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SUMMARY

The instrument described in this report is a device which attenuates, by known amounts, the light intensity received from a radiating source by use of a variable-density filter. The attenuated beams are photographed, and the measured film densities, together with their associated filter values, yield a time history of the temperature contour. The theory, experimental procedure, and errors associated with the prototype instrument and an advanced model are discussed. The "photographic pyrometer" is capable of yielding high surface-temperature contours for large surface areas. As presently calibrated, the blackbody-temperature range for the prototype is from 1800° to 3600° F (1255° to 2255° K) with a precision of approximately 2 percent for most applications. The advanced model theoretically extends the upper temperature limit to 4500° F (2755° K).

INTRODUCTION

The recent emphasis on reentry heating with attendant ablation has hastened the development of new facilities to simulate aerodynamic processes. Such studies involve not only materials at temperatures above those normally measured by thermocouples, but also refractory materials where temperature gradients prohibit the use of conventional metallic thermocouples. These problems have generated a need for a measuring technique with an increased temperature range and one that measures the true, undisturbed surface temperature of the material under consideration. Time-resolved temperature contours for the materials involved are also desired. To satisfy these criteria, an optical technique with photographic recording was chosen. The resulting "photographic pyrometer" can yield time-resolved temperature contours over a wide range of temperature.

Photographic pyrometry has been used since 1930 in many diverse ways. (See ref. 1.) The method makes use of the fact that increasingly bright objects produce increasingly dense images on film. The method is limited for a particular aperture, however, because of the exposure characteristic of films. In all techniques of this type, therefore, a method of controlling the exposure is needed if a wide temperature range is to be realized. These methods would include: (1) varying the exposure time, (2) varying the camera aperture, or (3) introducing filters into the optical path. A recent technique employed a camera with four lenses in which the aperture of each lens could be varied. (See ref. 2.) Later, the variable apertures were replaced with neutral density filters to increase the span in exposure control. Finally it was desired to construct a photographic pyrometer with an extremely wide latitude in exposure. This latitude was achieved in the present system with a rotating variable-density filter.

The photographic pyrometer described herein operates on the same principle as the one developed in reference 2 but incorporates a single device which attenuates, by known amounts, the light intensity received from a radiating source. The attenuation is performed by a rotating, variable-density filter. The attenuated beams are recorded by a framing camera, and the film densities, together with their associated values of filter transmission, yield a time history of the temperature contour.

The purpose of this report is to describe the theory and operation of the pyrometer and to discuss the possible sources of error and their relative importance. The prototype instrument has been calibrated for the blackbody-temperature range from 1800° to 3600° F (1255° to 2255° K), with a precision of approximately 2 percent for most applications. Theoretically, the advanced model should extend the upper temperature limit to approximately 4500° F (2755° K).

SYMBOLS

B	abscissa-intercept of linear portion of characteristic curve
c_1	first radiation constant, 3.74×10^{-12} watt-cm^2
c_2	second radiation constant, 1.43 cm-°K
D	film density, log opacity
E	exposure, watt-sec/cm^2
e	base of natural logarithm
J	material radiance, watts/cm^2
J_B	blackbody radiance, watts/cm^2
S	film spectral sensitivity
T	temperature

t	exposure time, sec
γ	slope of characteristic curve
ϵ	emittance
λ	wavelength, Å
τ	transmittance of filter

Subscripts:

x	unknown
eff	effective
std	standard
λ	spectral

THEORY

As a consequence of the major role played by photography, the pertinent film characteristics as related to this photographic pyrometer are presented first, followed by an examination of the radiative properties of materials, and finally, the several characteristics are analyzed in order to deduce the primary measurement criteria.

Film Characteristics

An important property of film as applied to photographic pyrometry is the relation between the exposure of the film and the density produced in the film as a result of this exposure. This relation is a familiar characteristic curve, known as an H and D curve - after Hurter and Driffield (ref. 3) - and is shown in figure 1. The curve exhibits two regions (overexposed and underexposed regions) in which the density produced is a slowly varying function of log exposure. The curve also exhibits a linear region in which the

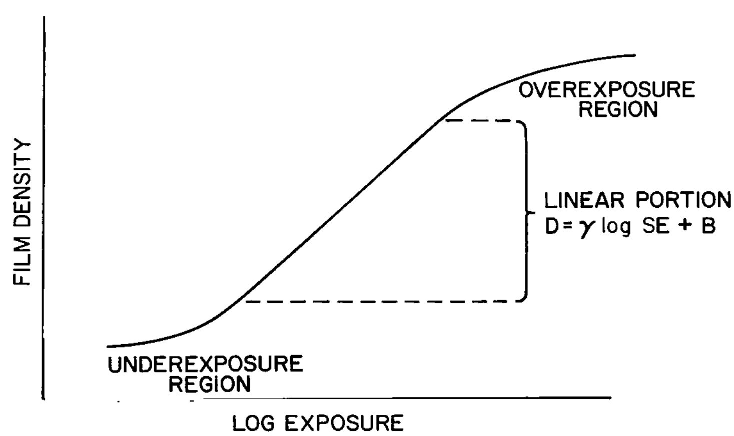

Figure 1.- Film characteristic (H and D) curve.

