

# Color Temperature and Spectral Profile of Some Propellant Grains

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## ABSTRACT

Spectroscopic observations were made on NRL propellant grains ignited in an evacuated environmental chamber. The purpose of these observations was to determine a color temperature and spectral profile of the propellant plumes. Spectrograms were obtained, using a static Hilger Medium Glass Spectrograph and an NRL time-resolved streak spectrograph, from stationary and oscillating propellant plumes. From these recordings, several color temperatures were determined from relative intensity measurements in the spectral range 6100 to 6700A. A time-resolved or "instantaneous" color temperature of 1690°K was determined from a very small area (5/64-in. diam.) of the stationary plume. This determination was made 3.4 seconds after ignition and for an exposure time of 3.88 milliseconds, which is equivalent to the time-resolution of the spectrograph. Other instantaneous color-temperature determinations made at 1.0, 2.0, and 6.0 seconds after ignition are in substantial agreement with the above temperatures. The time-integrated color temperature in the spectral interval 4000 to 5000A, for the complete steady burning time of the propellant, was recorded by the static spectrograph as 2700°K. This may be in error because of molecular emission in the spectral interval. The area of the plume used to determine the latter color temperature was more than fifteen times that of the former. The profile of the plume spectrum from 3700 to 9000A exhibited a continuum upon which is superimposed, for the most part, the atomic emission of aluminum and sodium and the molecular emission system of aluminum oxide. No zones or windows of continuous absorption were found in the continuum for the specified wavelength interval.

## PROBLEM STATUS

This is a final report on one phase of this problem; work is continuing on other phases.

## AUTHORIZATION

NRL Problem A02-17  
Project RR-004-02-42-5152

Manuscript submitted January 15, 1964.

## COLOR TEMPERATURE AND SPECTRAL PROFILE OF SOME PROPELLANT GRAINS

### INTRODUCTION

The Radiometry Branch, Optics Division, was requested to make spectroscopic observations of the plumes from burning NRL propellant grains for the purpose of determining the color temperature and spectral intensity profile of the flames. Observations were made during the week of June 24, 1963, with a static Hilger Medium Glass Spectrograph and a time-resolved NRL prismatic streak spectrograph. The propellant grains were activated by the Radar Techniques Branch, Radar Division, in an environmental chamber which was operated at a pressure of 82 mm of mercury. The chamber pressure was equivalent to an altitude of 15,614 meters, or 51,243 feet.

### SPECTROSCOPIC INSTRUMENTATION

#### Hilger Medium Glass Spectrograph

The optical system of the Hilger Medium Glass Spectrograph (Fig. 1) consists of a variable width slit, a 50-cm  $f/10$  glass collimating lens, a glass prism, and a glass focusing lens which forms a spectral image of the slit in the plane of the photographic emulsion. Both type F and type N emulsions on  $4 \times 10$ -in. glass plates were used to record the spectrum. These plates were later brush developed in Phenidone developer for 15 minutes. The type F emulsion has a useful wavelength range of 2500 to 6800A, and the range of the type N emulsion is from 2500 to 9000A. However, the low-wavelength cutoff of the system was limited to 3600A by the glass optics.

#### The $f/11.0$ Prismatic Streak Spectrograph

The  $f/11.0$  prismatic streak spectrograph (1,2) is a time-resolving instrument designed for use in the near-ultraviolet and visible regions. The optical system consists of crystalline quartz and lithium fluoride lenses for the collimating and imaging elements, and crystalline quartz prisms mounted in a Cornu dispersing arrangement. A pinhole serves as the entrance aperture of the spectrograph. The instrument is stigmatic and operates at a magnification of unity. The pinhole spectrum for a static exposure of a source with emission lines is a row of dots (spectral images) representing the emission wavelengths in the source. For a source radiating a continuum, the spectrum is a line oriented in the direction of dispersion. When the recording film is moved, the instrument records a streaked, or time-resolved, spectrum which represents the time-history of the radiating optical phenomenon. The linear speed of the film used in these spectroscopic observations was 3.04 in./sec. With this film speed and a 0.007-in.-diam entrance pinhole aperture, the spectrograph possessed a time-resolution of 3.88 milliseconds. The wavelength range of the spectrograph is from 2950 to well above 8000A. The reciprocal linear dispersion is 80A/mm at 4000A, 120A/mm at 5000A, and 360A/mm at 6000A.

Kodak Tri-X Aerecon 70-mm film was used to obtain the various time-resolved spectrograms from this streak spectrograph. The film was developed for 15 minutes at 68°F

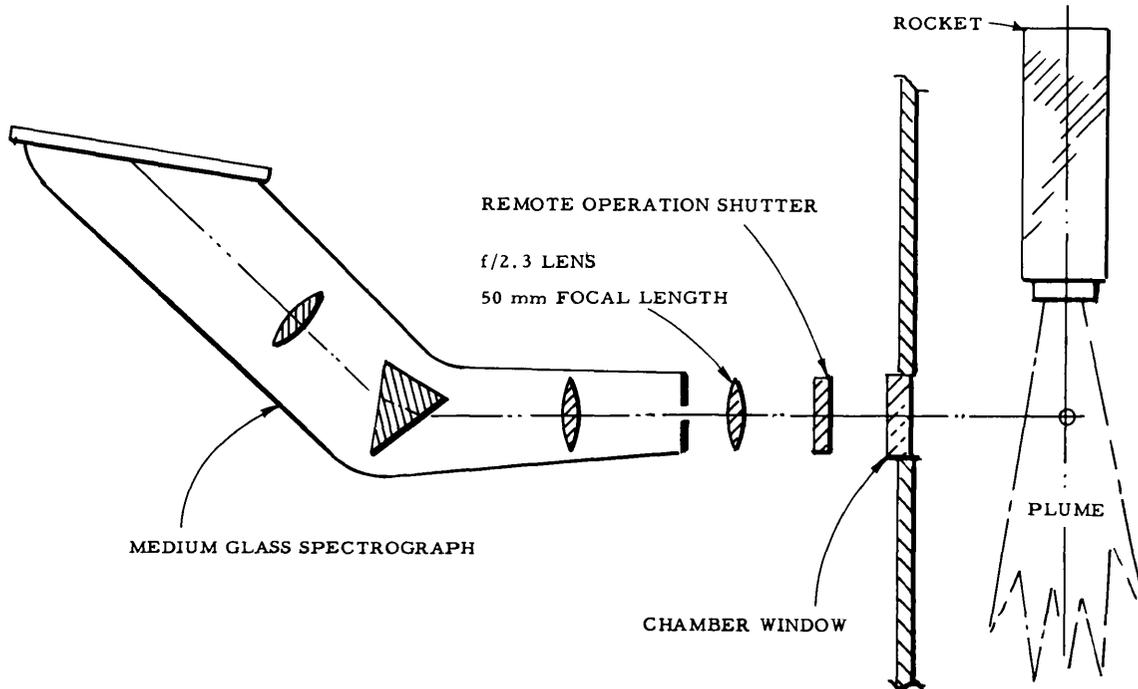


Fig. 1 - Schematic diagram of Hilger Medium Glass Spectrograph optical system

in x-ray developer in a Fairchild reciprocating tank. The spectral sensitivity of the film, as indicated from Kodak data, covers the range from 2500 to approximately 7200Å.

