for interpolation of optical constant values are: Cu (1400 K), Ag (1300 K), Au (1400 K), Ni (1800 K), Pd (1925 K), and Pt (2250 K). Pd (s) and Zr values represent mean values.

TABLE 5
Comparison of Normal Incidence Spectral Emissivities
with Selected Literature Values for $\lambda = 650 \text{ nm}$

Metal	RT*	REF.	IT*	REF.	Liquid	REF.
Copper	0.08	32	0.10	This work	0.13	This work
	0.12	31	0.10	5	0.13	21
					0.14	3
Silver	0.03	32	0.05	5	0.086	This work
					0.08	3
					0.09	21,23
Gold	0.17	31	0.15	5	0.30	This work
			0.22	33	0.31	21
					0.22	5
Nickel	0.35	32	0.36	5	0.40	This work
			0.38	33	0.35	3
					0.37	5
Palladium	0.23	This work	0.32	This work	0.38	This work
			0.32	5	0.37	5
Platinum	0.32	32	0.30	31	0.38	This work
	0.27	31	0.30	34	0.39	1,4
					0.38	5
Zirconium			0.32	5	0.41	This work
					0.30	5
					0.47	4
					0.32	3

* RT represents room temperature data; IT represents incandescent temperatures.

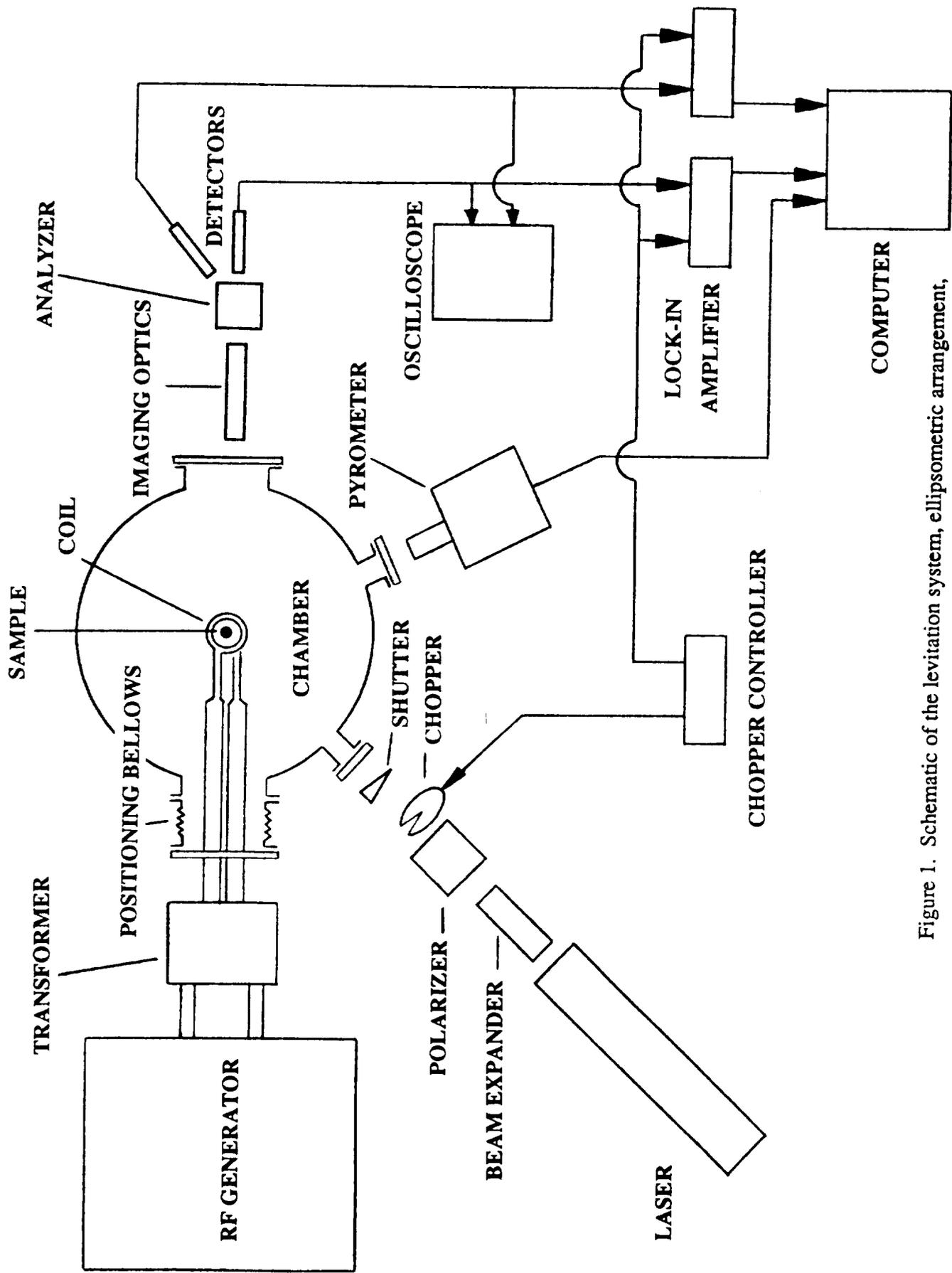


Figure 1. Schematic of the levitation system, ellipsometric arrangement, data acquisition and temperature measurement.

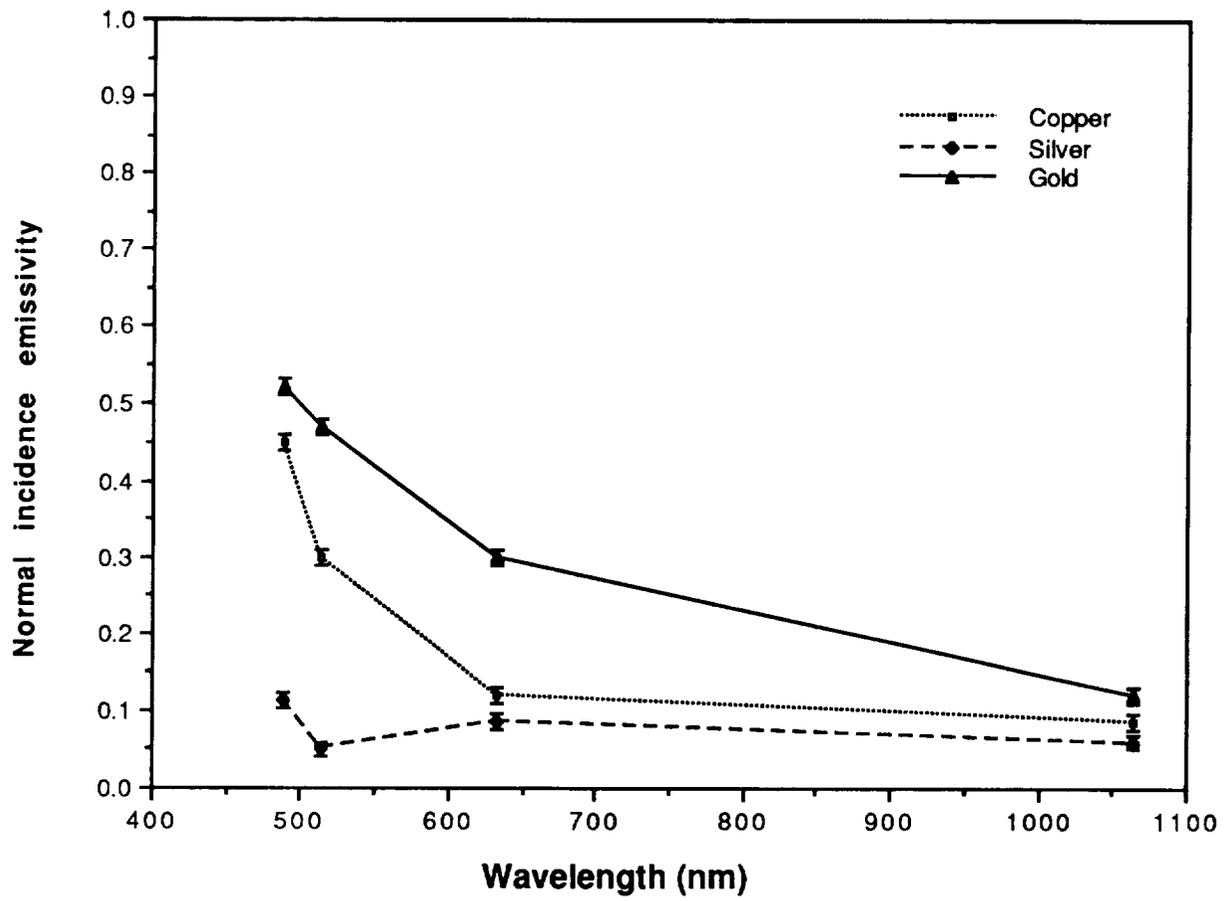


Figure 2. Spectral emissivities of liquid metals in the copper group as a function of wavelength.