density is a more sensitive function of the log exposure. This is the region in which the photographic pyrometer operates and which relates directly the density D and the unique exposure E which produced it. This region is described by the linear relation:

$$D = \gamma \log SE + B \tag{1}$$

where γ is the slope of the curve and B is the abcissa-intercept of the linear portion of the H and D curve. The value of γ for a given film depends on the method and time of development. The exposure E is a function of the spectral radiance of the source, the energy-transfer characteristic of the instrument, and the exposure time. The relative spectral response of the film S is always some function of wavelength and, therefore, only energy radiated in that wavelength region need be considered.

Radiative Properties of Materials

The energy radiated within a given wavelength interval and for a given temperature can be obtained by integrating the Planck blackbody distribution function $\left[c_1\lambda^{-5}\left(e^{c_2/\lambda T} - 1\right)^{-1}\right]$ over the wavelength range. However, because of its ease of handling, its close approximation to the Planck function, and for explanatory purposes, Wien's distribution function $\left[c_1\lambda^{-5}e^{-c_2/\lambda T}\right]$ (ref. 4) will be used to develop the form of the theory. The range most used in this work is the wavelength range from 3800 to 6700 Å corresponding to 320 ASA panchromatic film. Figure 2 shows the energy radiated by a blackbody in this region as a function of the true temperature of the body. The rapid change in energy with temperature in this wavelength region enhances the sensitivity of instruments using this technique.

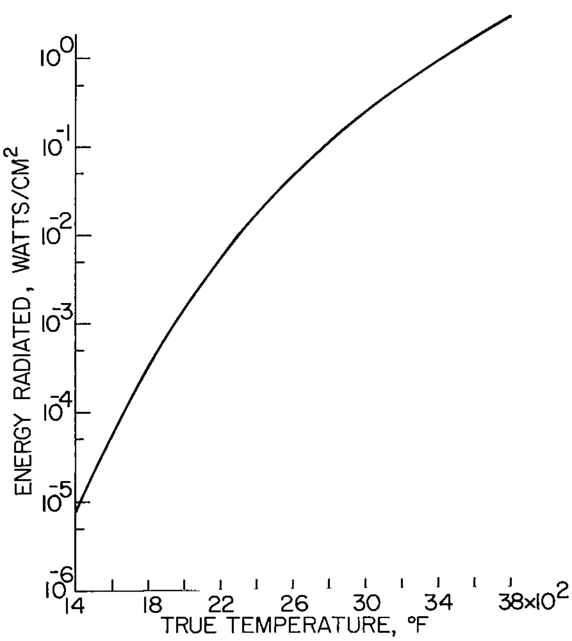

Figure 2.- Energy radiated by a blackbody in the wavelength range from 3800 to 6700 Å as a function of temperature.

The energy radiated by a blackbody in thermodynamic equilibrium is the maximum radiant energy for a given wavelength and temperature. Most bodies radiate less than this maximum. The ratio of the radiant intensity emitted by a material to that emitted by a blackbody at the same temperature and wavelength determines the spectral emittance given by

$$\epsilon = \frac{J}{J_B} \tag{2}$$

In general, the emittance is a function of wavelength and temperature as well as the surface condition. Radiation emitted from a blackbody is perfectly diffuse; obeying Lambert's cosine law. Many materials, however, do not radiate diffusely and the brightness of these non-Lambertion surfaces varies with the angle of observation (ref. 5).

Temperature Indicator Curve

With the aforementioned properties in mind, the major temperature criteria will be evaluated. Consider several regions of a surface at different temperatures. These regions radiate energy depending on their temperature which ultimately produces density on the film. The values of density produced in this manner may be correlated to a surface temperature with an appropriate density-temperature calibration. This method would suffice for the small temperature range during which the film density remained on the linear portion of the H and D curve and for which interpolations in density can be made. Higher temperatures, however, produce densities on the overexposed region of this curve. A density produced in this region could not be associated accurately with a single value of exposure and would not, therefore, yield a meaningful value of temperature. However, the densities may be held within the linear limits by attenuating the light intensity with an appropriate transmission filter for each temperature involved. Assume that any value of transmission can be selected to produce equal densities for different temperatures. By using this technique, the filter transmission could be used as a temperature indicator rather than density itself. To relate the transmission to temperature, equal film densities from two different frames are chosen and investigated to determine their origins. One of the densities will be produced by a surface at a known (standard) temperature T_{std} and the other by a surface at an unknown temperature T_x.

