THE EQUIPMENT OF A HIGH TEMPERATURE MEASUREMENT LABORATORY.

By G. A. SHOOK.

MEASUREMENT OF HIGH TEMPERATURES.

The first attempt to measure temperatures with any accuracy seems to be due to the celebrated potter, Wedgewood, although he was not the first by any means to recognize the importance of temperature estimation and temperature control in kilns in order to reproduce a given effect. In the time of the Romans the working of iron had undoubtedly reached an advanced stage, but their methods and knowledge of the metallurgy of iron were entirely empirical. In the eighth century a writer, in outlining a method for obtaining high temperatures, called attention to the most difficult part of the problem, namely, that "fire is not a thing which can be measured." Even within recent years the temperature of a steel kiln was not known within 500 degrees C. and the values given for the temperature of the sun ranged from 1,500 to 1,000,000 degrees C. Today, however, with our advanced methods of radiation pyrometry, the student of physics can measure the temperature of the sun, the highest known temperature, with as much ease and accuracy as he can determine the specific heat of a piece of lead.

It has been known for several years that numerous industrial processes, carried out at high temperatures, require a temperature control of 20 degrees C. Mr. C. E. Foster[1], in speaking of the successful production of finished castings, remarked that there are four main factors to be considered:

1—Composition of the material melted.
2—Atmosphere and surroundings.
3—Temperature.
4—Time.

The first two of these are taken care of by the chemist, but the third and fourth must be controlled by the man trained in pyrometry. It requires but a casual glance through the trade journals to convince one that the

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[1] The Foundry, May, 1909.

men who are handling this problem in the industries are not sufficiently trained to appreciate the limitations of its practical application. Therefore the engineer or chemist must be trained along this line if he expects to do the most efficient work. High temperatures were, until quite recently, estimated by the trained eye of a workman, and while they acquired with practice a surprising accuracy, such a procedure is entirely inadequate for present day requirements. Moreover, the observer's estimate is influenced manifestly by a number of circumstances, such as the amount of light in the room, fatigue of the eye, physical condition of the observer, etc. The greatest disadvantage is that a skilled workman in Pittsburg can not gain anything from the experience of a workman in Birmingham. In times past numerous methods have been devised and used for temperature estimation and temperature control, but the temperature scales used were so discordant that about six years ago the Bureau of Standards[2] made a thorough investigation of the most available methods.

There are today four precise laboratory methods for measuring high temperatures, each of which is the basis of an industrial pyrometer:

Electric-resistance Pyrometer.—In this pyrometer use is made of the variation of the electric resistance of metals with change of temperature. Since resistance can be measured with extreme precision this method permits of very precise measurements of temperature up to 1000° C.

Thermoelectric Pyrometer.—This instrument utilizes the variation of the electromotive force with temperature, developed at the junction of two dissimilar metals. This pyrometer may be used for temperatures up to 1600° C. when the thermo-couple consists of wires of platinum and platinum-rhodium or iridium.

Radiation Pyrometer.—In this type of pyrometer the total radiation from hot bodies is taken as a measure of their temperature. This instrument requires a device for determining very small changes in temperature, and does not admit of very great accuracy, but is very convenient for very high temperatures.

Optical Pyrometer.—In the case of pyrometers of this class temperature estimation is made by means of a photometric comparison, for a particular wave length, between the radiation from some standard lamp and the radiation emitted from the body under observation. This is a very precise method and is available for the highest known temperature.

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[2] Bulletin Bureau of Standards, Vol. 1, p. 189.

TEMPERATURE SCALE.

The usual method of measuring temperature is by the expansion of some substance, such as mercury in the ordinary glass thermometer, or gas in the more refined work. With such a method, however, the magnitude of a degree will depend upon the nature of the substance employed, which is undesirable in scientific work. A theoretical thermometric scale, independent of any substance used, has been worked out by Lord Kelvin and is known as the "Thermodynamic Scale." Temperatures on this scale are measured by the work done in carrying a substance around a Carnot's cycle working between two sources at constant temperature.

Without attempting any proof here, the theory gives the following relation,

$$\frac{T_1}{T_2} = \frac{Q_1}{Q_2}$$

where T is the absolute temperature and Q is the quantity of heat, which can be measured in terms of energy since by the first law of thermodynamics heat is proportional to work. Hence the ratio of any two temperatures may be determined from purely mechanical considerations and will furthermore be independent of the substance used in the conversion of work into heat. Experiment has shown, however, that no known gas is perfect, and that, furthermore, no gas is satisfactory throughout the entire range of temperatures which are used in gas thermometry.[3] The practical standard is the international Normal Scale of the constant volume hydrogen thermometer. Hydrogen can be used for very low temperatures, but above 300° C. it is unreliable. Nitrogen, on the other hand, can not be used for low temperatures, but is suitable for high temperatures. In the absence of a perfect gas we have practical standard gas thermometers, such as hydrogen and nitrogen, for which thermodynamic corrections have been determined. In practice, however, the gas thermometer is never employed by reason of the difficulties inherent in its use and, furthermore, because there are numerous other thermometers more convenient which can be compared with the gas thermometer.

In exact work, it is necessary, therefore, to define temperature in the terms of the thermodynamic scale rather than the "Normal" or "Gas Scale." Especially is this true in the case of radiation pyrometry, where the laws and formulas developed have their foundation in the second law

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[3] Bulletin, Bureau of Standards, Vol. 3, p. 237.

of thermodynamics. Consequently the "temperature" which occurs in the equations is the absolute thermodynamic temperature.

