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EMISSIVITY STUDIES ON SELECTED RARE EARTH METALS

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Emissivity studies on selected rare earth metals

by

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ABSTRACT

A method is presented for the experimental determination of the spectral emissivity of liquid metals by direct comparison of the brightness temperature of the sample surface to the true temperature of the sample. The surface brightness temperature is determined with an automatic optical pyrometer focused on the sample. The true sample temperature is determined with the automatic pyrometer focused on a blackbody approximation cavity located in the sample crucible. The method has been used to determine the spectral emittance, at wavelength 0.645μ , of solid surfaces of yttrium, neodymium, gadolinium, and erbium. It has also been used to determine the spectral emissivity at wavelength 0.645μ , of yttrium, neodymium, and gadolinium at temperatures above their melting points. The spectral emittances of the solid surfaces depend strongly on the condition of the surfaces but vary only slightly with changes in temperature. The spectral emissivities of the liquid metals are essentially constant with respect to changes in temperature and have mean values as follows: for yttrium, $\epsilon_{\lambda} = 0.134$; for neodymium, $\epsilon_{\lambda} = 0.280$; and for gadolinium, $\epsilon_{\lambda} = 0.342$.

INTRODUCTION

General

In the evaluation of the thermodynamic properties of materials at temperatures above 1000°K , it is often necessary to measure the temperature of the material with a reasonable degree of accuracy. Depending on the temperature of interest or the configuration of the equipment and nature of the experiments, the employment of thermocouples or resistance thermometers is not always possible. One example is the determination of high temperature heat contents of metals through levitation calorimetry. Levitation calorimetry utilizes an electro-magnetic field to levitate and heat a metal sample without the use of a crucible or other material support. Obviously, it is not practical to determine the temperature of a levitated sample by any method requiring actual physical contact with the sample. In cases such as this, it is common to utilize some type of radiation pyrometry in the determination of the sample temperature.

Determination of the sample temperature through the use of radiation pyrometry requires knowledge of the emission characteristics of the sample. The sample property which is related to the emission of energy over the entire spectrum by the sample is known as the emissivity and is defined as the ratio of the radiant flux emitted from the sample to the radiant flux emitted by a geometrically similar perfect

emitter (blackbody) at the same temperature (1, 2). In many cases, such as optical pyrometry, the radiant flux is not considered over the entire range of wavelengths. These methods utilize the radiant emission of the sample in a narrow wavelength band. The property of sample needed to relate the brightness temperature at a given wavelength to the true material temperature is known as the spectral emissivity. The spectral emissivity is defined as the ratio of the monochromatic radiant flux of a given wavelength λ emitted by the sample to that emitted by a geometrically similar blackbody at the same temperature (2).

When the sample considered is a solid, the emission of radiant energy from the solid surface is also influenced by the condition of the sample surface. Rather than describing the emission characteristics of the sample by the emissivity, which is independent of the surface condition, the sample emittance is used (3). The spectral emissivity of a material is normally considered to be a function of the material, the temperature of the material, and the wavelength. The spectral emittance is a function of the material, the temperature of the material, the surface condition of the material, and the wavelength. Many procedures have been developed for the determination of these properties for materials under a wide range of conditions. These methods can be broken down into two general groups. One group

consists of indirect procedures in which some related property is determined from which the emissivity is calculated using theoretical relationships. The second group consists of direct procedures in which the radiation from the sample is compared to the radiation from an experimental or theoretical blackbody at the same temperature.

Methods

De Vos (4) describes indirect methods for the determination of emissivity, one of which involves the measurement of reflectivity. According to Kirchhoff's law, the emissivity is equal to the absorptivity and for an opaque body the sum of the absorptivity and the reflectivity is unity. This means that the emissivity is simply unity minus the reflectivity, however the measurement of the reflectivity is not always a simple task. When the sample surface is not perfectly flat, it is necessary to measure the amount of radiation reflected in a hemisphere in order to determine the reflectivity of the sample. More difficulty is encountered when measurements are attempted at high temperatures. When the sample reaches a temperature high enough to become incandescent, it is difficult to separate reflected radiation from emitted radiation. McMahon and Wilder (5,6) have utilized two techniques in overcoming this problem. In the first case (5), a photocell with a known response to brightness temperature is used to detect

the intensity of the combined emitted and reflected radiation from a sample heated in an imaging furnace. By assuming that the measured intensity is due entirely to the reflected radiation, Kirchoff's law yields an estimate of the sample emissivity. This estimate is then used to calculate an estimate of the brightness temperature using Wein's equation, i.e.,

$$\ln \epsilon_{\lambda} = (C_2/\lambda) \left(\frac{1}{T} - \frac{1}{T_a} \right)$$

where C_2 is the second radiation constant, T is the true temperature determined by a thermocouple imbedded in the sample, λ is the wavelength of the radiation being considered, and T_a is the brightness temperature. By comparing the calculated brightness temperature to the known response of the photocell, a correction to the reflectance is found. The calculations are then repeated in a successive approximation approach until the calculated values of emissivity in successive approximations differ by less than some specified amount. The second method utilized by McMahon and Wilder (6) and also by Held and Wilder (7) involves comparing the intensity of the combined emitted and reflected radiation to the emitted radiation. The intensities are measured with an optical system containing two rotating quartz light pipes, synchronized with a shutter rotating at half the speed of the pipes. With this setup the intensity of the source

radiation, the combined emitted and reflected radiation of the sample, the source radiation, and the emitted radiation of the sample are measured in sequence. The measurements of the reflected plus emitted intensity and the emitted intensity alone are compared to determine the value of the reflected intensity. Then, knowing the source intensity, Kirchhoff's law is used to calculate the sample emissivity.

While both of the methods of separating the reflected and emitted radiation of a sample at high temperature discussed above give satisfactory results, both require the use of a thermocouple to determine the true sample temperature and also require specialized equipment.

Direct methods for the determination of emissivity as described by De Vos (4) involve the comparison of the radiant intensity of the sample surface to that of a blackbody at the same temperature. The intensity of the blackbody radiation may be determined in several ways:

a) The blackbody radiation intensity is calculated from the true temperature by application of Planck's radiation equation, which is

$$N_{b\lambda} = \frac{C_1 \lambda^{-5}/\pi}{\exp (C_2/\lambda T) - 1}$$

Where C_1 and C_2 are the first and second radiation constants, λ is the wavelength, T is the true temperature of the blackbody,

and $N_{b\lambda}$ is the spectral radiance of the blackbody. The true temperature is determined through the use of a thermocouple or resistance thermometer.

b) The radiant intensity of the blackbody is determined by measuring the intensity of an experimental blackbody which is mounted and heated as a separate unit. The use of such a method has been described by Limperis et al. (8). A system in which the blackbody source is heated separately requires a great deal of care in the control of sample and blackbody temperature to assure that they are the same.

c) The intensity of the radiation emitted by the blackbody is determined by the measurement of the brightness temperature of an experimental blackbody source which is contained within the sample or its container and is heated with the sample. Such a technique has been utilized by Ehlert and Margrave (9), Allen (10), and Bradshaw (11). De Vos (4) describes some of the advantages in this last method. They include easier realization of an equal temperature in the sample and blackbody and elimination of the need to correct for the absorption of a window or glass envelope in the experimental apparatus.

In this work, the method chosen for the measurement of the emissivities of the selected rare earth metals is the direct technique utilizing an experimental blackbody cavity in the crucible containing the sample. Employment of this

technique yields experimental values for the spectral emittance of the samples in the solid phase and the spectral emissivity of the samples in the liquid phase.