The external optical system used to image the observation spot or spatial area of the plume onto the entrance aperture of the spectrograph consisted of an f/4.5 Kodak Ektar 12-in. focal length glass lens and a periscopic arrangement of three front-surfaced mirrors. The mirror system projected the line of sight of the spectrograph through the port window of the evacuated chamber to the propellant plume. The magnification of the external imaging system was 11.26. The projected area of the 0.007-in.-diam aperture of the spectrograph upon the plume was 0.079 inch in diameter (approximately 5/64 inch).

The low-wavelength cutoff of the Ektar lens is approximately 3500Å, and the long-wavelength limit of the film is 7200Å. Hence, the wavelength range of the spectrograph under these conditions is 3500 to 7200Å.

#### EXPERIMENTAL PROCEDURE

The propellants in the chamber were held in a mechanism which could be adjusted to any desired position in the vertical plane. The mechanism could also be activated to sweep the flame in the vertical plane through an arc of 37°45'. One cycle of this oscillation consisted of an up and a down sweep of the plume. The time for a complete cycle was 3.49 seconds.

Light from the plume of the rocket emerged from the environmental chamber through a glass port. An f/2.3 achromatic lens, used to limit the field of view of the Hilger spectrograph, formed an image of a portion of the plume on the spectrograph slit. The width of

the slit was set at 0.10 mm. The light entering the slit was dispersed by the prism, and the spectrum was recorded on either I-F or I-N plates. A remotely controlled shutter placed between the chamber window and the achromatic lens was opened only after the rocket motor had begun to burn steadily.

The portion of the plume that was observed was a vertical strip 5 mm wide and 54 cm long, located 10 in. from the rocket throat. The plume was viewed approximately perpendicular to the axis of the plume.

The NRL time-resolved spectrograph made three types of observations, represented schematically in Fig. 2. As indicated in the figure at position A, the flame was swept across the spectrograph's observation spot in object space in such a manner that the flame entered this area, swept upwards to well beyond the center of the flame, and then reversed itself in a downward sweep. At position B in Fig. 2, the entire flame traversed the observation spot twice in each cycle of the mechanism, giving a complete up and down sweep of the plume. Also shown in Fig. 2 at position C, the plume was held stationary at an angle of 6.5 degrees below the horizontal. In order to present a composite diagram of the observations, the flame is shown as being stationary and the observation spot is illustrated as a moving aperture. In the actual experiment, the converse is true. The dimensions of the plume and observation positions are drawn to scale, and their dimensions and locations are readily obtained from the coordinate system incorporated in Fig. 2.

## RESULTS

Emission spectra were obtained with the Hilger medium spectrograph for both a stationary flame and a nutating flame. Figure 3 shows one of the spectra of a stationary firing, as recorded on a type I-F plate, and a mercury calibration spectrum beside it. The AlO bands are clearly visible, as are the Al lines in the violet and the Na doublet. A doublet and three other lines appeared in the violet region. The doublet, located at 4031 and 4033A, was attributed to Mn I, and the three lines of wavelengths 4254, 4275, and 4290A were attributed to Cr I. Other emission lines appeared in the ultraviolet but were not readily identifiable.

Two exposures of a nutating flame were made on an N plate (Fig. 4) which extends the wavelength coverage beyond the 6800A cutoff of the F plate to 9000A. The darker area in the 5000 to 6000A region is characteristic of the N emulsion. Densitometer traces, such as the one for an F plate in Fig. 5, were made through the central portion of each spectrum.

An estimate of the temperature of the plume was made by a method described by Curcio and Sanderson (3) in their early investigations of rocket flames. The method employs Wien's equation

$$N_{\lambda} = \epsilon_{\lambda} C_1 \lambda^{-5} e^{-C_2/\lambda T} \quad (1)$$

where

$N_{\lambda}$  = spectral radiance (watts-cm<sup>-2</sup>) at wavelength  $\lambda$

$\epsilon_{\lambda}$  = spectral emissivity at wavelength  $\lambda$

$C_1$  = first radiation constant (ergs-cm<sup>2</sup>-sec<sup>-1</sup>)

$\lambda$  = wavelength (cm)

$C_2$  = second radiation constant ( $C_2 = 1.439$  cm-°K)

$T$  = temperature in °K.