The standardization of pyrometers is generally made by means of certain fixed points, such as the fusion of platinum, palladium, gold, etc., and the ebullition of water, aniline, naphthaline, sulphur, etc., which have been carefully determined by means of the gas thermometer. The platinum thermoelectric pyrometer, on account of its ease of manipulation, convenience, and accuracy, has come into general use for temperature measurements between 1200° C., the upper limit of the gas thermometer, and 1600° C. The thermo-couple may be directly compared with the gas thermometer up to 1200° C., but beyond this we must rely on extrapolation up to 1600° C., which is the limit of the thermo-couple. Beyond this range, the scale must depend upon radiation laws which have some theoretical support and can be tested within the range of the gas scale.

It is seen from the above that high temperature measurements may be made in terms of the thermodynamic scale, but that the actual precision is entirely subordinate to that of the various intermediate steps, which lead from the perfect gas thermometer to the radiation pyrometer.

APPARATUS.

Electric-resistance Pyrometer.—Pyrometers of this type are more or less familiar to persons who have had any experience whatever in Heat or Electrical Measurements' laboratories. To illustrate the application of resistance thermometry, in the laboratory, a number of pure metals such as nickel, iron, silver, and copper may be used for temperatures up to 300° C., and there are several types of cheap, compact, serviceable instruments now on the market. For practical use and calibration the coil of wire used should be inclosed in a tube or stem of some suitable material, such as glass, iron, or porcelain, depending upon the temperature to which it is subjected. This stem should terminate in a head provided with binding post for making connections to lead wires. As the resistance of the lead wires will vary with the depth of immersion it is necessary to provide compensating leads which are put in the adjacent arm of a Wheatstone bridge. For all temperatures, from the lowest obtainable up to 1000° C., and especially for the higher temperatures, platinum[4] is the most satisfactory. When used for high temperatures (up to 1000° C.) the platinum coil is generally wound over a mica frame and inclosed in an infusible porcelain stem.

Thermoelectric Pyrometer.—Numerous materials have been used around the laboratory for thermo-couples, but the cheapest and at the same time the most reliable is the copper-constantan. The latter metal is known in this country as Advance, or Ia Ia. This couple can be used up to about 900° C. An extended investigation of this thermoelement has been carried out by White,[5] who recommends it as a precision thermometer. For temperatures between 300° C. and 1600° C. platinum and some alloy of platinums must be used.

The choice of a couple depends entirely upon the conditions under which it is to be used. For high temperatures the platinum couple (Pt——Pt + 10%Rh) is perhaps the only one that is used with success, but for low temperatures, say up to 1000° C., a number of alloys are used in industrial processes with good success. For low temperatures it is necessary to choose metals that will produce a higher P.D. than that used at high temperatures. For temperatures below 100° C., the couple may be calibrated by direct comparison with mercury thermometer, but for high temperatures fixed points are necessary.

The method of measuring the P.D. depends upon the accuracy required. For precise work the cold junction should always be kept at constant temperature (generally melting ice) and the P.D. should be measured on a potentiometer, using a standard cell. For work when great precision is not necessary, a d'Arsonval galvanometer or even a sensitive millivoltmeter is sufficiently accurate. In industrial practice the outfit must be as portable and compact as possible so that a direct reading instrument is generally used, which is substantially a millivoltmeter calibrated to read direct in temperature °C. or °F. The cold junction in such cases is generally maintained at 25° C. or 75° F., and the instrument is calibrated to be correct at that temperature. Any slight variation will not cause a great error, but an approximate correction can always be made by adding to the indicated temperature the difference between the temperature of the cold junction and 25°, when the former exceeds 25°, and subtracting the difference when it is less than 25°. Correction can also be made by means of an automatic

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[4] Bulletin Bureau of Standards, Vol. 6, p. 149.

[5] Phys. Rev., Aug., 1910, p. 135.

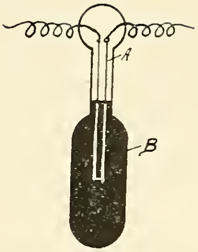

Fig. 1.

compensator as shown in Fig I. It consists of a fine platinum wire A, which is partially immersed in mercury B. When the bulb is heated the mercury in the capillary tube expands and short circuits the platinum loop, thus diminishing the resistance of the circuit. This balances a change in e. m. f., due to a rise of temperature of the cold junction.

All the contacts of the different parts of the circuit should be carefully made, and wherever possible this should be done by soldering. The hot junction of the wires used in the couple should be fused together. For easily fusible metals, such as copper, this can be done in the Bunsen flame, but for platinum oxygen is required. Platinum may also be fused in the electric arc. At the cold junction the lead wires should be soldered to the thermoelement wires. The wires composing the couple, which are subjected to high temperatures, should be insulated throughout their entire length by glass tubes or pipe stems. Asbestos thread may also be used for temperatures below 1300° C. Small fire clay tubes pierced by two holes may also be procured and are very convenient. For industrial work the couple should be inclosed by an iron or porcelain tube. The former should not be used for temperatures over 800° C.