Samples

Four metals were selected from the rare earths for this work. They are yttrium, neodymium, gadolinium, and erbium. Although yttrium is not technically a member of the rare earth elements, it is normally found in nature along with the heavy rare earths and has properties similar to them (12). For these reasons it is normally considered with the rare earth metals and no distinction will be made in this work. The samples used in this work were prepared within the Ames Laboratory (13, 14) and were of the following purities: the yttrium was approximately 99.9% pure and contained 539 ppm oxygen by weight; the neodymium was approximately 99.95% pure and contained 56 ppm oxygen by weight; the gadolinium was approximately 99.98% pure and contained 43 ppm oxygen by weight; the erbium was approximately 99.95% pure and contained 38 ppm oxygen by weight. A complete analysis of the samples is given in Table 1. Values for the transition temperature, melting point, and vapor pressure of the four metals are given in Table 2 (12, 15, 16).

Table 1. Impurities in the rare earth metal samples in ppm by weight

Impurity	Metal			
	Y	Nd	Gd	Er
O	539	56	43	38
H	-	6	2.4	1.9
N	11	9	26	-
C	50	12	-	5
F	-	228	-	296
Mg	< 10	1.6	-	0.3
Al	-	1.8	-	0.2
Si	200	7.8	-	1.7
Cl	-	0.9	-	10.6
Ca	< 10	1.6	-	0.2
Ti	80	-	-	0.1
Cr	20	3.6	-	1.5
Mn	-	-	0.02	2
Fe	94	4	25	9.2
Ni	60	4.1	1.5	0.4
Cu	10	4.4	4	3.8
Zr	-	6.3	-	0.3
Mo	-	2.6	-	0.5
Ta	500	70	2.3	5.4
W	-	-	11.7	11

Table 1. (Continued)

Impurity	Y	Metal			Er
		Nd	Gd		
Sc	-	0.2	-		0.1
Y	-	6.2	5.6		1
La	-	1	0.8		1.6
Ce	-	1	0.5		1.1
Pr	-	3	3.6		0.7
Nd	-	-	4		0.6
Sm	-	0.2	-		0.2
Eu	-	0.3	< 9.7		-
Gd	-	≤ 10	-		6
Tb	-	≤ 7	2		0.1
Dy	-	≤ 0.8	5.2		5.4
Ho	-	≤ 2	10.5		0.5
Er	-	≤ 3	3.3		-
Tm	-	≤ 0.1	0.3		0.4
Yb	-	≤ 2	< 6.6		0.6
Lu	-	2	1.1		0.2
Other	-	-	-		< 17

Table 2. The transition temperature, melting point, vapor pressure of yttrium, gadolinium, and erbium.

Metal	At. N.	Transition temperature ^c °C	Melting point ^c °C	Vapor pressure at transition temperature ^{a,b,c} atm	Vapor pressure at melting point ^{a,b,c} atm
Y	39	1479 ± 6	1526 ± 5	1.43 x 10 ⁻⁶	2.96 x 10 ⁻⁶
Nd	60	955 ± 9	1016 ± 5	1.29 x 10 ⁻⁹	8.02 x 10 ⁻⁸
Gd	64	1260 ± 2	1312 ± 2	1.80 x 10 ^{-5^d}	2.80 x 10 ^{-5^d}
Er	68	-	1522	-	8.56 x 10 ^{-4^d}

^aSee Reference 12.

^bSee Reference 15.

^cSee Reference 16.

^dEstimated by extrapolating curves given in Reference 15, p. 99.

Literature

Work has been reported on band structure and secondary electron emission for some rare earth metals (17-20) and McMahon and Wilder (5, 6) have reported values for the spectral emittance of several rare earth oxides. Values for the spectral emissivity of the rare earth metals are not available at this time.

THEORY

The use of an optical pyrometer in the measurement of temperature depends on the fact that the spectral radiance of the sample is a function of the temperature of that sample. In the case of a perfect emitter, i.e., a blackbody, the spectral radiance is related to the temperature by the Planck radiation equation (21), which is

$$N_{b\lambda} = \frac{C_1 \lambda^{-5/\pi}}{\exp(C_2/\lambda T) - 1}.$$

$N_{b\lambda}$ is the spectral radiance at wavelength λ of a blackbody at the thermodynamic temperature T . C_1 and C_2 are the first and second radiation constants. For the case of a nonblackbody radiator, the spectral radiance is related to the spectral radiance of a blackbody at the same temperature by

$$N_{\lambda} = \epsilon_{\lambda} N_{b\lambda}$$

where ϵ_{λ} is the spectral emissivity. The value of N_{λ} can also be represented by Planck's radiation equation through the use of an apparent temperature, T_a . This apparent temperature is defined as the temperature at which a blackbody would have a spectral radiance equal to N_{λ} and is often called the brightness temperature. Thus, utilizing Planck's radiation equation, one writes

$$N_{\lambda} = \frac{C_1 \lambda^{-5/\pi}}{\exp(C_2/\lambda T_a) - 1}.$$

Since the spectral emissivity is defined as the ratio of the spectral radiance of the sample to that of a blackbody at the same temperature, ϵ_λ is given by

$$\epsilon_\lambda = \frac{N_\lambda}{N_{b\lambda}} = \frac{\frac{C_1 \lambda^{-5}/\pi}{\exp(C_2/\lambda T_a) - 1}}{\frac{C_1 \lambda^{-5}/\pi}{\exp(C_2/\lambda T) - 1}} = \frac{\exp(C_2/\lambda T) - 1}{\exp(C_2/\lambda T_a) - 1}.$$

For small values of λT , one sees that

$$\exp(C_2/\lambda T) \gg 1.$$

Therefore Wein's formula (22) provides a good approximation to the value of

$$\epsilon_\lambda = \frac{\exp(C_2/\lambda T) - 1}{\exp(C_2/\lambda T_a) - 1}.$$

For values of λT less than $3200\mu^\circ\text{K}$, the error associated with this approximation is less than 1% (23). Replacing Planck's radiation equation with Wein's formula gives

$$\epsilon_\lambda = \frac{\exp(C_2/\lambda T)}{\exp(C_2/\lambda T_a)} = \exp\left[\frac{C_2}{\lambda} \left(\frac{1}{T} - \frac{1}{T_a}\right)\right]$$

or, by taking logarithms of both sides,

$$\ln \epsilon_\lambda = \frac{C_2}{\lambda} \left(\frac{1}{T} - \frac{1}{T_a}\right).$$

The above expression relates the spectral emissivity of the sample to its true and brightness temperatures. These are the two variables which are measured in this work and the expression is used to calculate the spectral emissivity of the samples.

The brightness temperature is measured by focusing the automatic optical pyrometer on the sample surface and recording the indicated temperature. The true temperature is measured by focusing the pyrometer on the blackbody cavity and recording the temperature indicated for the cavity which is located in the sample crucible.

The main assumption involved in the calculation of the spectral emissivity by this method is that the true temperature of the sample is accurately known. This requires that the blackbody cavity be a good approximation of a true blackbody. Several methods have been presented for the evaluation of blackbody approximation cavities (24-26) and some are applicable to the case considered here. Weber (2) indicates that for a cylindrical cavity in a material of emissivity 0.5, the blackness of the cavity is greater than 99% for a depth of diameter ratio of 7.0. The cavity provided in this work has a depth to diameter ratio of 8.6 and measurements of the rough worked surface of the tantalum crucible indicate that its emittance is greater than 0.8. This indicates that the blackbody cavity utilized in this work is at least

99% "black". In the temperature range involved in this work, a 1% deviation from blackbody conditions produces an error in the determination of the true temperature of less than 1°K . The assumption also requires that the temperature of the walls of the cavity be the same as the temperature of the sample surface. Studies have indicated that for the sample configuration used in this work, the temperature gradients are negligible. Details of these studies are given in the discussion.