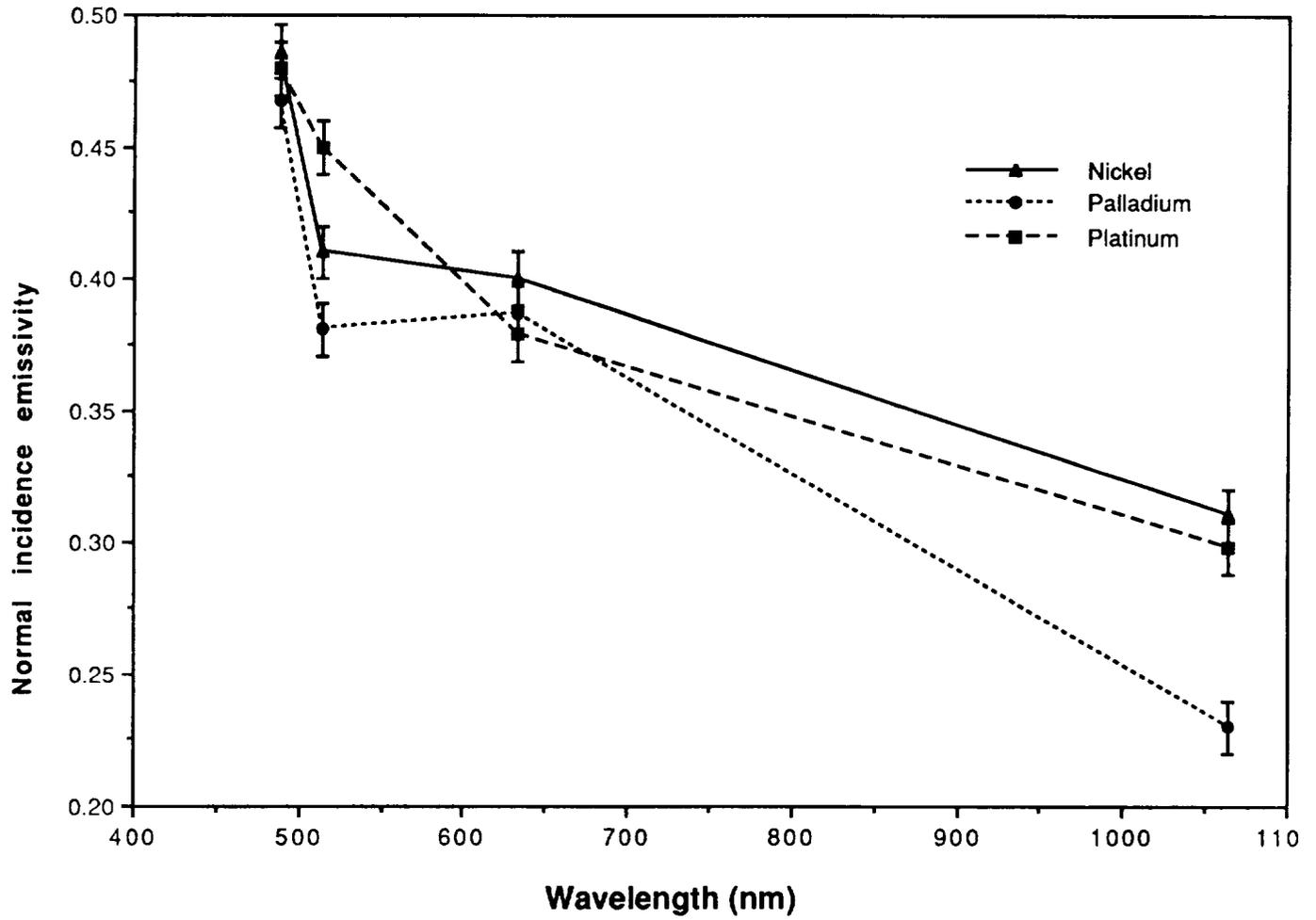


Figure 3. Spectral emissivities of liquid metals in the nickel group as a function of wavelength.

