NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3033

APPLICATION OF AN ELECTRO-OPTICAL TWO-COLOR PYROMETER TO MEASUREMENT OF FLAME TEMPERATURE FOR LIQUID OXYGEN - HYDROCARBON PROPELLANT COMBINATION

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SUMMARY

The development and application of an electro-optical two-color pyrometer for the measurement of temperature and emissivity in the exhaust gases from an open-tube combustor using liquid oxygen and a hydrocarbon fuel are described. Measurements were made during both normal and oscillatory combustion. Temperature variations up to 1000° R and emissivity variations of 10 to 1 were found to occur during combustor operation; the variations were sporadic and periodic during normal and oscillatory operation, respectively. Periodic variations at a frequency of 1000 cycles per second were predominant; however, smaller amplitude oscillations at higher frequencies were also present. Satisfactory correlation was obtained between temperatures measured simultaneously by the two-color method and by a microwave absorption technique. Agreement between temperature and sound intensity change was also found to exist. During many combustion experiments radiation intensity varied inversely with temperature and directly with emissivity, indicating a need for caution in the interpretation of combustion photographs on the basis of light intensity.

INTRODUCTION

Methods for the instantaneous measurement of combustion parameters to assist in studies of oscillatory and transient combustion conditions in rocket engines are being investigated by the NACA Lewis laboratory. This report describes an experimental investigation of the use of a two-color electro-optical pyrometer as a means for measuring rapid changes in combustion temperatures. On the basis of response to temperature changes, a review of existing techniques for the measurement of temperature indicated that this method was most desirable of those applicable to rocket engines.

The two-color method of determining the temperature of luminous gases appears to have been first reported by Hottel and Broughton (ref. 1). They obtained an accurate measurement of gas flame temperature in a furnace by measuring the apparent temperature of the gases with an optical pyrometer using both red and green filters. From such data they were able to calculate the gas temperature. Their method was satisfactory for measurement of furnace gas temperatures where conditions remain relatively constant over a long period of time. The technique was expanded at the University of Wisconsin (ref. 2) by substituting for the optical pyrometer a spectroscope and photosensitive vacuum tubes as a means for determining the apparent temperature or radiation intensity of the flame simultaneously at two different wavelengths. The frequency response of the system was increased considerably and temperature variations up to several thousand cycles per second could be measured. The technique has been applied successfully to the measurement of temperature in internal combustion engines and in fuel-air burners.

A description of an electro-optical two-color pyrometer developed at the NACA Lewis laboratory for the measurement of temperature is given herein, and its application to the measurement of temperature and emissivity in the exhaust of an open-tube combustor using liquid oxygen and a hydrocarbon fuel as the propellant combination is discussed. The open-tube combustor appeared ideal for the instrument development and initial application because of its operating simplicity and its performance. It consisted of a tube 27 inches long and 2 inches in diameter burning 0.2 pound of propellant per second. The combustor installation was the same as that used successfully in the measurement of time-average temperatures by the previously developed modified sodium-line reversal method (ref. 3). With a hydrocarbon fuel, rather than alcohol as in the previous application, oscillatory combustion was encountered over a limited range of operating conditions. The audible sensation during this oscillatory condition was typical of "screaming" combustion in rocket engines. Temperature measurements were made in the exhaust of the combustor during both normal and oscillatory operation. Comparisons between measured temperature changes and simultaneously measured sound intensity changes were also made during the course of the investigation. In addition, correlations were attempted between temperatures measured simultaneously by the two-color method and a microwave absorption technique. The experimental investigation consisted essentially of an evaluation of the adequacy of the two-color measurement instrumentation for rocket research. The preliminary survey of temperature, emissivity, and sound intensity exhibited during both normal and oscillatory operation was made in view of basic similarities in the combustion process of this combustor and a rocket engine.

THEORETICAL CONSIDERATIONS

The theory of the two-color method of measuring temperature is described in detail in references 1 and 2. The following discussion describes the basic principles involved in the measurement of temperature by this method.

The two-color method of temperature measurement utilizes the theoretical and experimental spectral radiation relations for luminous gases as the basis for evaluating temperature. The entire theory may be described by the use of two expressions. The first is essentially Wien's law for spectral distribution of radiation intensity and is applicable to combustion temperatures in the visible spectrum:

$$J_\lambda = C_1 \lambda^{-5} E_\lambda e^{-C_2/\lambda T} \tag{1}$$

where

C_1, C_2 known physical constants

E_λ monochromatic emissivity

J_λ spectral radiation intensity

T thermodynamic equilibrium temperature

λ monochromatic wavelength

For a black body, emissivity being equal to unity at all wavelengths, the well-known spectral distribution curves are expressed by this equation.

The second relation defines monochromatic emissivity for grey-body conditions. Hottel and Broughton (ref. 1) showed that for gases made luminous by the presence of carbon particles, the monochromatic emissivity can be expressed by the following equation:

$$E_\lambda = 1 - e^{-KL/\lambda^\alpha} \tag{2}$$

where

KL carbon concentration factor, including concentration, path length, and absorption coefficient

α constant, assumed equal to 1.2

The value of this equation is that it establishes the relation between emissivity and wavelength for any given value of the concentration

factor KL. Experimental evidence shows that the constant α varies with wavelength; however, references 1 and 2 indicate that the assumption of a constant value will introduce an error of approximately 15° R or less in absolute temperature when applied to the two-color method of determining temperature.

Equations (1) and (2) may be combined as follows:

$$J_{\lambda} = \left(1 - e^{-KL/\lambda^{\alpha}}\right) C_1 \lambda^{-5} e^{-C_2/\lambda T} \tag{3}$$

In this equation the radiation intensity J at a particular wavelength is seen to be a function of two variables, the carbon concentration KL and the temperature T. If, however, the radiation intensity at two different wavelengths is considered, two independent equations of the form of equation (3) may be written. The two equations may therefore be combined, eliminating either the carbon concentration or the temperature. Equations (4) and (5) express the two relations thus obtained:

$$\left[1 - \frac{J_a}{C_1 \lambda_a^{-5} e^{-C_2/\lambda_a T}}\right]^{\lambda_a{}^{\alpha}} = \left[1 - \frac{J_b}{C_1 \lambda_b^{-5} e^{-C_2/\lambda_b T}}\right]^{\lambda_b{}^{\alpha}} \tag{4}$$

$$\left[\frac{J_a}{C_1 \lambda_a^{-5} \left(1 - e^{-KL/\lambda_a^{\alpha}}\right)}\right]^{\lambda_a} = \left[\frac{J_b}{C_1 \lambda_b^{-5} \left(1 - e^{-KL/\lambda_b^{\alpha}}\right)}\right]^{\lambda_b} \tag{5}$$

The subscripts a and b refer to two different wavelengths.

Equations (4) and (5) cannot be expressed in easily usable form; however, graphical representations of these equations may be made, and these are shown in figures 1 and 2. In figure 1, lines of constant temperature are shown as a function of radiation intensity at wavelengths of 4800 and 6300 A. Arbitrary scale values for radiation intensity were used. These values are proportional to the term $J/C_1\lambda^{-5}$ appearing as a group in equations (4) and (5). The wavelengths used in figure 1 are the values that were used in applying the two-color technique. The particular tungsten lamp characteristics shown in the figure are described in the following section. From figure 1 it is seen that the gas temperature is defined from a knowledge of the radiation intensities at two wavelenths. The black-body curve is a limiting condition for radiation intensity. Lines of constant carbon concentration as a function of radiation intensities at wavelengths of 4800 and 6300 A, as

expressed by equation (5), are shown in figure 2. The lines of constant carbon concentration are parallel to the black-body curve on the logarithmic plot. The carbon concentration factor is shown to be defined from a knowledge of the radiation intensities at two different wavelengths.

From the preceding discussion it has been shown that known radiation intensities at two different wavelengths are sufficient to evaluate both the temperature and carbon concentration of gases. The entire theory of accurate temperature determination is contingent upon the absence of atomic and molecular line or band spectra at the two wavelengths used. For the liquid oxygen - hydrocarbon propellant combination, no predictable radiation of this nature was found at the 4800 and 6300 A wavelength band regions.

ELECTRO-OPTICAL INSTRUMENTATION

Description

The method used to measure the radiation intensity from combustion gases is similar to that described in reference 2. A double refracting spectroscope with an f/1.9 objective lens was constructed (fig. 3). At the spectrum image a double-slit arrangement was used to separate the light at the wavelength regions of 4800 and 6300 A. This light was permitted to fall on independent photomultiplier tubes. The spectrum width was 30 A for the slit located at the 4800 A position and 100 A for the slit located at the 6300 A position. These band widths were selected analytically as being desirable for the assumed temperature and carbon concentration of the gases to be measured. They represented a compromise between the absolute intensity level of the gases and the response of the photomultiplier tubes, which also varies with wavelength, so that the output voltage of both photomultiplier tubes would be approximately equal.

The instrumentation used to obtain recorded signals of radiation intensity is schematically shown in figure 3. Cathode-follower stages with a low impedance output were used in conjunction with the photomultiplier tubes in order to maintain a relatively high over-all frequency response of the system. A dual-channel oscilloscope with direct-current amplifiers was used to observe the signals visually. The signals were recorded photographically from the oscilloscope screen. Oscilloscope deflection as a function of incident light on the photomultiplier tubes was evaluated to assure linearity in the electro-optical system. The absence of microphonic oscillations and stray illumination was checked by operating the electro-optical system during combustor operation but not sighting directly on the combustion flame.

High-frequency transients in radiation intensity are encountered from the combustion gases and success of the two-color technique in

evaluating these transients required good resolution of the recorded signal. For all combustion records, therefore, a pulse-driven single sweep of the two oscilloscope beams of from 2- to 4-millisecond duration was recorded with an oscilloscope camera. For some data recordings periodic interruptions of the oscilloscope beam were used to obtain better synchronization of the two oscilloscope traces.

Calibration

Because of the unknown amplification factors involved in the conversion of light intensity into oscilloscope deflection, reference conditions of radiation intensity are required to evaluate the scale value of measured intensities. Such reference conditions were obtained by sighting the spectroscope on a broad-ribbon tungsten lamp. From the data on tungsten emissivity evaluated by Forsythe and Worthing (ref. 4) and from apparent tungsten lamp temperatures measured with an optical pyrometer, it is possible to calculate the radiation intensity levels of the lamp at the 4800 and 6300 A wavelengths. Such a condition was calculated for a lamp current of 12 amperes, and radiation intensities were evaluated in terms of the scale values used in figures 1 and 2. Radiation intensities for other lamp currents were then measured with the two-color apparatus using the 12-ampere points as the reference condition. Figure 4 shows the radiation intensities obtained at various lamp currents. The variation in the two radiation intensities with lamp current defines an apparently straight line on the logarithmic plot, which is expected because of the nearly constant emissivity ratio of tungsten over this range. These tungsten lamp characteristics were superimposed on the curves of figures 1 and 2. The factor necessary for converting oscilloscope deflections into units of radiation intensity used in figures 1 and 2 can therefore be evaluated by sighting on the tungsten lamp at a measured current flow. In application, the tungsten lamp was generally sighted from 5 to 15 seconds prior to recording intensity levels of the combustion gases.

A simplification of the method for evaluating temperature from radiation intensities at two different wavelengths but over a limited range of carbon concentration is described in the appendix.

The accuracy of the absolute temperature level of measured gas temperatures is believed to be within $\pm 100^{\circ}$ R. This accuracy may be improved by the use of a precisely calibrated optical pyrometer at several wavelengths or possibly by the use of a carbon cavity with unit emissivity as a reference source. For the purpose of measuring temperature transients and relative temperatures, the calibration appears adequate. For temperature changes as large as 1000° R at a temperature level of 5000° R, the calibration accuracy will result in an error of approximately ± 2 percent of the change. The average

accuracy incurred in reading the photographic records is of approximately the same magnitude.

Several indications of the adequacy of the over-all instrumentation were demonstrated. The tungsten lamp characteristic shown on figure 2 is seen to follow a line of constant carbon concentration. Such a characteristic is expected from the radiation properties of tungsten. However, if the ratio of the two wavelengths used to calculate figure 2 had been different from that used in the spectroscope in measuring the lamp characteristics, the slopes of the two lines would show appreciable variation.

The temperature of a luminous Bunsen flame was also measured by both the two-color instrumentation and a visual spectral-line reversal method. The temperatures agreed to within $\pm 100^{\circ}$ R in the several attempts which were considered satisfactory in view of the fact that both measurements could not be made simultaneously.

The frequency response of the over-all system was evaluated up to a frequency of 3500 cycles per second. This was accomplised by mechanically interrupting a light from a tungsten lamp at various frequencies and photographically recording the oscilloscope deflection. The frequency response data thus obtained are shown in figure 5. At a frequency of 3500 cycles per second, the deflections for both wavelengths have decreased to 0.9 of the original value. Also shown in figure 5 is the average frequency response curve of a photomultiplier tube with an S-4 response as given in reference 5 (Data Sheet 92CM-6864). The experimental data appear to fall close to this curve, indicating that the phototube is the component limiting frequency response. If both phototubes have similar response, it may be generally assumed that a measured temperature change at a given frequency is less than the actual change by a factor equivalent to the response of the system. For example, an actual temperature change of 1000° R at a frequency of 3500 cycles per second will result in a measured temperature change of 900° R for the response shown in figure 5.

EXPERIMENTAL PROCEDURE

The developed instrumentation was applied to the measurement of combustion gas temperatures and emissivities in the exhaust of an open-tube combustor using liquid oxygen and a hydrocarbon fuel as the propellant combination. The combustor installation is the same as that used in reference 3. It consisted of a tube 27 inches long and 2 inches in diameter. A triplet injector consisting of two oxidant streams impinging on one fuel was used. All firings were made at a total flow rate of 0.2 pound per second and oxidant-fuel weight ratios of approximately 1.2, 1.6, 2.0, or 2.4 were used. Temperature measurements were made along a combustor diameter in the exhaust, approximately 2 inches

from the tube exit. The hydrocarbon fuel consisted of a mixture of 75 percent heptane and 25 percent turpentine. It was found that heptane alone resulted in a low level of luminosity and necessitated a high order of amplification of the radiation intensity signals. Turpentine was added to the heptane in these initial tests to increase the spectral emissivity.