$$D_x = D_{std} \tag{3}$$

From equation (1)

$$\gamma_x \log S_x E_x + B_x = \gamma_{std} \log S_{std} E_{std} + B_{std} \tag{4}$$

Identical processing yields

$$\left.\begin{aligned} B_x &= B_{std} \\ \gamma_x &= \gamma_{std} \end{aligned}\right\} \tag{5}$$

and therefore

$$S_x E_x = S_{std} E_{std} \tag{6}$$

Recalling that the exposure E is the product of the intensity of the radiation incident on the film J and the time in which it acts on the film t, modified by the filter transmission τ

$$S_x J_x \tau_x t_x = S_{std} J_{std} \tau_{std} t_{std} \tag{7}$$

Utilizing a constant shutter speed $(t_x = t_{std})$

$$S_x J_x \tau_x = S_{std} J_{std} \tau_{std} \tag{8}$$

In order to tie in the emittance of both the standard and unknown, equation (2) is substituted for J_x and J_{std} in equation (8) yielding

$$S_x \epsilon_x J_{B,x} \tau_x = S_{std} \epsilon_{std} J_{B,std} \tau_{std} \tag{9}$$

Collecting the emittance and transmission terms gives

$$\frac{\epsilon_x \tau_x}{\epsilon_{std} \tau_{std}} = \frac{S_{std} J_{B,std}}{S_x J_{B,x}} \tag{10}$$

To illustrate the form of this equation, a flat wavelength response $(S_x = S_{std})$ will be assumed. The blackbody intensities can then be evaluated by integrating Wien's function over the wavelength range.

$$\frac{\epsilon_x \tau_x}{\epsilon_{std} \tau_{std}} = \frac{J_{B,std}}{J_{B,x}} = \frac{\int_{\lambda_1}^{\lambda_2} c_1 \lambda^{-5} e^{-c_2/\lambda T_{std}} \, d\lambda}{\int_{\lambda_1}^{\lambda_2} c_1 \lambda^{-5} e^{-c_2/\lambda T_x} \, d\lambda} \tag{11}$$

In order to indicate the form of the intensity ratio, it is assumed that an "effective" wavelength can be chosen within the range $\Delta\lambda = \lambda_2 - \lambda_1$ such that the integrals may be expressed as the product of $\Delta\lambda$ and the value of the integrand evaluated with λ effective (λ_{eff}).

$$\frac{\epsilon_x \tau_x}{\epsilon_{std} \tau_{std}} = \frac{J_{B,std}}{J_{B,x}} = \frac{c_1 \lambda_{eff}^{-5} e^{-c_2/\lambda_{eff} T_{std}} \Delta\lambda}{c_1 \lambda_{eff}^{-5} e^{-c_2/\lambda_{eff} T_x} \Delta\lambda} \tag{12}$$

and therefore

$$\frac{\epsilon_x \tau_x}{\epsilon_{std} \tau_{std}} = \frac{J_{B,std}}{J_{B,x}} = e^{\frac{c_2}{\lambda_{eff}}\left(\frac{1}{T_x} - \frac{1}{T_{std}}\right)} \tag{13}$$

taking the natural logarithm of both sides, yields,

$$\ln \frac{\epsilon_x \tau_x}{\epsilon_{std} \tau_{std}} = \ln \frac{J_{B,std}}{J_{B,x}} = \frac{c_2}{\lambda_{eff}}\left(\frac{1}{T_x} - \frac{1}{T_{std}}\right) \tag{14}$$

Equation (14) indicates that a plot of $\ln \frac{J_{B,std}}{J_{B,x}}$ against temperature is a hyperbola.

Reverting to equation (10), it is seen that if the sensitivity is a function of wavelength, then the blackbody intensities are weighted according to this function. In practice, the product of sensitivity and intensity is evaluated piecewise over the wavelength range considered and a summation of the products is formed. The ratios obtained in this manner deviate slightly from the hyperbola developed in equation (14). Figure 3 shows the temperature indicator curve, commonly called the master curve plotted for a standard temperature of 2500° F (1645° K) true. In actual temperature determinations, it is the transmission ratio which is determined experimentally. These are the values of transmission needed to produce equal densities for both the standard and unknown temperatures. This ratio is then modified by the emittance ratio in order to determine the value of the ordinate to be used on the