Radiation Pyrometry.—From the fact that the intensity of light emitted from a body increases very rapidly with rise of temperature the optical method is well adapted to the measurement of high temperatures. For example, the luminous intensity of the red part of the light emitted by a body of 1500° C. is 130 times the intensity of 1000° C., and at 2000° C. it is more than 2100 times as great as at 1000° C. It thus appears that a comparatively rough measurement of the luminous intensity of an incandescent body would give a pretty accurate measurement of its temperature. This conclusion, however, is modified by the fact that different bodies at the same temperature emit very different amounts of radiant energy. The radiating power of a body depends not only upon the temperature but also the composition and nature of the surface. In order that the radiation and optical methods can be used for comparison of temperatures it is necessary that the effect of differences of surfaces be eliminated. This can be done by reducing the radiation from all surfaces to the radiation that would occur from some ideal surface arbitrarily taken as a standard of comparison.

A body that would absorb all the radiant energy incident upon it is called a perfectly black body. From a consideration of Prevost's theory of exchange it can be shown that a body inside an inclosure all parts of which are at the same temperature is a perfectly black body. Kirchoff has shown that the radiation from a perfectly black body depends only upon its temperature. For this reason the radiant energy emitted by a perfectly black body is taken as the basis for the comparison of high temperature. Radiation and optical pyrometers are calibrated by comparing a series of actual temperatures of a perfectly black body with the amounts of energy radiated at the respective temperatures. Two bodies are at the same black body temperature when they emit equal amounts of radiant energy. Two bodies at the same actual temperature, determined by means of a gas thermometer, will not be at the same black body temperature unless their surfaces have the same radiating power. For example, a piece of iron and a piece of porcelain each at an actual temperature of 1200° C., if examined by means of an optical pyrometer calibrated in terms of the red rays emitted by a perfectly black body, would indicate 1140° C. and 1100° C. respectively. If, however, two bodies be placed inside a uniformly heated inclosure they will not only attain the same temperature, but they will also emit radiant energy equally. That is, they will have the same black body temperature. In other words, the actual temperature of a body inside a uniformly heated inclosure equals the black body temperature.

A pyrometer then, which has been calibrated by comparison with a black body, when sighted upon an incandescent body, reads not its true temperature (thermodynamic temperature), but its black body, which will be somewhat lower than its true temperature. The difference will depend upon the emission power of the body. If, however, the body sighted upon is a black body, for example a heated inclosure, then the pyrometer indicates its true or thermodynamic temperature. A few substances such as platinum black, carbon and iron oxide radiate approximately as black bodies, but as yet there is no known substance which is absolutely black. In using the term in this sense we must remember that the temperature must be involved as well as the emission and absorption powers. Thus, any body whose radiation is proportional to that of a black body, for all wave lengths, is considered *black* if its temperature is the same as a black body. If its true temperature is higher (it could never be lower) it is considered *gray*. A carbon lamp filament is gray because its spectral distribution is the same as a black body, but not black because its true temperature is slightly higher than a black body.

A uniformly heated inclosure is the nearest approximation to our ideal black body.

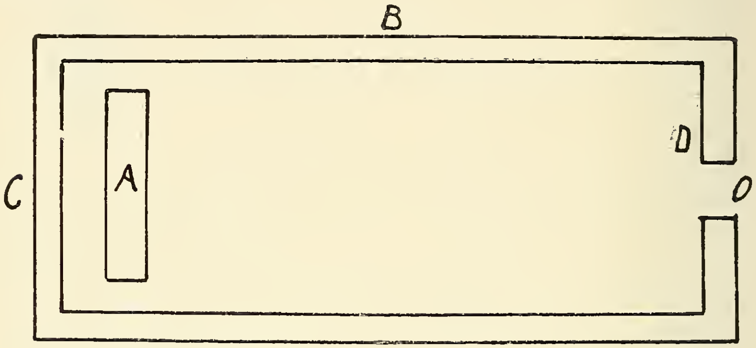

Fig. 2.

Consider a body A within a heated inclosure B, Fig. 2, both at the same temperature throughout. A receives a certain amount of thermal radiation from the wall of the envelope C and radiates to C an equal amount if they are in temperature equilibrium. Also A radiates a certain amount to D and receives the same amount, if D is at the same temperature. Since A, on the whole, neither gains nor loses it radiates to D the same amount it receives from C, consequently the radiation from A towards D is the same as that from C towards D. Not only is the quantity the same but also the quality, for the coefficient of absorption depends upon the quality (i. e., it is different for different parts of the spectrum), so that if C and A radiate the same amount they must radiate the same quality. If the spectral distribution of A were different from C its coefficient of absorption would be different and therefore it would not radiate the same quantity. Hence any other body within B and at same temperature would radiate the same as A so that no detail could be detected, i. e., the objects could not be distinguished from one another or the walls of the inclosure.

Moreover any body outside of B at the same true temperature could not radiate more energy than A, consequently, A is a *complete radiator* or a perfectly black body when within B, and it also follows that the interior of B radiates as a perfectly black body. A piece of polished platinum and a piece of carbon would appear equally bright within B, if viewed through a small hole, but if quickly removed the platinum would appear less bright than the carbon, for it gives out less light that is proper to itself since it is a good reflector but a poor absorbent and consequently a poor radiator, while C gives out more light that is proper to itself since it is a poor reflector but a good absorbent and a good radiator.

Now if the wall D were partly removed or were cooler than the rest of the walls it could not radiate to A as much as C does because it receives less from D. In this case we would have a slight departure from black body conditions. Hence the general statement:

The true temperature as indicated by a thermo-couple, of all substances heated in an inclosure, is the same as the black body temperature, as indicated by a pyrometer, which has been calibrated against a black body. If, however, the walls of the inclosure, wholly or in part, are cooler than the radiating object, its true temperature will in general be higher than the black body temperature. However, if the walls are reflecting, but at the same time cold, the difference in the two temperatures is less. This difference will be still less if the objects considered are of carbon or platinum black, etc.