EQUIPMENT

The equipment utilized in this work consists of four main sections which are: 1) the sample containment and support; 2) the system enclosure and vacuum system; 3) the heating equipment; and 4) the temperature measurement equipment.

Sample Containment and Support

The sample containment and support equipment includes the crucible and the crucible support stand. The crucible is constructed from $3/4$ in. diameter seamless tantalum tubing with a 0.015 in. wall thickness, $1/4$ in. diameter tantalum rod, and 0.015 in. thick tantalum sheet. A $3/4$ in. diameter disk is punched from the tantalum sheet and a $1/4$ in. diameter hole is punched in the center of the disk. Pieces of the tubing and rod are cut to a length of $1/2$ in. and are electron beam welded to the disk as shown in Figure 1. The sample material is held in the annular space surrounding the solid central post. The experimental blackbody cavity is drilled into the central post and the post is then turned down to leave about 0.015 in. between the edge of the post and the side of the cavity. The cavity has a diameter of 0.035 in. and is 0.30 in. deep, giving an approximate depth to diameter ratio of 8.6. The interior of the cavity is left rough to increase the emittance of the tantalum which in turn increases the quality of the blackbody approximation.

Figure 1. Tantalum crucible containing central post with blackbody cavity

TOP VIEW

FRONT VIEW

In the system, the crucible is supported on a piece of 1/4 in. diameter tantalum tubing which is secured inside a piece of 1/4 in. i.d. stainless steel pipe with a set screw as shown in Figure 2. The tantalum tubing is split lengthwise for approximately one-half of its total length to prevent its acting as a susceptor in the magnetic field of the induction heater. Tantalum was chosen for the support tubing because it can withstand the high temperature in contact with the crucible. Also the thin walls of the tantalum tubing do not conduct a large amount of heat away from the crucible. The top of the stainless steel pipe is provided with cooling coils to dissipate any heat reaching the pipe either by radiation from the crucible or by conduction down the support tube. The pipe wall is turned down at the bottom of the pipe to provide a lip on which the pipe rests in the vacuum port of the baseplate. The pipe has a 1/8 in. wide slot in the wall extending the full length of the pipe. This slot connects the enclosure to the vacuum system through the vacuum port in the baseplate.

System Enclosure and Vacuum System

The system enclosure consists of a 3 in. i.d. Pyrex glass column which is closed at the top and bottom with stainless steel plates. The headplate is a 4 in. o.d. plate containing a 1 in. diameter hole through which the sample is viewed and two smaller holes through which the protective

Figure 2. Cross section of baseplate and crucible support assembly

shutters for the quartz window are operated. The headplate and shutters are more fully described in Figure 3. The baseplate is a 5 in. o.d. plate containing two cooling water inlets and outlets to provide cooling water to the support pipe assembly and to the field current concentrator. A port in the center of the baseplate secures the sample support pipe and provides a connection to the vacuum system. The vacuum system used is a Veeco VS-400 high vacuum pumping station and provides a reduction in pressure to less than 1×10^{-5} mm Hg in the system.

Heating Equipment

Sample heating is achieved through the use of a high frequency induction furnace. The induction furnace includes three main pieces of equipment. These are the high frequency generator, the work coil, and the field concentrator.

The high frequency generator used in this work is a Lepel model T-20-3-KC which has a 20 kw power output operating on a frequency range from 180 kh to 450 kh.

The work coil is constructed from 1/4 in. diameter soft copper tubing and consists of four turns approximately 3-1/2 in. i.d. The coil is located on the outside of system enclosure as shown in Figure 4.

The field concentrator shown in Figure 5 is patterned after one described by Johnson (27). As shown in Figure 4, the concentrator is located inside the glass enclosure tube

Figure 3. Headplate and shutter assembly. Headplate, shutter operating rod, and holder are stainless steel. Shutter window is glass

PART ONE
STAINLESS STEEL HEADPLATE

PART TWO
SHUTTER ASSEMBLY

Figure 4. Cross section showing assembled equipment

CROSS SECTION
NOT TO SCALE

- A. SHUTTER HANDLE
- B. "O" RING
- C. WINDOW
- D. HEADPLATE
- E. GASKET
- F. GLASS SHUTTER
- G. SHUTTER FRAME
- H. PYREX COLUMN
- I. FIELD CONCENTRATOR
- J. COOLING CHANNEL
- K. CRUCIBLE
- L. BLACKBODY CAVITY
- M. COOLING LEAD
- N. SUPPORT TUBE
- O. SUPPORT PIPE
- P. COOLING COIL
- Q. SET SCREW
- R. BASE PLATE
- S. COOLING LEAD
- T. WORK COIL

Figure 5. Field current concentrator constructed from copper pieces joined with soft solder

and is surrounded by the work coil of the induction furnace. When the induction furnace is on, the high frequency current in the work coil sets up a magnetic flux which alternates direction at the same frequency as the current. A magnetic field alternating at the frequency of the generator used in this work penetrates the copper of the concentrator to a depth on the order of 10^{-5} cm, which is negligible. Therefore the magnetic flux is forced to pass through some space which is not blocked by the concentrator such as the hole in the center which contains the sample. The magnetic field strength, which has units of flux per unit area, is much larger in the sample region with the concentrator present than without the concentrator. The power generated in a conducting sample by an alternating magnetic field is proportional to the square of the magnetic field strength, therefore the heating effect of the induction furnace is greatly increased by the use of a concentrator. The concentrator is constructed from copper pieces which are fastened together with soft solder. Cooling water is supplied to dissipate the heat generated within the concentrator during a run.

Temperature Measurement Equipment

The temperature measurement equipment consists of the pyrometer and its associated equipment, the prism, the window, and the shutters.

The pyrometer used is a Leeds and Northrup 8641 Precision Automatic Optical Pyrometer with output on a L & N Speedomax W Adjustable Zero-Adjustable Range (AZAR) single point recorder. The pyrometer determines the brightness temperature of the object on which it is sighted by automatically adjusting the current passing through an internal standard lamp to match its brightness to that of the object being measured. The standard lamp current is then converted to a millivolt signal which is output either to a suitable millivolt recorder or to a potentiometer. The pyrometer operates over four temperature ranges which are from 775 to 1225°C, 1075 to 1750°C, 1500 to 2800°C and 2000 to 5800°C. The accuracy of the pyrometer is governed by the calibration and by the stability of the standard lamp. The absolute accuracy of temperature measurements within the range of the pyrometer is defined by limits to which the National Bureau of Standards will specify conformance to the International Practical Temperature Scale. At the present time the limits of error are the same as those stated for manually-operated optical pyrometers which are given in Table 3. Uncertainty in N.B.S. calibration reports for L & N manually-operated pyrometers are usually given as $\pm 4^{\circ}\text{C}$ at 800°C, $\pm 3^{\circ}\text{C}$ at 1063°C, and $\pm 8^{\circ}\text{C}$ at 2800°C. With the higher resolution and precision of the automatic pyrometer it is expected that closer reproducibility can be obtained.

Table 3. Limits of error for manually-operated L & N optical pyrometers

Range	Temperature °C	Limits of error °C
Low	815	± 4
Low	980	± 4
Low	1225	± 4
Medium	1225	± 6
Medium	1425	± 7
Medium	1750	± 8
High	1750	± 14
High	2540	± 18

The pyrometer resolution is given as 0.5°C for a one second balance time at 1063°C and the response time is given as one second. The filters on the pyrometer have an approximate passband of $350 \text{ \AA}$ and the effective wavelength is approximately 0.645μ . The pyrometer has been provided with a 135 mm, f3.5 lens which allows focusing on a target 0.029 in. in diameter at a distance of 11-1/2 in. from the optical center of the lens. Calibration curves which give the indicated temperature as a function of the millivolt output of the pyrometer were furnished by Leeds and Northrup and new calibration of the pyrometer itself is not necessary.