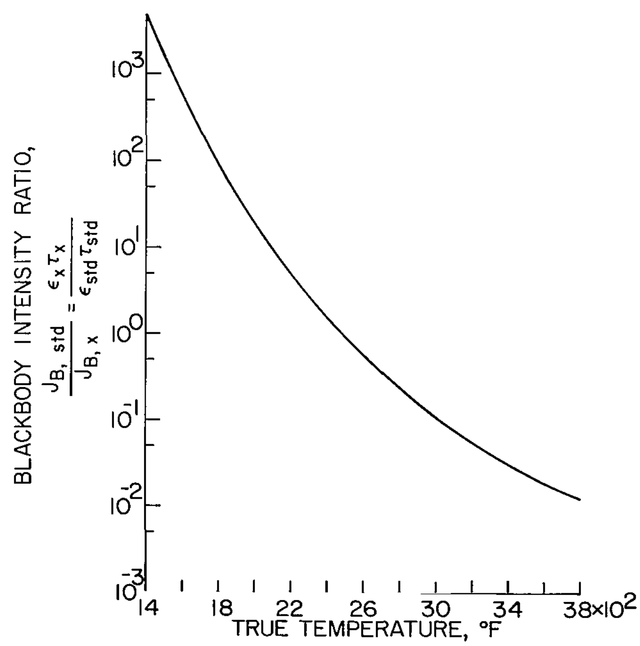

Figure 3.- Temperature indicator curve (master curve) for 320 ASA panchromatic film.

master curve. Referring this value to the master curve yields a value of true temperature for the unknown body.

DESCRIPTION OF APPARATUS

Prototype

The prototype photographic pyrometer consists of a camera and rotating filter (fig. 4) and of a power and triggering unit (fig. 5). The camera used

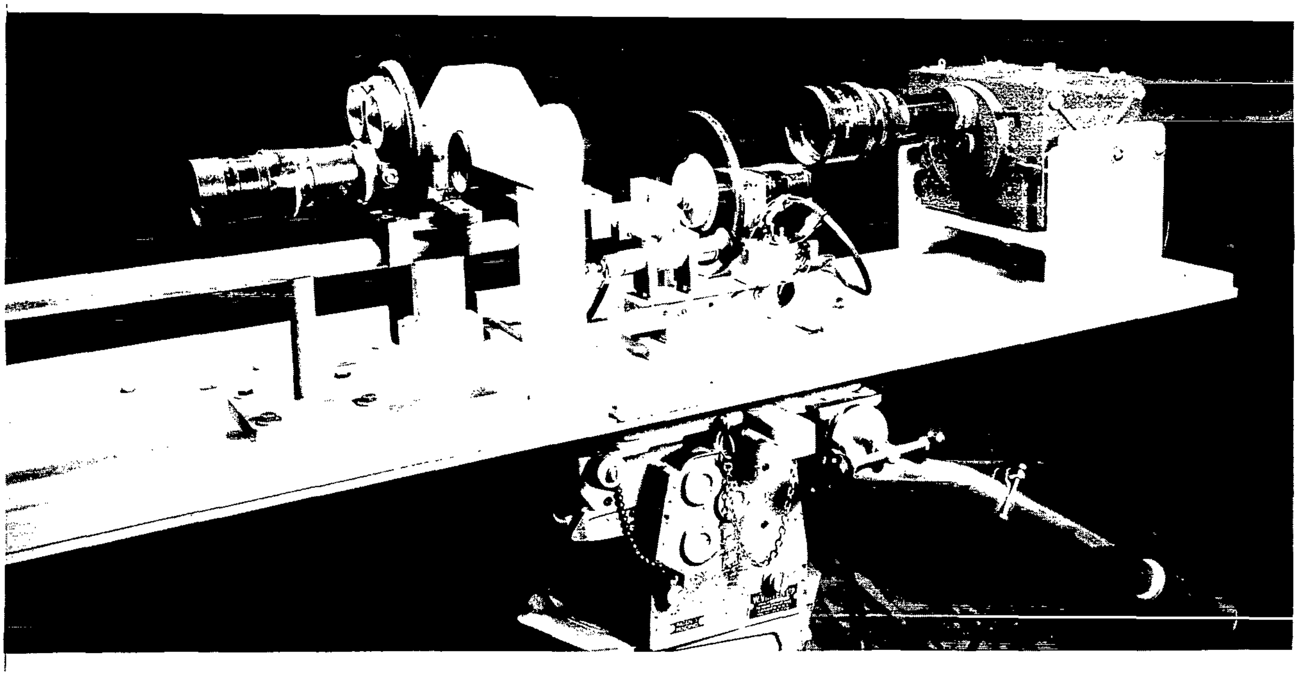

Figure 4.- Prototype photographic pyrometer optical system. L-61-7699

is a 35mm framing camera. The rotating filter is a neutral density circular wedge with a density range of 0 to 4 (transmission range, 100 to 0.01 percent). These components are shown schematically in figure 6. The incident radiation is collimated by the first lens system and then passes through the variable filter which is rotating with a frequency of 1 cycle per second. By passing collimated light through the filter, the image is attenuated uniformly as if the filter were an aperture stop. Exposures must be made through portions of the filter of known transmission and this is accomplished by starting the camera at a preselected angle of rotation of the filter. The camera triggering mechanism consists of a photocell pickup which receives light from a source through the perimeter of the rotating filter. The light is interrupted by the perimeter tab at a preselected angle of rotation at which time a signal is generated that starts the preset counter and the camera. The camera then