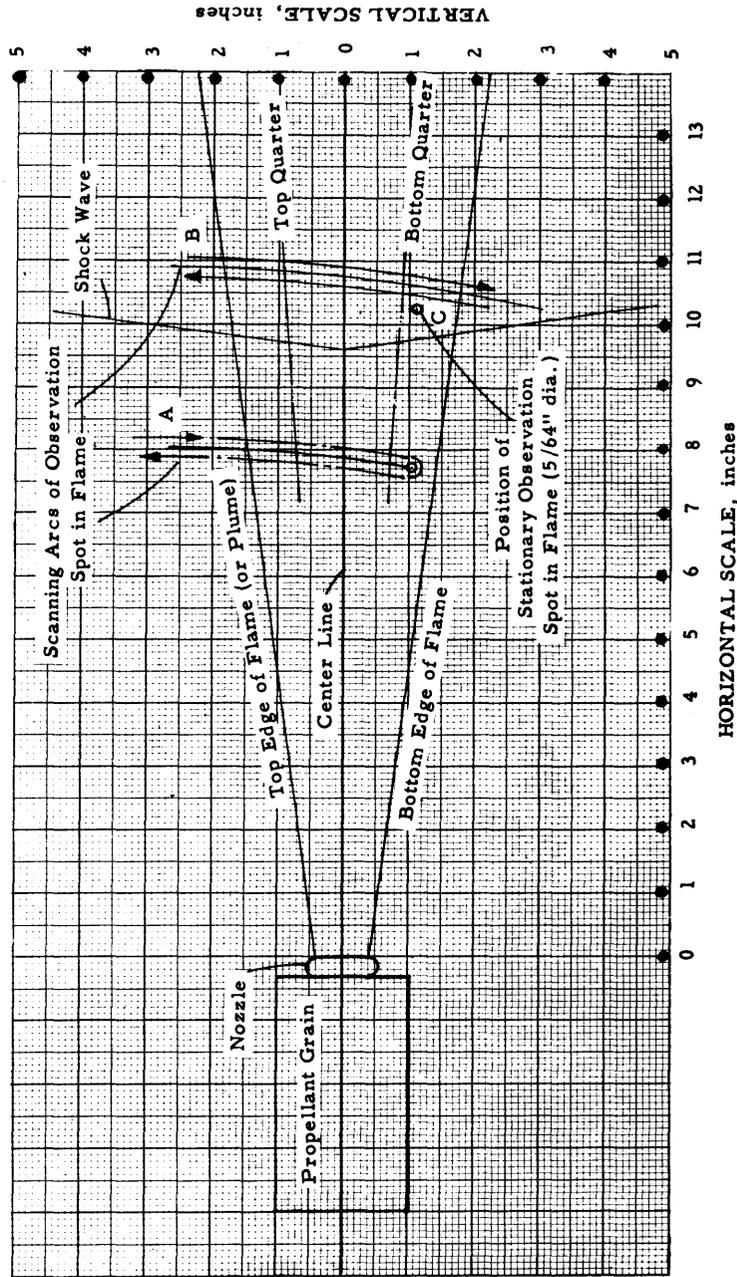


Fig. 2 - Schematic representation of three types of observations made on propellant plume by NRL time-resolved spectrograph. The dimensions and locations of the plume and observation positions are drawn to scale.

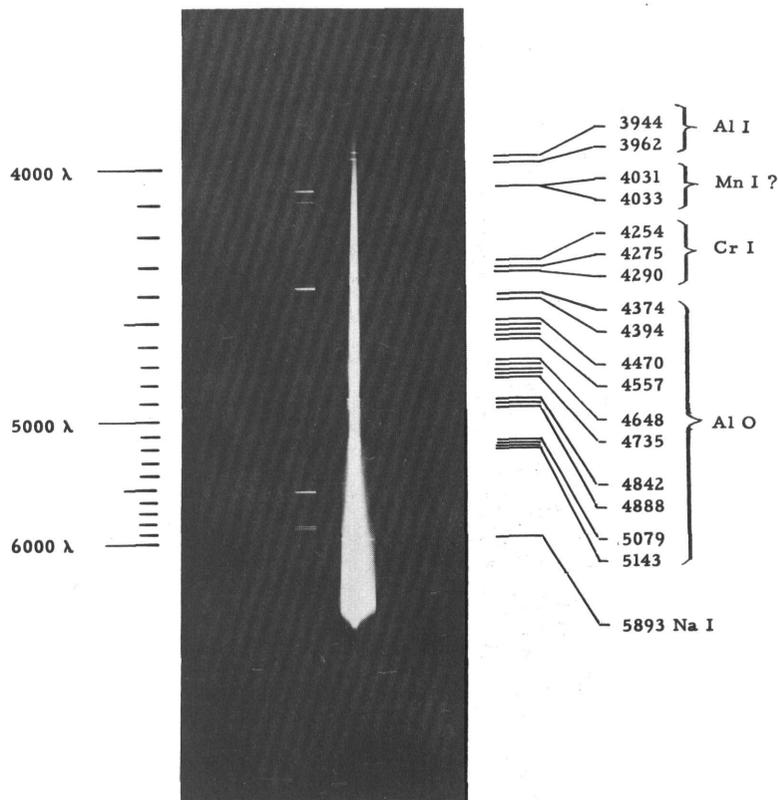


Fig. 3 - Spectrum of stationary plume on type I-F spectrographic plate

Transferring  $\lambda^{-5}$  to the left-hand side and taking logarithms to the base 10,

$$\log (N_{\lambda} \lambda^5) = \log (\epsilon_{\lambda} C_1) - 0.6219 / \lambda T \quad (2)$$

If  $\epsilon_{\lambda}$  varies only a little with  $\lambda$ ,  $\log (\epsilon_{\lambda} C_1)$  can be considered to be constant. Hence Eq. (2) represents a straight line of slope  $-0.6219/T$ , relating the variables  $\log (N_{\lambda} \lambda^5)$  and  $1/\lambda$ .

The values used for  $N_{\lambda}$  were relative spectral radiance values obtained from densitometric measurements of the data plates as follows. Separate density vs relative exposure (H & D) curves were obtained, using a tungsten lamp, for each wavelength at which the flame's relative radiance was to be determined. Tungsten-strip lamp exposures of varied durations were made through the spectrograph on a I-F plate. This plate was then processed in the same manner as the data plate. Data plate densities were converted by means of these curves to relative exposure values which, in turn, were multiplied by the values of the relative spectral radiance of the lamp to obtain relative spectral radiance values  $N_{\lambda}$ .

The logarithm of  $N_{\lambda} \lambda^5$  vs  $1/\lambda$  is shown in Fig. 6 for  $N_{\lambda}$  values observed at 4000, 4400, and 5000 Å. A straight line was fitted to the points and the slope measured was  $-2.3 \times 10^{-4}$ . Therefore

$$T = \frac{0.6219}{2.3 \times 10^{-4}} = 2700^{\circ} \text{K.} \quad (3)$$

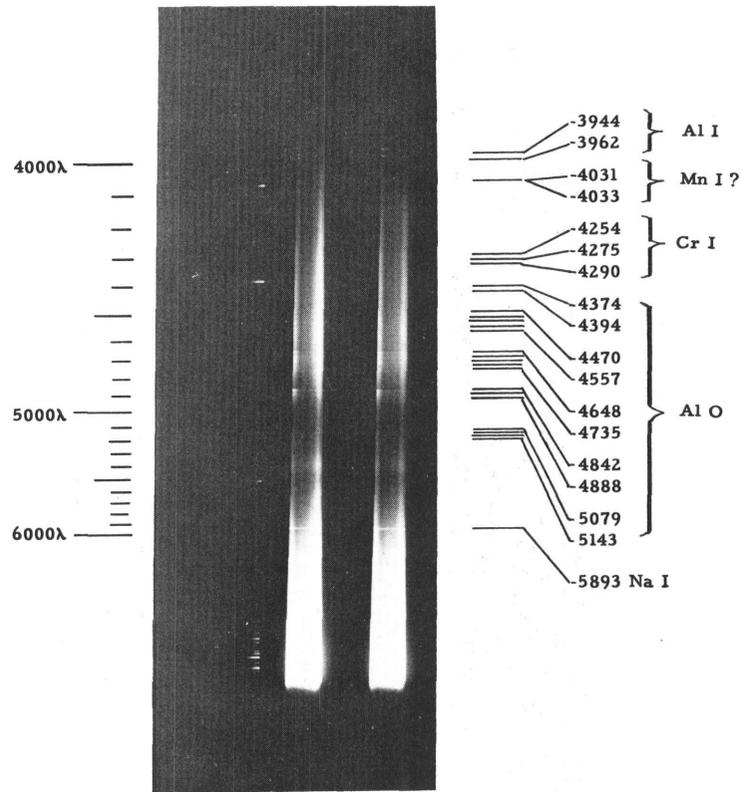


Fig. 4 - Spectrum of plume in motion recorded on type I-N spectrographic plate

The color temperature as determined in Eq. (3) is actually a time-integrated quantity determined over the duration of the complete steady burning time of the propellant grain. The line and band emission superimposed on the continuum contribute only a small percentage to the total emission.