During a portion of the experimental program, simultaneous measurements were made of sound intensity, and of temperature by a microwave absorption technique and by the two-color method. Sound intensity was measured with a crystal microphone located at the exit of the tube approximately 4 inches from the path of the exhaust gases. Temperatures were determined by the microwave absorption technique by measuring the attenuation of the K band (1/2-in. wavelength) microwaves caused by free sodium electrons in the combustion gases (refs. 6 and 7). The attenuation is a function of the temperature and of a predetermined quantity of sodium salt in the fuel. Difficulty was incurred in dissolving a sodium salt in the hydrocarbon fuel. The technique evolved after considerable experimentation was to dissolve sodium iodide in acetone before adding it to the fuel. The final mixtures consisted of 2.5 percent by weight acetone and 0.01 percent by weight sodium iodide in the hydrocarbon fuel.

A condition of audible oscillatory operation, typical of "screaming" combustion in rocket engines, was encountered during operation of the combustor. With only the heptane-turpentine fuel, these oscillations occurred at an oxidant-fuel ratio of 1.6. The oscillations as defined by the audible sound were not present at oxidant-fuel ratios of 1.2 or 2.0. With the addition of the acetone-salt mixture, this region expanded, causing oscillatory combustion at oxidant-fuel ratios of 2.0 and 1.6, and occasionally at an oxidant-fuel ratio of 1.2.

RESULTS AND DISCUSSION

Typical Steady-State Combustion

Radiation intensity variations obtained during a typical firing of the combustor are shown in figure 6. This figure contains the information generally recorded on a single photographic plate. Such information includes a reference base line for zero intensity level, calibration levels obtained from tungsten lamp illumination at 4800 and 6300 A, and the intensity changes of the combustion gases at the same wavelengths. The amplification factors in the electro-optical system are different for the two wavelengths, and therefore independent scale factors are assigned to the recorded signals. In figure 6 they are shown as percentages of maximum values.

The combustion radiation intensities for both wavelengths shown in figure 6 are seen to be quite similar, particularly with respect to detail caused by high-frequency components. For many analyses of such records, temperature evaluations were made at the maximums, minimums, and inflection points caused by the high-frequency components. Although temperature changes continuously throughout the record, such changes are not readily evident from a casual visual observation. In some cases, however, a proportionately larger change in one signal with respect to the other can be seen, indicating a large change in temperature. The intensity level of both signals is seen to vary by a factor of 3 to 1. Variations of 5 to 1 in intensity level were common and occasional variations greater than 10 to 1 were encountered.

The data shown in figure 6 are for an oxidant-fuel ratio of 2.0. The audible sound of combustor at operating condition indicated steady burning. An analysis of these data is shown in figure 7(a). Shown over a time increment of 2 milliseconds or 1/500 second are the temperature, the emissivity of the 6300 A radiation, and the radiation intensity at 6300 A. The radiation intensity is shown for comparative purposes. The emissivity calculated from the carbon concentration factor by means of equation (2) is used in this and all succeeding analysis because of its more general usage and readily understandable significance. An examination of equation (2) shows that emissivity varies linearly with the carbon concentration factor when this factor is small. This linearity exists for values of the 6300 A emissivity of approximately 0.5 and less.

The temperature in figure 7(a) is shown to vary over a range of approximately 800° R. Although the temperature variations indicate some evidence of oscillatory conditions, the changes are more generally described as sporadic. The variations in emissivity are similar to the temperature variations, but an inverse relation is indicated. At conditions of high temperature the emissivity is low, and, conversely, at low temperatures the emissivity is high. The variation in emissivity is large, varying over a range of 10 to 1. The radiation intensity in this case does not vary consistently with either the temperature or the emissivity. Partial agreement between emissivity and intensity does exist, which indicates that at these instances the emissivity is more effective in controlling radiation intensity than is the temperature. It can be concluded, however, that the radiation intensity is not in itself an adequate indication of temperature. In view of such conditions, a cautious interpretation of combustion photographs is indicated. The degree of exposure of a photographic plate may or may not be directly related to the temperature or completeness of combustion.

The temperature, emissivity, and radiation intensity variations at an oxidant-fuel ratio of 2.4 are shown in figure 7(b). The temperature variations are again sporadic; however, there is evidence of a greater

degree of high-frequency components. Such rapid changes are also present in the emissivity and radiation intensity. The temperature variation is again 800° R, and emissivity variations of more than 10 to 1 are present. In general, the emissivity varies inversely with temperature and directly with radiation intensity. Although the average temperature and emissivity appear to be the same at oxidant-fuel ratios of 2.4 and 2.0, no attempt was made in the present investigation to correlate these average values with the oxidant-fuel ratio. Average values obtained over a time increment of 2 milliseconds do not appear adequate for such analyses. Average values are more readily and accurately obtained by reducing the frequency response of the recording instrumentation and obtaining data over a longer time increment.

Typical Periodic Combustion

The predominant frequency present during audible oscillatory combustion is approximately 1000 cycles per second. Occasionally, however, oscillations at the fundamental mode of 333 cycles per second occur during a portion of the firing. Figure 8 shows continuous-film sound-intensity records for both modes of oscillation obtained at the same operating condition during different portions of the firing. The oscillation at 1000 cycles per second appears more consistent, although both records indicate the presence of some irregularities.

An analysis of conditions under audible oscillatory operation is shown in figure 9(a). The oxidant-fuel ratio is 1.6, and the time increment is 2 milliseconds. The radiation intensity, emissivity, and temperature are shown. A periodic oscillation is more readily evident in the temperature than in the radiation intensity. An oscillation in temperature frequency of approximately 1000 cycles per second over a range of 1000° R is indicated. The frequency corresponds to a harmonic oscillation of the open tube. The oscillation at 1000 cycles per second is also present in the emissivity, although the variation is an inverse of the temperature change.

A variation in temperature which appears as an oscillation at the fundamental tube resonant frequency is shown in figure 9(b). The record shows the variations obtained over a time interval of 3 milliseconds and one major oscillation is indicated. The evaluation of data with the recording technique used became increasingly difficult as a time increment of 3 milliseconds was approached. The small time increments used and the presence of only 1 or 2 cycles in the record therefore do not permit the exact evaluation of the frequency and characteristics of oscillatory combustion. The presence of the frequencies mentioned, however, was substantiated by continuous-film recording of the signals obtained from sound intensity and microwave attenuation.

Temperature measurements made at an oxidant-fuel ratio of 1.2 exhibited two types of combustion at this operating condition. The characteristics shown in figure 10(a) are typical of one form of combustion. Over the 3-millisecond time increment, sporadic oscillations in temperature over a range of 600° R are shown. The results are similar to those obtained at higher oxidant-fuel ratios, although the average temperature is lower and the emissivity, higher. Variation of the type shown in figure 10(b), however, occurred frequently at this operating condition. The radiation intensity is shown to rise from apparently zero radiation intensity. Temperature could be evaluated over only a portion of this pulse, but a peak temperature condition is indicated. The emissivity is shown to decrease during the pulse in radiation intensity. Such a variation may be associated with the "chugging" phenomenon in rocket engines, with the variation in propellant flow controlling both the temperature and the radiation intensity. The oxidant injection pressure drop is reduced at this operating condition, being approximately 100 pounds per square inch, which may have induced fluctuating propellant flow conditions.

Comparison of Simultaneous Measurements

The result of simultaneous measurement of temperature and sound intensity during audible unstable combustion is shown in figure 11. Both temperature and sound intensity show a predominant frequency of approximately 1000 cycles per second and, except for high-frequency detail in the temperature record, the two are quite similar. A direct relation between temperature and sound intensity appears to exist in the exhaust gases. The phase shift between the temperature and sound intensity is due to the displacement of the microphone from the point of temperature measurement. This displacement varied somewhat for different firings but generally corresponded to a displacement of 4 inches and a phase shift of approximately 0.25 millisecond.

Simultaneous measurements of temperature made by the two-color and microwave absorption techniques are shown in figure 12. The comparison is shown for a pulsing temperature condition. The correlation is considered good both with respect to average temperature and to temperature change.

A comparison of mean temperatures evaluated over 2-millisecond time increments for all simultaneous measurements made by the two-color and microwave techniques is shown in figure 13. The comparison is considered good in view of basic differences in the two methods. Theory predicts a difference in the measured temperature of a nonuniform temperature zone by the two methods, which may account for some variation in figure 13. Variations may also have resulted from the calibration for absolute temperature, which was made independently from different sources of information for the two methods.

In the measurement of temperature changes, considerably better agreement between the two methods was obtained for periodic oscillation in temperature than for sporadic high-frequency variations; the agreement also improved for the lower frequency periodic oscillations. This may be a result of the basic differences in the measurement techniques. The temperature measured by the two-color technique represented average conditions along a path through the combustor exhaust roughly 1/4-inch in diameter. The microwave absorption technique averages conditions in the exhaust along a path approximately 2 inches in diameter. The average conditions in these two sections are not exactly comparable, especially with respect to high-frequency changes or local variations in temperature. Similarly, sound intensity cannot be compared in detail with the temperature measurement.

A typical comparison of sound intensity and temperature measured by the two-color and microwave techniques during nonoscillatory combustion is shown in figure 14. At the oxidant-fuel ratio of 2.4, the temperature variations consist primarily of sporadic high-frequency changes. Although some comparison can be made between any of the three curves, it is evident that complete agreement does not exist. In view of the differences in the two temperature-measurement techniques, however, the correlation is considered adequate, particularly with respect to the time-average temperature.

A comparison of all measured quantities obtained simultaneously during oscillatory combustion is shown in figure 15. Temperatures measured by the two-color and microwave techniques, sound intensity, emissivity, and radiation intensity over a 2-millisecond time increment are shown. The oscillation is at a frequency in the region of 1000 cycles per second. Radiation intensities were recorded while interrupting the oscilloscope beam at a frequency of 33,000 cycles per second, which resulted in the availability of considerably more points for temperature evaluation than previously. The agreement between the two temperature curves for the oscillation at 1000 cycles per second is considered good; the two-color temperature, however, more strongly indicates the presence of higher harmonics. Sound intensity basically agrees with the temperature changes. The peaked condition exhibited by sound intensity in contrast to temperature change may be a characteristic of the crystal microphone rather than of fundamental significance. Emissivity again is shown to vary inversely with temperature, and a resemblance between emissivity and radiation intensity is evident.

In many of the analyses it was noted that exact agreement in phase between corresponding changes in emissivity and radiation intensity does not exist. This characteristic is evident in figure 15. It is interesting to speculate on the possible significance of this characteristic with respect to response times in the combustion process. In the present investigation, however, no conclusive evidence of its significance was found.

High-Frequency Oscillations

The use of periodic interruptions of the oscilloscope beam resulted in the detailed analysis of some data records that indicated the presence of extreme high-frequency oscillations. Such a record for an oxidant-fuel ratio of 1.6 is shown in figure 16. The total time increment is 1.6 milliseconds, and the record appears to show a portion of a low-frequency temperature oscillation. The presence of a high-frequency temperature oscillation, however, is clearly indicated. The frequency of oscillation appears to be of the order of 6000 cycles per second.

A similar result was obtained at an oxidant-fuel ratio of 2.4, as shown in figure 17. Emissivity, sound intensity, and radiation intensity are also shown in this figure. Two distinct cycles of a high-frequency oscillation are shown in the initial portion of the temperature record, and the presence of oscillations at the same frequency is indicated in the remaining portion of the record. The oscillations are not adequately defined for the exact evaluation of frequency; values of from 5000 to 10,000 cycles per second are obtained in such an evaluation. Theoretically, measured temperatures in this frequency region are smaller than actual as a result of instrument frequency response, and the lack of resolution at this frequency may be the result of such conditions. Emissivity and radiation intensity also indicate the presence of high-frequency oscillations. Sound intensity, however, shows only low-frequency changes. If a phase shift in sound intensity equivalent to 0.3 millisecond is assumed, the sound intensity changes are seen to correspond to peak temperature conditions.

A more thorough investigation of the presence and significance of high-frequency oscillations in temperature may be meaningful in the study of oscillatory combustion in rocket engines. The nature of such oscillations within the combustor, without the disturbances caused by exiting flow, would be desirable.

CONCLUDING REMARKS

The elctro-optical two-color pyrometer is a useful tool in the study of oscillatory combustion in rocket engines because of its ability to measure the rapidly changing temperature conditions exhibited by this type of combustion.

The inverse variation of temperature and radiation intensity exhibited during many oscillatory changes in temperature suggests a cautious interpretation of combustion photographs. The degree of exposure of a photographic film is not necessarily related to the temperature or completeness of combustion.

SUMMARY OF RESULTS

A two-color electro-optical pyrometer was applied to the measurement of temperature and emissivity in the exhaust gases of a combustor using liquid oxygen and a hydrocarbon fuel as the propellant combination. Measurements in the exhaust of the combustor with the two-color instrumentation, a microwave attenuation apparatus for an additional independent measurement of temperature, and a crystal microphone for the measurement of sound intensity may be summarized as follows:

1. During audible steady combustor operation, sporadic temperature variations up to 800° R and emissivity variations of approximately 10 to 1 are generally present.

2. During audible oscillatory combustion, periodic temperature oscillations of approximately 1000° R at a predominant frequency of approximately 1000 cycles per second are present.

3. An approximate inverse relation between temperature and emissivity is generally present during all operating conditions.

4. An inverse relation between temperature and radiation intensity existed during many oscillatory conditions for the particular combustion gas conditions used.

5. Periodic variations in temperatures at frequencies of 5000 cycles per second and greater were evident in several combustion records.

6. A correlation between temperature and sound intensity was obtained for periodic oscillation in combustion.

7. Sound intensity appeared to vary directly with temperature.

8. The correlation of time-average temperatures measured by the two-color and microwave techniques was satisfactory for all operating conditions.