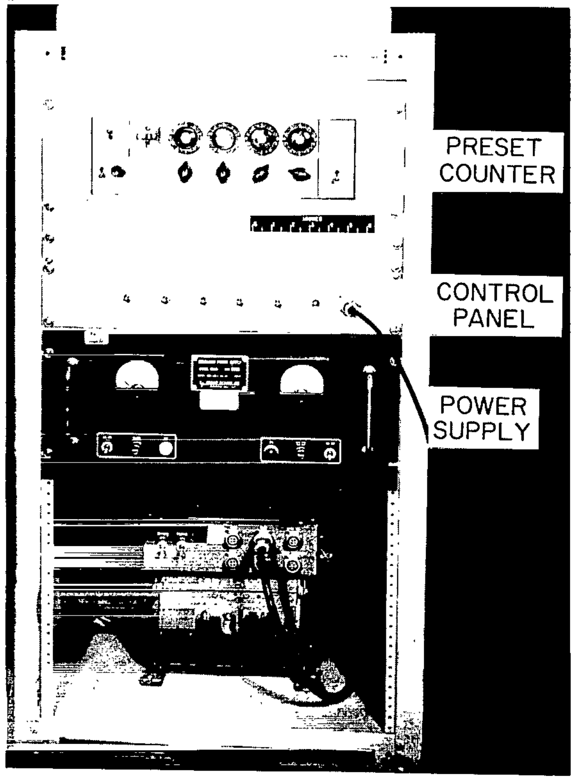

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Figure 5.- Prototype photographic pyrometer power and triggering system.

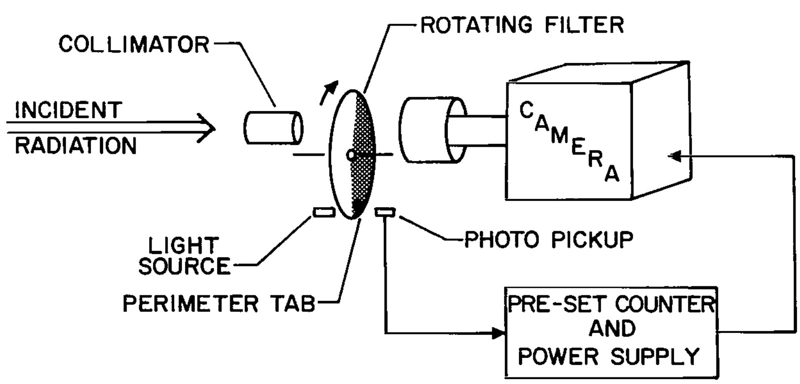

Figure 6.- Prototype photographic pyrometer.

exposes the preset number of frames (one sequence) at the rate of 20 frames per second. At the conclusion of each sequence, usually 18 frames, the triggering mechanism is reset and the entire procedure is repeated each second for the duration of the test. The response time for the temperature range of the instrument is therefore 1 second corresponding to one sequence. Exposure time is constant for all frames of the sequence since the camera shutter is started by a clutch which engages a continuously running motor. The standard light source used for calibration is a tungsten filament lamp. The emittance for tungsten over the range from 3800 to 6700 Å is taken to be 0.44.

Film Processor

The foremost requirement in film development is that the slope of the H and D curve γ remain constant throughout the film strip. Precise control of development time, temperature, and developer materials applied to each segment of film is thus a necessity for accurate temperature determination. These factors are controlled by a processor which maintains a temperature of $75 \pm 1^\circ$ F and develops at a rate of 1.5 ft/min for 4.5 minutes.

Densitometer

Density measurements are normally required at many positions on a model surface. In order to increase the spatial resolution obtainable at the model surface, a projected image densitometer is utilized. This system projects an enlarged image upon a screen in which a density probe is mounted. The projected image is then moved about on the screen, and densities are recorded for points of interest as seen by the aperture of the probe. For photographs taken with the prototype pyrometer at 6 feet, the system yields an overall spatial resolution of 0.1 inch on the model surface.

