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A VARIABLE EXPOSURE PHOTOGRAPHIC PYROMETER

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A VARIABLE EXPOSURE PHOTOGRAPHIC PYROMETER

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ABSTRACT

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 resultant film densities, coupled with their associated filter values, yield a time history of the temperature contour. The black-body temperature range is 1800°-3600° F with a precision of approximately 2 percent for most applications.

INTRODUCTION

Photographic pyrometry has been used since 1930 in many diverse ways.[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 range in temperature is to be realized. These methods would include: (1) varying the exposure time, (2) varying the camera aperture, or (3) by 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.[2] Later, the variable apertures were replaced with neutral density filters in order to increase the span in exposure control. Finally it was desired to construct a photographic pyrometer with an extremely wide latitude in exposure. This was achieved in the present technique with a rotating, variable-density filter.

The photographic pyrometer described herein operates on the same principle as the one developed by Siviter and Strauss (ref. 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, coupled with their associated values of filter transmission, yield a time history of the temperature contour.

The purpose of this report is to evaluate the prototype instrument and to discuss briefly an advanced model with respect to the errors involved including methods of eliminating these errors.

THEORY

As a consequence of the major role played by photography, the pertinent film characteristics as related to this instrument will be presented first, followed by an examination of the radiative properties of materials, and, finally, the several characteristics will be 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. The relation is a familiar characteristic curve, known as an H and D curve - after Hunter and Driffield[3] and is shown in Fig. 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 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 and is described by the linear relation

$$D = \gamma \log SE + B \qquad (1)$$

where γ is the slope and B is the Y-intercept of 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 characteristics 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 region need be considered.

Superior numbers refer to similarly-numbered references at the end of this paper.

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Radiative Properties of Materials

The energy radiated within a given wavelength interval and for a given temperature can be obtained by integrating the Planck black-body distribution function over the wavelength range.[4] The range most used in this work is for $\Delta\lambda = 3800\text{-}6700\ \mathring{A}$ corresponding to Tri-X Pan film. Fig. 2 shows the energy radiated by a black-body in this region as a function of the true temperature of the body. The rapid change in energy with temperature in this region enhances the sensitivity of instruments using this technique.

The energy radiated by a black body in thermodynamic equilibrium is the maximum radiant energy possible for a given temperature. Most bodies radiate less than this maximum. The ratio of the radiant intensity emitted by a material J to that emitted by a black body J^{BB} at the same temperature and wavelength determines the emissivity ϵ given by

$$\epsilon = \frac{J}{J^{BB}} \qquad (2)$$

In general, the emissivity is a function of wavelength and temperature as well as the surface condition. Radiation emitted from a black body 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.[5]

Temperature Indicator Curve - "Master" 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 will radiate energy depending on their temperature which will ultimately produce density on the film. The values of density produced in this manner could 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, will 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. The densities may be held within the linear limits, however, by attenuating the light intensity with an appropriate transmission filter for each temperature involved. Assume any value of transmission can be selected arbitrarily to produce equal densities for different temperatures. Using this technique, the filter transmission could be used as a temperature indicator rather than density, per se. To relate the transmission to temperature, equal film densities from two different frames will be chosen and will be 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).

$$D_x = D_{std} \qquad (3)$$

Using equation (1), we have

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

Identical processing yields

$$B_x = B_{std} \quad \text{and} \quad \gamma_x = \gamma_{std} \qquad (5)$$

and therefore

$$S_x E_x = S_{std} E_{std} \qquad (6)$$

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

$$S_x J_x \tau_x t_x = S_{std} J_{std} \tau_{std} t_{std} \qquad (7)$$

Utilizing a constant shutter speed $t_x = t_{std}$, yields

$$S_x J_x \tau_x = S_{std} J_{std} \tau_{std} \qquad (8)$$

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

$$S_x \epsilon_x J_x^{BB} \tau_x = S_{std} \epsilon_{std} J_{std}^{BB} \tau_{std} \qquad (9)$$

Collecting the emissivity and transmission values gives

$$\frac{\epsilon_x}{\epsilon_{std}} \frac{\tau_x}{\tau_{std}} = \frac{S_{std} J_{std}^{BB}}{S_x J_x^{BB}} \qquad (10)$$

The intensities are, therefore, weighted according to the relative spectral response of the film. In practice, the product of the film response and intensity is evaluated piecewise over the wavelength range considered and a summation of the products is formed for several temperatures. Fig. 3 shows the temperature indicator curve, commonly called the "master" curve, plotted for Tri-X Pan film and for a standard temperature of 2500° F 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 emissivity ratio in order to determine the value of the ordinate to be used on the "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 single rotating filter and camera, powered and triggered by an external unit. A schematic of these components is shown in Fig. 4. The optical components (Fig. 5) consist of a 35-mm framing camera, neutral density circular wedge with a density range of 0-4 (transmission range 100-0.01 percent), and a collimating lens. Referring to the schematic diagram, the incident radiation is first collimated before passing 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 then be made through portions of the filter of known transmission. This is accomplished by starting the camera at a preselected angle of rotation of the filter. The camera triggering mechanism consists of a photo-cell 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 which starts the preset counter and the camera. The camera then 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. 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.