9. The correlation of temperature variations measured by the two-color and microwave techniques during periodic oscillation was considered good in view of basic differences in the two techniques.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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APPENDIX - METHOD OF TEMPERATURE EVALUATION FOR LOW CARBON CONTENT

The two equations used in the two-color method of evaluating temperature are Wien's law and Hottel and Broughton's expression for monochromatic emissivity (ref. 1). They are

$$J_\lambda = C_1 E_\lambda \lambda^{-5} e^{-C_2/\lambda T} \tag{1}$$

and

$$E_\lambda = 1 - e^{-KL/\lambda^\alpha} \tag{2}$$

where

C_1, C_2 known physical constants

E_λ monochromatic emissivity

J_λ spectral radiation intensity

KL carbon concentration over path length L

T thermodynamic equilibrium temperature

α constant, assumed equal to 1.2

λ monochromatic wavelength

With radiation at two wavelengths, a and b, assumed, the ratio of the radiation intensities may be expressed in terms of equation (1).

$$\frac{J_a}{J_b} = \frac{E_{\lambda,a}}{E_{\lambda,b}} \left(\frac{\lambda_a}{\lambda_b}\right)^{-5} e^{-C_2(1/\lambda_a - 1/\lambda_b)/T} \tag{3}$$

The emissivity ratio is expressed in terms of equation (2) and the limiting value as the carbon concentration factor approaches zero is obtained to give

$$\lim_{KL \to 0} \frac{E_{\lambda,a}}{E_{\lambda,b}} = \lim_{KL \to 0} \frac{1 - e^{-\frac{KL}{\lambda_a^\alpha}}}{1 - e^{-\frac{KL}{\lambda_b^\alpha}}} = \left(\frac{\lambda_b}{\lambda_a}\right)^\alpha \tag{4}$$

For this condition the ratio of the radiation intensities may be expressed as

$$\frac{J_a}{J_b} = \left(\frac{\lambda_b}{\lambda_a}\right)^{\alpha+5} e^{-C_2(1/\lambda_a - 1/\lambda_b)/T} \tag{5}$$

Values of $a = 6300$ A, $b = 4800$ A, and $C_2 = 2.57$ cm $^{\circ}$R are assumed to write the following expression:

$$\frac{J_{6300\ A}}{J_{4800\ A}} \cong e^{\frac{12,690}{T}} \tag{6}$$

The units of radiation intensity employed in the text of this report are used to express the variation of temperature with intensity ratio shown in figure 18. Tungsten lamp characteristics (fig. 4) are also shown in figure 18 in terms of intensity ratio, permitting conversion of oscilloscope deflection into intensity ratio.

The error introduced by the assumption of a constant emissivity ratio is dependent on the characteristics of the combustion flame. The error as a function of the monochromatic emissivity for 6300 A is shown in figure 19 for temperatures of 4000°, 5000°, and 6000° R.

In many combustion flames the emissivity does not exceed a value of 0.05. In such cases, the error introduced would be approximately the same as the experimental accuracy. Dependent on the range of emissivities encountered and the accuracy derived, this method of evaluating temperature may be used at larger values of emissivity. When applicable, this method suggests the direct measurement of temperature by the use of suitable electronic components rather than independent measurement of two radiation intensities.

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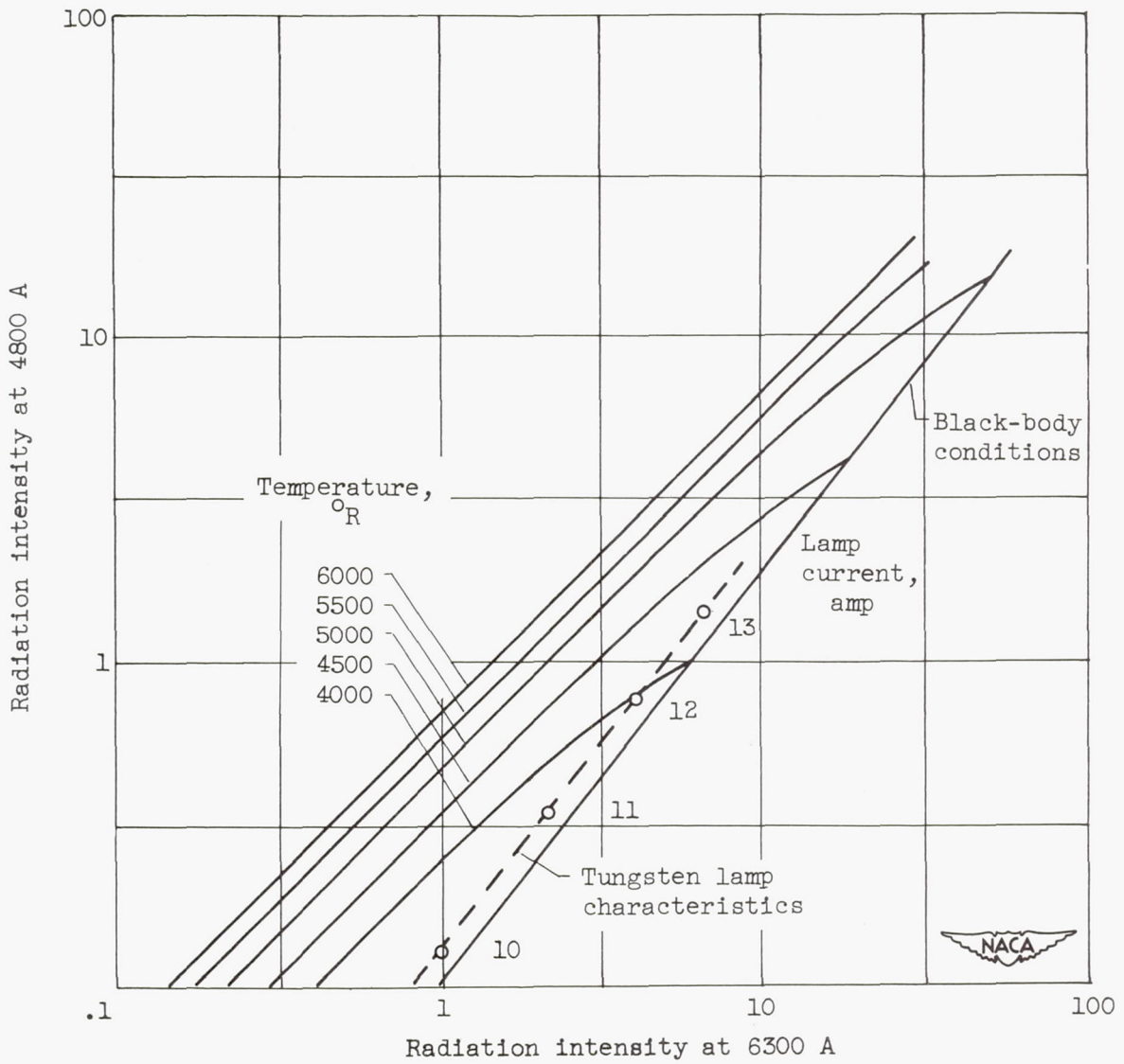


Figure 1. - Theoretical relation between radiation intensities at 4800 and 6300 A for various temperatures (eq. (4)). Arbitrary scale values.

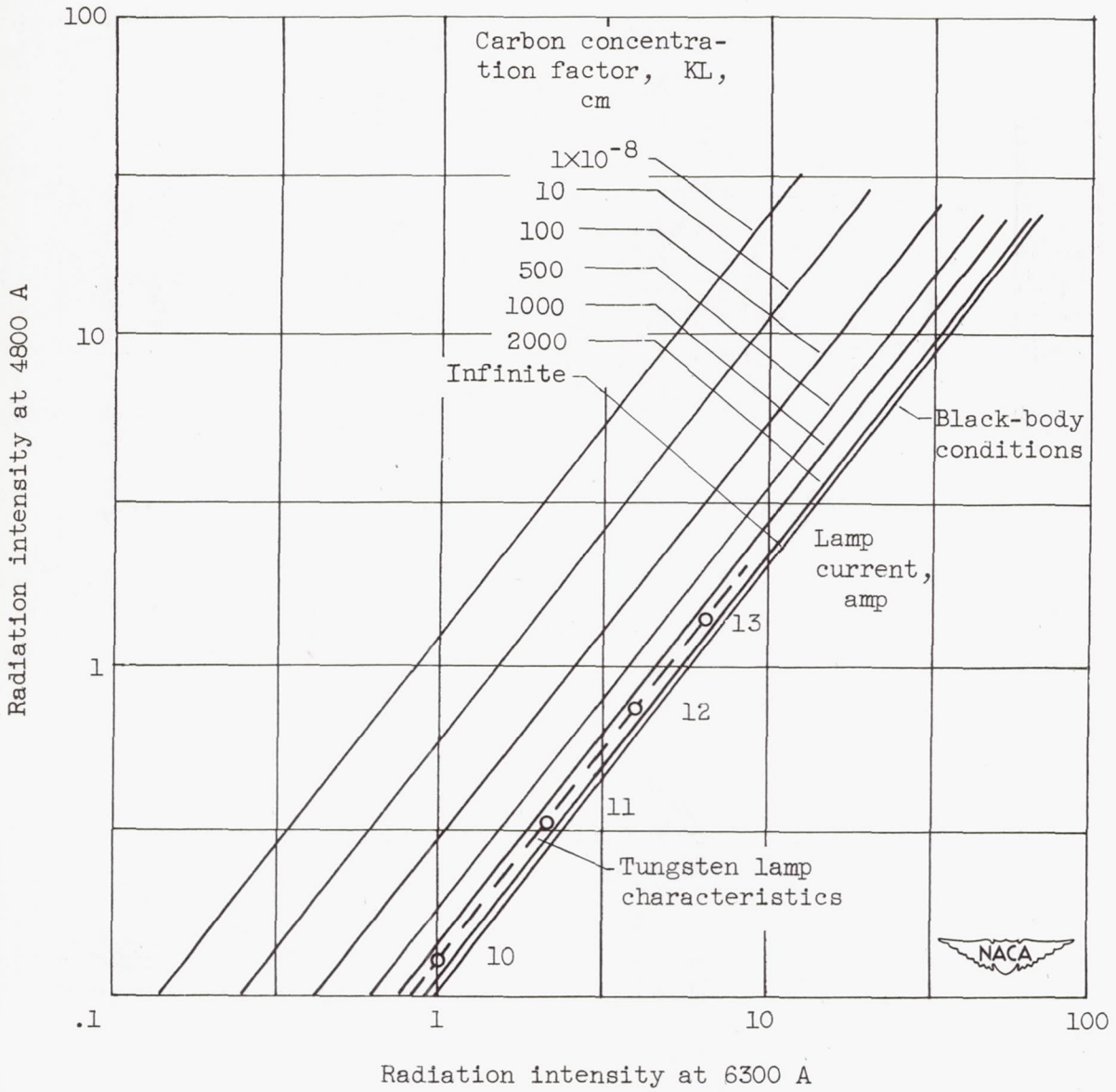


Figure 2. - Theoretical relation between radiation intensities at 4800 and 6300 A for various carbon concentration factors KL (eq. (5)). Arbitrary scale values.

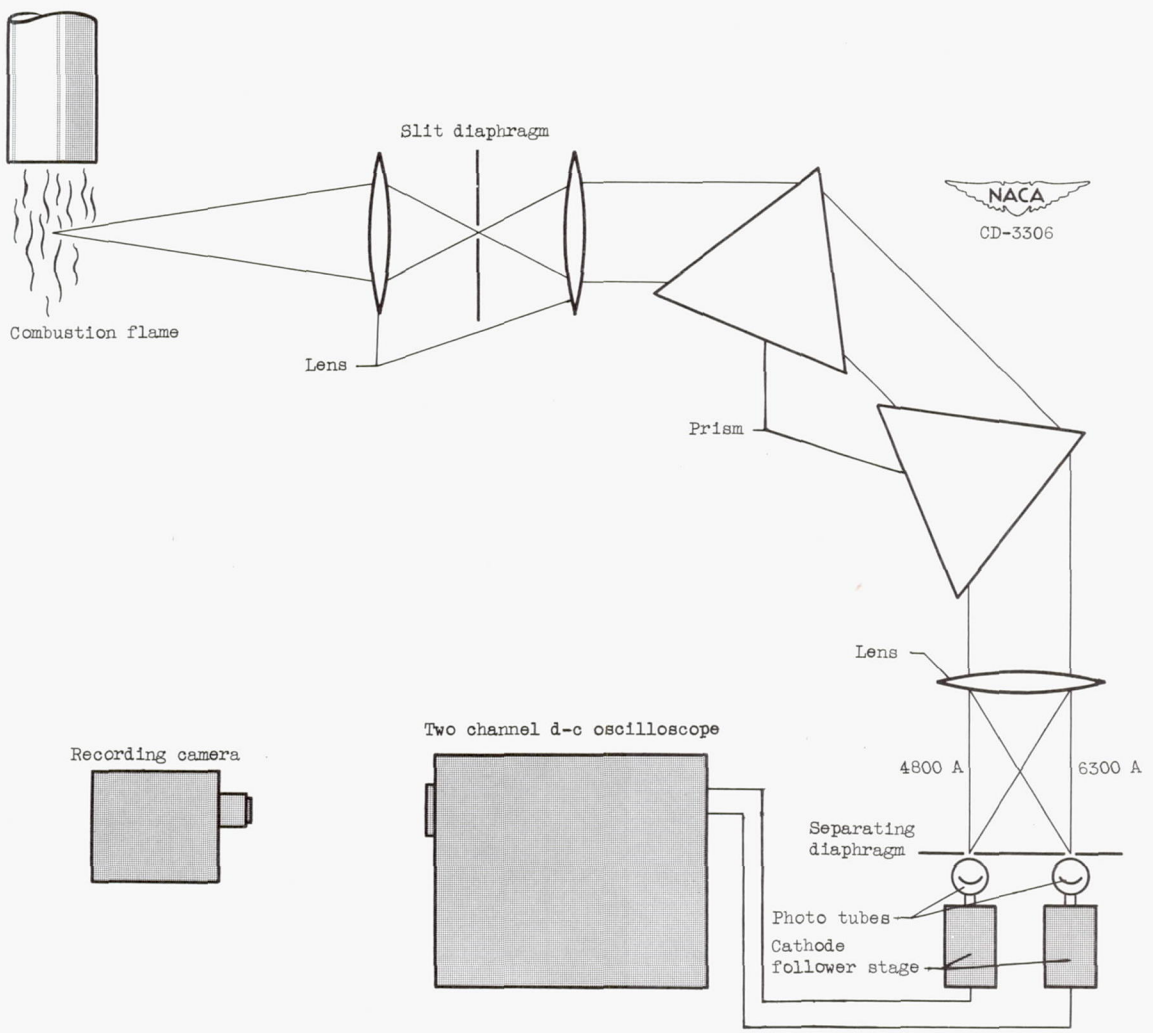


Figure 3. - Schematic plan view of two-color temperature measurement instrumentation.