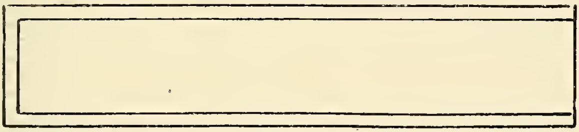

Fig. 3.

An experimental black body should therefore be as uniformly heated as possible and the aperture should be small, or if one end is entirely removed, as in Fig. 3, the length should be large compared with its cross-section.

It thus appears that in order to attain actual temperature by radiation methods the body whose temperature is desired must be made as nearly a black body as possible. In many cases this can be done with little difficulty. For example, if the temperature of an annealing oven is required, one could insert into the oven the closed end of a long metal or porcelain tube. The radiant energy coming from the bottom of this tube will be a close approximation to that of a perfectly black body. If black body conditions are not realized as an incandescent sheet of metal the temperature may be expressed merely as black body temperature, Kirchoff's absolute scale.

Laws of Black Body Radiation.—Stefan deduced from experiment, and Boltzmann deduced from thermodynamic considerations, the law that the total radiant energy emitted from a black body is proportional to the fourth power of the absolute temperature, or.

$$J = KT^4$$

where K is a constant.

The radiant energy emitted by a heated body is in the form of waves of diverse wave length. Most of the radiant energy is due to waves that are too long to affect the eye. As the temperature of the body is increased, the energy of all the emitted waves is increased, but the energy of the shorter waves increases more than that of the longer waves. That is, the distribution of energy among the waves of different lengths depends upon the temperature of the body.

Wien has also shown that the product of the absolute temperature T of some source and the wave length having maximum energy. λm in spectrum is a constant.

$$\lambda m T = \text{constant} \quad A$$

This is generally known as the displacement law or Wien's First Law. Wien also combines his first law with the Stefan-Boltzmann Law giving his second law.

$$J_{max} T^{-5} = \text{constant} \quad B$$

His most important investigation, however, was the investigation of spectral distribution of energy in the radiation of a black body in which he shows that for any particular wave length the relation between the energy emitted and the absolute temperature is as follows:

$$J = C_1 \lambda^{-5} e \frac{-C_2}{\lambda T} \tag{1}$$

where J is the energy corresponding to wave length λ and T is the absolute temperature. C_1 and C_2 are constants and e is the base of the natural system of logarithms.

The working principles of the following experiments are based upon these two laws, i. e., the total radiation and spectral radiation laws. In the first case black body temperature is determined by measuring the total energy, as in a Féry pyrometer which allows radiations of all wave lengths to fall upon a sensitive thermo-couple connected to a direct reading galvanometer. In the second case some particular wave length is used and the measurement of temperature is made photometrically by adjusting to equality two photometric fields produced by a standard source and the body to be measured. The intensity of radiation is varied by cutting down the objective aperture, as in Le Chatelier, or by a polarizing device, as in the Wanner, or by varying the intensity of the standard itself, as in the Holborn.

Since we are using mono-chromatic light a measure of the luminous intensity may be taken as a measure of the radiant energy. The intensity of radiation of a source may be defined as the ratio of the total energy emitted (including all wave lengths) to the energy falling upon unit surface. A part of the energy emitted by a heated body, however, may be luminous and both the luminous and total energy emitted by a body increases with temperature, but the total luminous energy is not proportional to the total energy emitted. The luminous energy of any particular wave length, however, is directly proportional to the total radiant energy emitted. Hence in any optical pyrometer when photometric comparison is made if mono-chromatic light is used the above radiation laws will hold.

Wanner Pyrometer.—It has been shown that the luminous intensities of two bodies may be taken as a measure of their temperatures, if monochromatic light is used, and since luminous intensities may be compared by the rotation of a Nicol prism we have a convenient means of measuring high temperatures.

In this method comparison is made between a standard lamp and the body whose temperature is sought. The standard used is a 6-volt incandescent lamp which is in turn compared with some primary standard as an amyl acetate lamp. For this work the primary standard is used merely as a check for the more convenient electric lamp and so long as it is reproducible so that the comparison lamp can always be brought to the same condition, we are not concerned with its intrinsic intensity or temperature. Photometric comparison is made of the comparison lamp and the unknown source by adjusting to equal brightness two halves of a photometric field by means of a polarizing arrangement, monochromatic red light being produced by a direct vision prism.

The intensity of the unknown source in terms of the comparison lamp, taken as unity, is

$$J = \tan^2\phi$$

where ϕ is the rotation of the Nicol prism.

Le Chatelier Pyrometer.—Le Chatelier's optical pyrometer compares the luminous intensity of the red radiation from the body whose temperature is derived with the red radiation from a standard light source. The radiation from the body whose temperature is to be measured, traverses the diaphragm S, Fig. 4, and the objective O. A part of the radiation grazes the right edge of the mirror M and is brought to a focus at the focal plane of the eye-piece A. Light from the central portion of the flame of the comparison flame L traverses the objective O′, is reflected from the inclined mirror M and is also brought to a focus in the focal plane of the eye-piece. Thus two images, one of the source whose temperature is sought, and one of the comparison flame, are found side by side, in the focal plane of the eye-piece. These two images are simultaneously observed by means of the eye-piece A provided with a piece of red glass for rendering the radiations that enter the eye of the same wave lengths. By adjusting the size of the aperture in the diaphragm S. these two images can be brought to the same luminous intensity. The distance from the objective O to the focal plane of the eye-piece can be varied in order to focalize the radiation from the luminous source, and the distance can be read directly from a scale engraved on the draw tube. The aperture in the diaphragm S is square and the length of one side can be read directly from the screw head which operates it.