Film Processor

The foremost requirement in film development is that the slope of the H and D curve (γ) remains 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 determinations. These factors are controlled by a processor which maintains a temperature of 75° ± 1° F and develops at a rate of 1.5 ft/min for a development time of 4.5 minutes.

Densitometer

Density measurements are normally required at many positions on a material surface. In order to increase the spatial resolution obtainable at a material 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 this instrument is the same as for the prototype. The purpose in building this instrument was to extend the temperature range and the angular field of view. In order to satisfy the last requirement, two matched Inconel thin film wedges were built. These two wedges when used in a counterrotating manner 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 100-0.00013 percent, which theoretically extends the temperature range to 4500° F. Fig. 6 shows the optical components of the advanced model. The standard lamp shown in the figure can be photographed automatically by mechanically rotating a deflecting prism into the field of view.

The optical components, mounted in a protective chamber, are shown in Fig. 7. This chamber was designed to protect the components from adverse conditions of pressure, temperature, and contaminating atmospheres when used in hypersonic wind-tunnel facilities.

EXPERIMENTAL PROCEDURE

Alignment

Alignment of the prototype instrument is facilitated by use of a borescope supplied with the camera. The camera objective is always focused at infinity to perceive the collimated beam passing through the filter. The area to be examined is focused, therefore, 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 lenses 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 alignment. This will be true 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 surface 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 constant with wavelength and if the standard source is photographed through the same attenuators. For this case, the additional value of transmittance or reflectance involved is applied to both the standard and unknown intensities alike. These values appear on the ordinate of the "master" curve as a ratio of one (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.

Calibration

The standard lamp used to calibrate the film is a tungsten ribbon filament lamp set at a true temperature of 2500° F. The emissivity for tungsten over the range 3800-6700 Å is taken to be 0.44. 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, placing the standard on the same strip allows the same developing process to be applied to all sequences equally. 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 knowing the values of attenuation involved. A calibrated optical pyrometer is used to set the standard true temperature by incorporating the known emissivity. The true temperature is needed here since the intensity ratios for the "master" curve were computed using Planck's law for black-bodies at various true temperatures.

ERRORS

The sources of error can best be classified into three phases according to their origins. These are the source, observational, 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 emissivity has to be independent of wavelength - since the "master" curve was computed on the basis of a black-body $(\epsilon_\lambda = 1)$. Assuming that the body satisifes the "grey" body condition, it remains to determine the temperature error due to an inaccuracy in the emissivity. Referring to the "master" curve, a variance of 20 percent in the emissivity 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 emissivity 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 using the additional weighting factor. A similar solution might be achieved by choosing a film with a more advantageous spectral response.

Observational Errors

The observation of material surfaces often involves reflecting and absorbing media which add additional errors to the measurement. The interposition of these media is often justified, however, in order to minimize other large scale errors. For many tests, front surface mirrors are used in order to eliminate possible errors due to nondiffuse properties of materials. If the reflection coefficient of the mirror is constant throughout the wavelength range used and the standard and unknown are photographed using the mirror, no additional corrections are needed.

Readout Errors

The controls exercised on the film development were discussed under 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, per se.

CONCLUSIONS

The energy received by the instrument 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 emissivity also require only a small correction.

Attenuation external to the instrument in the form of mirrors and windows is a necessity for 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 1800°-3600° F 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.