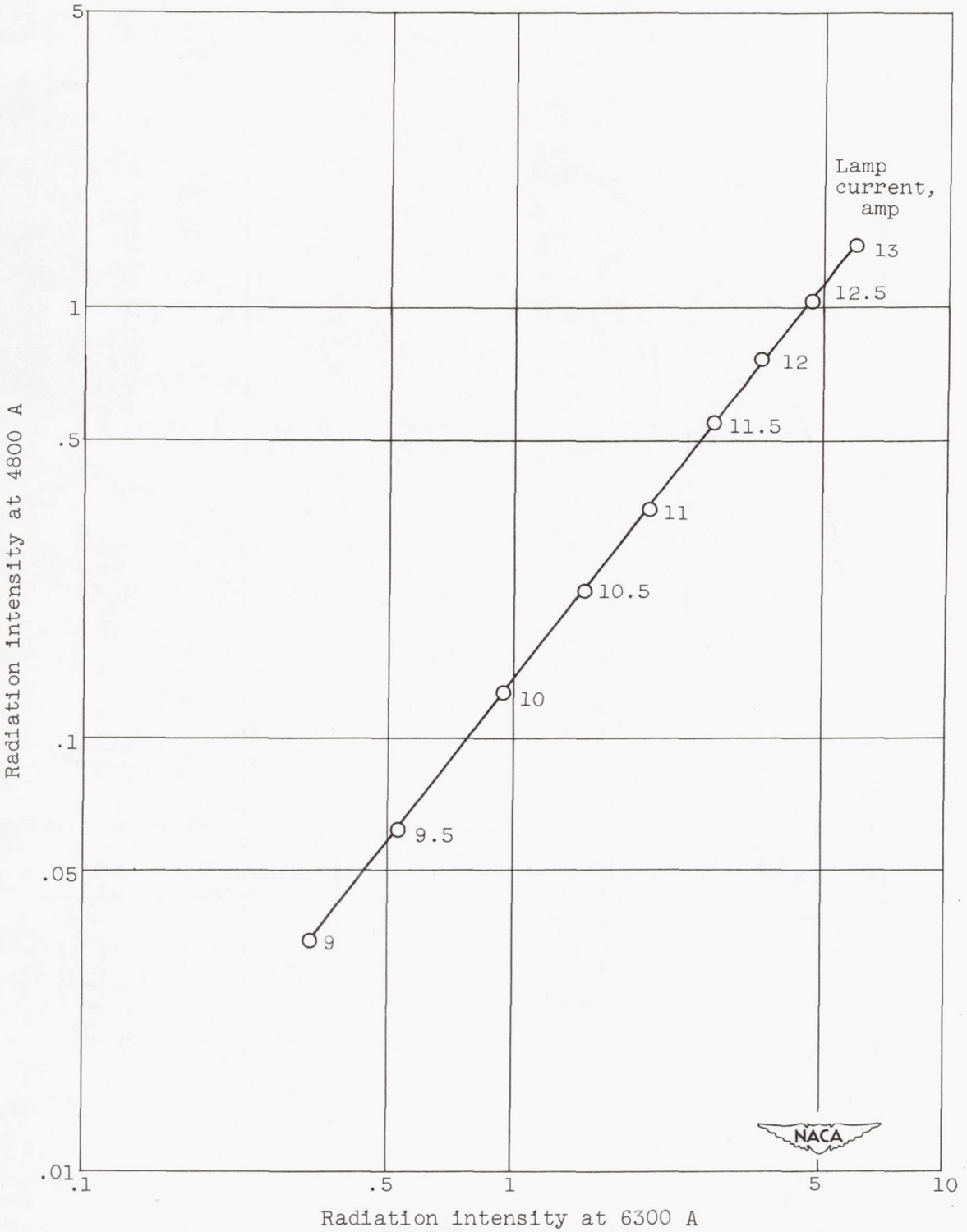


Figure 4. - Radiation intensity of broad-ribbon tungsten lamp at 4800 and 6300 A. Scale values correspond to figures 1 and 2.

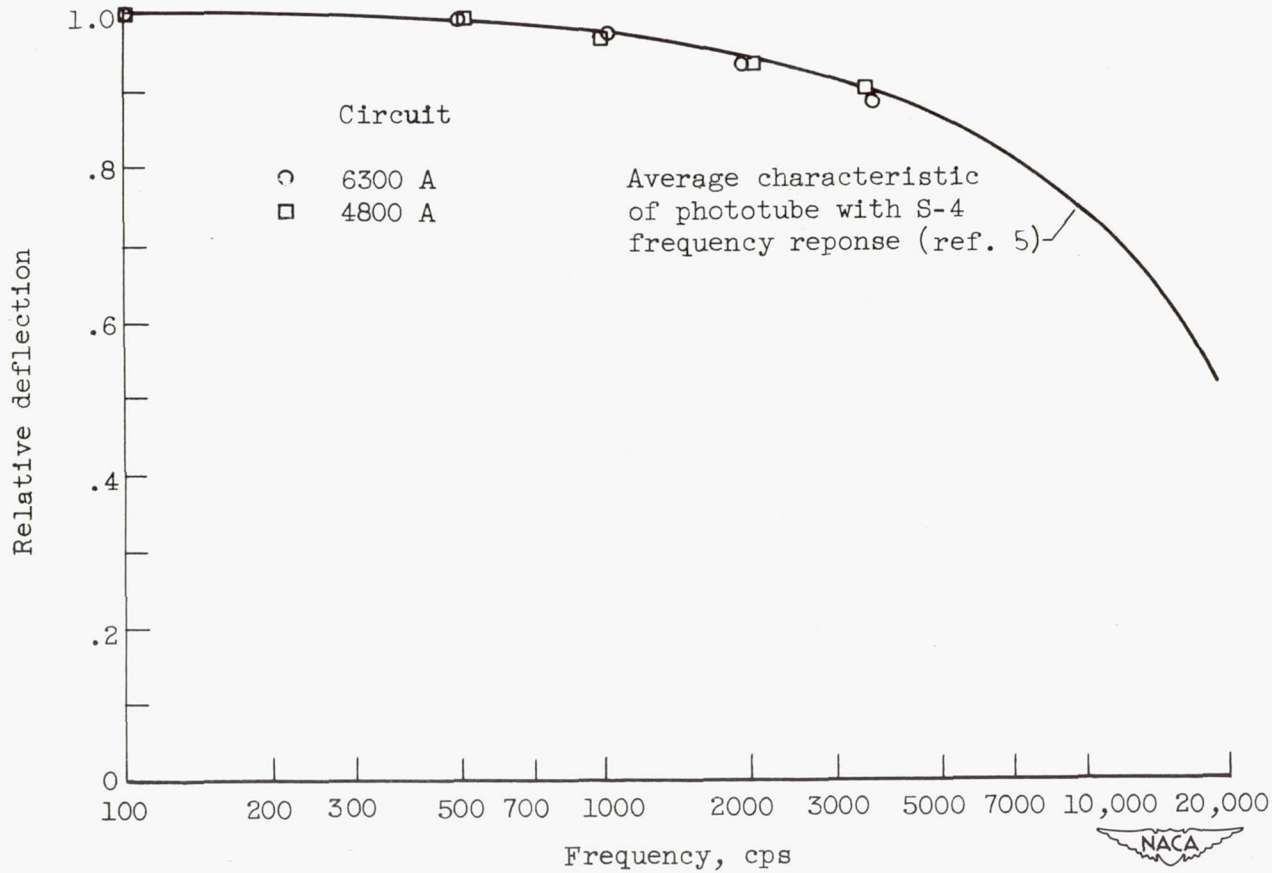


Figure 5. - Frequency response of 6300 and 4800 A photomultiplier tube circuits compared with average response of phototube.

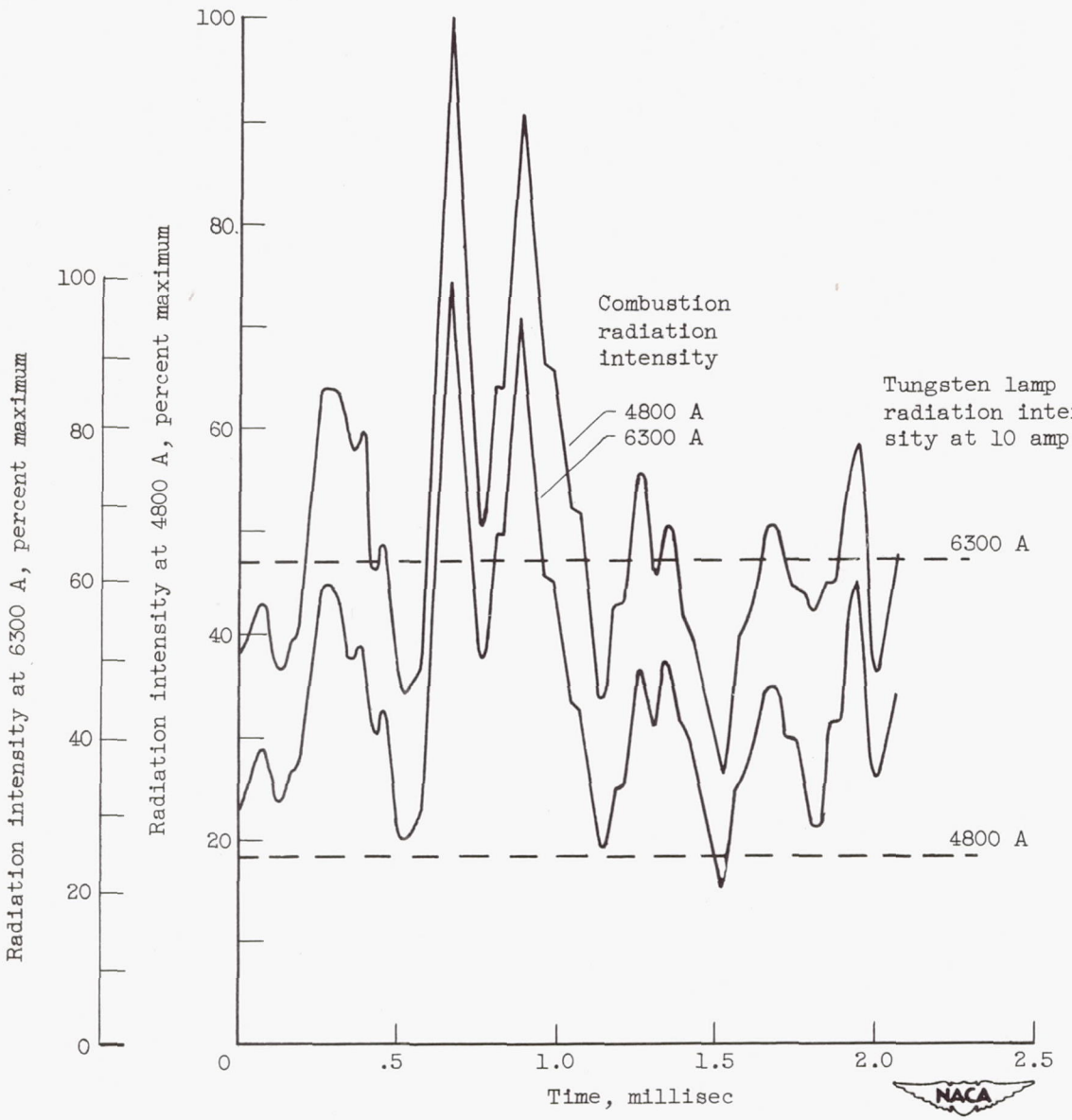
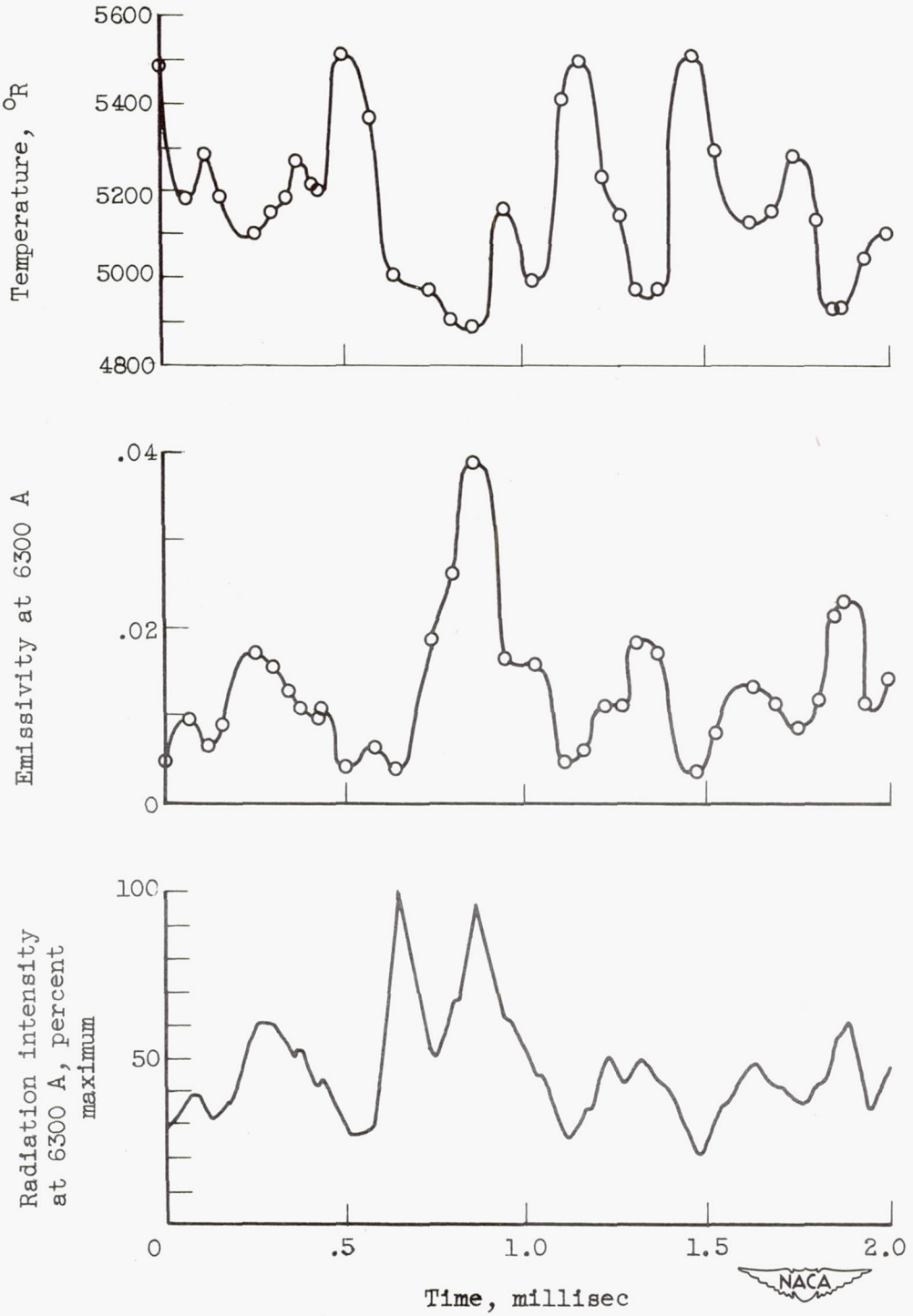
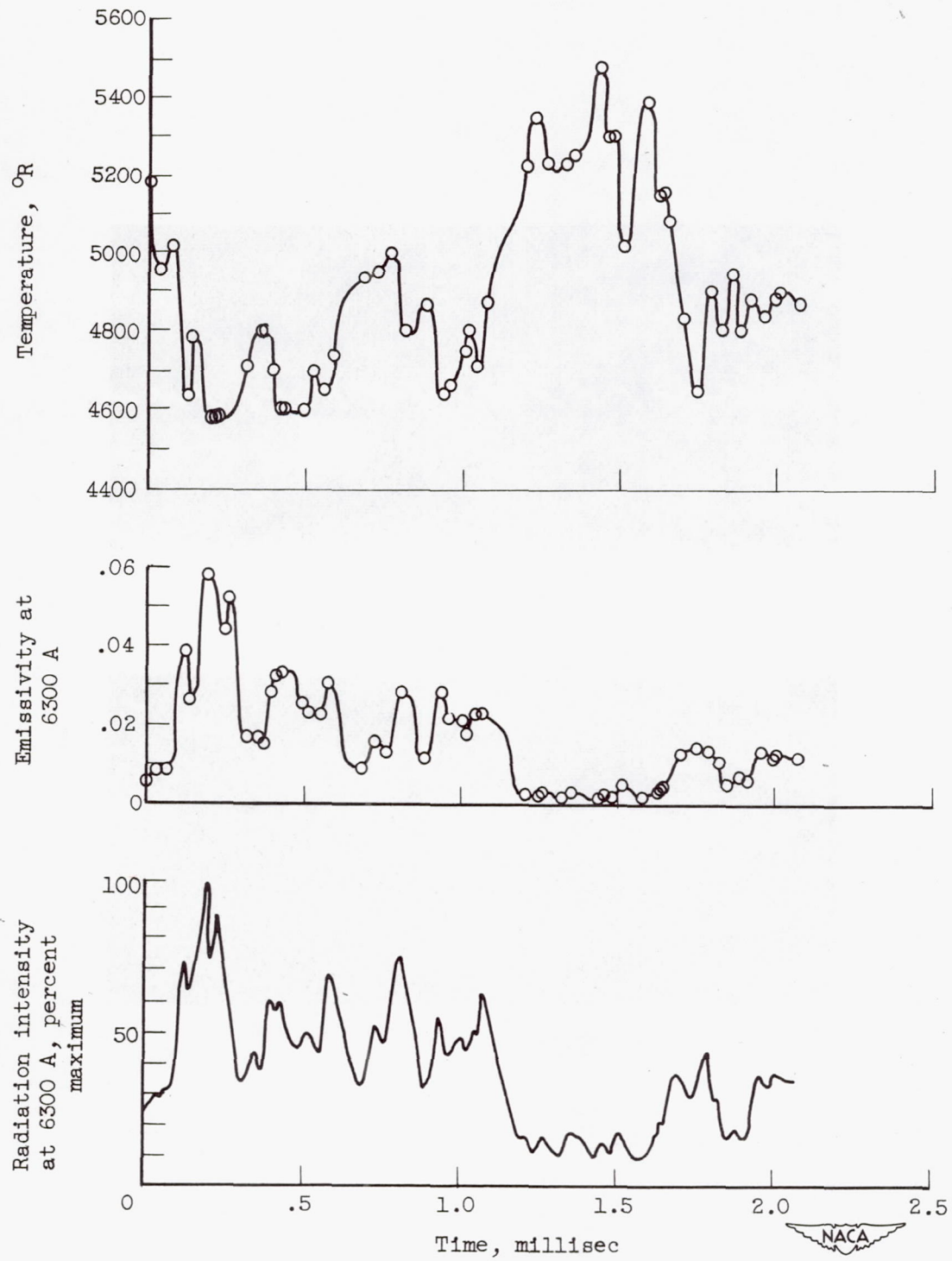