The output from the pyrometer is recorded on the L & N Speedomax recorder as previously mentioned. The recorder responds to 99% of full scale in one second after a step change in input. The AZAR feature of the recorder allows adjustment of recorder zero from -100 to +100 mv and adjustment of full scale span from 67 μ v to 100 mv with major calibrated spans of 0.2, 0.5, 1, 2, 5, 10, 20, 50, and 100 mv. Continuous span adjustment is made by setting a span trimmer which can reduce the span from any of the major calibrated spans to 1/3 its value. The recorder is also operational for recording emf of -100 to +100 V. In this work the recorder was normally operated with a full scale span of 20 mv and from 20 to 40 mv zero suppression. Normal pyrometer output ranges from 25 to 55 mv.

A right prism is used to bend the optical path 90° so that the sample can be viewed from the top of the system while the pyrometer remains in a horizontal position for ease of operation.

The window is made of polished quartz and is located on top of the headplate of the system enclosure.

Two shutters are located in the system and are designed to protect the quartz window from "fogging", i.e., the condensation of sample vapor, while measurements of sample or blackbody brightness temperatures are being made. The shutters consist of a stainless steel operating rod, a

stainless steel holder, and a glass shutter window. The operating rods extend through the headplate and are sealed with o-rings between a flange on the rod and the top of the headplate. The use of glass for the shutter windows allows the pyrometer to be aligned with the blackbody cavity while the shutters are in the closed position. Two shutters are used so that when the bottom shutter becomes "fogged" to an extent that pyrometer alignment with the shutter closed is not possible, the bottom shutter can be opened without exposing the quartz sighting window.

EXPERIMENTAL PROCEDURE

An unused crucible is loaded with sample material by filling the sample space with clean pieces of the sample. The crucible is then placed in the system and the system is evacuated. The material is melted using the induction furnace so that the sample forms a unit in the crucible. This process is then repeated until the crucible is filled. The sample surface is then prepared either by polishing to a smooth, clean surface or by etching with dilute nitric acid to form a clean, rough surface. The polished surface is prepared by overfilling the crucible and polishing away the excess material with fine polishing paper on a polishing wheel. The surface is then rinsed to remove any residue from the polishing process. The etched samples are prepared in the same manner, except that after the surface has been polished down, it is treated with a dilute solution of nitric acid, rinsed to remove excess acid, buffed with a soft cloth, and rinsed to remove any remaining residue.

The crucible with a prepared sample is then placed on the sample support tube as shown in Figure 4, and the height of the tube is adjusted to place the crucible within the hole of the current concentrator. The system is then closed and evacuated. After the system has been allowed to pump down to a pressure less than 1×10^{-5} mm Hg, the induction furnace is turned on at low power to outgas the

sample. The sample is allowed to outgas for approximately one hour before the run is started. At the start of the run the induction furnace power is increased to a level high enough to cause the sample to become incandescent and is left at that level until the temperature of the sample stabilizes. The lower shutter is then opened (necessary only if the lower shutter window is obstructed) and the pyrometer is carefully aligned with the blackbody cavity located in the central post of the crucible. The top shutter is then opened and the output of the pyrometer is recorded, after which the top shutter is closed. Next, the pyrometer is sighted on the sample surface and the top shutter is opened. The pyrometer output is again recorded and both shutters are closed. The measurement of the blackbody and sample surface temperatures are both completed in less than one minute and the quartz window is exposed for only one to three seconds per reading. When both readings are completed, the induction furnace power is set to a new value. Approximately three to five minutes are required for the temperature to stabilize after a change in furnace power. When the temperature does stabilize, the measurement process is repeated.

Since the system is operated at less than 1×10^{-5} mm Hg pressure, the vaporization of sample material can lead to problems with the window "fogging". The shutters previously described reduce this problem to a great extent and at temperatures where the vapor pressure of the sample is well

below the system pressure, readings may be made at several different temperatures before terminating a run. However, at temperatures where the vapor pressure of the sample material approaches the system pressure, window "fogging" is experienced in the short time necessary to take the sample measurements. Under these conditions it is often impossible to take readings at more than one or two temperatures per run.

After each run, the window is removed from the system and checked to determine the degree of "fogging" that occurred during the run. This is done by sighting the pyrometer on a light source with the window in the optical path and noting the brightness temperature of the source. The window is then cleaned to remove any deposited sample material and the brightness temperature of the source is again determined. If a significant change is noted, appropriate corrections are made to the measurements obtained in the run. If the degree of "fogging" is too great for correction, the run must be discarded and repeated with a clean window.

The values obtained in the runs described may be termed the "apparent" blackbody temperature and the "apparent" surface brightness temperature. To obtain the actual blackbody temperature and the actual surface brightness temperature, it is necessary to correct for the effect of the

quartz window and the prism in the optical path. This correction is made with the curve shown in Figure 6 which is a calibration curve obtained by measuring the brightness temperature of a standard lamp, standardized in N.B.S. test No. 174783, with the automatic optical pyrometer by sighting on the lamp through the window and prism. This curve indicates the temperature increment which must be added to the "apparent" temperature to obtain the corrected temperature.

With the corrected temperatures, the spectral emittance of a solid sample or the spectral emissivity of a liquid sample can be calculated using

$$\ln \epsilon_{\lambda} = \frac{C_2}{\lambda} \left(\frac{1}{T} - \frac{1}{T_a} \right)$$

where C_2 is the second radiation constant with a value of 14380.0 μ $^{\circ}\text{K}$, T is the blackbody or true temperature, T_a is the brightness temperature of the sample surface, and λ is the effective wavelength of the pyrometer. As previously reported, the effective wavelength of the pyrometer utilized in this work is 0.645 μ and all values of spectral emittance or spectral emissivity reported hereinafter refer to that wavelength.

Figure 6. Correction curve for optical path containing window and prism

RESULTS AND DISCUSSION

Prior to beginning work with the rare earth metal samples, the temperature gradients present in the crucible were investigated and the technique of emissivity determination was evaluated with a metal for which the emissivity of the liquid is known.

Evaluation of Temperature Gradients

It was important to determine if any significant temperature gradients existed within the samples during runs due to the possibility of their influence on the indication of true temperature using the blackbody cavity. Four basic checks were made to determine if gradients did exist and to determine the magnitude of any that were found.

The first check was made to determine if temperature gradients existed on the sample surface. This was done by scanning the surface of the sample with the automatic pyrometer and noting any changes in the pyrometer output. With a solid sample in the crucible, small gradients were noted in the radial direction with the surface temperature being higher near the outside edge of the crucible. From pyrometry data, the magnitude of the gradient appeared to be less than 1°C from the outer edge of the crucible to the edge of the center post. No gradient was detected on the top of the center post. With the sample in the crucible in

the liquid phase, no gradients were detected on the surface. This uniformity was probably due in part to the circulation induced in the liquid by the magnetic field.

The second check was made to determine if there were any gradients beneath the sample surface between the sample and the central post which would affect the indicated true sample temperature. This was checked by drilling several blackbody cavities in the solid sample, heating the sample, and comparing the brightness temperatures of the cavities in the sample to the brightness temperature of the cavity in the central post. The average difference indicated in this check was less than 1.5°C . Sample cavities near the central post indicated temperatures less than 1°C higher than that of the cavity in the post. These measurements indicate that some gradient is present, but the magnitude of this gradient is negligible.

The third check was a simplified calculation to determine the possibility of significant axial gradients existing. The simple model for which the calculation was made consisted of a solid rod with the dimensions of the crucible and sample. The cylinder was considered to have a constant heat rate input at the surface and a constant temperature at the ends. Under steady state conditions the heat input must equal the heat output and the heat output was assumed to be entirely by radiation from a surface of emissivity 1.0.