Results obtained with the time-resolved spectrograph are also based on the use of relative intensities because there was insufficient time to prepare a rigorous calibration of the spectrograph. Wien's radiation law [Eq. (1)] expresses the true radiance  $N_\lambda$  to within 1 percent if the value of  $\lambda T$  is  $\leq 0.3$  cm-deg. The largest value of  $\lambda T$  for the experiment was less than the prescribed limit.

The relative spectral radiance  $N'_\lambda$  can be expressed, using Eq. (1), as

$$N'_\lambda = B_\lambda N_\lambda = B_\lambda \epsilon_\lambda \lambda^{-5} C_1 e^{-C_2/\lambda T} \quad (4)$$

where  $B_\lambda$  is some unknown constant. By rearranging Eq. (4), taking the natural logarithm, and differentiating, the resultant relation

$$d[\ln(N'_\lambda \lambda^5)]/d(1/\lambda) = -C_2/T \quad (5)$$

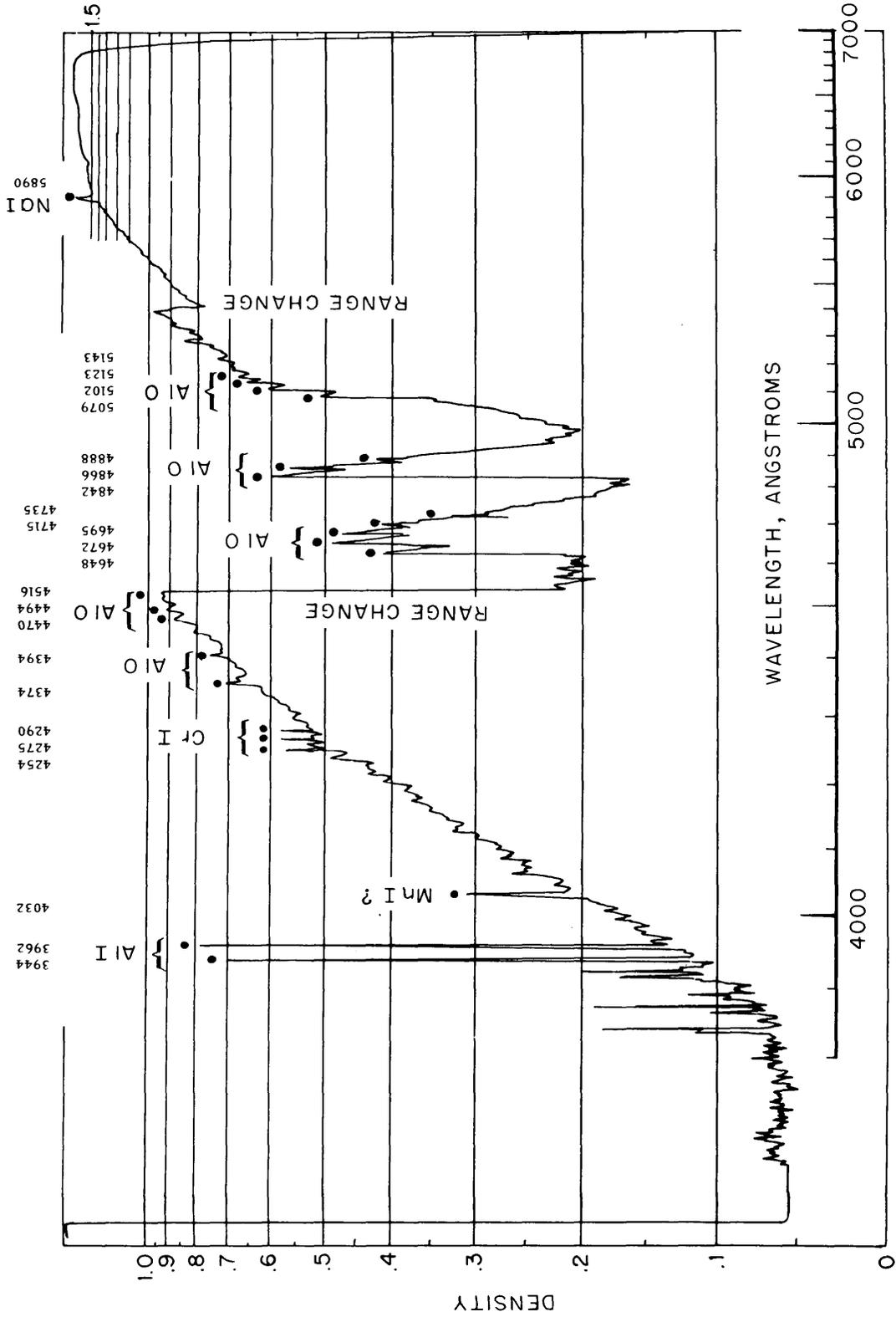


Fig. 5 - Densitometer trace of stationary plume spectrum recorded on a type I-F plate

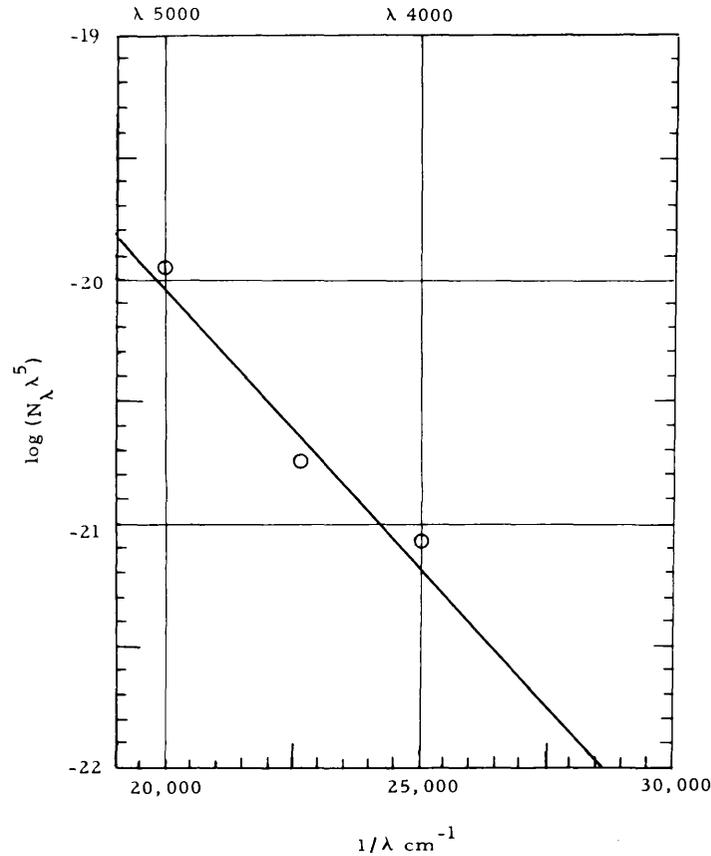


Fig. 6 - Plot of  $\log(N_\lambda \lambda^5)$  vs  $\lambda^{-1}$  data determined from the static spectrograph recordings, and best-fitted straight line to the data

indicates that the color temperature  $T$  is proportional to the slope of a straight line relating the variables  $\ln(N'_\lambda \lambda^5)$  and  $1/\lambda$ .