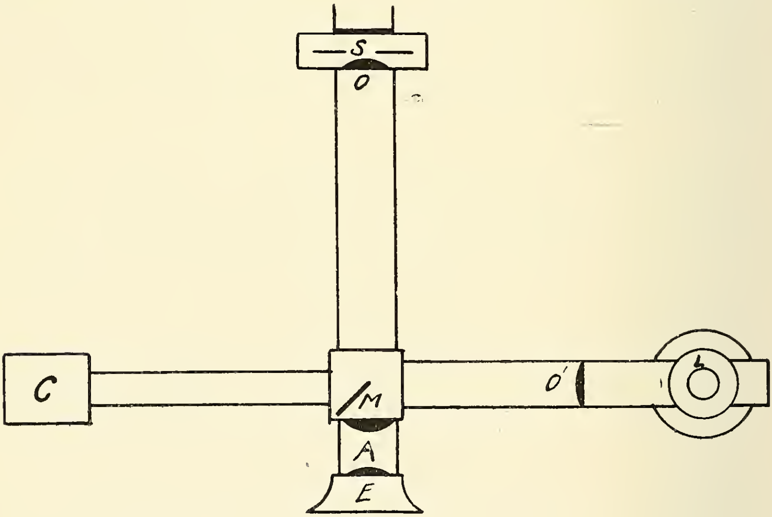

Fig. 4.

The intensity of the unknown source in terms of the intensity of the comparison lamp taken as unity, becomes

$$J = \left(\frac{1}{d}\right)^2$$

where d denotes the length of one side of the square aperture S. Due to the lack of monochromatism of the red glass this instrument is not so accurate as the Wanner.

Holborn-Kurlbaum Pyrometer.—In this method the luminous intensity of the comparison source is varied until a photometric balance is obtained between its image and the image of the incandescent object in question. In the H.-K. (Holborn-Kurlbaum) pyrometer shown in Fig. 5 a small electric lamp L is placed in the focal plane of the objective O and the same is viewed by means of an eye-lens E. In making an observation the pyrometer is focused upon the object whose temperature is sought, thus bringing the image of the object in the plane of L. The current through the lamp is adjusted by means of a rheostat until the lamp filament disappears against the bright background. The value of the current strength can be read direct from a milli-ammeter.

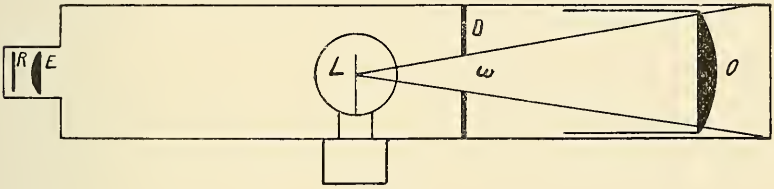

FIG. 5.

In order to measure temperature with this instrument it must be empirically calibrated by means of a black body. A curve may then be plotted with current in milli-amperes, I, and temperature, t, in degrees C. To determine an unknown temperature, it is only necessary to focus the instrument upon the object in question and adjust the current through the lamp until the filament disappears against the bright object. The pyrometer then indicates the black body temperature unless black body conditions are realized, in which case it indicates true temperature, i. e., thermodynamic temperature.

The reading of the ammeter will be independent of the distance of pyrometer from object so long as the solid angle w, Fig. 5, is constant. This is accomplished by means of the diaphragm D. When the instrument is focused for distant objects, i. e., when O is drawn near L, the solid angle w would be increased if it were not for the diaphragm D.

The light which reaches the eye is rendered approximately monochromatic by a red glass R placed before the eye-piece but for temperatures below 800° C. this is not necessary and above 1,200° C. two glasses are generally used. For the extrapolation of the experimentally determined curve for high temperatures Wien's third law may be used. For these high temperatures beyond the safe limit of the lamp three different methods are used for cutting down the incident radiation a determinate amount; absorbing glasses, mirrors, and sector discs.

Since the absorbing power of the absorption glasses is different for different wave lengths, if there is any lack of monochromatism in the red transmission glasses, which is generally the case, Wien's law will not hold for high temperatures.

To overcome this difficulty Henning[6] has combined an H.-K. pyrometer with a Hilger constant deviation spectrometer so that homogeneous light may be used. This instrument has the further advantage that any part of the spectrum may also be employed. Dr. Mendenhall has recently devised a spectroscopic eye piece to accomplish the same purpose.

The H.-K. pyrometer is probably the most sensitive pyrometer now in use.

Féry Total Radiation Pyrometer.—From a consideration of the Stefan-Boltzmann radiation law we have seen that the energy radiated by a black body is proportional to the fourth power of the absolute temperature, or,

$$J = KT^4 \qquad (2)$$

From this relation it is evident that a comparatively rough method of determining the energy radiated would yield fairly accurate results of temperature measurements.