The thermal conductivity of the sample was taken to be $0.02 \text{ cal-cm/sec-cm}^2\text{-}^\circ\text{C}$ which is slightly lower than the thermal conductivity of most rare earth metals (12). The results of the calculation indicate a gradient of less than 4°C from the center to the end of the rod (axial gradient).

The fourth check involved imbedding two thermocouples in the sample near the central post of the crucible. One thermocouple was placed near the surface of the sample and the other at the center of the sample. The indicated temperature gradient was less 2°C which is less than the error attributable to the thermocouples. The method indicates that the axial gradient is negligible.

From these four checks it is apparent that no gradients exist which will greatly affect the determination of the true sample temperature through the use of the blackbody cavity in the central post.

Evaluation of Technique

A sample of 99.999% pure, oxygen free, high conductivity copper was chosen to evaluate the technique proposed for the measurement of spectral emissivity. Values for the spectral emittance of solid copper and the spectral emissivity of molten copper are available (28) and are listed in Table 4. Copper samples were prepared and subjected to two sequences of runs. The first sequence of runs was made beginning with a smooth, clean surface prepared as described in the

Table 4. The spectral emissivity of copper at wavelength λ

Surface condition	λ μ	Temperature $^{\circ}\text{C}$	ϵ_{λ} ^a
Smooth, clean	0.625	991	0.130
	0.625	1035	0.150
	0.625	1090	0.171
	0.625	1174	0.167
	0.650	991	0.104
	0.650	1035	0.124
	0.650	1090	0.148
	0.650	1174	0.146

^aSee Reference 28.

procedure. This sequence of runs started in the solid phase and extended to temperatures well above the melting point of copper. In the second sequence of runs the surface of the copper was allowed to oxidize before the beginning of the runs and the runs were limited to temperatures below the melting point. The results of the runs on copper are presented in Figure 7. The spectral emittance of the solid is greatly affected by the presence of the oxide film. The values of spectral emittance obtained for the clean, smooth surface indicate a rise in ϵ_{λ} with increasing temperature.

Figure 7. Spectral emissivity at $\lambda = 0.645 \mu$ versus $T^{\circ}\text{C}$ for pure copper

The variation is from $\epsilon_\lambda = 0.090$ at 950°C to $\epsilon_\lambda = 0.125$ at 1083°C . These values are somewhat lower than the reported values (28) for solid copper, but there is no assurance that the condition of the surface was the same in each determination. The value of the spectral emissivity obtained for the molten copper is independent of the sample temperature in the temperature range evaluated. The mean value is 0.134 and the standard deviation of the data from the mean value is 0.011. The spectral emissivity of 0.134 compares to a reported value of 0.148 (28). The determination of the reported spectral emissivity of copper was originally done by Stubbs (29). His method involved the determination of the true temperature of the sample through the use of a blackbody source which was separate from the sample. The difference in the values of the spectral emissivity obtained in this work and that reported by Stubbs could be generated by an error of less than 1% in the determination of the blackbody temperature. Due to the difficulty in reproducing experimental conditions as is required in the technique utilized by Stubbs, it is felt that the method of this work, utilizing the sample and blackbody in the same unit, is more accurate.

Yttrium

Two sequences of runs were made on yttrium samples. The first sequence was made beginning with a solid surface which

had been etched with dilute mineral acid solution to remove surface contamination and provide a clean, roughened surface. This sequence of runs extended from the solid phase into the liquid phase. The second sequence of runs started with a clean, smooth surface and also extended to temperatures well above the melting point of yttrium. The results of these runs are presented in Figure 8. As expected, the spectral emittance of the solid is dependent on the condition of the sample surface. The etched surface has a considerably higher emittance than the smooth surface in the solid phase, but above the melting point the surface roughness of the etched sample is no longer present and the spectral emissivities coincide. There is no change in the spectral emittance of the etched sample with changing temperature but the smooth sample showed a slight decrease in spectral emittance with increasing temperature. The decrease was only 0.030 over the temperature range evaluated and the assumption of a mean value for the emittance is a good approximation. It was noted that when the samples in runs beginning with the etched surface are melted and then cooled to return to the solid phase, the emittance obtained for the new solid surface is the same as that obtained in runs beginning with the smooth surface. This indicates that the high emittance observed for the etched sample is indeed due to roughness in the surface.

Figure 8. Spectral emissivity at $\lambda = 0.645 \mu$ versus $T^{\circ}\text{C}$ for yttrium

The mean value of the spectral emittance for a clean, smooth surface of yttrium is 0.374 with a standard deviation in the data from the mean value of 0.015. The spectral emissivity of the liquid yttrium is 0.370 and the standard deviation is 0.010.

Neodymium

Neodymium is one of the lighter rare earths and has a tendency to oxidize readily. In spite of care taken to assure a clean surface at the beginning of a run, an oxide film invariably appeared on the sample surface during the outgassing of the sample. The decision was made to run the samples with the oxide film present. Two sequences of runs were made on the neodymium samples. The first sequence of runs started with an etched surface while the second sequence started with a smooth surface. In both cases a light film of oxide was present on the sample surface. When the runs were extended into the liquid phase, a reasonably oxide free surface was created by the continual surface renewal set up by circulation of the molten metal within the crucible. This circulation occurs naturally in liquid samples heated in induction furnaces and is caused by differences in the magnetic field strength at various points in the sample. The results of the runs on neodymium are given in Figure 9. As is the case with yttrium, limited dependence on sample temperature is noted in the values obtained.

Figure 9. Spectral emissivity at $\lambda = 0.645 \mu$ versus $T^{\circ}\text{C}$ for neodymium

The spectral emissivity of liquid neodymium was determined to be 0.280 with a standard deviation of 0.014 from the mean value.

Gadolinium

With gadolinium samples, the trends observed are similar to those observed with yttrium samples. Little variation in either the solid emittance or the liquid spectral emissivity is observed with changes in temperature. The emittance of the etched solid surface is greater than that of the smooth surface, but the magnitude of the difference is not as great as in the case with yttrium. Results of the runs on gadolinium are presented in Figure 10. The observed spectral emittance of the smooth solid is 0.337 and the standard deviation of the data is 0.008 from the mean value. The spectral emissivity of molten gadolinium was determined to be 0.342 with a standard deviation of 0.009. The emittance of the etched surface was found to be 0.399 with a standard deviation of 0.013. The emissivity of the liquid surface determined in runs beginning with an etched solid surface is the same as that reported from runs beginning from smooth solid surfaces. After the etched surface has been melted and cooled below the melting point, the emittance of the surface is the same as that determined for a smooth gadolinium surface.

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Figure 10. Spectral emissivity at $\lambda = 0.645 \mu$ versus $T^{\circ}\text{C}$ for gadolinium

Erbium

As in the case with neodymium, erbium shows a tendency to develop an oxide film during the outgassing procedure. The run sequences on the smooth and etched surface were made with an oxide film present and the emittances obtained are higher than would be expected for clean surfaces. The high vapor pressure of erbium metal at temperatures approaching its melting point made it impossible to extend measurements into the liquid phase with the present equipment. Results of the runs on the solid surfaces are given in Figure 11.

Possible Future Work

Future work on the determination of the spectral emissivities of rare earth metals could extend to other metals not studied in the present work. Other possibilities for future work involve modification of the equipment to provide an inert atmosphere for the samples in order to reduce vaporization and allow metals with higher vapor pressures, such as erbium, to be studied in the liquid state. Such a modification might also be useful in reducing the oxidation problem experienced with neodymium and erbium.