Figure 6. - Radiation intensity signals obtained from combustion during typical firing and reference levels from tungsten lamp.



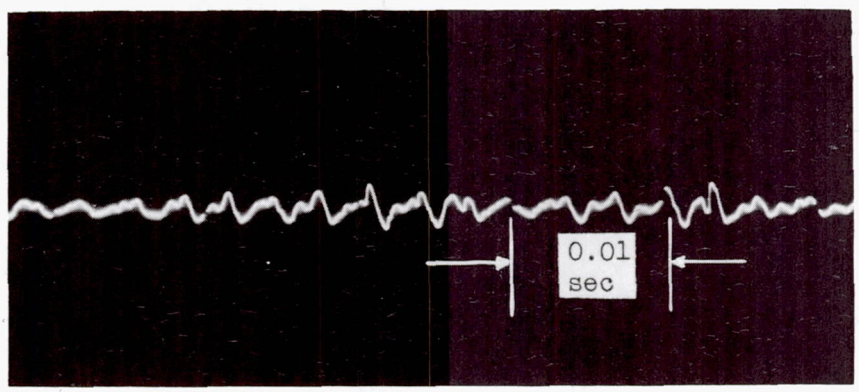
(a) Oxidant-fuel ratio of 2.0.

Figure 7. - Typical temperature, emissivity, and radiation intensity variations during steady burning.

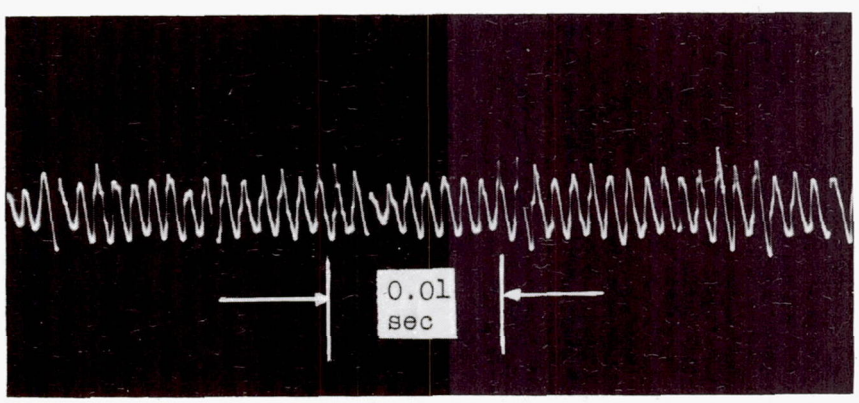


(b) Oxidant-fuel ratio of 2.4.

Figure 7. - Concluded. Typical temperature, emissivity, and radiation intensity variations during steady burning.



Fundamental frequency, 333 cycles per second



Harmonic frequency, 1000 cycles per second

Figure 8. - Typical sound-intensity variations obtained during audible oscillatory combustor operation.

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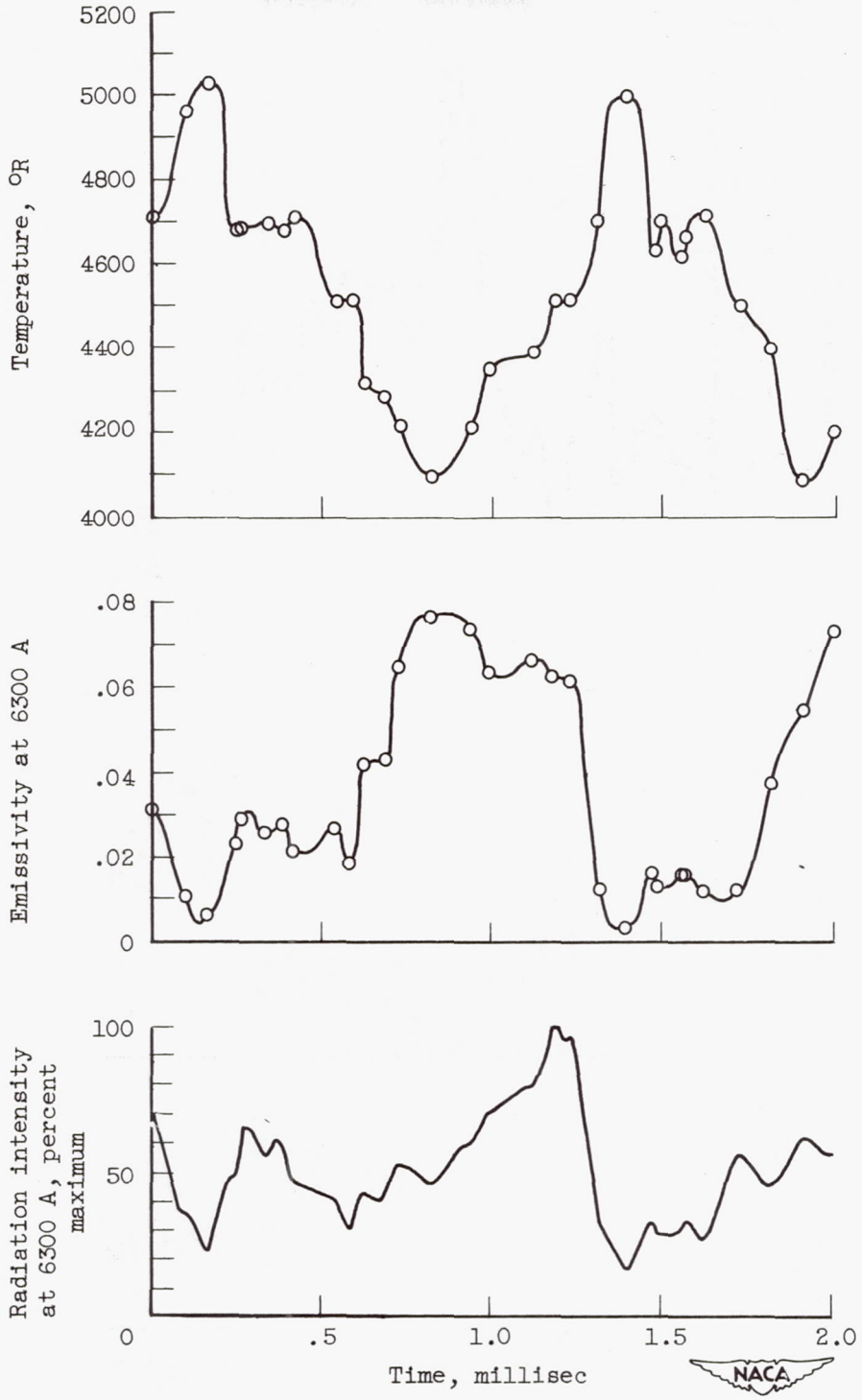
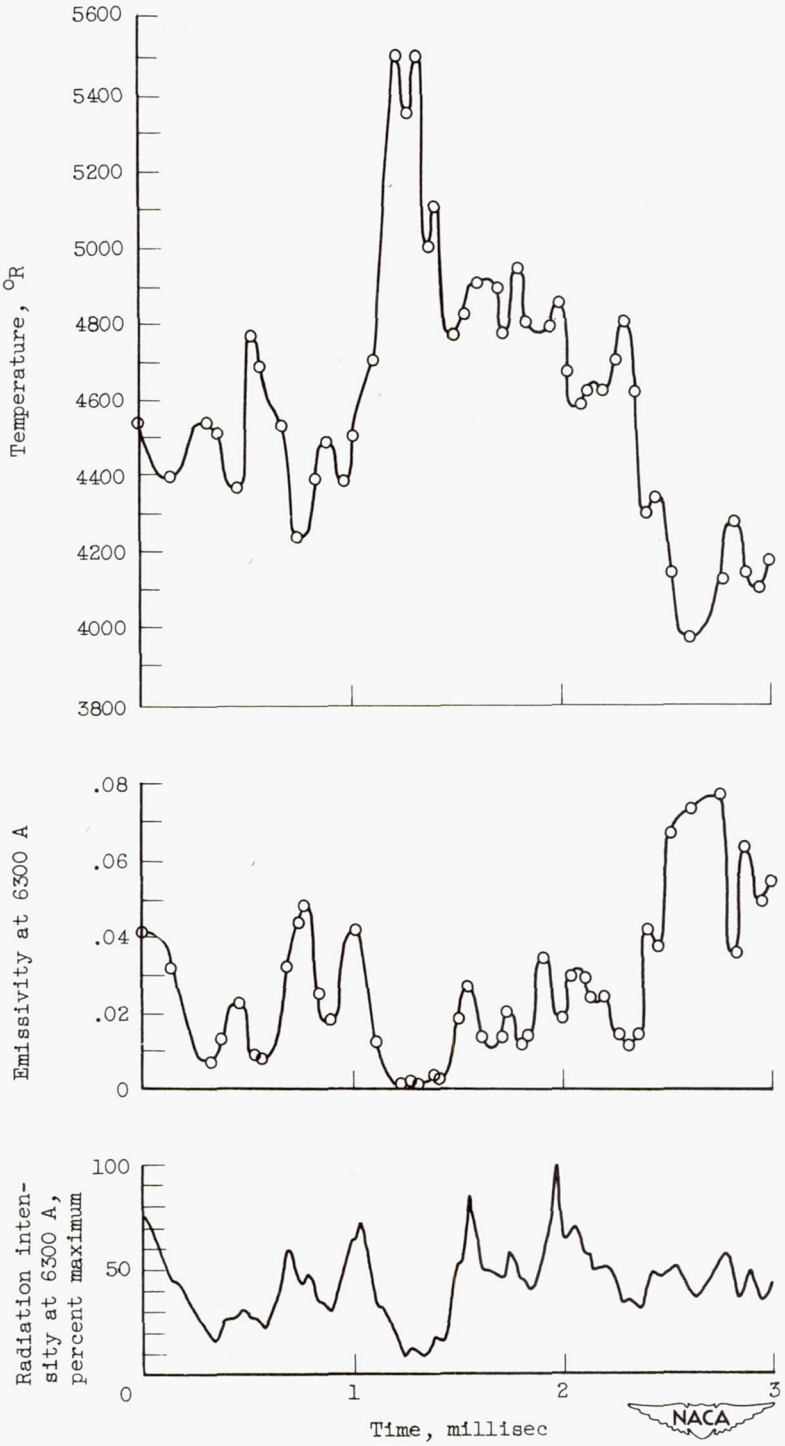