In order that the relative spectral radiance of the plume may be obtained for calculating the color temperature from Eq. (5), the filament of a ribbon tungsten lamp was imaged on the slit plane of the time-resolved spectrograph. The resulting tungsten continuum obtained on the photographic film was recorded and developed under the same conditions as that for the flame spectrogram. The continuum on this spectrogram incorporates the spectral transmission characteristics of the external optical imaging system, as well as that of the spectrograph. In a selected wavelength region (6100 to 6700Å), the optical densities of the continuum were converted to relative exposures by means of a film H & D curve. The relative exposure values of the tungsten lamp are represented on the recording emulsion by the relation

$$E_c(\lambda) = \frac{(N_\lambda)_{\text{cal}} t_c(\lambda) T(\lambda)}{K_\lambda} \quad (6)$$

where

$E_c(\lambda)$  = relative exposure of lamp continuum

$(N_\lambda)_{c a 1}$  = rated spectral radiance of tungsten filament

$t_c(\lambda)$  = spectral transmission of imaging optical system (filament to spectrograph slit)

$T(\lambda)$  = internal spectral transmission of spectrograph

$K_\lambda$  = some unknown constant which varies with  $\lambda$ .

In considering the same wavelength region of the flame continuum, the relative exposures of its optical densities are similarly expressed by

$$E_F(\lambda) = \frac{(N_\lambda)_{f l a m e} t_d(\lambda) T(\lambda)}{K_\lambda} \quad (7)$$

where

$E_F(\lambda)$  = relative exposure of the flame continuum

$(N_\lambda)_{f l a m e}$  = true spectral radiance of flame

$t_d(\lambda)$  = spectral transmission of imaging optical system (flame to spectrograph slit).

The ratio of Eqs. (6) and (7) gives the relation

$$\frac{E_c(\lambda)}{E_F(\lambda)} = \frac{(N_\lambda)_{c a 1} t_c(\lambda)}{(N_\lambda)_{f l a m e} t_d(\lambda)}. \quad (8)$$

For the spectral region 6100 to 6700A the values of  $t_c(\lambda)$  and  $t_d(\lambda)$  are practically constant, and the ratio of these two quantities can be termed as another constant, C. Therefore, the true spectral radiance of the flame is denoted by the relation

$$(N_\lambda)_{f l a m e} = \frac{E_F(\lambda) (N_\lambda)_{c a 1} C}{E_c(\lambda)}. \quad (9)$$

The relative spectral radiance values  $N'_\lambda$  of the flame for calculating the color temperature of the source from Eq. (5) can be obtained by rearranging Eq. (9) to give

$$N'_\lambda = \frac{(N_\lambda)_{f l a m e}}{C} = \frac{E_F(\lambda) (N_\lambda)_{c a 1}}{E_c(\lambda)}. \quad (10)$$

Figure 7 represents the entire time-resolved spectrum of the propellant plume as photographed for observation spot C (shown in Fig. 2). In Fig. 7 (a) the spectrum was not observed until the propellant grain was fully activated. From the data illustrated in Fig. 7 (b), film densities vs wavelength were determined from a microphotometer trace of the envelope of the spectrum at approximately 3.4 seconds after ignition of the propellant. The film densities were converted to relative exposure by the film H & D curve.

Figure 8 is a profile of the spectrum obtained from the trace of Fig. 7 (b), and it is shown in terms of relative exposure vs wavelength. Figure 8 does not represent a true