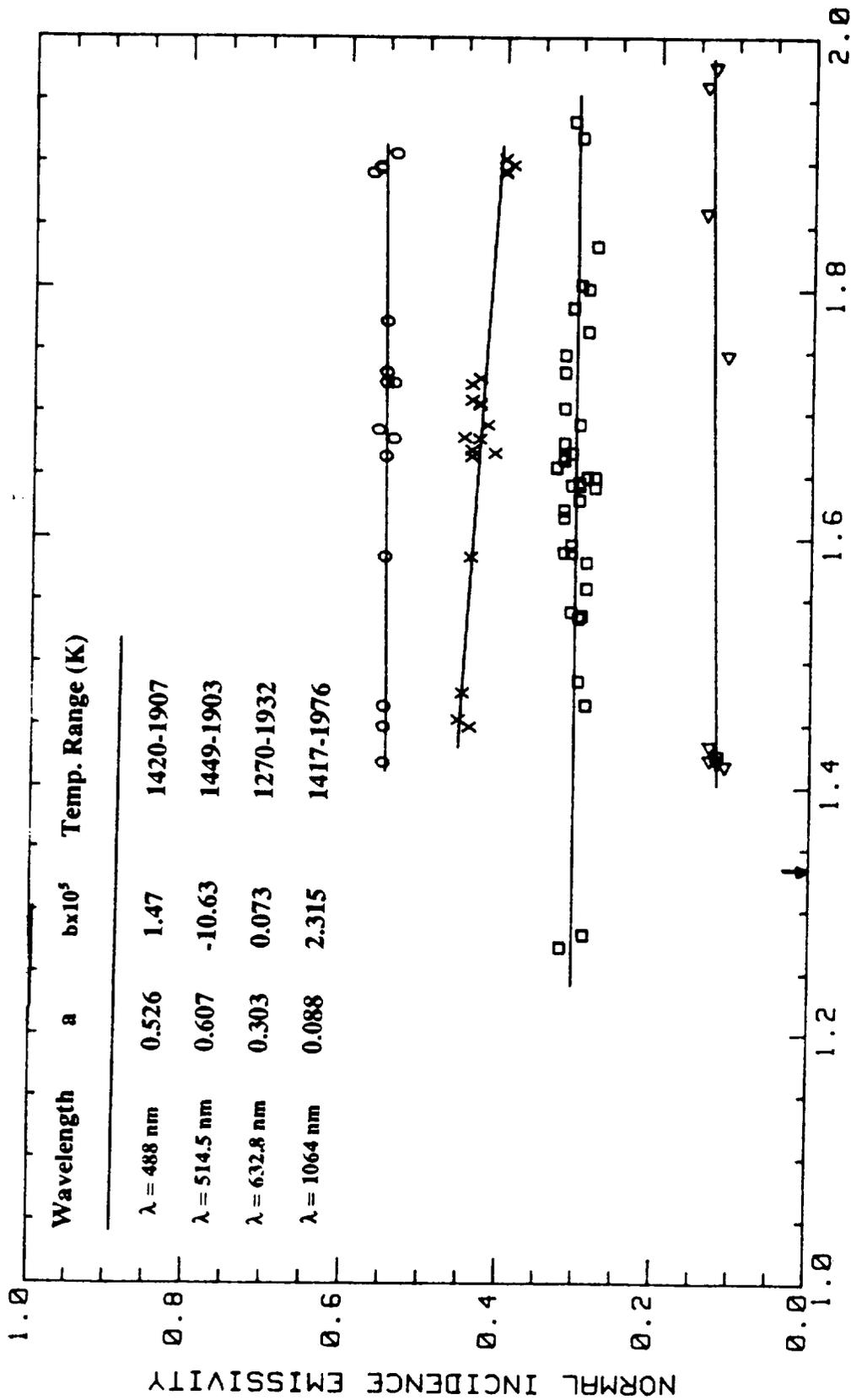