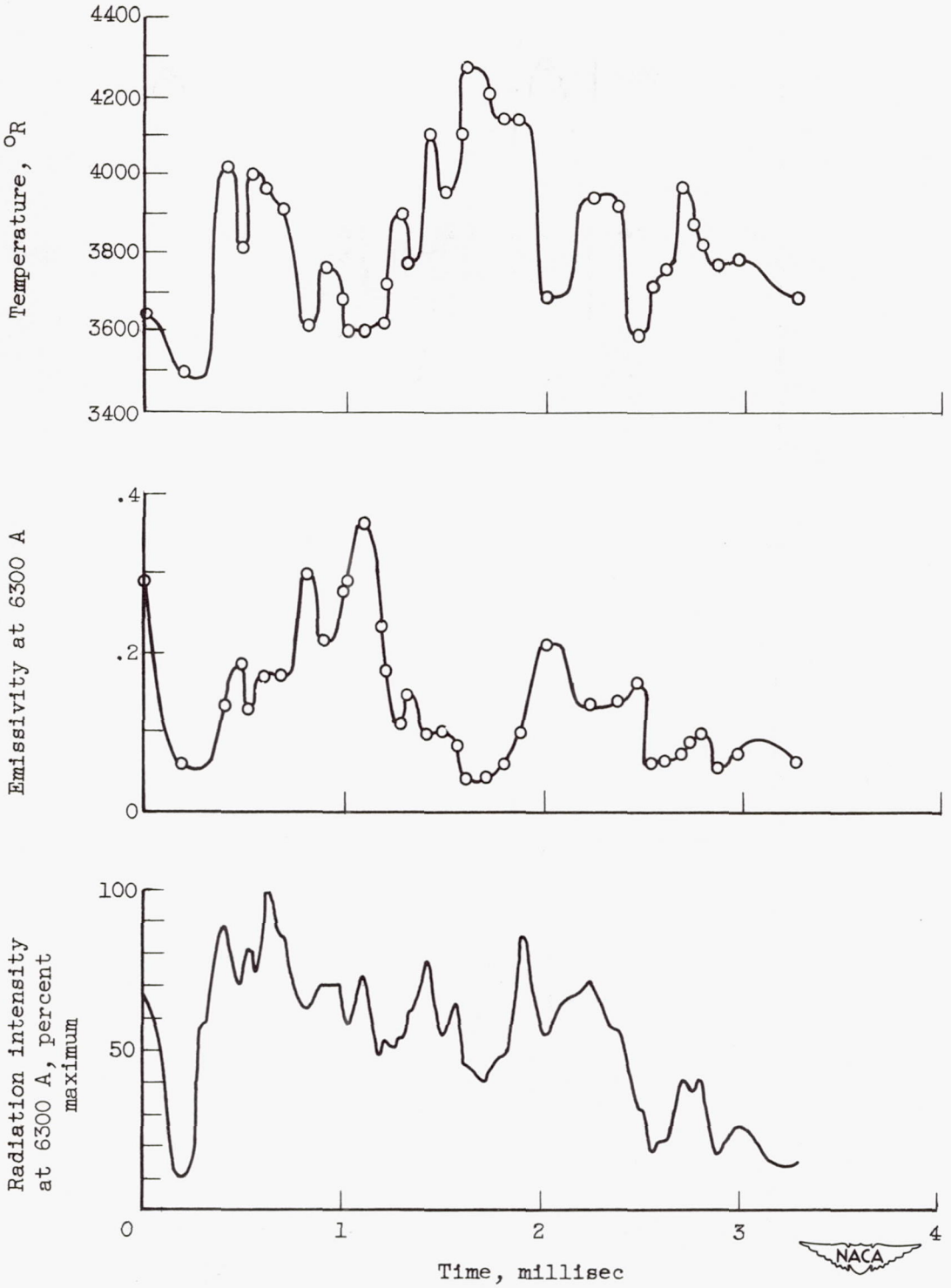
(a) Harmonic frequency.

Figure 9. - Typical temperature, emissivity, and radiation intensity variations for oscillatory combustion at oxidant-fuel ratio of 1.6.



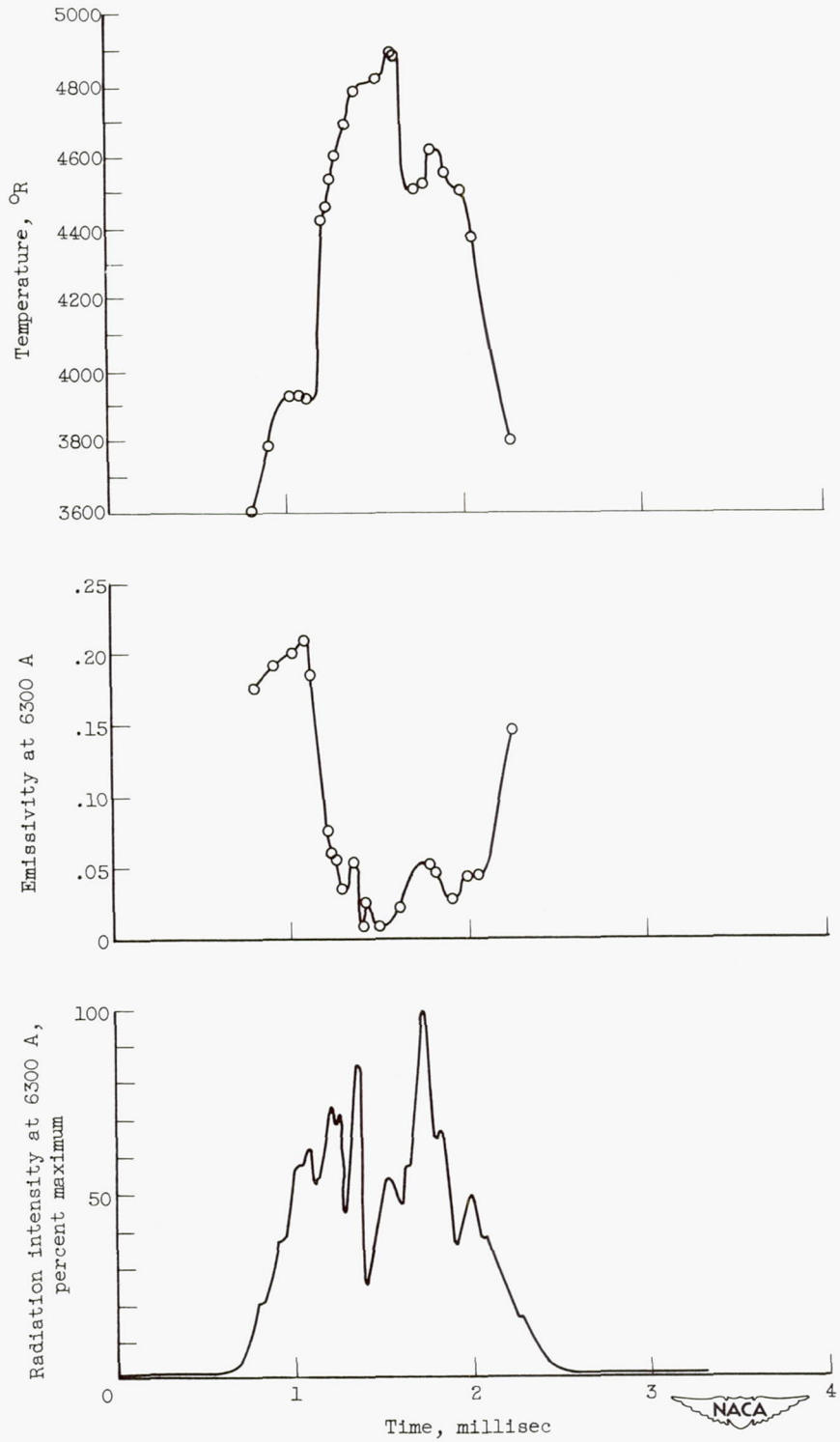
(b) Fundamental frequency.

Figure 9. - Concluded. Typical temperature, emissivity, and radiation intensity variations for oscillatory combustion at oxidant-fuel ratio of 1.6.



(a) Steady burning.

Figure 10. - Typical temperature, emissivity, and radiation intensity variations for firing at oxidant-fuel ratio of 1.2.



(b) Unstable burning.

Figure 10. - Concluded. Typical temperature, emissivity, and radiation intensity variations for firing at oxidant-fuel ratio of 1.2.

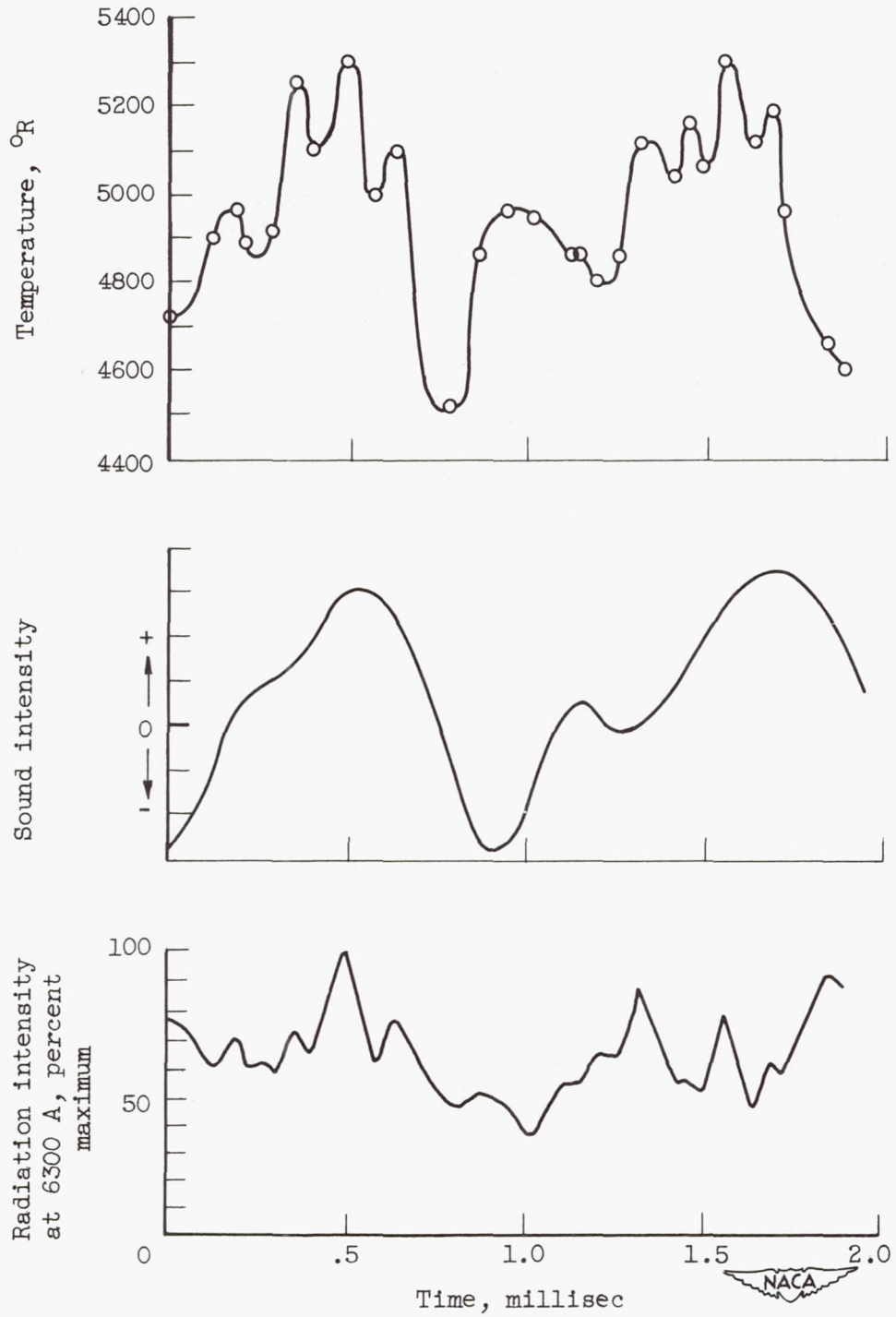


Figure 11. - Temperature and sound intensity measured simultaneously during audible oscillatory combustion at oxidant-fuel ratio of 1.6. Radiation intensity also shown.