NOMENCLATURE

B	Y-intercept of linear portion of characteristic curve
D	film density, log opacity
E	exposure, watt-sec/cm^2
J	material radiance, watts/cm^2/$\Delta\lambda$
J^{BB}	black-body radiance, watts/cm^2/$\Delta\lambda$
S	relative spectral sensitivity of film, dimensionless
T	temperature, °F
t	exposure time, seconds
τ	transmittance of filter, dimensionless
γ	slope of characteristic curve, cm^2/watt-sec
ϵ	emissivity, dimensionless
λ	wavelength, Å

Subscripts:

x	unknown
std	standard
λ	spectral

ACKNOWLEDGMENT

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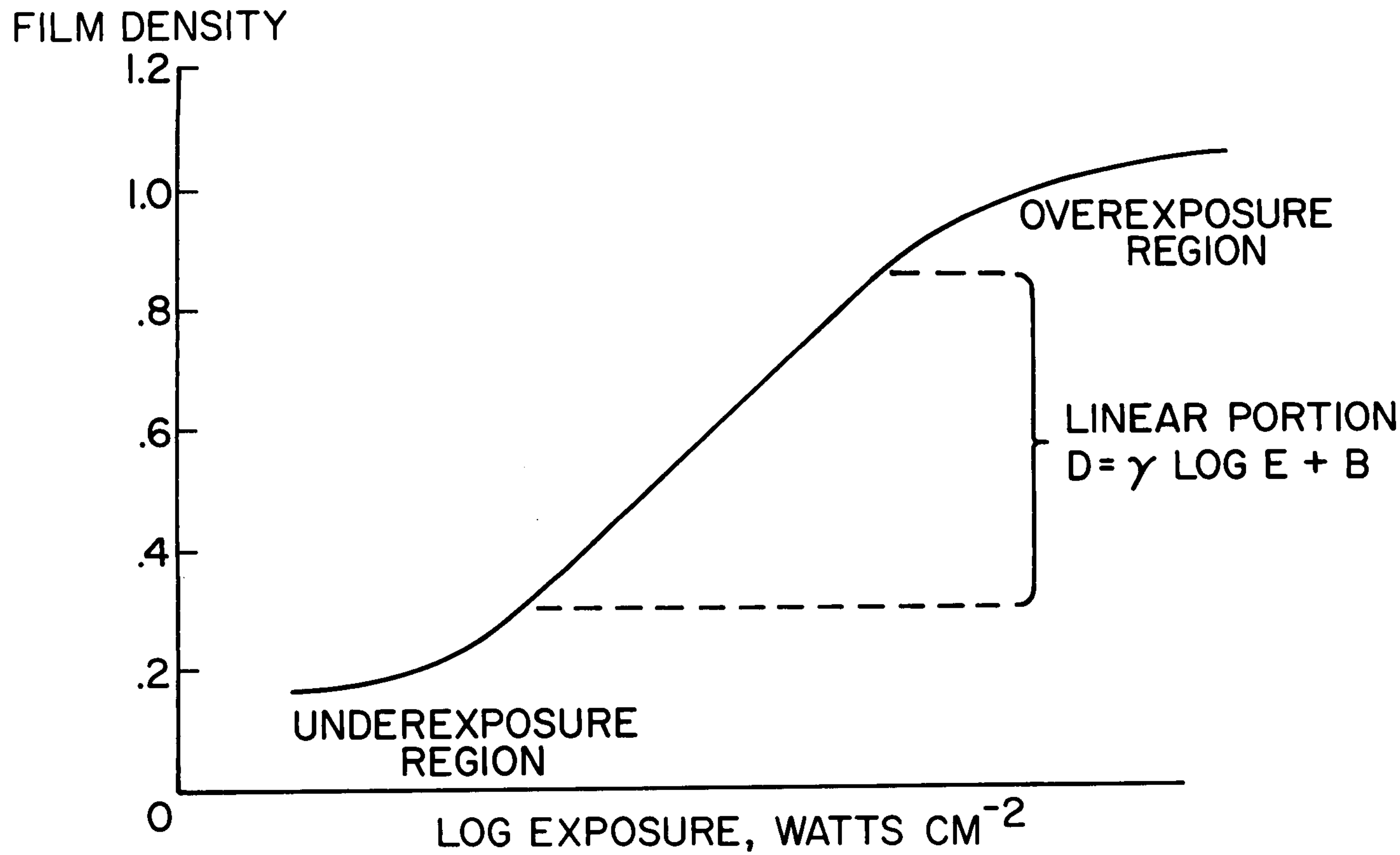

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Figure 1.- Characteristic curve.