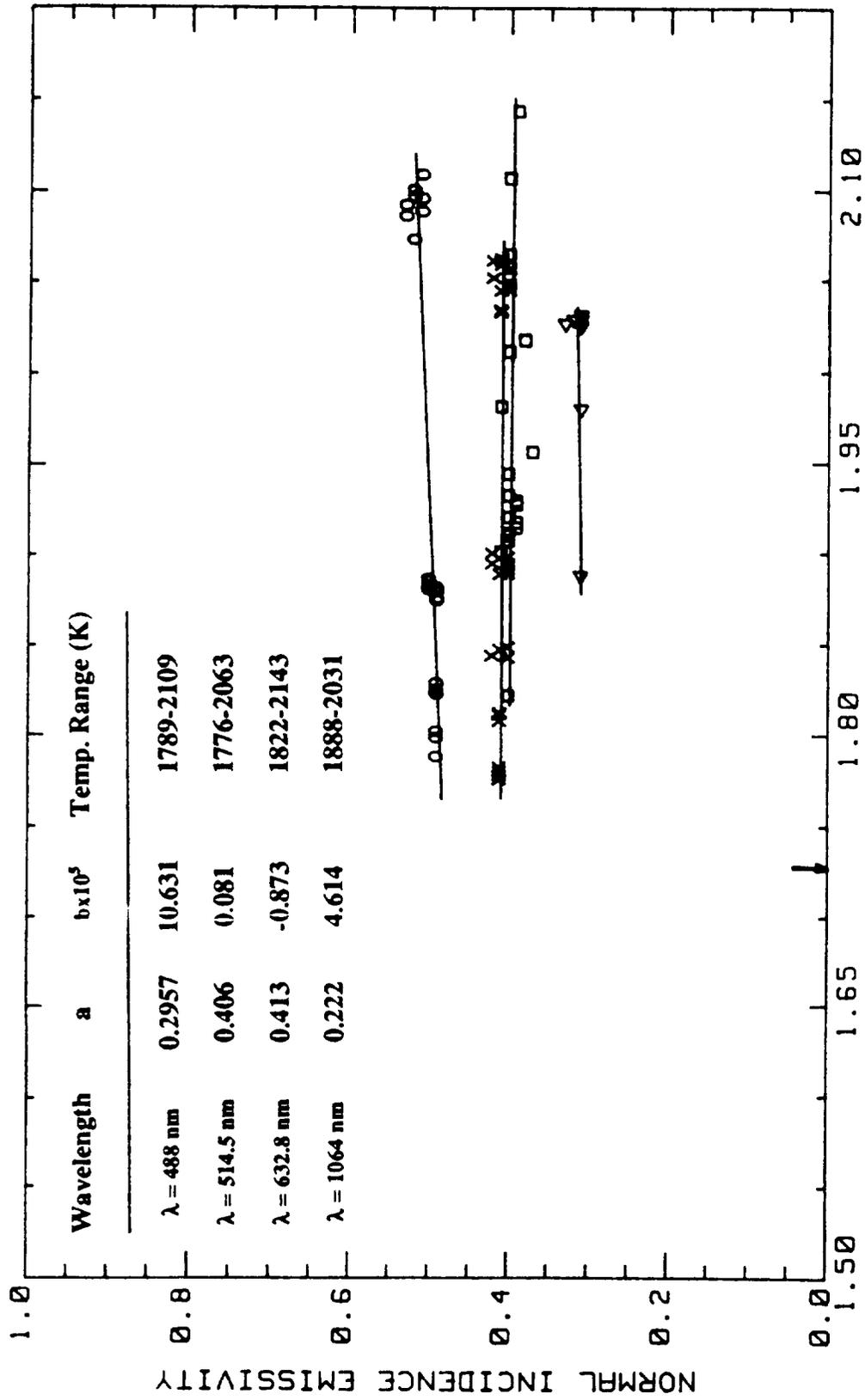