The Féry radiation pyrometer is shown in detail in Fig. 6. Radiation from an incandescent body is focused upon a minute and sensitive thermocouple C, by means of a lens A′. In order to calibrate the pyrometer directly in terms of the Stenfan-Boltzman law the lens should be transparent for all radiations and this is best effected by using a fluorite lens which for temperatures above 900° C. does not absorb an appreciable portion of the incident radiation. F is a rack and pinion for focusing the radiation upon the thermo-junction. The screens C and D protect the junction from

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[6] Zeitschrift Für Instrumentenkunde, März, 1910.

extraneous rays. The diaphragm E provides a constant angle aperture, which is a necessary condition for the instrument to be independent of focusing. The thermo-junction leads are connected to the posts b and b₁, which are in turn connected to a galvanometer. In making a temperature measurement the image of the incandescent object is focused upon the thermo-couple by means of the eye piece E, and care must be taken that the image is larger than the thermo-couple. It is evident from Equa. 2 that if the galvanometer has a uniform scale and the temperature T_1 is known corresponding to a scale reading R_1, the temperature T_2 for any other reading R_2 may be found from the relation.

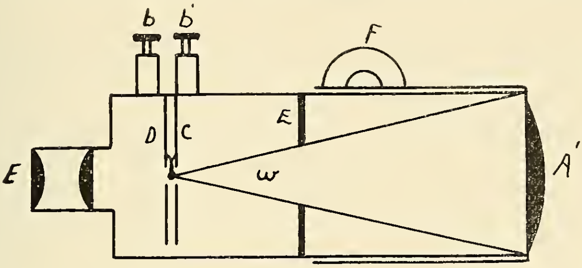

Fig. 6.

$$T_2 = T_1 \sqrt[4]{\frac{R_2}{R_1}}$$

When the limit of the scale is reached the calibration may be extended by means of a diaphragm placed before the objective or by shunting the galvanometer. In technical practice, however, a glass lens is used and the instrument is calibrated empirically against a black body whose temperature can be determined. This instrument is also made with a gold reflector instead of a lens. Féry[7] has recently brought out a new pyrometer which is similar to the above with the exception that the temperature of the incident radiation is measured by means of a minute expansion spiral consisting of two metals with dissimilar expansion coefficients. This mechanical device renders the instrument more robust but does not admit of so great accuracy as the thermoelement.

Morse Thermo-Gage. This is somewhat similar to the Holborn-Kurlbaum pyrometer in that it utilizes the disappearing filament principle but it is not nearly so precise since it is not provided with any lens system

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[7] Engineering, May 14, 1909.

or monochromatic glasses. It is simply an incandescent electric lamp in a black tube and it is operated and calibrated in a similar manner to the Holborn instrument.

While there are a number of instruments, more or less reliable, which may be bought from scientific shops, the above list represents the ones in most common use. In the opinion of the author it is neither necessary nor advisable to equip a high temperature laboratory with an elaborate outlay of expensive commercial apparatus. The object of such a laboratory should be to teach the student the fundamental principles of the subject, the application and limitations of these principles to commercial instruments and to train the student in the use of a few types of instruments. After having mastered the principles of radiation pyrometry the student will have no difficulty in making a temperature observation by means of a direct reading Féry spiral pyrometer or any other similar instrument.

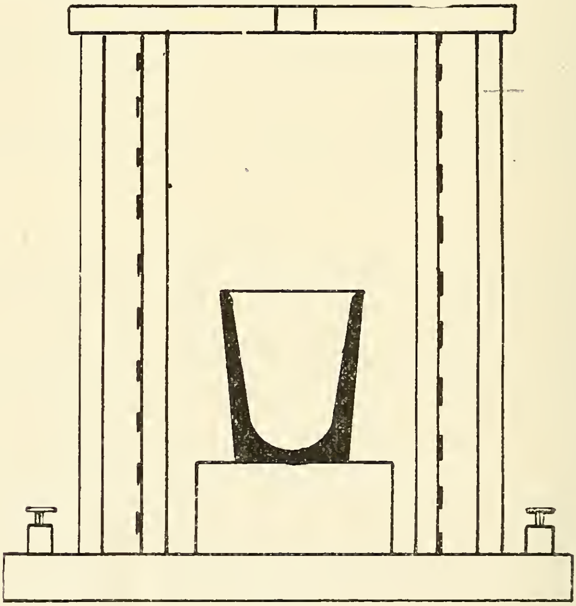

Fig. 7.

For the purposes of calibration or standardization of instruments the laborator should also include a boiling point apparatus for each of the fixed points, or if the fusion temperatures of the metals are used, a melting furnace.

To calibrate a platinum couple, the most convenient fixed points are the fusion temperature of copper, antimony and zinc. These metals may be melted in small graphite crucibles. The size of crucible chosen and the quantity of metal used should be such that at least 5 cm. of the couple may be immersed in the metal. The crucible may be heated in any suitable manner, but an electric resistance furnace is perhaps the most convenient. Fig. 7.

One form of furnace consists of two concentric cylinders of fire clay, or porcelain, placed upon a base of the same material. A suitable cover also is provided with a hole for admitting the couple. The inner cylinder is overwound with fine nickel wire or ribbon and the crucible, to be heated, is placed within this cylinder. It should be placed at about the center so as to be uniformly heated.

Another form of furnace which is less likely to get out of order, but which on the other hand is not so satisfactory for precise work, is shown in Fig. 8. This consists of a rectangular trough of brick work (a, Fig. 8).