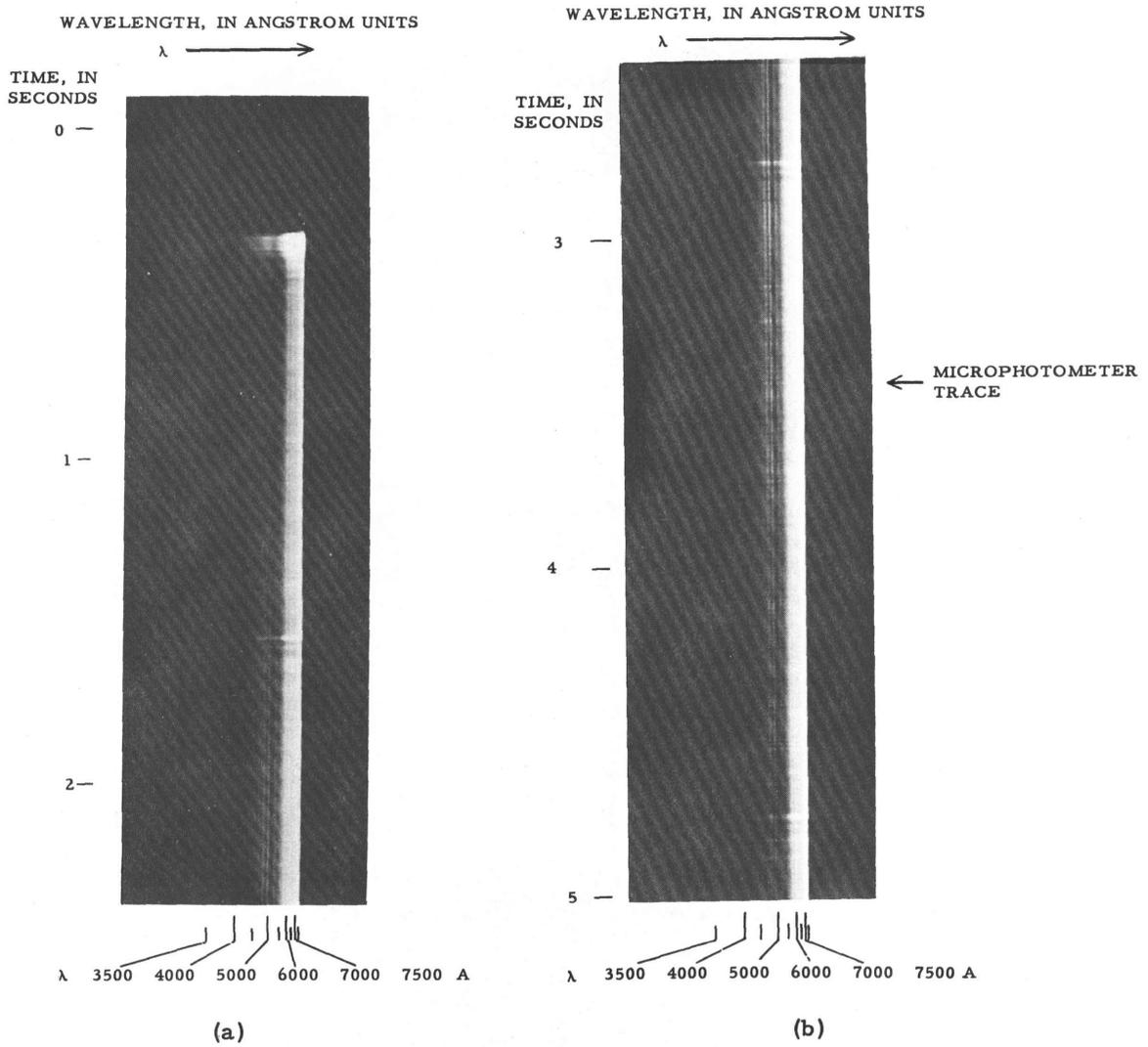


Fig. 7 - Time-resolved spectra of stationary propellant plume, starting with propellant ignition time. The time intervals are (a) 0 to 2+ sec, (b) 2+ to 5 sec, (c) 5 to 7+ sec, and (d) 7+ to 10 sec. The spectra were recorded for the observation spot C (shown in Fig. 2).

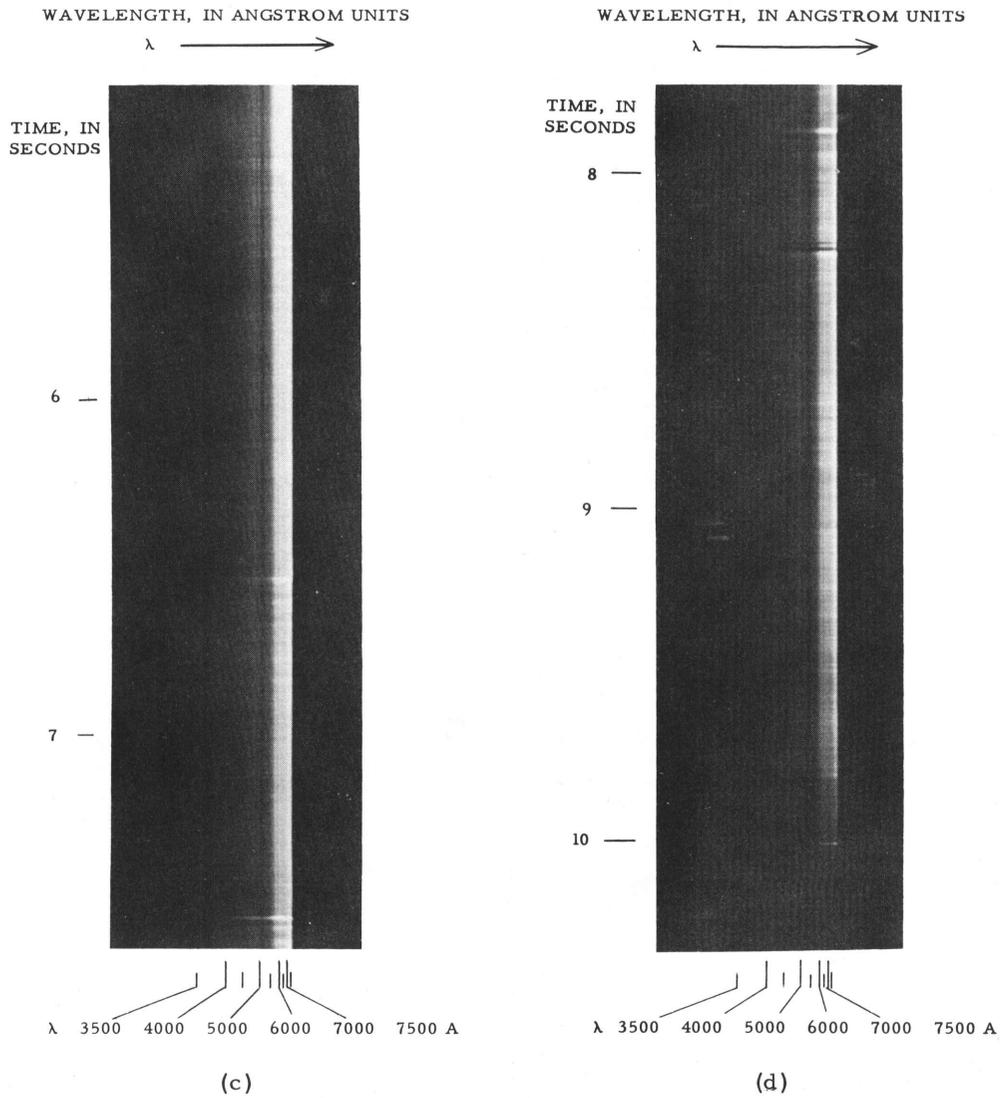


Fig. 7 (Cont'd) - Time-resolved spectra of stationary propellant plume, starting with propellant ignition time. The time intervals are (a) 0 to 2+ sec, (b) 2+ to 5 sec, (c) 5 to 7+ sec, and (d) 7+ to 10 sec. The spectra were recorded for the observation spot C (shown in Fig. 2).