Advanced Model

The theory of the advanced photographic pyrometer is the same as for the prototype. The purpose in building this advanced instrument was to extend the temperature range and the angular field of view. In order to satisfy the latter requirement, two matched inconel thin-film wedges were built. When used in a contra-rotating manner, these two wedges render a variable, but spatially uniform, density to light traversing the wedges. The uniform density enables the camera to receive light which is not collimated, thereby rendering a larger field coverage. The resulting system, has a transmission range of 100 to 0.00013 percent which theoretically extends the temperature range to 4500° F (2755° K). Figure 7 shows the optical components of the advanced model. The standard lamp shown in the figure can be photographed automatically by mechanically rotating a prism into the field of view.

The optical components, mounted in a pressure-tight chamber, are shown in figure 8. This chamber was designed to protect the components from adverse conditions of pressure, temperature, and contaminating atmospheres when used in hypersonic wind-tunnel facilities.

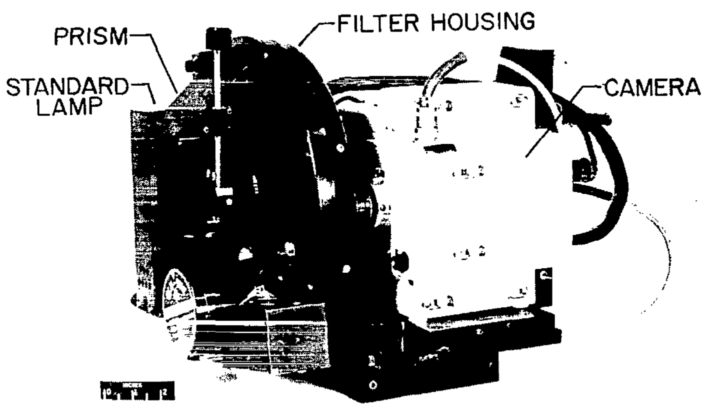

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Figure 7.- Advanced model of photographic pyrometer optical system.

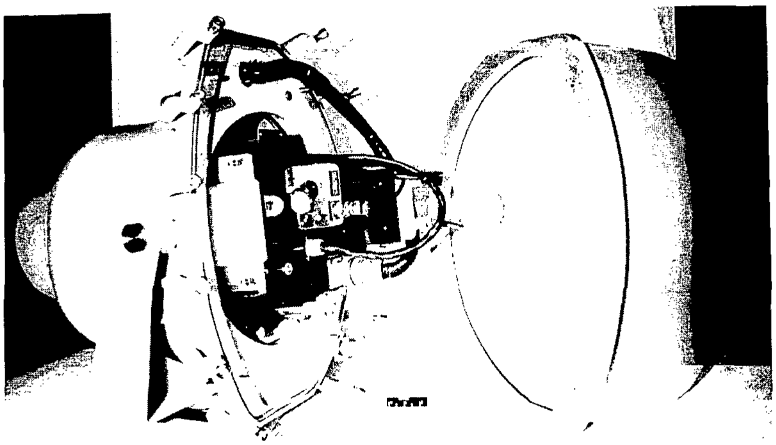

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Figure 8.- Advanced model of photographic pyrometer mounted in protective chamber.

EXPERIMENTAL PROCEDURE

Alinement

Alinement of the prototype instrument is facilitated by use of a borescope supplied with the camera. The camera objective is always focused at infinity to receive the collimated beam passing through the filter. The area to be examined is focused by adjusting the position of the lenses preceding the filter while observing the image in the borescope. When this is accomplished, the object is at the focal length of the initial lens system. Generally, the object should be examined from a direction nearly normal to the plane of the surface in order to minimize errors due to nondiffuse characteristics of radiators. For hard-to-reach surfaces, this requirement can be accomplished by the use of mirrors. Another benefit of photographic pyrometry is realized in areas where vibrations affect the constancy of alinement. This advantage will be realized if the field of view is large enough to cover the amplitude of the vibrations.

External Attenuation

External attenuation can take many forms, some of which are necessary for the operation of the instrument. In almost all applications, space limitations dictate the use of mirrors and windows in order to view the model under consideration from the desired direction. Each of these elements reduces the intensity of light which the photographic pyrometer receives. As a rule, external attenuation is not a hindrance to operation if the standard source is photographed through the same attenuators. For this case, the additional value of transmission involved is applied to both the standard and unknown intensities. These values appear on the ordinate of the master curve as a ratio of 1 which does not affect the temperature determination. The added attenuation does, however, raise the lowest temperature that can be perceived with a given type of film. A correction for the reflectances and transmittances involved can be applied to the calibration procedure if needed. These corrections are not required, however, if the standard source is photographed through the same attenuators as the unknown. Care should be exercised in the positioning of mirrors, in order that extraneous light does not enter the optical path.

In cases where background conditions produce unavoidably high light levels, they may sometimes be minimized by the use of linear polaroid sheets. A polaroid sheet placed in front of a flood lamp, for instance, will still transmit light to be used for whatever purpose it was originally intended. Another sheet of polaroid, crossed 90° with respect to the first, and inserted into the optical train of the instrument proper, will not allow the flood-lamp intensity to interfere with the light emanating from the material under surveillance.