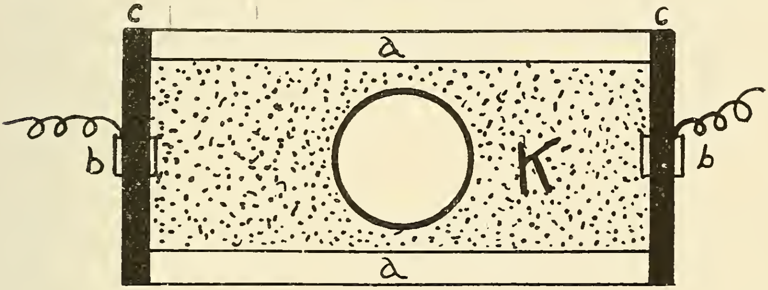

FIG. 8.

The inside width should be somewhat greater than the diameter of the crucible to be used and the depth slightly greater than the height of the crucible. The ends of the trough are closed with carbon plates cc, which carry binding posts bb, for the connecting wires. The intervening space K is filled with a granular resisting material, commercially known as "Kryptal." The connectors at bb are connected to some source of e.m.f. either DC or AC. The amount of current may be regulated by varying the density of the mass of kryptal used. Thus, when a large amount is used and when it is packed down well a large current will pass through the furnace. The top of the entire furnace should be covered over with bricks.

In order to calibrate or standardize a pyrometer it is necessary to have a luminous source whose black body temperature is accurately known. The primary standard must be some form of a heated inclosure whose walls can be maintained at a uniform constant temperature. Some means must also be used for determining the true temperature of the inside of the inclosure.

This is generally accomplished by some form of an electric resistance furnace, as shown in Fig. 9. It consists of a central porcelain tube overwound with thin platinum foil through which passes an electric current which can be adjusted to maintain any desired temperature up to about 1,600° C. Concentric with this tube are two shorter ones which, with the intervening air spaces, minimize the radiation. Some form of thermo-couple is placed in one end so that the hot junction is near the center of the tube. If there is a cold junction it should be placed in crushed ice. The thermo-couple may be either connected to a potentiometer or a sensitive potential galvanometer which reads millivolts, and by means of a previously determined calibration any temperature may be determined. Except in refined work the ice point is not necessary. The furnace is connected in series with a rheostat and 110 v. DC.

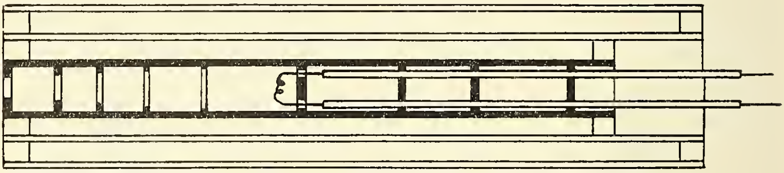

Fig. 9.

For the calibration of the Wanner or Le Chatelier pyrometer it is not necessary, as will be shown on the following pages, to know but one black-body temperature so that as a working standard any convenient luminous object such as a frosted globe incandescent lamp, which would give a uniformly illuminated area of about 1 sq. cm., might be used if its black-body temperature at some particular current strength were accurately known.[8]

For pyrometers like the Holborn-Kurlbaum (H.-K.), however, which can only be calibrated empirically, it is necessary to have a black body

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[8] Physical Review, Vol. 31, No. 4. Oct., 1910.

whose temperature can be varied. This is generally done by means of an electric furnace, but when a Wanner, Le Chatelier, or a calibrated H.-K. is at hand it is easiest accomplished by direct comparison.

The comparison source may be a thin platinum strip, heated electrically or a wide filament incandescent lamp. The H.-K. may be sighted on one side of the strip and the calibrated pyrometer on the opposite side. The black body temperature of the strip can be determined by means of the calibrated instrument and at the same time the reading of the H.-K. comparison lamp can be taken.

In the case of a wide filament carbon incandescent lamp it has been shown that if it is properly aged for about 20 hours at 1,760° C. it will remain sufficiently permanent for a secondary standard for 15 or 20 hours.

If a lamp is calibrated in terms of black body temperature and current strength by means of a pyrometer it may be used as a standard of comparison for calibrating pyrometers just as a black body would be used.

CALIBRATION.

In the foregoing a number of instruments have been described for the estimation of high temperature, each class utilizing some effect of temperature such as the change of resistance, development of small electromotive force, change of luminous intensity, etc., and it now remains to indicate how each of these instruments may be calibrated to read in terms of temperature, °C.

Electric-resistance Pyrometer. A resistance pyrometer may be calibrated by comparison with a calibrated instrument or by a number of known temperatures such as the boiling points of liquids or fusion points of metals, and in general three points are quite sufficient to completely calibrate the pyrometer, but no simple equation can be given for all metals. For platinum, however, the case is somewhat different, as an extensive study has been made of platinum resistance thermometry.

Callender[9] defined platinum temperature Pt as follows:

$$pt = 100 \frac{R-R_0}{R_{100}-R_0}$$

where R = the observed resistance at the temperature t.
where R = the observed resistance at 0° C.
where R = the observed resistance at 100° C.

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[9] Proc. Roy. Soc. 41, p. 231, 1886.

The relation between platinum temperature and centigrade temperature from — 100 to 1.100° C. is given by the equation

$$t - pt = \delta \left(\frac{1}{100} - 1 \right) \frac{1}{100}$$

where δ is a constant depending upon the purity of the platinum. For pure platinum δ is 1.50 and for impure it is somewhat higher. Such a pyrometer is usually calibrated by measuring its resistance at the melting point of ice (0° C.), boiling point of water (100° C.), and some other temperature, such as the boiling point of sulphur (444.7° C).