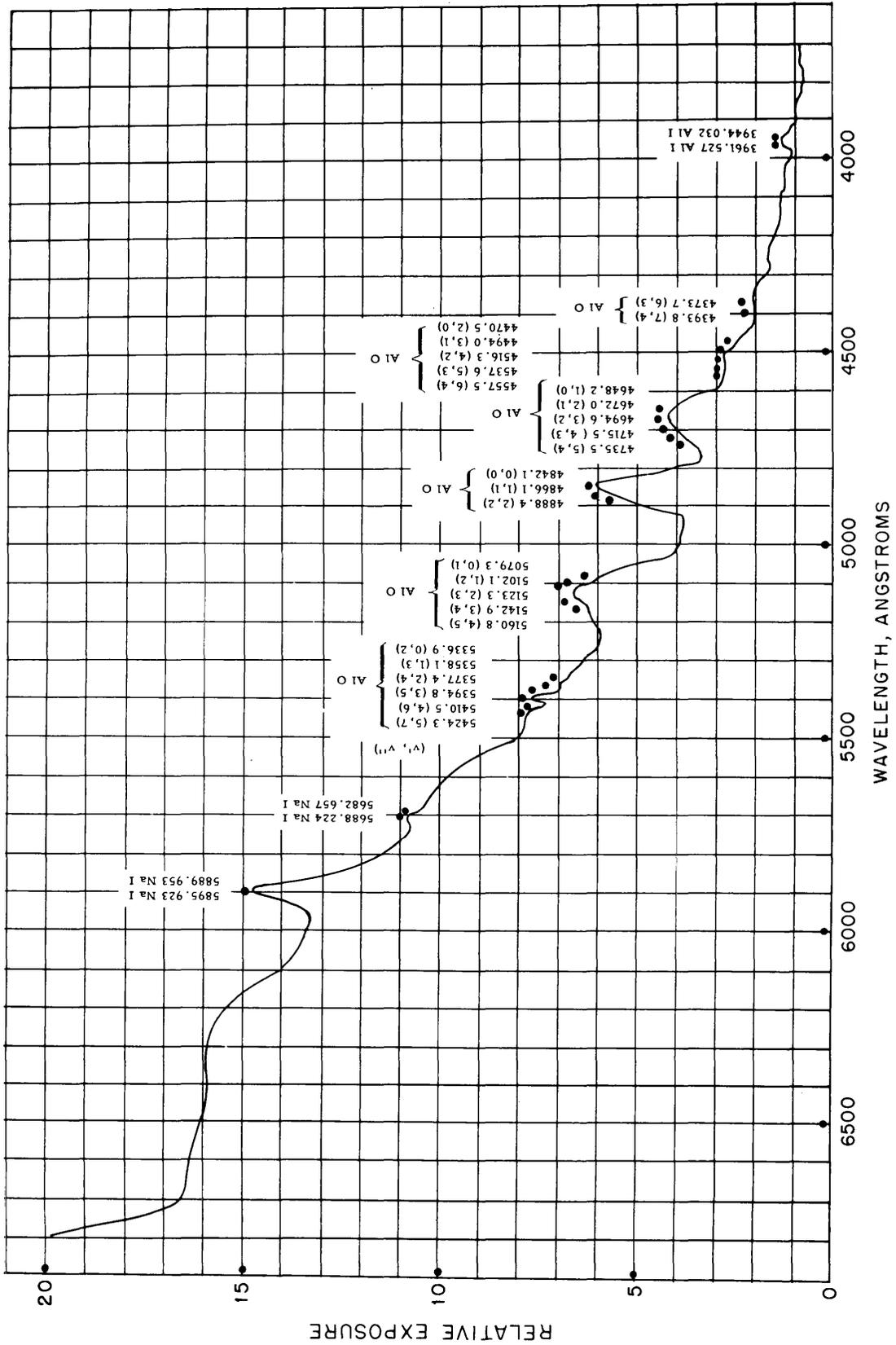


Fig. 8 - Relative exposure profile of stationary propellant plume obtained from microphotometer traces at 3.4 seconds after ignition (see Fig. 7 (b))

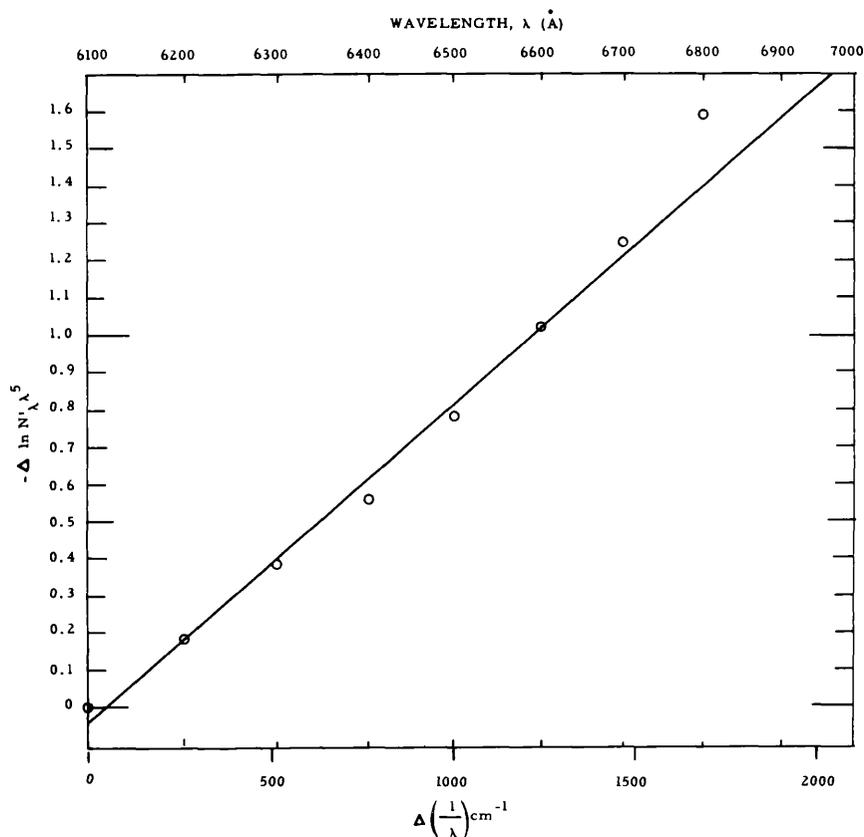


Fig. 9 - Plot of  $\Delta \ln(N'_\lambda \lambda^5)$  vs  $\Delta(\lambda^{-1})$  as determined from the time-resolved spectrograph recordings, and best-fitted straight line to the data

profile of the spectrum because the effect of the dispersion of the spectrograph (which is wavelength dependent), as well as several unknown factors such as the spectral transmission of the spectrograph and of the external optical system, is not compensated for in these relative exposure values. The profile exhibits a continuum on which is superimposed the atomic emission of sodium and aluminum and the molecular emission of aluminum oxide. The specific wavelengths of the emission lines and bands are recorded in Fig. 8. No apparent absorption regions were observed in the continuum of the plume profile for this observation. The unusual shape of the profile from 6000 to 7000Å is due to the instrumental characteristics of the spectrograph, and this same shape occurs in the presentation of the lamp continuum profile obtained with the same spectrograph. Relative exposures were likewise obtained from a time-resolved spectrograph which contained the continuum of the tungsten lamp operating at 2200°K.

In a selected wavelength region (6100 to 6700Å) where the continuous spectrum of the plume is not complicated by emission lines, the relative spectral radiances  $N'_\lambda$  were determined for the calculation of color temperature. By substituting the relative exposures of the lamp, the plume, and the rated spectral radiance of the lamp into Eq. (10), the relative spectral radiances of the flame were determined. These relative spectral radiance values were then multiplied by  $\lambda^5$  to obtain the quantity  $N'_\lambda \lambda^5$  for all the wavelengths being considered.