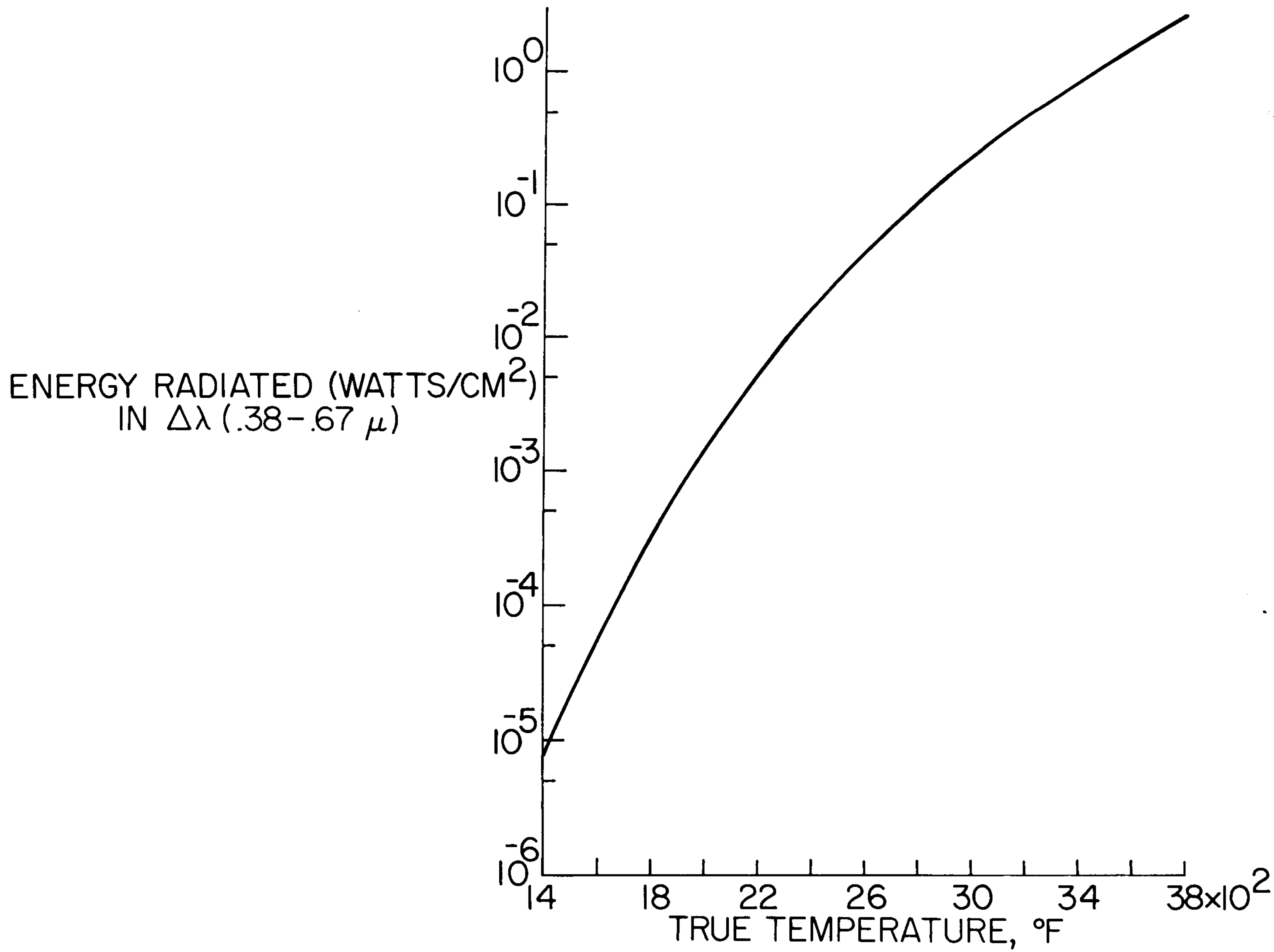

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Figure 2.- Energy radiated versus true temperature.