Figure 11. Spectral emittance at $\lambda = 0.645 \mu$ versus $T^{\circ}\text{C}$ for erbium

SUMMARY AND CONCLUSIONS

The method for the determination of the spectral emissivity of liquid metal samples by comparing the brightness temperature of the surface to the brightness temperature of a blackbody reference contained in the sample crucible gives good results in this work. Deviations noted in the data are attributable to errors in the measurement of temperature of less than 1%. Such errors are expected and are within the stated reproducibility of measurement with the automatic pyrometer.

The spectral emissivities of the rare earth metals studied are independent of temperature over the temperature ranges considered. Application of the technique to solid samples yields values for the spectral emittance of the sample surfaces which are dependent upon the condition of the surface. From the work on yttrium and gadolinium, the spectral emittance of the smooth solid surface does not differ greatly from the spectral emissivity of the liquid. No severe discontinuity is noted at the sample melting point. Although one might expect some change in the spectral emittance of the solid surface at the solid transition temperatures, due to reorientation of the surface, no such change was noted in this work. A summary of the results is given in Table 5.

Table 5. Summary of results

Metal	Surface condition	Spectral emittance ^a $\lambda = 0.645 \mu$	Spectral emissivity ^a $\lambda = 0.645 \mu$	Temperature range °C
Cu	Smooth, lightly oxidized	0.448 ± 0.010	-	925-1083
	Smooth, clean	0.101 ± 0.020	-	890-1083
	liquid	-	0.134 ± 0.01	1083-1200
Y	etched	0.694 ± 0.016	-	950-1526
	smooth, clean	0.374 ± 0.015	-	950-1526
	liquid	-	0.370 ± 0.010	1526-1675
Nd	etched, oxidized	0.676 ± 0.013	-	800-1016
	smooth, oxidized	0.405 ± 0.015	-	800-1016
	liquid	-	0.280 ± 0.014	1016-1300

^aMean values $\pm$ standard deviation of data points from mean value.

Table 5. (Continued)

Metal	Surface condition	Spectral emittance ^a $\lambda = 0.645 \mu$	Spectral emissivity ^a $\lambda = 0.645 \mu$	Temperature range °C
Gd	etched	0.399 ± 0.013	-	1025-1312
	smooth, clean	0.337 ± 0.008	-	1025-1312
	liquid	-	0.342 ± 0.009	1312-1600
Er	etched, oxidized	0.750 ± 0.017	-	990-1350
	smooth, oxidized	0.624 ± 0.007	-	990-1400

The values of spectral emittance and spectral emissivity determined in this work are valuable in the determination of heat losses by radiation and in measurement of metal temperatures utilizing optical pyrometry.

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APPENDIX

Raw Data and Sample Calculations

The pyrometer output data for the runs on copper, yttrium, neodymium, gadolinium, and erbium are given in Tables 6 through 10, respectively. The pyrometer output is converted to apparent brightness temperatures by linear interpolation of the pyrometer calibration data given in Table 11. The apparent brightness temperatures are then corrected for the prism and window of the equipment through the use of the correction curve given in Figure 6. The corrected brightness temperatures are then substituted into the equation

$$\ln \epsilon_{\lambda} = \frac{C_2}{\lambda} \left(\frac{1}{T} - \frac{1}{T_a} \right)$$

where T is the brightness temperature of the blackbody cavity in $^{\circ}\text{K}$ and T_a is the brightness temperature of the sample surface in $^{\circ}\text{K}$. The sample calculation given below is for the first point in run one for copper:

Calculation of apparent blackbody temperature from pyrometer output.

$$\begin{aligned} (T) &= \frac{mv - mv_1}{mv_{1+1} - mv_1} (T_{1+1} - T_1) + T_1 \\ &= \frac{36.20 - 35.819}{36.384 - 35.819} (960 - 950) + 950 \\ &= 956.7^{\circ}\text{C} \end{aligned}$$

Calculation of apparent surface brightness temperature from pyrometer output.

$$(T_a) = \frac{33.40 - 33.375}{33.638 - 33.375} (910 - 905) + 950 = 905.5^{\circ}\text{C}$$

Correction of temperatures from Figure 6.

$$T = (T) + 34.2 = 990.9^{\circ}\text{C}$$

$$T_a = (T_a) + 30.5 = 936.0$$

Calculation of spectral emittance from the corrected temperatures.

$$\begin{aligned} \ln \epsilon_{\lambda} &= \frac{C_2}{\lambda} \left(\frac{1}{T} - \frac{1}{T_a} \right) \\ &= \frac{14380}{0.645} \left(\frac{1}{990.9 + 273.2} - \frac{1}{936.0 + 273.2} \right) \end{aligned}$$

$$\epsilon_{\lambda} = 0.449 .$$

Melting Points and Transition Temperatures of Yttrium, Neodymium, and Gadolinium

After the completion of a run on one of the metal samples, the pyrometer is focused on either the blackbody cavity or the surface of the sample and the cooling curve is observed after the induction furnace has been shut down. When the pyrometer is focused on the blackbody cavity, discontinuities in the cooling curve as revealed in the pyrometer output allow the determination of the melting points and transition

temperatures of the samples. Values for the melting points and transition temperatures of yttrium, neodymium, and gadolinium determined by this method are presented in Table 12. The values are in good agreement with the values presently accepted and reported (14).

Table 6. Raw data for runs on copper

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
1	S,O	36.20	33.40	
		35.60	32.90	
		36.30	33.40	
		37.80	34.90	
		40.90	37.50	
		33.30	31.20	
2	S,O	40.00	36.50	
		40.70	37.10	
		39.88	36.42	
		39.70	36.80	N
		45.70	44.20	N
		34.11	32.25	N
		36.11	34.43	N
		36.44	34.87	N
3	S,C	39.88	37.95	N
		34.10	27.70	
		36.55	29.75	
		39.00	31.15	
		40.15	32.10	
		40.15	32.50	
		43.30	35.55	F
4	S,C	40.40	31.80	F
		31.30	25.70	
		32.90	26.60	
		35.80	28.25	

^aPyrometer output: BB = blackbody cavity, S = sample surface.

^bSurface condition at beginning of run: S = smooth, C = clean, O = oxidized.

^cA note in the comments column means the point has been discarded for the reason noted: N = nonuniform surface, F = window fogging.

Table 6. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
4 cont.		38.70	31.15	
		40.45	31.00	N
		45.00	40.85	N
		46.70	43.45	N
		33.30	31.75	N
		37.37	35.10	N
		39.65	32.80	N
5	S,C	32.50	25.80	N
		33.10	26.20	N
		34.20	26.85	N
		35.20	27.50	N
		36.85	28.50	N
		38.05	29.30	N
		38.70	29.80	N
		38.80	29.90	N
		39.20	30.05	N
		39.85	30.70	N
		40.55	31.55	N
		40.70	33.90	N
		41.20	31.30	N
6	S,C	42.60	33.75	
		42.60	33.60	
7	S,C	44.00	35.60	
		44.10	38.10	F
8	S,O	32.95	30.70	
		34.65	32.10	
		35.25	32.55	
		38.50	35.35	
		39.30	35.90	
		39.70	36.40	
9	S,C	41.60	33.55	
		42.20	33.90	
		42.70	34.10	
		43.00	34.60	

Table 6. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
9 cont.		43.70	34.90	
		44.00	34.80	
		44.70	35.70	
		45.10	35.60	
		45.90	36.40	
		46.60	36.70	
		47.40	37.60	
10	S,C	34.95	28.15	
		35.50	28.65	
		35.95	29.30	
		37.50	30.15	
		37.90	30.75	
		41.15	33.20	

Table 7. Raw data for runs on yttrium

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
1	E,C	32.45	30.95	0
		33.20	31.80	0
		33.60	32.30	0
		34.35	32.90	0
		35.20	33.75	0
		36.35	34.80	0
		40.85	38.70	0
		40.70	37.30	0
		41.65	38.40	0
		42.30	39.05	0
		42.60	38.65	0
2	E,C	35.95	34.55	
		37.10	35.80	
		38.10	36.65	
		39.75	38.20	
3	S,C	44.70	39.80	
		46.25	41.15	
		46.55	41.35	
		46.40	41.25	
		46.60	41.35	
		47.10	41.80	
		47.65	42.20	
		48.45	42.95	
		49.45	43.75	
		50.25	44.40	
		51.95	45.90	

^aPyrometer output: BB = blackbody cavity, S = sample surface. An M following a reading indicates medium range.