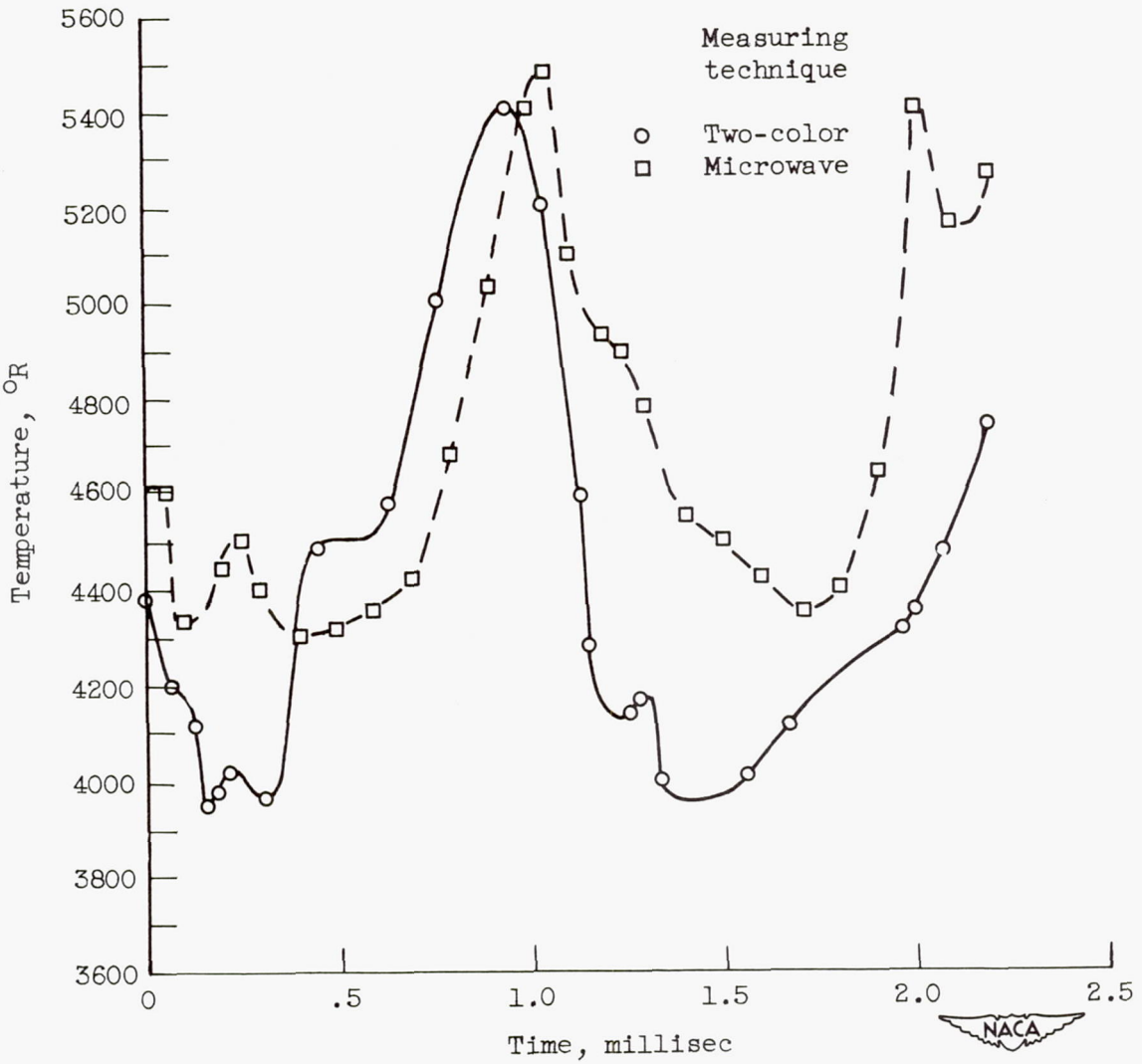


Figure 12. - Comparison of simultaneous measurements of temperatures by two-color and microwave techniques during oscillatory combustion at oxidant-fuel ratio of 2.0.

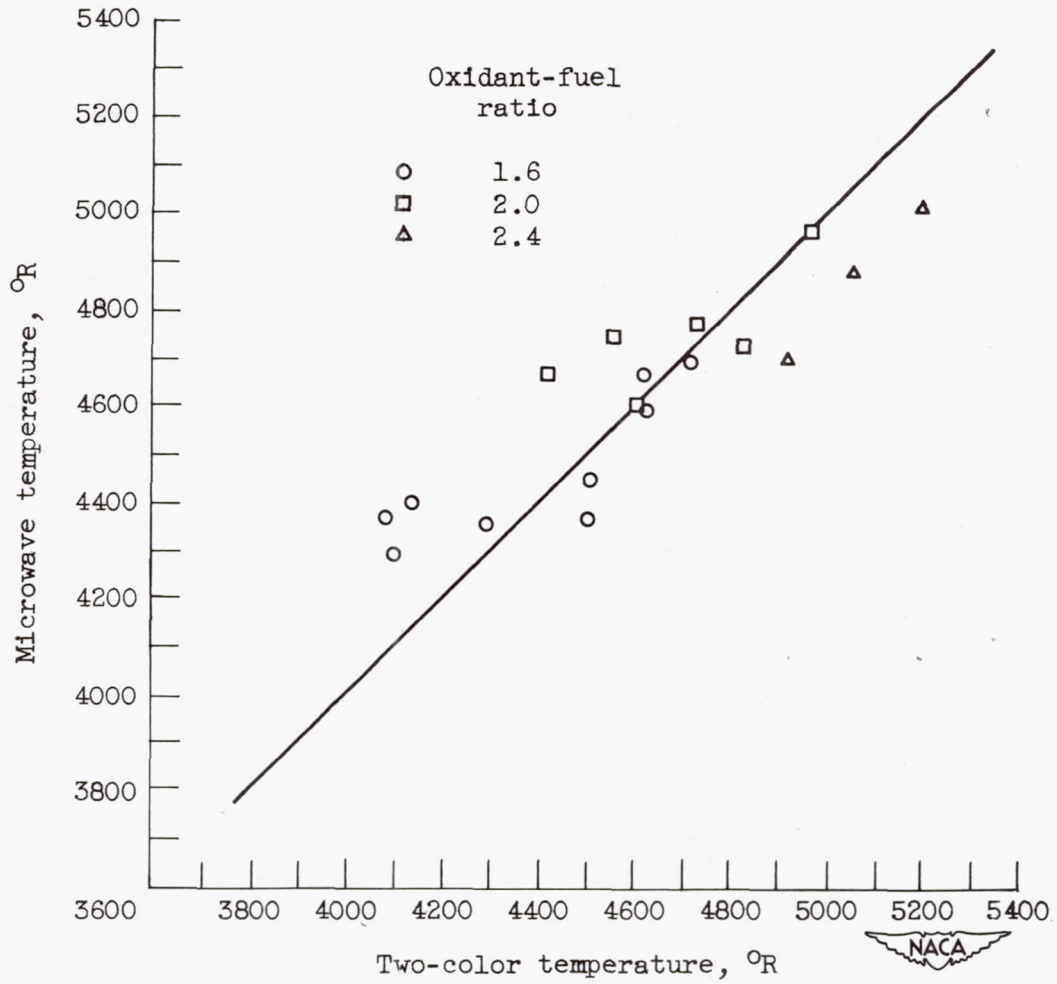


Figure 13. - Comparison of simultaneous measurements of mean temperatures by two-color and microwave techniques over 2-millisecond time intervals.

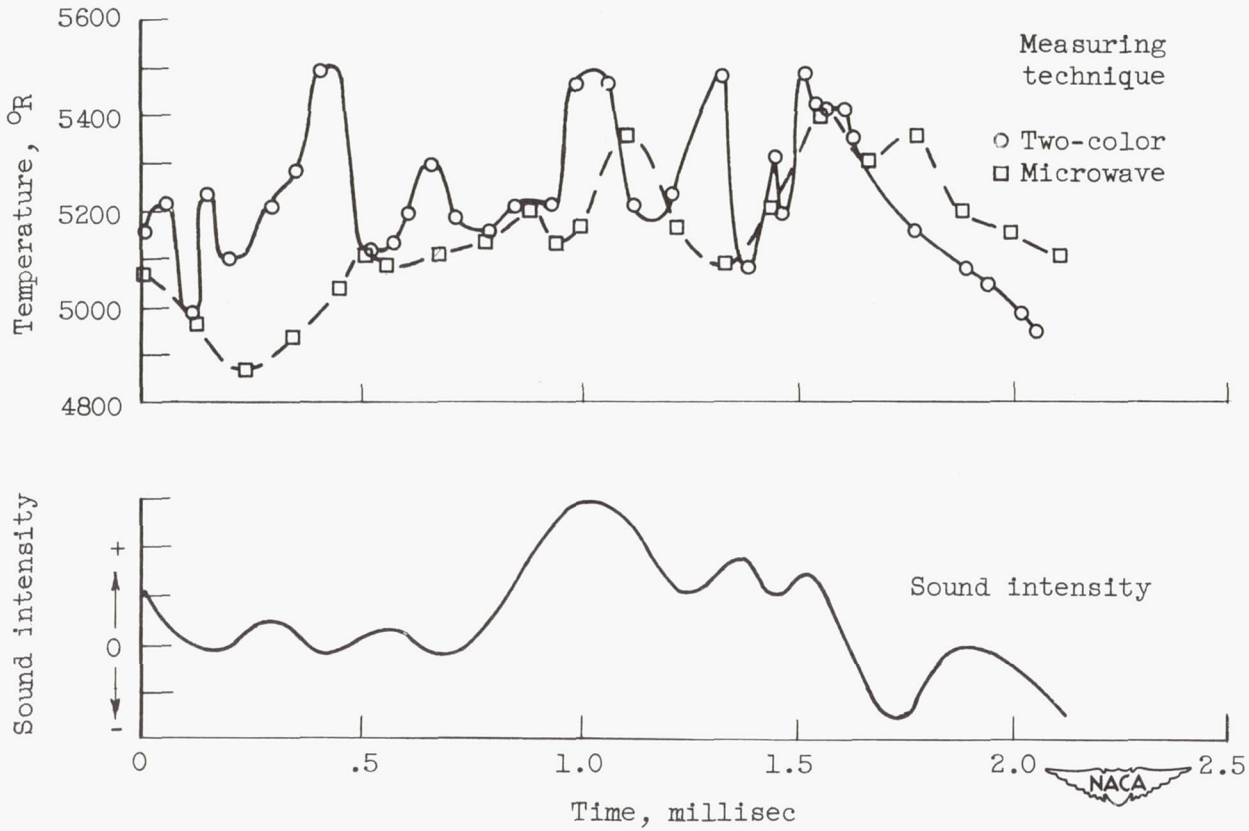


Figure 14. - Comparison of simultaneous measurements of temperatures (by two-color and microwave techniques) and sound intensity during nonoscillatory combustion at oxidant-fuel ratio of 2.4.

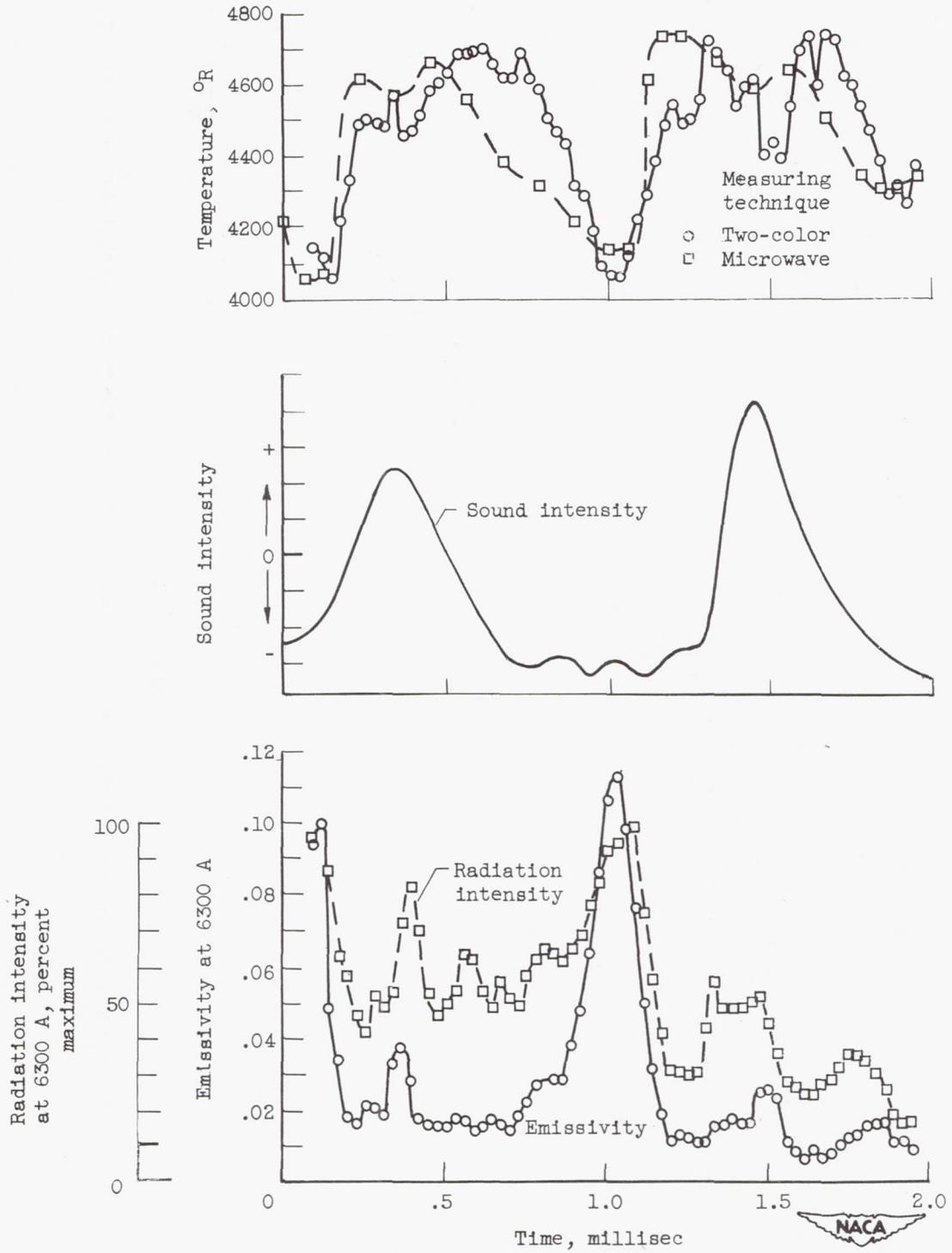


Figure 15. - Comparison of temperatures measured by two-color and microwave techniques, sound intensity, emissivity, and radiation intensity during audible oscillatory operation at oxidant-fuel ratio of 1.6.