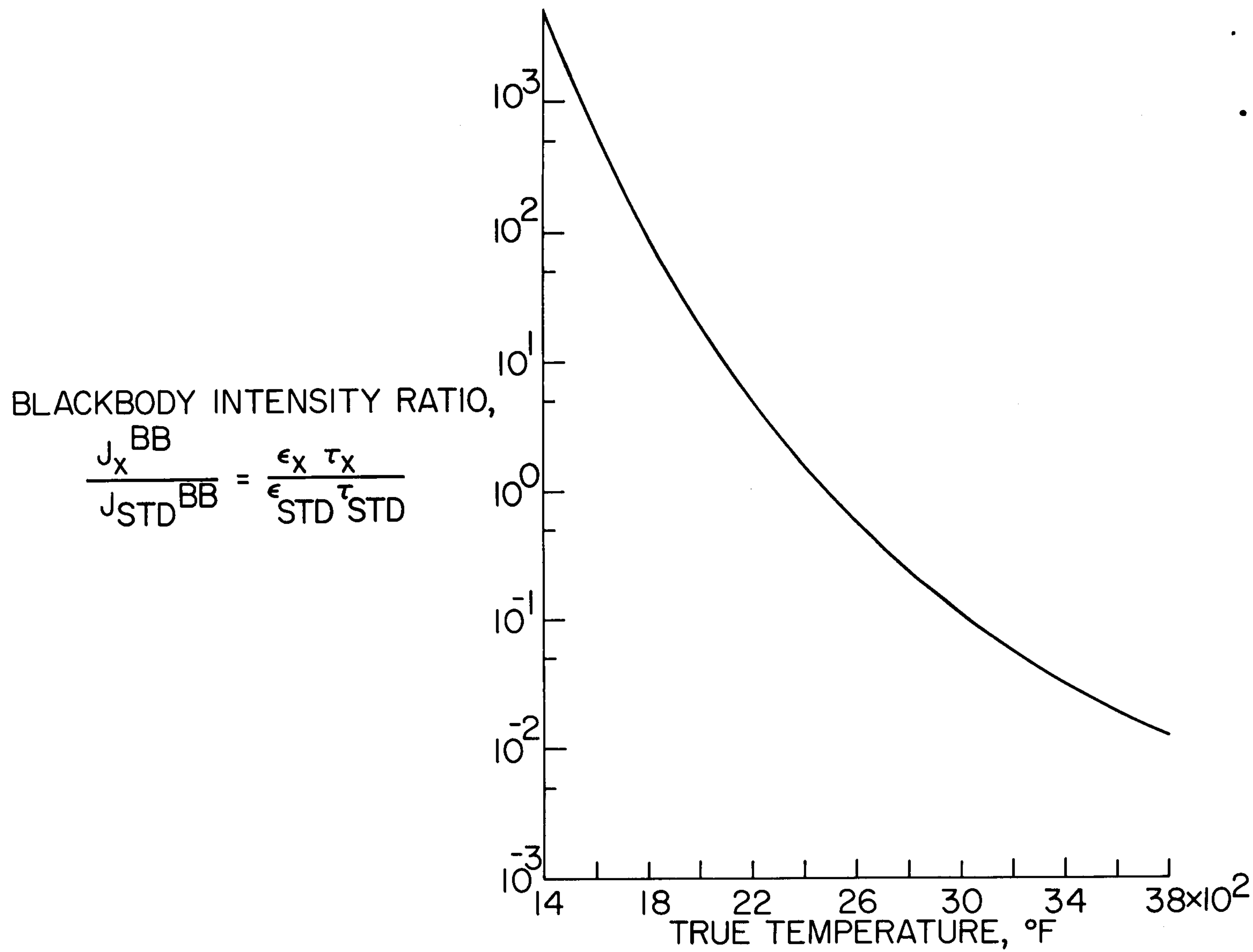

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Figure 3.- "Master" curve - blackbody intensity ratio versus true temperature.

