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KINETIC ELECTRON TEMPERATURE MEASUREMENT TECHNIQUES FOR HELIUM

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16. Abstract

Spectroscopic techniques for measuring the temperature of helium for temperatures between 1.3eV (15,000°K) and 100eV (1.16×10^6°K) have been investigated. To carry out this study, a transient plasma source capable of temperature variation by changing input current amplitude and frequency was developed.

A systematic study was made of four spectroscopic measurement techniques for temperatures in the range 1.3eV to 100eV. Recommendations are made for the development of an instrument capable of measuring temperatures with an estimated accuracy of 20 percent.

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KINETIC ELECTRON TEMPERATURE MEASUREMENT TECHNIQUES FOR HELIUM

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SUMMARY

A systematic study of spectral methods for measuring the temperature of helium has been completed. Kinetic electron temperatures varying from 1.3eV to 100eV were considered ($1eV = 1.16 \times 10^{4} °K$).

To facilitate this study, an arc source, which generates temperatures throughout the range of interest, by varying the magnitude and frequency of current through the arc, was developed. A monochromator with a P.M. detector at the exit slit, was used to measure the gas temperature by various spectral techniques. Experimental measurements which illustrate these methods are presented.

INTRODUCTION

In many aerospace applications, a need exists for instruments and techniques to measure temperatures in the plasma region, for common gases such as hydrogen, helium, nitrogen, and air. Since these gases are partially ionized at temperatures above 1.3eV, spectral methods were chosen for this investigation.

The spectra of ionized nitrogen and air are very complex, while spectra of H and He are simpler. Since the techniques cover an almost continuous range of temperatures from 1.3eV to 100eV, helium was chosen for this experimental study. The methods developed in the study of He will later be applied to more complex gases such as nitrogen and air.

A novel transient arc source, which permits a variation of the helium electron temperature by varying the current through the arc, has been developed. Temperatures varying from $3 \times 10^{4} °K$ to $5 \times 10^{5} °K$ have been measured.

The transient arc source uses needle electrodes having a tip diameter of 100 microns, so that high current densities (10^{6} - 10^{7} amps/cm^{2}) are obtained with relatively low total currents (100 - 1000 amps).

TEMPERATURE MEASUREMENT TECHNIQUES

Helium was chosen as a test gas to investigate methods of measuring the electron temperature of various gases by spectral techniques. A literature search indicated that various temperature measuring techniques have been extensively considered for helium, both theoretically and experimentally, for most of the temperature range extending from 1.3eV to 100eV. From the work reported, four spectral techniques were chosen for a systematic, experimental study of this entire temperature region, using a single high temperature source.

The spectral intensity ratios from which electron temperatures were deduced in this study are plotted in Figure 1 as a function of electron temperature. As indicated in Figure 1, spectral methods are available for most temperatures between 1.5×10^4°K and 1.16×10^6°K.