Figure 4. Normal incidence spectral emissivity of liquid gold as a

function of temperature at 1064 (\triangleright), 632.8 (\square), 514.5 (\times), and

488 nm (\circ). Solid line represents the least squares fit to the data.

Melting point indicated by arrow. The results of the fit ($a + bT$) are indicated on the plot.



TEMPERATURE (K) / 10³

Figure 5. Normal incidence spectral emissivity of liquid nickel as a

function of temperature at 1064 (\triangleright), 632.8 (\square), 514.5 (\times), and

488 nm (\circ). Solid line represents the least squares fit to the data.

Melting point indicated by arrow. The results of the fit ($a + bT$) are

indicated on the plot.

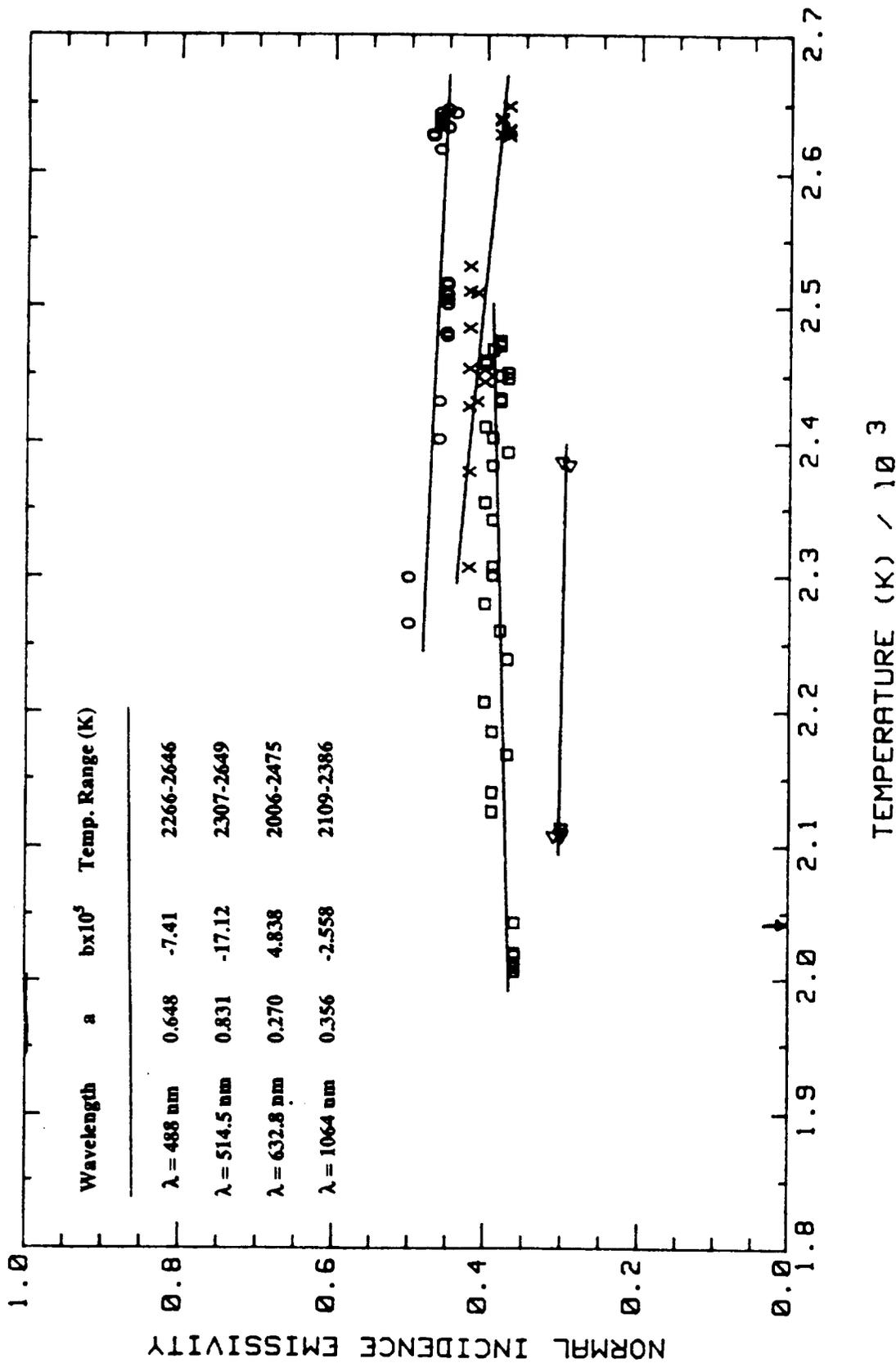


Figure 6. Normal incidence spectral emissivity of liquid platinum as a function of temperature at 1064 (▷), 632.8 (◻), 514.5 (x), and 488 nm (o). Solid line represents the least squares fit to the data. Melting point indicated by arrow. The results of the fit ($a + bT$) are indicated on the plot.