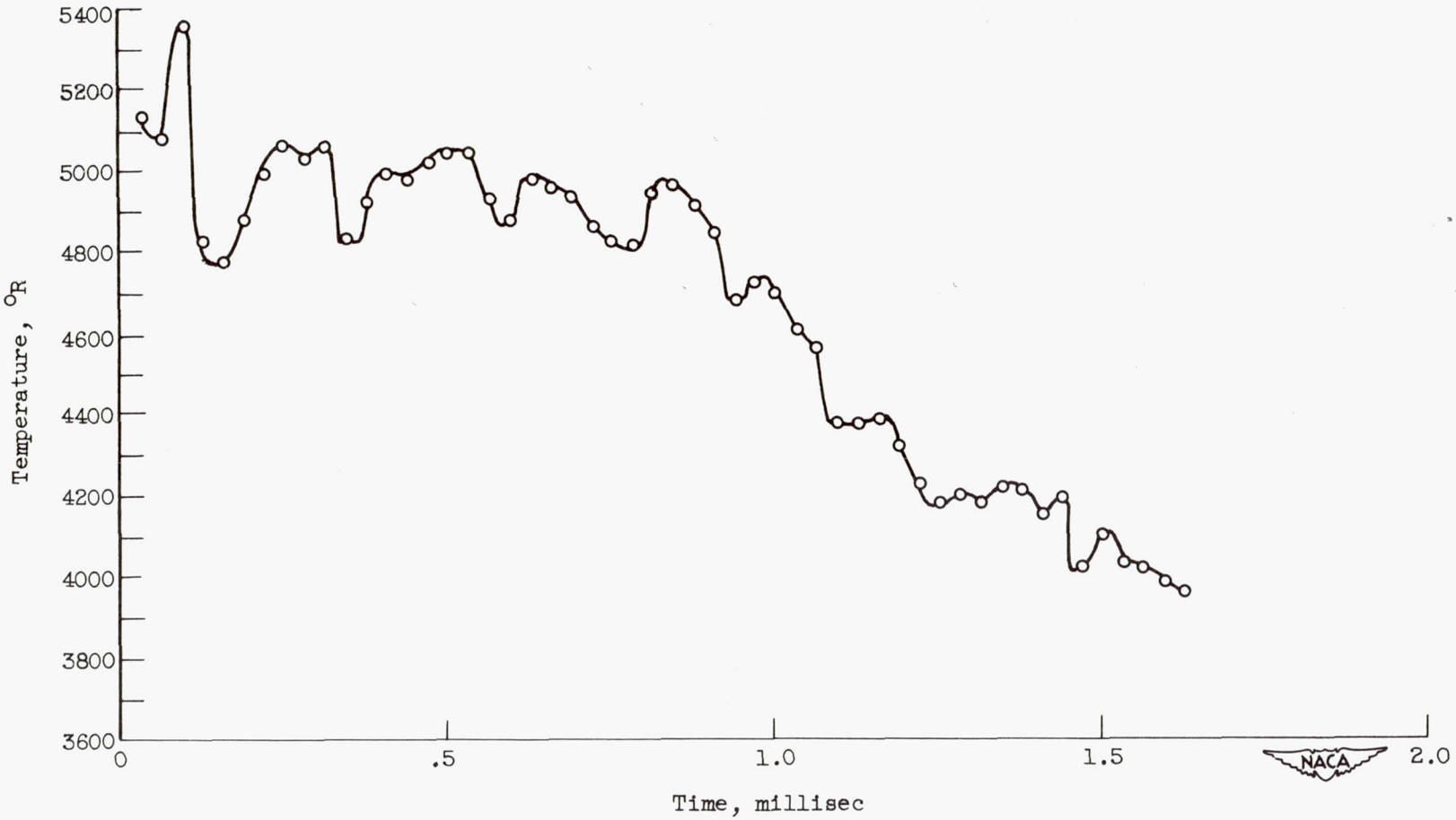


Figure 16. - Temperature variations indicating presence of high-frequency oscillations at oxidant-fuel ratio of 1.6.

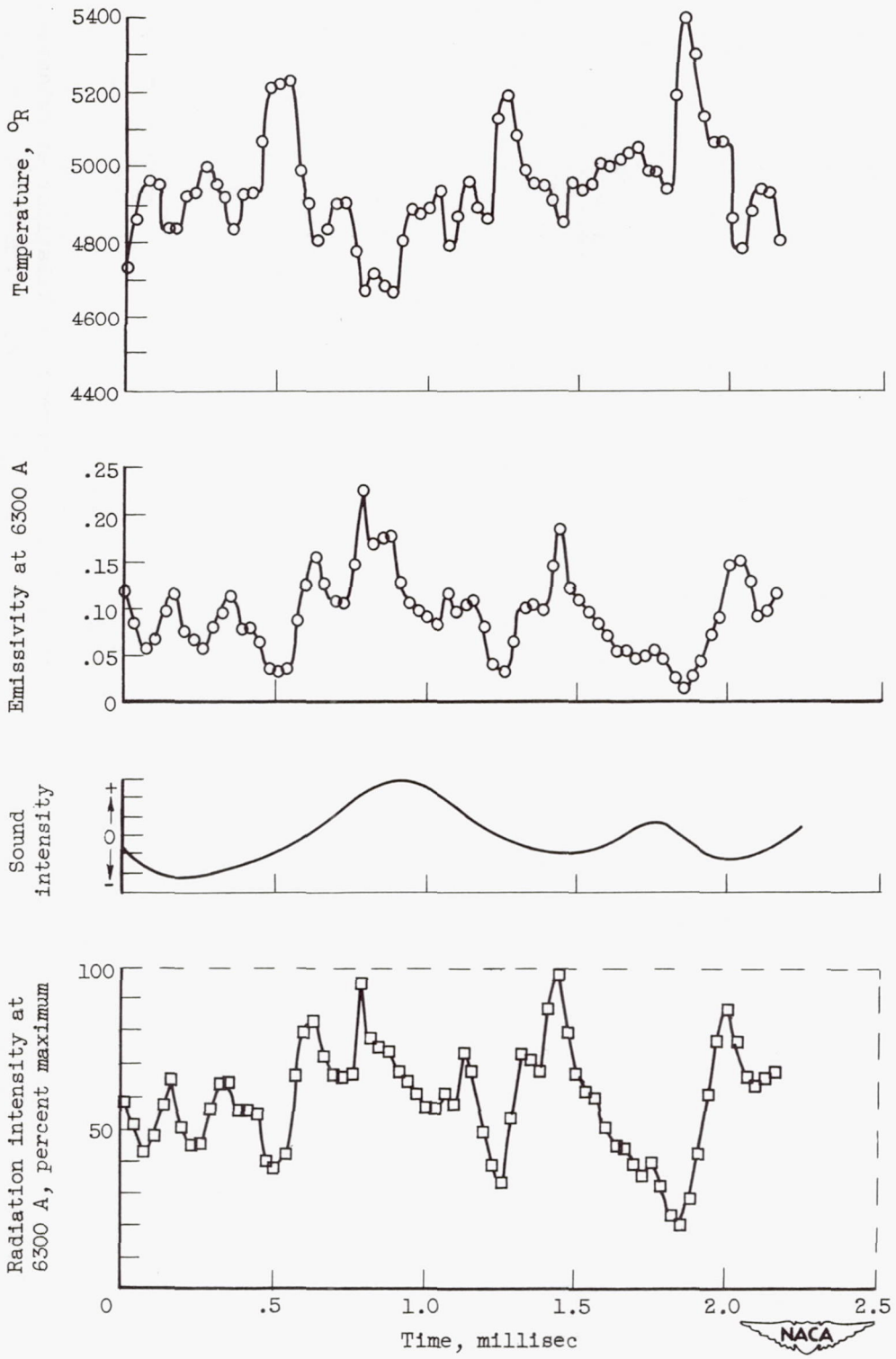


Figure 17. - Comparison of temperature, emissivity, sound intensity, and radiation intensity indicating presence of high-frequency oscillations at oxidant-fuel ratio of 2.4.

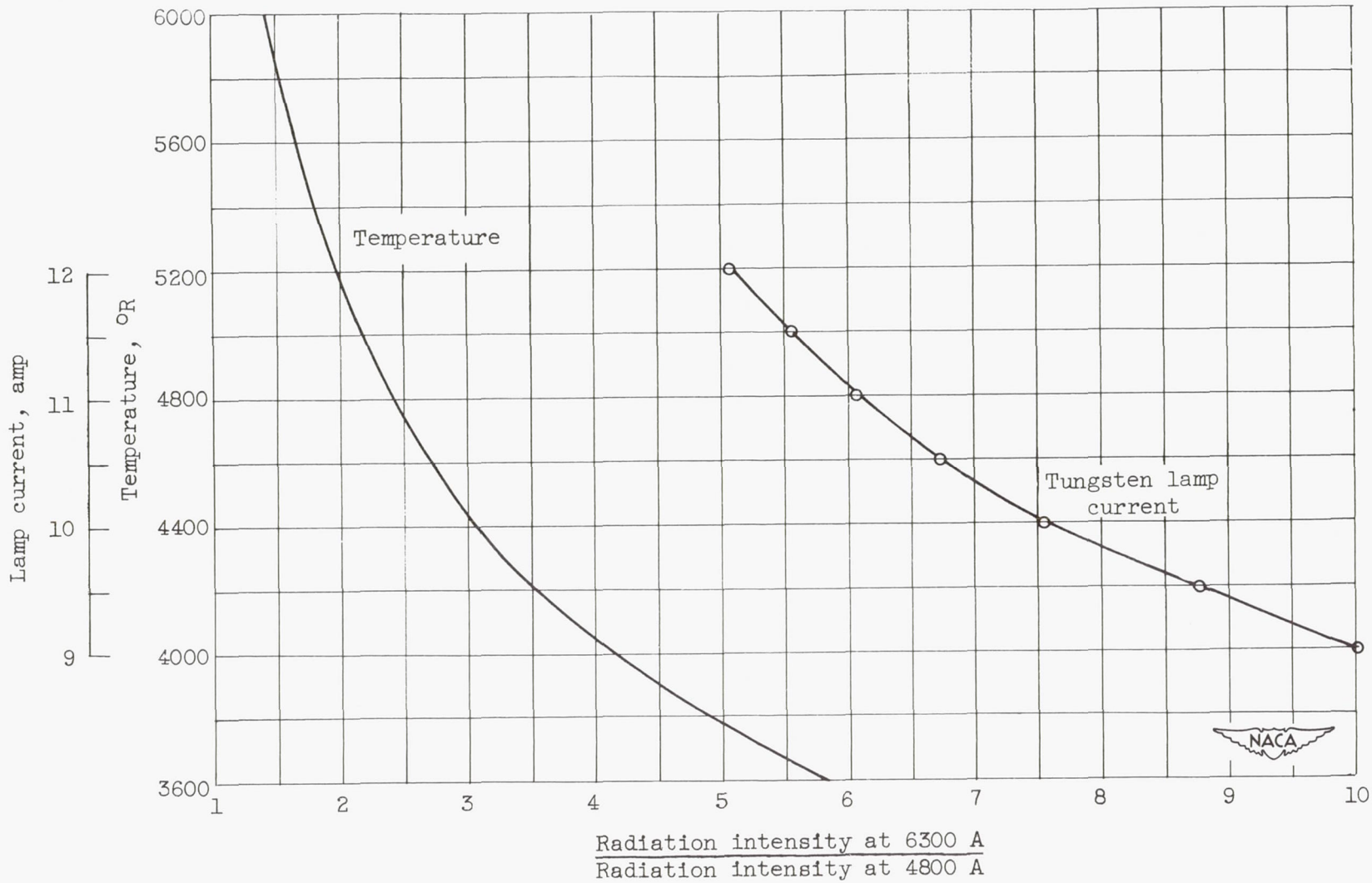


Figure 18. - Variation of temperature with radiation intensity ratio assuming constant emissivity ratio. Tungsten lamp reference conditions also shown.

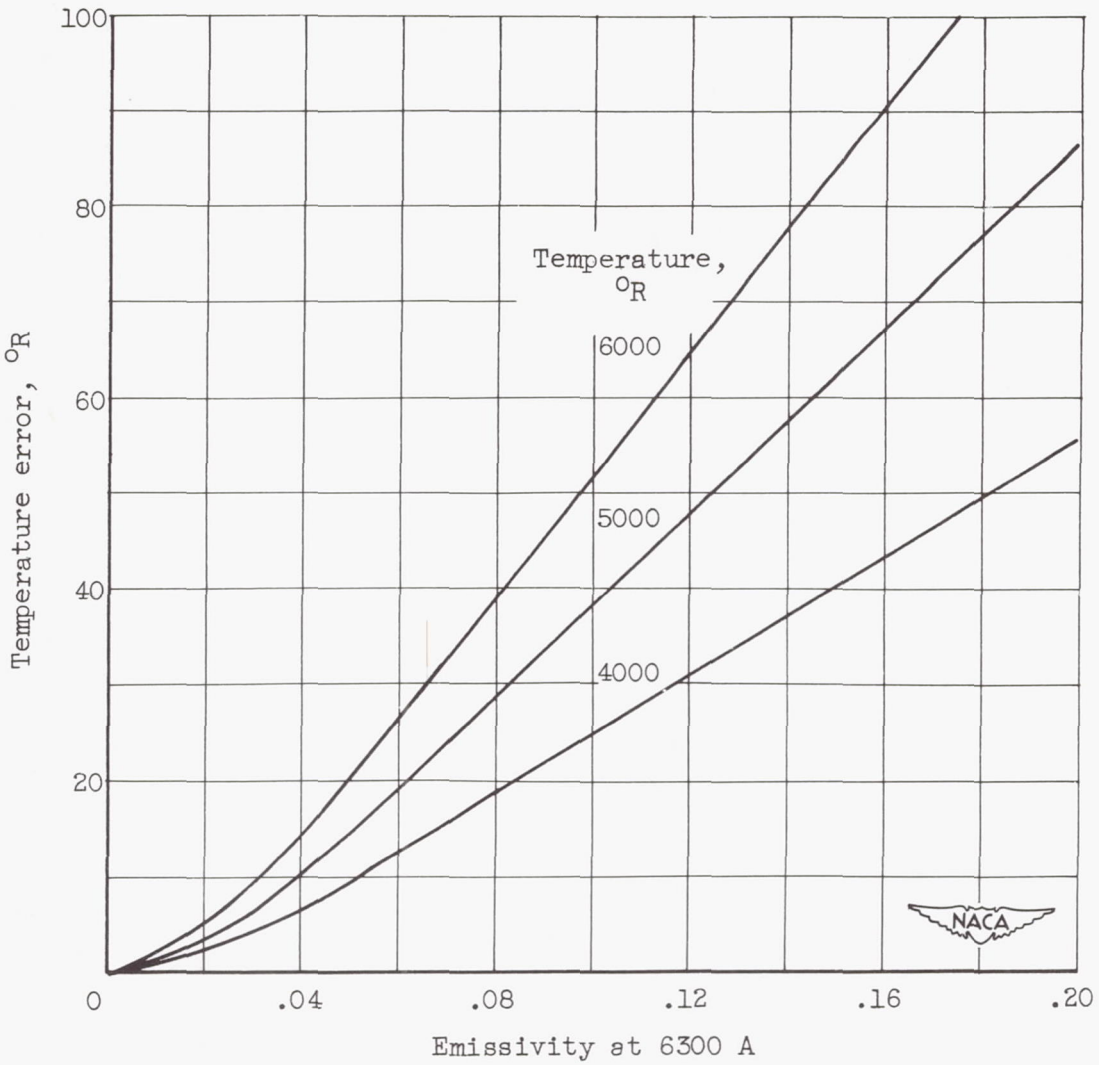


Figure 19. - Error induced by assuming constant emissivity ratio as function of emissivity at 6300 A for various temperatures.

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