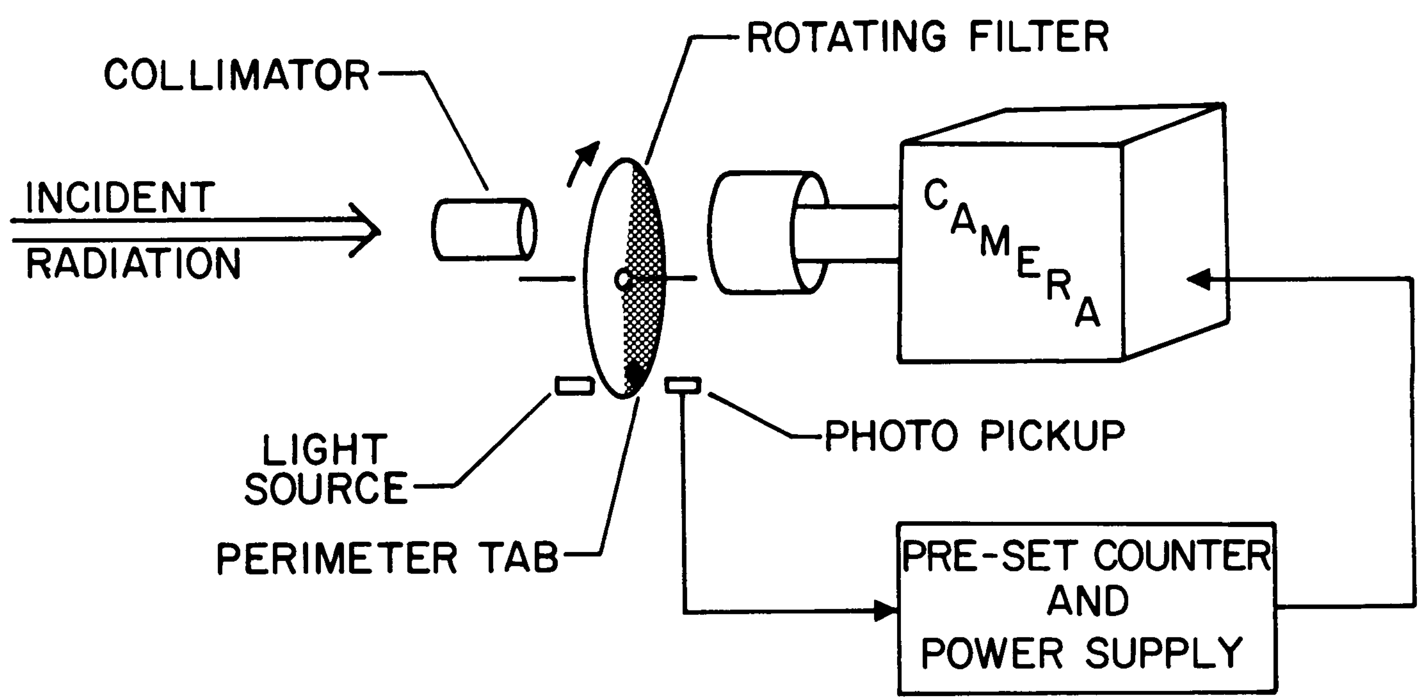

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Figure 4.- Prototype pyrometer - schematic.