^bSurface condition at beginning of run: S = smooth, C = clean, E = etched.

^cA note in the comments column means the point has been discarded for the reason noted: O = oxidation, F = window fogging.

Table 7. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
4	S,C	33.10M	30.35M	0
		33.65M	30.90M	0
		34.95M	32.00M	0
		36.15M	33.00M	0
		37.45M	34.10M	0
5	S,C	35.70M	32.50M	
		39.95M	35.45M	
		41.65M	37.20M	
		44.85M	40.00M	
		35.00M	31.75M	
		51.80	45.25	
		36.90M	33.15M	
		40.40M	35.90M	
		43.50M	38.65M	F
		45.60M	40.00M	F
		47.55M	41.10M	F
		45.40M	39.75M	F
		34.20M	30.85M	F
6	S,C	49.45	43.10	F
		35.10	32.10	
		37.75	34.30	
		41.30	37.10	
		39.25M	35.20M	
		39.90M	35.60M	
		42.10M	37.55M	
		42.75M	38.05M	
		44.65M	39.65M	
		45.10M	39.85M	
7	S,C	46.30M	40.75M	
		47.25M	41.15M	
8	S,C	46.70M	41.15M	
		46.25M	40.95M	
9	S,C	43.00M	38.20M	
		41.70M	37.10M	

Table 7. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
9 cont.		37.60M	33.85M	
		43.25	38.60	
		39.35	35.40	
		36.25	32.95	
10	E,C	45.00	42.95	
		48.30	45.95	
		34.20M	33.00M	
		36.45M	35.15M	
		38.00M	36.40M	
		41.05M	39.45M	
11	E,C	40.85M	39.05M	
		41.95M	40.15M	
		42.50M	40.75M	
		42.85M	40.95M	
		47.65M	40.55M	
		44.15M	39.10M	
		42.30M	37.60M	
		40.35M	36.15M	
		38.55M	34.40M	
		35.85M	32.40M	
12	S,C	46.00M	40.55M	
		47.95M	42.15M	

Table 8. Raw data for runs on neodymium

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
1	S,0	33.05	30.35	
		35.25	32.25	
		37.00	33.55	
		39.80	35.50	N
		44.05	38.85	N
		46.55	40.70	N
		30.80M	28.20M	N
		32.60M	29.40M	N
		47.55	41.95	N
		47.35	41.10	N
		46.80	40.50	N
		31.60	29.85	N
2	S,0	35.20	32.50	
		36.15	33.05	
		41.45	35.85	
		44.60	38.50	
		46.65	40.10	
		47.65	40.35	
		46.95	40.00	
		47.25	40.15	
		48.70	41.15	
		47.25	40.00	
		46.70	39.90	
3	S,0	51.25	43.20	
		37.15M	30.10M	F

^aPyrometer output: BB = blackbody cavity, S = sample surface. An M following a reading indicates medium range.

^bSurface condition at beginning of run: S = smooth, E = etched, O = oxidized.

^cA note in the comments column means the point has been discarded for the reason noted: N = nonuniform surface, F = window fogging.

Table 8. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
4	S,0	34.60M	30.50M	F
		34.80M	31.10M	
		39.10M	29.80M	
5	S,0	38.95	33.55	N
		40.70	38.40	N
		37.40	35.40	N
6	E,0	34.25	32.65	N
7	E,0	34.90	33.50	N
		34.90	33.70	
		36.45	35.15	
		37.30	36.05	
		40.85	39.30	
		45.85	39.75	
		38.25	36.35	
		38.25	38.00	
		38.70	30.20	
8	E,0	29.30	28.40	N
		33.40	32.00	N
		34.35	32.90	N
		38.35	36.95	N
		40.00	38.25	N
		46.65	40.40	N
9	E,0	27.40	26.65	
		28.15	27.35	
		29.05	28.10	
		30.25	29.35	
		31.45	30.40	
		32.75	31.55	
		35.20	33.80	
		35.20	33.80	
		35.60	34.20	
		36.15	34.75	
		36.30	34.90	
		36.65	35.25	
		46.15	39.75	
		47.15	40.45	

Table 8. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
9 cont.		47.55 48.00 48.20 50.10	40.80 41.00 41.40 42.95	
10	E,0	54.45 38.55M	46.15 31.40M	F
11	S,0	29.35 30.45 31.40 32.65 34.20 37.65 39.95 40.90 41.90 43.40	27.45 28.30 29.15 30.10 31.45 34.25 34.85 35.70 36.40 37.65	
12	E,0	29.35 33.90 34.30 37.20 37.40 37.65 37.70 40.80 41.50 45.15 46.15	28.45 32.60 32.95 35.71 35.95 36.10 36.20 35.40 36.05 38.55 39.40	
13	S,0	38.55 39.60 43.00 43.85 48.65 49.40 50.30	33.80 34.50 37.05 37.75 41.50 41.95 42.65	

Table 8. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
14	S,0	50.50	43.05	
		51.95	44.00	
15	S,0	34.10M	30.30M	

Table 9. Raw data for runs on gadolinium

Run #	condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
1	E,C	38.55	35.05	
		41.05	37.05	
		43.10	38.75	
		45.05	40.30	
		46.85	41.80	
		48.15	43.05	
		48.80	43.40	
		49.30	44.00	
		49.85	44.20	
		51.35	45.50	
		53.00	46.90	
		54.80	48.20	
		34.40M	31.40M	
		34.90M	31.80M	
		35.20M	32.05M	
2	E,C	38.35	34.65	0
		54.00	48.70	0
		35.35M	32.30M	0
3	E,C	38.35	34.95	
		40.95	37.05	
		43.75	39.40	
		46.80	41.90	
		48.45	43.30	
		49.25	44.00	
		49.30	43.95	

^aPyrometer output: BB = blackbody cavity, S = sample surface. An M following a reading indicates medium range.

^bSurface condition at beginning of run: S = smooth, C = clear, E = etched.

^cA note in the comments column means the point was discarded for the reason noted: O = oxidation, F = window fogging.