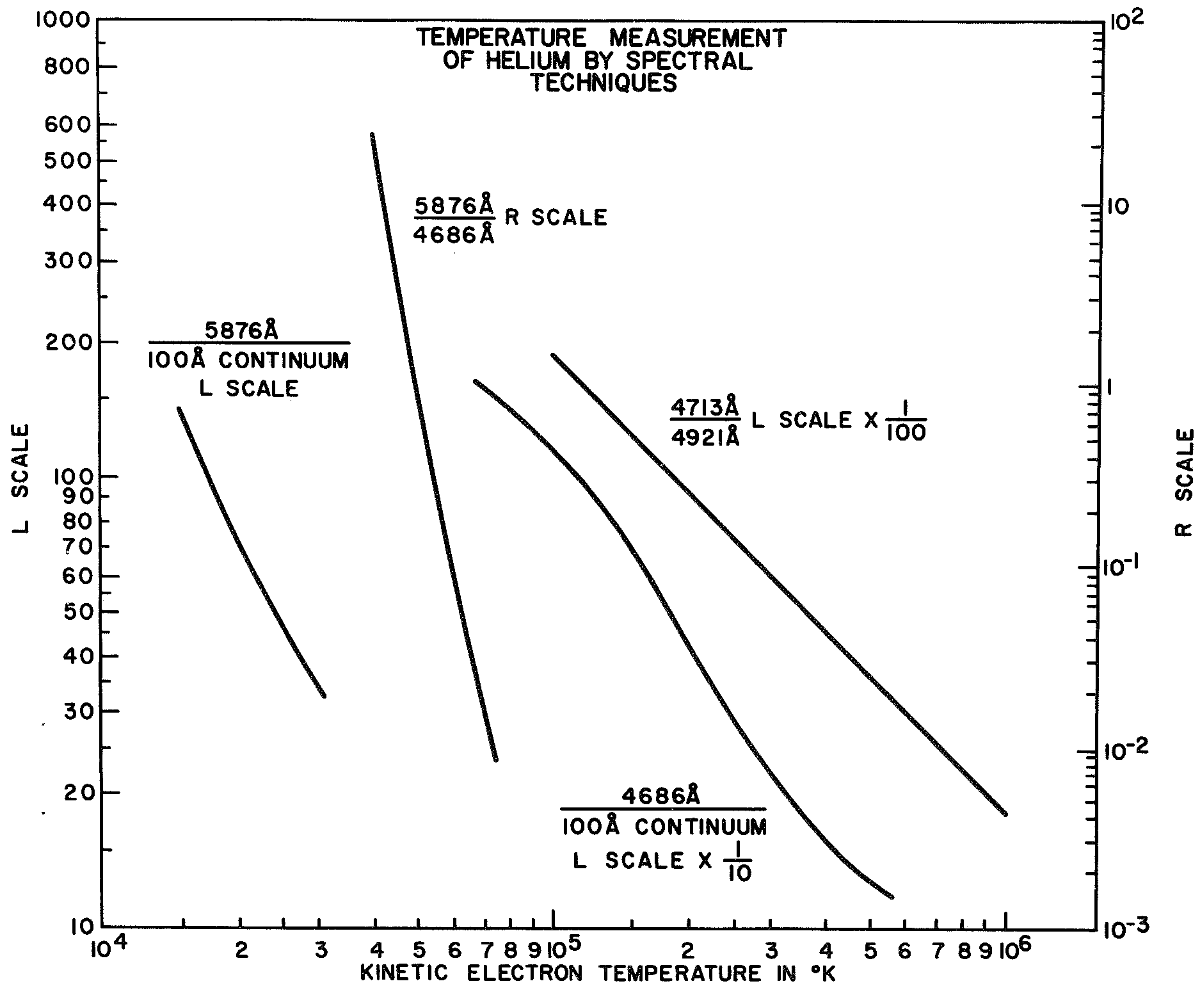

Figure 1.- Electron temperature measurement techniques

DESCRIPTION OF THE EXPERIMENT

A schematic diagram of the experiment is shown in Figure 2. The plasma was formed when the helium gas between two needle shaped electrodes was resistively heated by the discharge of current from a pulsed power supply. This supply stored 10 joules of energy at 20 kv and discharged through the arc with a maximum frequency of 1 mHz. The current through the arc was monitored by a single turn, low inductance transformer, followed by a current integrator and oscilloscope. The current density in the arc was estimated from streak photographs of the luminous material in the arc (giving the area of the arc) and measurements of total current through the arc.