Temperatures measured on such a pyrometer will agree with the temperatures measured on the gas scale in the range 0 to 1,100° C. to within the degree of reproducibility of the latter.[10]

Thermoelectric Pyrometer.—It has been shown by a number of experimenters that in order to completely calibrate a thermo-couple, point by point comparison is unnecessary, but that three or four known temperatures or fixed points are sufficient. No general equation can be given that will accurately fit all thermo elements, but for most metals, at least within a limited region, the relation between the potential difference in millivolts and the temperature in degrees centigrade is sufficiently well represented by the general quadratic equation

$$e = a + bt + ct^2 \tag{3}$$

where a, b and c are constants that can be determined if three temperatures are used. It can easily be determined by experiment how well this formula will hold for any given couple. Three points should be chosen which will cover the region for which the couple is to be used, and a curve drawn through these points. If the curve is nearly a straight line it can be represented by Equa. 3.

The fixed points are generally the ebullition of water, analine, naphthaline, sulphur, etc., or the freezing of such metals as tin, zinc, antimony, copper, silver, gold, etc. The former, with the exception of sulphur, are obtained with less difficulty than the latter, but are of value only for low temperatures.

For a copper-constantan couple the most convenient fixed points are the fusion temperature of antimony (630.7° C.), zinc (419.4° C.), and tin (231.9° C.), and for a platinum couple zinc, antimony and copper (1,083° C.).

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[10] Bulletin Bureau of Standards, Vol. 6, p. 196.

Radiation Pyrometers.—Equa. (1) may be written in the form

$$\log_{10} J = K_1 - K_2 \frac{1}{T}, \qquad (4)$$

where

$$K_2 = C_2 \frac{\log e}{\lambda}.$$

C_2 for a black body temperature equals 14,500 when λ is given in terms of μ.

Equa. (4) may be applied to any pyrometer, using monochromatic light, in which the luminous intensity can be varied in a continuous and determinate manner as in the Wanner and Le Chatelier. Either of the instruments will, therefore, indicate temperature indefinitely high, but the limit of accuracy is reached at about 2,000° C., so that at higher temperatures the incident radiation is usually cut down by means of one or more absorption glasses. The amount by which it is cut down is determined as follows:

Let J′ equal the luminous intensity of the incident radiation and J_1 the value as indicated by the instrument when one glass is used, then

$$J' = JR,$$

where R is the absorption factor. For two absorption glasses

$$J' = (JR)\ R = JR^2,$$

and for n glasses

$$J' = JR^n \qquad (5)$$

also

$$R = J'/J. \qquad (6)$$

The general expression, then, for the relation between energy and absolute temperature, is from (4)

$$\log J' = K_1 - K_2 \frac{1}{T}.$$

From (5)

$$\log J + n \log R = K_1 - K_2 \frac{1}{T},$$

whence

$$t = \frac{K_2}{K_1 - \log J - n \log R} - 273, \qquad (7)$$

where t is temperature in degrees C.

Equa. (7) is a general equation for connecting the relation between temperature t and luminous intensity J and can be applied to any pyrometer in which J can be determined theoretically. For the Wanner pyrometer $J = \tan^2 \phi$, where ϕ is the angle of rotation of the nicol analyzer, and for the Le Chatelier $J = (1/d)^2$ where d is the length of one side of the iris diaphragm. K_1, K_2 and R are constants and can all be determined without reference to any temperature observation.

Wanner Pyrometer.—This method of calibration will be made clear by an example. For a particular Wanner pyrometer the value of λ was 0.656 μ.

Therefore

$$K_2 = \frac{14.500 \times 0.4343}{.656}$$
$$= 9,600.$$

It is seen from (4) that if K_1 were known, various values of ϕ might be substituted in the equation and the corresponding temperatures calculated. Now by assuming some angle of rotation ϕ for some particular temperature T, as in the above case, K_1 may be found. For example, let

$$T = 1273 \text{ and } \phi = 45°.$$

Then from (4)

$$K_1 = \log \tan^2 \phi + K_2 \frac{1}{T}$$
$$= 0 + \frac{9,600}{1,273} = 7.55.$$

For $\varphi = 10$, and $n = 0$. t may be calculated from (7),

$$t = \frac{9,600}{7.55 + 1.51} - 273$$
$$= 787° \text{ C.}$$

Le Chatelier Pyrometer.—The wave length for the red glass used on a Le Chatelier pyrometer was found to be 0.649 μ. The constant K then becomes

$$K_2 = \frac{14,500 \times 0.4343}{0.649}$$
$$= 9,700.$$

Holborn-Kurlbaum Pyrometer.—Such an instrument must be calibrated empirically and the calibration will be different for every lamp used. It has been shown[11], however, that the relation between temperature and current through the lamp may be represented by the general quadratic equation

$$I = a + bt + ct^2,$$

so that three known temperatures are sufficient to completely calibrate the instrument. Such a pyrometer may be readily calibrated, without the use of a black body, by means of a standard pyrometer comparison lamp as explained above. If such a lamp is not properly calibrated in terms of temperature and current its black body temperature, for any value of current, may be determined by means of another calibrated pyrometer. A platinum ribbon may be used in the same way.

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[11] Bulletin, Bureau of Standards. Vol. I, p. 255.