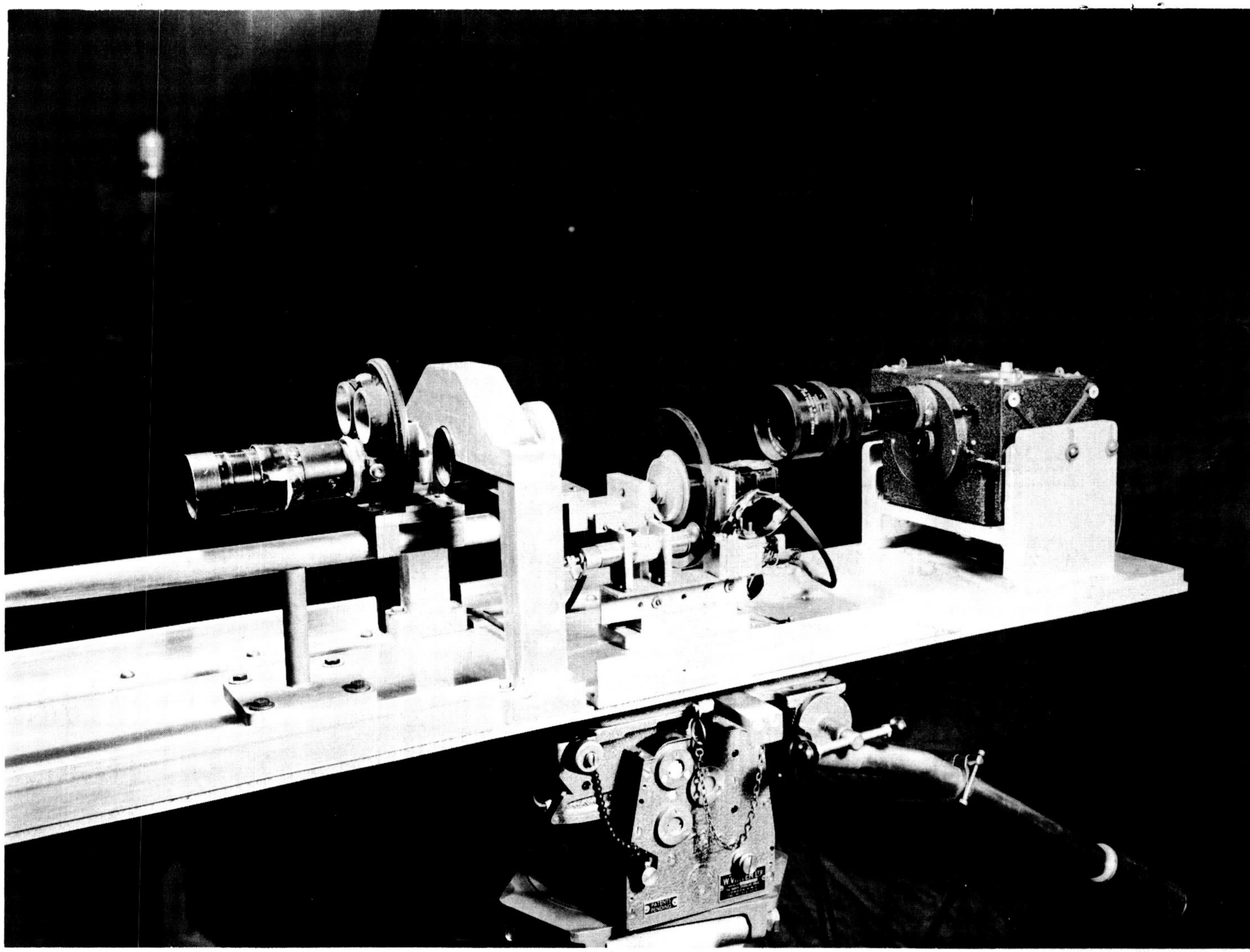

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Figure 5.- Optical components - prototype instrument.

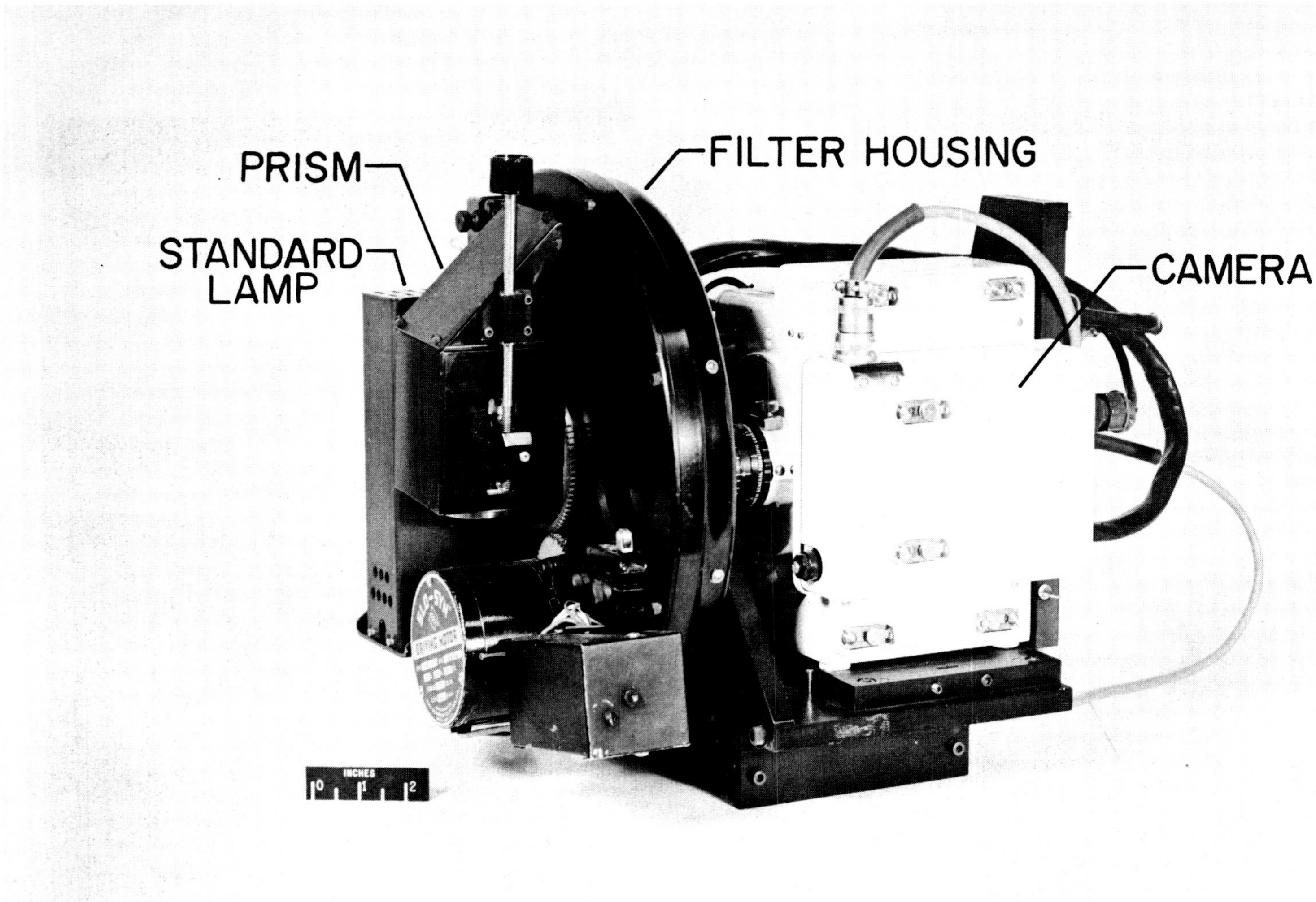

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Figure 6.- Optical components - advanced model.