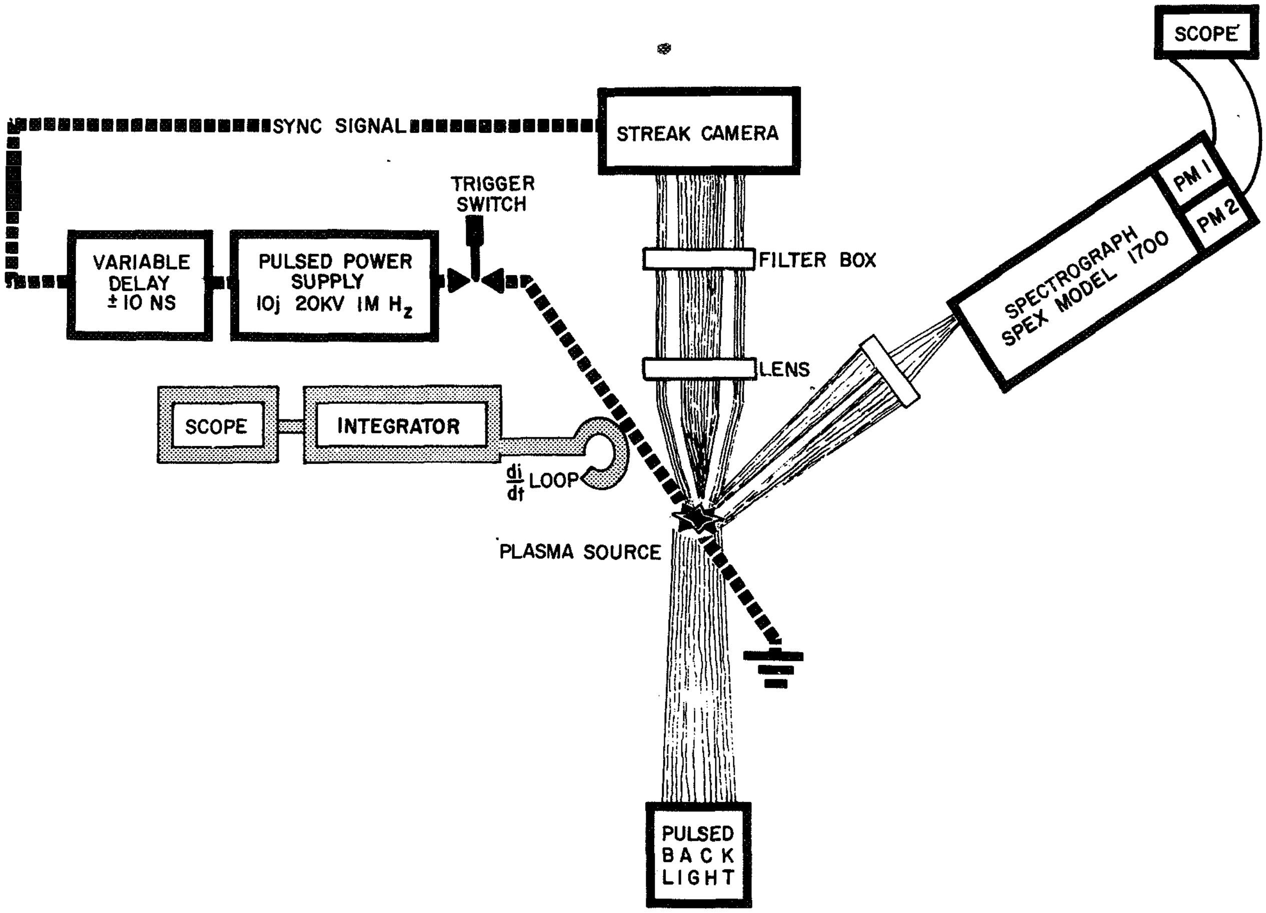

Figure 2.- Schematic diagram

The hydrodynamic motion of the heated material was observed by a streak camera (time resolution = 20ns) using a pulsed back-lighting source and a shadowgraphic optical system.

Spectral observations were made with a SPEX Model 1700 spectrograph. The spectrograph had a two-slit exit aperture plate with an Amperex model XP-1023 P.M. detector mounted to view each exit slit. Signals from the two P.M. detectors were recorded on a Tektronix Model 555 dual-beam oscilloscope. The two exit slits were spaced 19 mm apart for simultaneous observations of the HeI(4921Å) and the HeI(4713Å) spectral lines. All other spectral lines were observed by using only one of the exit slits of the spectrograph, one P.M. detector and one beam of the oscilloscope.

A picture of the arc structure is shown in Figure 3. The transient arc occurred between two needle-shaped electrodes having