Calibration

The standard lamp used to calibrate the film is a tungsten ribbon filament lamp set at a true temperature of 2500° F. Several sequences are taken on the same strip of film as the unknown sequences. This is done on each new strip in order that differences in emulsion between rolls will not affect the temperature determination. In addition, photographing the standard on the same strip allows the same developing process to be applied to all sequences equally. As mentioned under the section entitled "External Attenuation," the calibration procedure is simplified if the standard can be photographed through the same optical train as was the unknown. If this is impossible, a simulated calibration temperature can be computed when the values of attenuation involved are known. A calibrated optical pyrometer is used to set the standard true temperature by incorporating the known emittance. The true temperature is needed here since the intensity ratios for the master curve were computed from Planck's law for blackbodies at various true temperatures.

Film Analysis

In order to determine the temperature of a selected area, the area has to be resolvable with the densitometer system. As mentioned in the section entitled "Densitometer," the film is projected onto a screen in which a detector is mounted. A clear portion of the film is used to "zero" the densitometer. The densities of the selected areas are then read and recorded as a function of their areal positions and of the frame in which the density is read. The standard images are also recorded in this manner and a matching of densities is ultimately obtained as dictated by the theory. Normally, the "zeroing" or subtracting of background densities in this manner does not yield a measure of the added intensity which produced the density (ref. 6). Here, however, "zeroing" is valid since the process ultimately requires the equating of densities. The procedure of "zeroing" in the clear portion of the film also adds a rough check on the development process since this value (fog level) should remain constant for the entire strip of film used.

The readout presents varied problems depending on the types of materials used. When reading temperatures of metals or metallic-like substances, the density values are easily obtained since there are usually no discontinuities in the heated areas. However, in the case of certain ablative materials, hot spots appear which are difficult to read if the projected size of the spot is of the same order of magnitude as the aperture of the densitometer. In addition, these hot spots flake off from time to time exposing cooler regions behind. Since there are hot spots and cool regions adjacent to each other, the radiation from a hot spot may produce halation to such an extent that it covers the cooler region completely. This phenomenon could occur in the initial frames of a sequence when the radiative energy for the hot spot has not been sufficiently reduced to prevent halation. The first frames, however, are also those frames in which the instrument perceives the lower temperatures. In later frames, no density would be produced in these regions as a result of the larger attenuation. Consequently, the instrument cannot record the temperatures of the cooler regions under these conditions.

Sample Calculation

A sample calculation will be made by using the density sequences shown in the following chart:

Frame	1	2	3	4	5	6	7	8	9	10
Transmission, percent	43	27	17	11	7.0	4.4	2.8	1.8	1.2	0.82
Density T_x	0.94	0.86	0.72	0.50	0.28	0.16				
Density T_{std}					0.98	0.90	0.78	0.56	0.33	0.20

The value of transmission associated with each frame is shown along with densities produced by a standard tungsten lamp $\left(\epsilon_\lambda = 0.44\right)$ set at 2500° F true and a stainless-steel sample $\left(\epsilon_\lambda = 0.88\right)$ at an unknown temperature.

Figure 9 shows the densities read in each frame as a function of the logarithm of the transmission associated with each frame. A frame of the unknown sequence, frame 4, is chosen for which the density lies on the linear portion of the curve. The value of transmission needed to produce the same density for the standard is then interpolated from the graph. The equi-density line drawn through the T_x curve at the fourth frame (τ = 11 percent) intersects the standard curve at a transmission of 1.6 percent. The ratio of the unknown to standard transmissions (11/1.6), modified by their respective emittances $\left(\frac{0.88}{0.44}\right)\left(\frac{11.0}{1.6}\right) = 13.7$, may now be applied to the master curve (fig. 3) to yield a true temperature of the steel of 2040° F. A plot of the unknown densities is unnecessary since, as shown in the calculation, only the value of density produced in a particular frame is needed. The plot of standard densities is needed, however, in order to interpolate between frames.