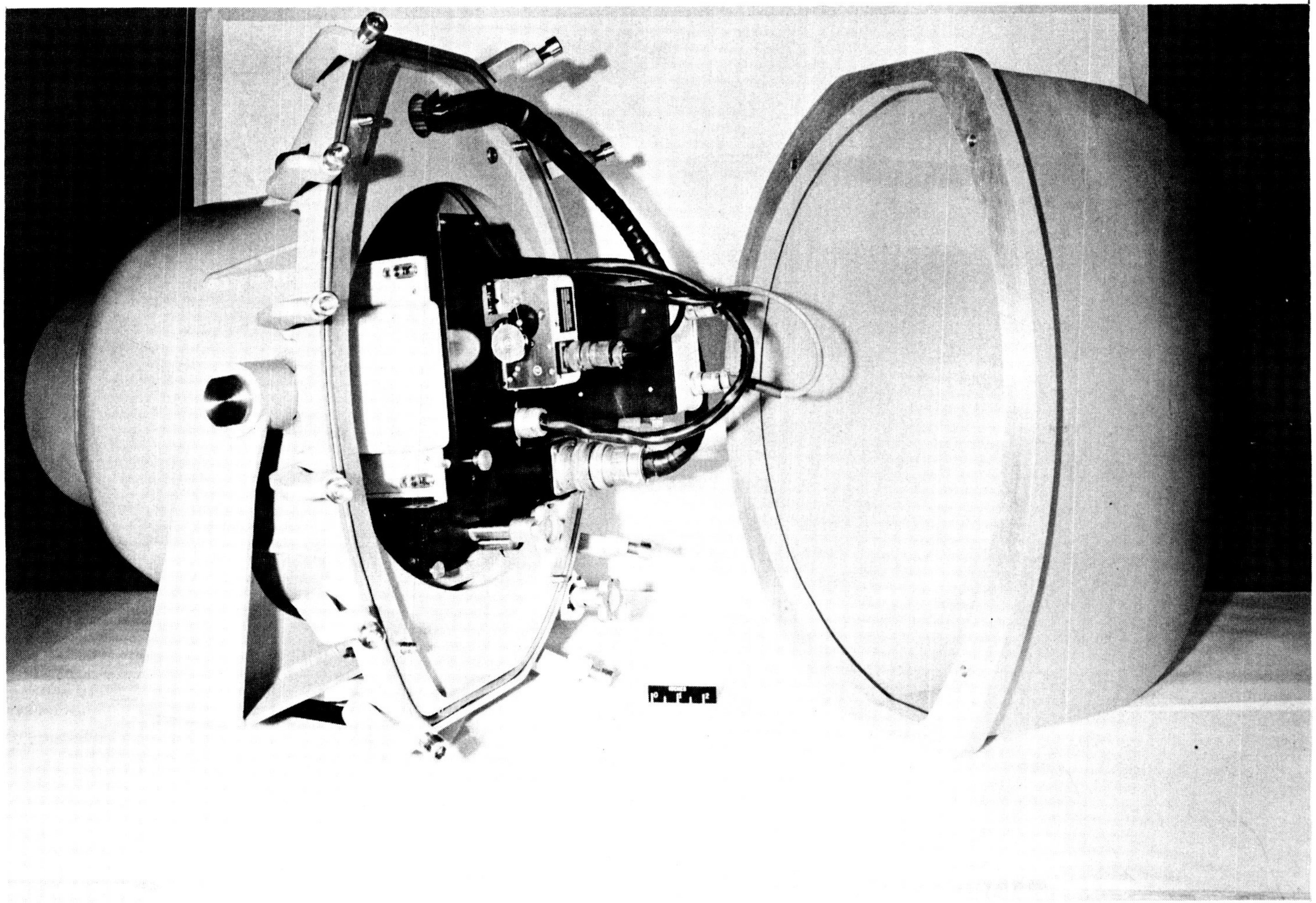

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Figure 7.- Advanced model and protective chamber.

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ERRATA

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The equation in the ordinate scale of figure 3 should be corrected to read as follows:

$$\frac{J_{STD}^{BB}}{J_x^{BB}} = \frac{\epsilon_x \tau_x}{\epsilon_{STD} \tau_{STD}}$$