Table 9. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
3 cont.		50.45	44.85	
		53.05	46.80	
4	E,C	35.65	32.45	
		43.55	39.00	
		45.80	40.70	
		46.80	41.60	
		48.10	42.70	
		49.05	44.00	
		51.90	45.85	
		54.10	47.75	
		34.35M	31.40M	
		37.90M	33.90M	
		40.20M	35.70M	
		35.70M	32.00M	
		54.45	47.20	
		51.90	44.90	
		50.25	43.65	
5	S,C	36.20M	32.40M	
		37.60M	33.60M	
		42.50M	37.00M	F
		45.30M	38.95M	F
		45.60M	37.85M	F
6	S,C	42.20M	37.35M	
		44.75M	38.30M	F
		46.75M	38.90M	F
		47.30M	39.80M	F
7	S,C	51.45	44.90	
		52.75	46.00	
		54.15	47.05	
		34.70M	31.45M	
		35.20M	31.80M	
		36.80M	32.80M	
		37.80M	33.75M	
		38.70M	34.50M	
		40.05M	35.60M	
		41.70M	36.90M	

Table 9. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
7 cont.		42.85M	37.90M	F
		42.50M	37.40M	
		43.45M	38.35M	
		44.95M	39.40M	
		46.90M	40.40M	
8	S,C	40.85	36.15	
		42.15	37.10	
		43.15	37.90	
		44.80	39.20	
		47.00	41.20	
		48.30	42.10	
		49.60	43.05	
		49.70	43.15	
		51.10	44.25	
		52.80	45.80	
		53.75	46.50	
		55.50	48.00	
		55.35	48.00	
		52.90	45.90	
		53.05	46.00	
		51.60	44.90	
		37.30M	33.45M	
		39.65M	35.20M	
9	S,C	41.25M	36.35M	
		38.20M	34.15M	
		36.30M	32.55M	
		53.60	46.45	
		54.95	47.65	
		50.85	44.10	
		49.05	42.70	
		47.80	41.75	
		45.85	40.10	
		44.00	38.60	
		42.70	37.50	
		41.55	36.70	
		40.15	35.65	

Table 10. Raw data for runs on erbium

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
1	E,0	31.80	31.20	N
		33.00	32.50	N
		35.05	34.35	N
		37.10	35.85	N
		37.65	36.90	N
		38.55	37.15	N
		42.35	41.25	N
2	E,0	31.10	30.45	
		34.35	33.50	
		36.45	35.45	
		37.65	36.50	
		39.45	38.20	
		40.15	38.85	
		42.60	41.00	
		44.85	43.20	
3	S,0	48.80	45.95	
		50.05	47.05	
		48.35	45.70	
		50.95	47.95	
		54.10	49.75	F
		36.75M	34.25M	F
		40.25M	36.45M	F
4	S,0	52.80	48.75	N
		43.60	41.65	N

^aPyrometer output: BB = blackbody cavity, S = sample surface. An M following a reading indicates medium range.

^bSurface condition at beginning of run: S = smooth, E = etched, O = oxidized.

^cA note in the comments column means the point was discarded for the reason noted: N = nonuniform surface, F = window fogging.

Table 10. (Continued)

Run #	Surface condition ^b	Pyrometer output ^a		Comments ^c
		BB mv	S mv	
4 cont.		43.55	41.65	N
		45.15	44.25	N
		46.30	45.70	N
5	S,0	36.55M	35.10M	F
		38.80M	37.65M	F
		38.00M	34.35M	F
6	S,0	31.25	30.00	
		36.25	34.55	
		39.20	37.25	
		39.95	37.85	
		42.05	39.80	
		44.30	41.75	
		34.00M	32.45M	
		34.75M	33.20M	
		36.60M	34.75M	
7	E,0	38.00M	36.55M	
		32.65	31.90	
		35.20	34.25	
		41.35	39.95	
		43.75	42.15	
		46.55	44.80	
		51.80	49.75	
		36.20M	35.00M	

Table 11. Pyrometer calibration

Low range		Low range		Low range	
T°C	mv	T°C	mv	T°C	mv
760	26.735	965	36.668	1165	49.683
765	26.936	970	36.956	1170	50.033
770	27.139	975	37.245	1175	50.384
775	27.345	980	37.539	1180	50.740
780	27.552	985	37.837	1185	51.095
785	27.761	990	38.137	1190	51.454
790	27.973	995	38.436	1195	51.810
795	28.186	1000	38.741	1200	52.168
800	28.401	1005	39.044	1205	52.528
805	28.617	1010	39.348	1210	52.892
810	28.833	1015	39.657	1215	53.249
815	29.052	1020	39.964	1220	53.608
820	29.273	1025	40.271	1225	53.963
825	29.495	1030	40.583	1230	54.323
830	29.720	1035	40.900	1235	54.696
835	29.947	1040	41.212	1240	55.057
840	30.174	1045	41.530		
845	30.404	1050	41.847		
850	30.635	1055	42.173		
855	30.871	1060	42.499		
860	31.110	1065	42.828		
865	31.349	1070	43.157		
870	31.592	1075	43.491		
875	31.838	1080	43.825		
880	32.087	1085	44.156		
885	32.340	1090	44.492		
890	32.595	1095	44.834		
895	32.853	1100	45.172		
900	33.113	1105	45.512		
905	33.375	1110	45.858		
910	33.638	1115	46.200		
915	33.904	1120	46.544		
920	34.171	1125	46.887		
925	34.441	1130	47.238		
930	34.712	1135	47.580		
935	34.987	1140	47.926		
940	35.263	1145	48.274		
945	35.540	1150	48.627		
950	35.819	1155	48.978		
960	36.384	1160	49.328		

Table 11. (Continued)

Medium range T°C	mv	Medium range T°C	mv	Medium range T°C	mv
1000	27.363	1205	33.674	1405	40.936
1005	27.504	1210	33.845	1410	41.127
1010	27.645	1215	34.015	1415	41.317
1015	27.786	1220	34.186	1420	41.511
1020	27.929	1225	34.357	1425	41.702
1025	28.072	1230	34.530	1430	41.895
1030	28.216	1235	34.704	1435	42.092
1035	28.361	1240	34.877	1440	42.288
1040	28.506	1245	35.052	1445	42.484
1045	28.651	1250	35.227	1450	42.682
1050	28.796	1255	35.402	1455	42.881
1055	28.940	1260	35.577	1460	43.078
1060	29.088	1265	35.754	1465	43.276
1065	29.235	1270	35.931	1470	43.478
1070	29.383	1275	36.108	1475	43.677
1075	29.531	1280	36.287	1480	43.876
1080	29.680	1285	36.466	1485	44.073
1085	29.830	1290	36.644	1490	44.272
1090	29.981	1295	36.823	1495	44.471
1095	30.130	1300	37.005	1500	44.673
1100	30.282	1305	37.185	1505	44.875
1105	30.434	1310	37.367	1510	45.076
1110	30.587	1315	37.551	1515	45.276
1115	30.740	1320	37.736	1520	45.478
1120	30.896	1325	37.922	1525	45.681
1125	31.052	1330	38.107	1530	45.884
1130	31.209	1335	38.294	1535	46.085
1135	31.365	1340	38.479	1540	46.285
1140	31.524	1345	38.667	1545	46.487
1145	31.684	1350	38.856	1550	46.691
1150	31.845	1355	39.042	1555	46.890
1155	32.006	1360	39.230	1560	47.097
1160	32.169	1365	39.418	1565	47.300
1165	32.335	1370	39.607	1570	47.498
1170	32.498	1375	39.794	1575	47.699
1175	32.664	1380	39.983	1580	47.900
1180	32.831	1385	40.172	1585	48.101
1185	32.998	1390	40.362	1590	48.306
1190	33.167	1395	40.551	1595	48.509
1200	33.505	1400	40.743	1600	48.711

Table 11. (Continued)

Medium range	
T°C	mv

1605	48.915
1610	49.118
1615	49.321
1620	49.524
1625	49.727
1630	49.930
1635	50.130
1640	50.332
1645	50.532
1650	50.737
1655	50.940
1660	51.141
1665	51.344
1670	51.549
1675	51.751
1680	51.955
1685	52.157
1690	52.361
1695	52.566
1700	52.769
1705	52.973
1710	53.175
1715	53.375
1720	53.576
1725	53.775
1730	53.975
1735	54.177
1740	54.380
1745	54.589
1750	54.791

Table 12. Melting points and transition temperatures of yttrium, neodymium, and gadolinium

Metal	Transition temperature °C	Melting point °C
Y	1481 ± 9	1528 ± 9
Nd	954 ± 5	1014 ± 5
Gd	1261 ± 8	1314 ± 8