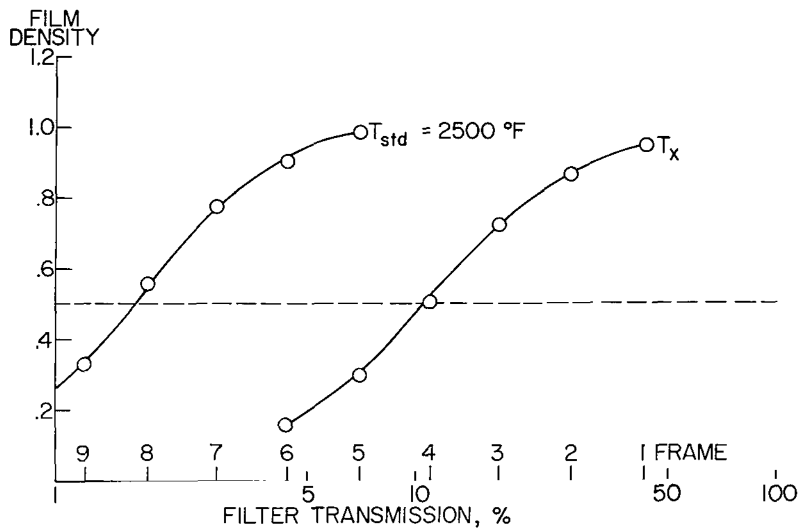

Figure 9.- Film density against filter transmission and frame number.

ERRORS

Thus far in the report, several sources of error have been mentioned as they occurred in the various phases of the theory, apparatus, and procedure sections. These and other sources of error can best be classified into three phases according to their origins. These are the source, instrument, and readout errors and will be considered individually in this section.

Source Errors

The source phase is concerned with the errors arising from the properties of the radiating body under investigation and its immediate surroundings. In order that the theory apply strictly to a given material, the material has to have the property of a "grey" body - that is, the emittance has to be independent of wavelength - since the master curve was computed on the basis of a blackbody $\left(\epsilon_\lambda = 1\right)$. Assuming that the body satisfies the "grey" body condition, it remains to determine the temperature error due to an inaccuracy in the emittance. Referring to the master curve (fig. 3), a variance of 20 percent in the emittance ratio shows up as a $1\frac{1}{2}$-percent variance in temperature at 2000° F and a $2\frac{1}{2}$-percent variance at 3600° F. This again illustrates that the major factor in determining the master curve is the rapid change in energy and that the effect of errors in emittance is small in comparison.

In addition to the radiation emanating from the surface of a body, gaseous emission may also be present adjacent to the surface. This emission, if within the spectral sensitivity of the film, will cause the pyrometer to indicate a higher temperature than it should. One solution is to select a spectral region free from such emission by the use of wide-band filters. The master curve will necessarily have to be reevaluated by using the additional weighting factor. A similar solution might be achieved by choosing a film with a more advantageous spectral response.

A unique reflection problem is encountered in facilities in which the source of heat for the gas stream is perceived indirectly by the pyrometer. The radiation from these sources is reflected off the model and simulates a high surface temperature. The simulated temperature should be measured and the corresponding energy which would be radiated by a material at this temperature obtained from figure 2. It will then be possible to select a true model temperature, above which the reflected energy can be ignored.

Instrument Errors

The most important characteristic of the photographic pyrometer is the filter transmission since it has a range of values identical to that of the incident light intensity. For this reason, the precise value of transmission associated with a given frame is fundamental to a temperature determination. Optical components, such as lenses, mirrors, and aperture, also affect the overall transmission of the instrument, but these values are usually constant for each unknown and standard sequence. For all of these components, it is assumed that an effective transmission for the wavelength range of the film can be specified. In the case of a component with a complicated transmission curve, it may be necessary to include it in the calculation of the master curve in order to evaluate its effect properly.

In addition to the attenuation from the components just mentioned, the amount of light which reaches the film is controlled by the shutter speed. The variations in shutter time for a continuously rotating shutter, however, have an extremely small effect on the temperature measurement.

Readout Errors

The controls exercised on the film development were discussed in the section entitled "Description of Apparatus." Any large scale variations in the development process will invalidate the data. A gross indicator of such variances will be the film background densities which should be read at several points on the strip of film used. Small density changes, however, will inherently occur due to slight changes in emulsion, development time, and developer. These density variances will appear mainly on the linear portion of the characteristic curve. For this reason, a given density in a given frame may be read with a variance of 10 percent which corresponds to only a 1-percent variance in temperature at 2000° F and a $1\frac{1}{2}$-percent variance in temperature at 3000° F. The main point to be emphasized in this connection is that the density read in a particular frame is the important measurement and not just the density itself.

CONCLUDING REMARKS

The energy received by a photographic pyrometer has been shown to vary rapidly with temperature. The spectral sensitivity, consequently, is a minor factor in determining the temperature indicator curve. Similarly, inaccuracies in the emittance also add a small correction.

Attenuation external to the instrument in the form of mirrors and windows is present in most applications. This attenuation is not normally a hindrance to operation if the standard source is photographed through the same attenuators as the unknown.

The prototype photographic pyrometer has been calibrated for the temperature range from 1800° to 3600° F (1255° to 2255° K) with a precision of 2 percent for most applications. The advanced model exhibits a wider field of view than the prototype and theoretically extends the temperature range to 4500° F (2755° K).

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 2, 1964.

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