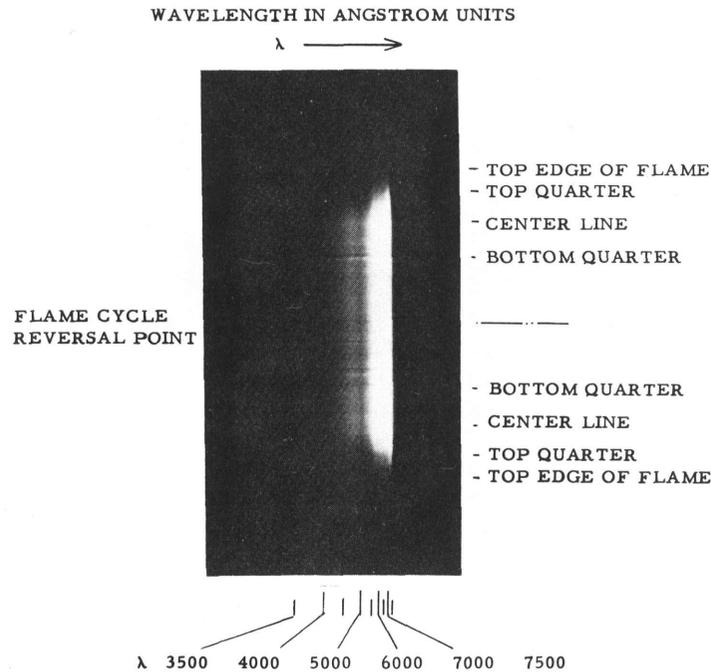


Fig. 10 - Time-resolved spectrum of oscillating propellant plume for observation area A (shown in Fig. 2)

By subtracting  $\ln(N'_\lambda \lambda^5)$ , for a specific wavelength, from the value for  $\lambda = 6100\text{\AA}$  and plotting the differences as ordinates, and similarly, plotting the differences of  $1/\lambda$  subtracted from  $1/6100\text{\AA}$  as the abscissas, the slope of the best straight line drawn through these points represents the average color temperature for the wavelength region from 6100 to 6700 $\text{\AA}$ . A least-squares solution was made for these points in order to determine the slope of the most appropriate line through these data. Using this slope in conjunction with Eq. (5), the color temperature was found to be 1690°K. Figure 9 is a plot of relative spectral radiance  $\Delta \ln(N'_\lambda \lambda^5)$  vs  $\Delta(1/\lambda)$  and illustrates the above method. Other similar determinations, which were made at 1.0, 2.0, and 6.0 seconds after ignition, gave temperatures of 1779°, 1746°, and 1735°K, respectively.

Figure 10 represents the time-resolved spectrum of the plume for observation area A (see Fig. 2). The profile is very much like that exhibited in Fig. 7 (d), but the emission structure is somewhat depressed.

Figure 11 shows the time-resolved spectra of the up-and-down sweep of the plume through the observation area B (see Fig. 2). The upsweep spectrum is very much like that of Fig. 10, whereas that for the downsweep is similar to the spectrum of Fig. 7.

## CONCLUSION

The combined observations of the time-resolved and the static spectrographs showed that in the spectral regions from 4000 to 5000 $\text{\AA}$  and 6100 to 6700 $\text{\AA}$  the continuous emission appeared to be that radiated by a blackbody. No zones or windows of continuous absorption

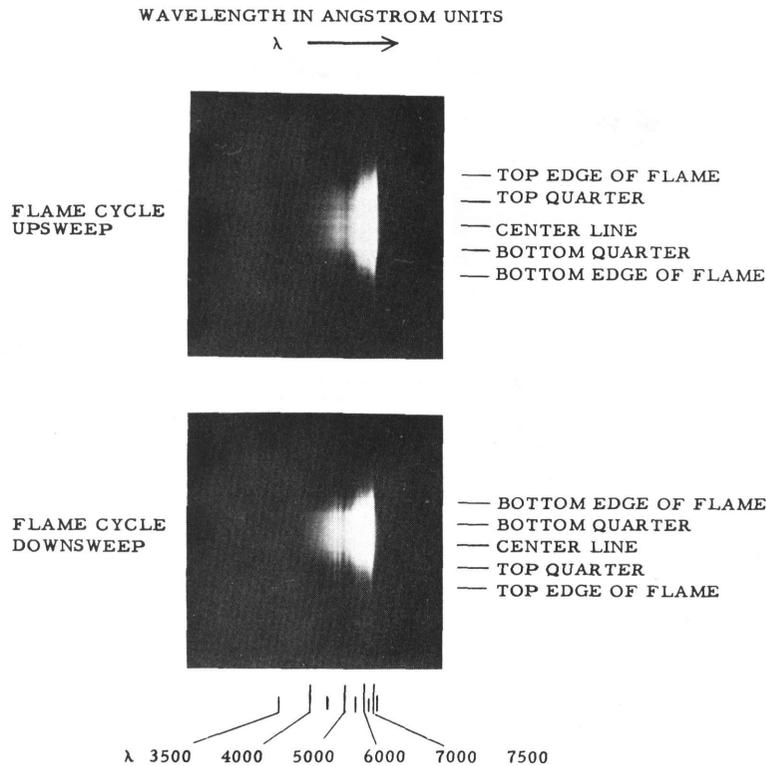


Fig. 11 - Time-resolved spectrum of oscillating propellant plume for observation area B (shown in Fig. 2)

were noted in the continuum for the wavelength interval 3700 to 9000A. The profile of the plume spectrum from 3700 to 9000A exhibited a continuum on which were superimposed, mainly, the emission structures of atomic aluminum and sodium and molecular aluminum oxide. The line and band emissions, however, contributed only a small percentage to the total emission of the plume.

The instantaneous color temperatures of about 1700°K, as determined by the time-resolved spectrograph, are lower than the 2700°K obtained with the static spectrograph. The former are "instantaneous" temperatures obtained with an exposure equal to the time resolution of the spectrograph (3.88 msec) and from a very small spatial area of the plume, whereas, the latter temperature is derived on a total-time basis (greater than 9 sec) for a very much larger flame area. The time-resolved temperature determination is greatly affected by rapid changes in the burning characteristics of the plume due to the very short duration of the spectrograph's exposure and the small flame area observed. It is impossible to record the rapid flame variations from a large plume area and for a total-time observation since the two tend to be averaged out. The disagreement in temperatures calculated at the two spectral regions appears to be experimental. The substantial similarity of the four independent instantaneous temperature measurements indicates that the single time-integrated temperature measurement may be in error. Additional evidence supporting this view is the poor fit of the data points in Fig. 6. This may be caused by molecular band emission, at the selected wavelengths, which is not readily apparent.

In any future plume observations made with time-resolving and static instrumentation, it is recommended that a full time history of the color temperature be explored in order to determine if a correlation between time-resolved and total-time observations can be established for equal spatial areas of the flame.

#### ACKNOWLEDGMENTS

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