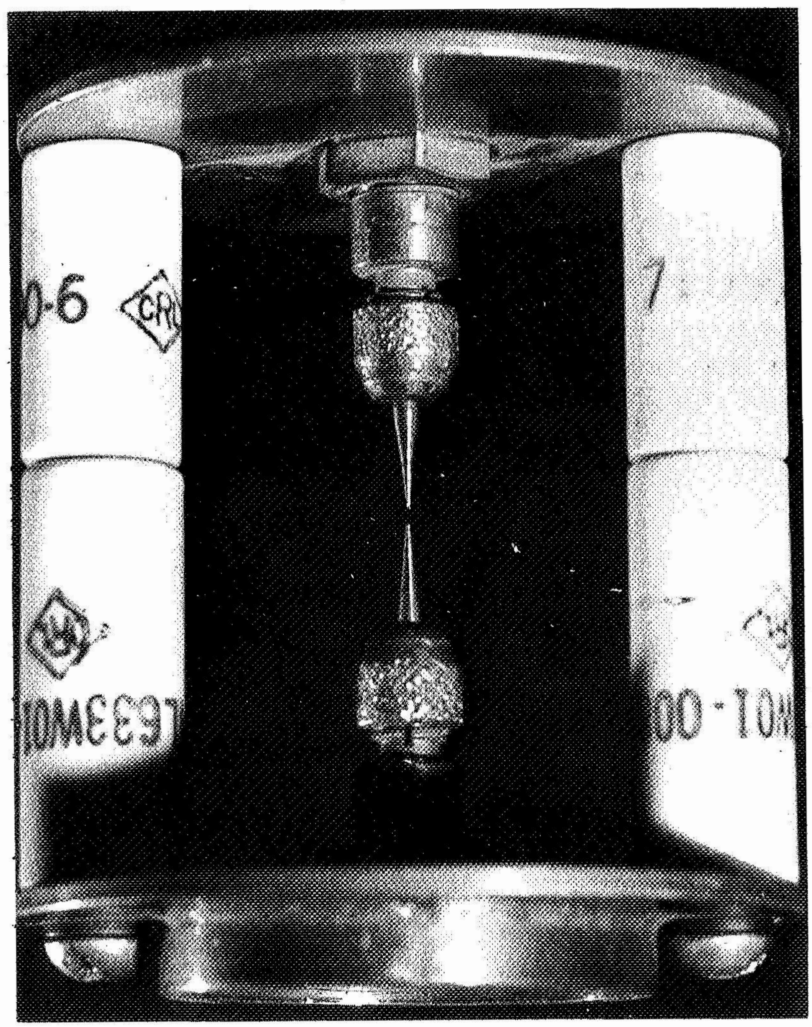

Figure 3.- Picture of electrode structure

tip radii of 50 microns. For developing high temperatures, the sharp needles have two advantages over larger diameter electrodes: (1) the small radius of curvature results in high electrostatic fields ($7x10^5$V/cm) at the surface of the electrodes, and (2) the small diameter electrodes channel the current into a small discharge, with a maximum current density estimated to be $2x10^7$ amps/cm^2.

The SPEX Model 1700 spectrograph is basically a monochromator, but is also capable of producing spectral records on Polaroid film. It gives a 500Å record centered on the monochromator wavelength setting. The dispersion is 11Å/MM. The basic monochromator has been modified by adding an exit slit so that spectral line intensities may be recorded as a function of time for two wavelengths. The monochromator was calibrated to read spectral wavelength, by calibrations with various wavelength standards (i.e., Hg, He, H, and Na). The optical sensitivity of the spectrograph, its external optical system, and the P.M. detectors, were measured with the aid of a tungsten ribbon lamp calibrated for black body temperature by the National Bureau of Standards. The radiated intensity of the lamp at each calibration wavelength was corrected for source emissivity (ref. 1). The resulting system response curves are shown in Figure 4 for the two detectors.

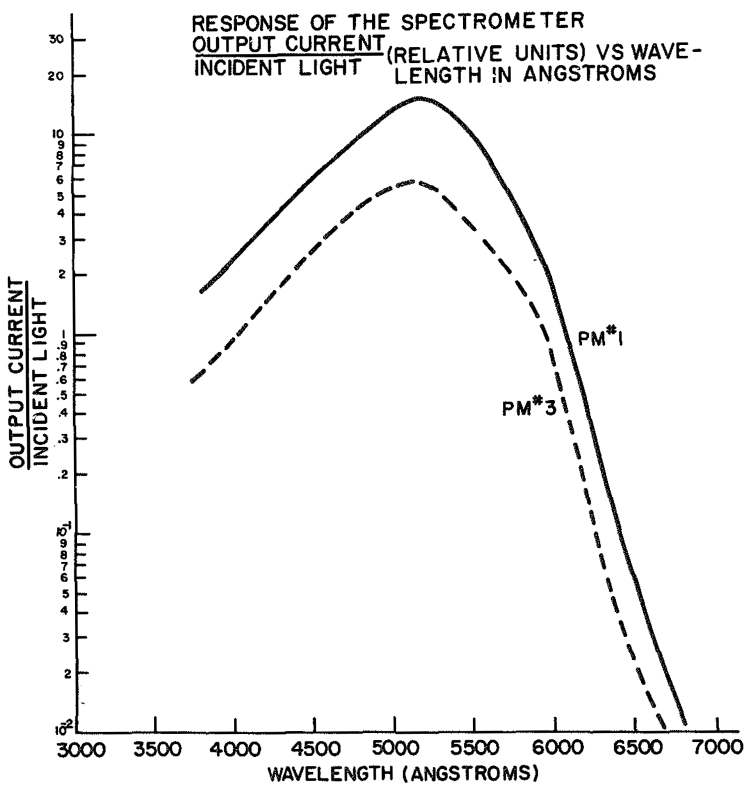

Figure 4.- Spectrometer response curve

EXPERIMENTAL RESULTS

The objectives of these measurements were to: (1) develop spectral techniques for the measurement of the electron temperature of helium over a wide range and (2) gain an understanding of the transient arc source so that it can better be used with other gases such as nitrogen and air for real time temperature measurements. The various spectral lines of interest were scanned by varying the monochromator wavelength setting and firing one discharge of the capacitor through the arc for each wavelength setting. The source was reproducible on a shot-to-shot basis.

The electron temperature range, applicable for each spectral measurement technique, is shown in Figure 1. The source temperature was adjusted to a desired temperature by changing the frequency and amplitude of current through the arc. To obtain profiles of the HeI 5876Å line (temperatures between 15,000°K and 30,000°K), a 30 ohm damping resistor was placed in series with the source. This resistor overdamped the electrical discharge. The results of scanning the HeI 5876Å line are shown in Figure 5. Line profiles are shown corresponding to 2 μsec and 6 μsec after initiation of the discharge. The helium electron temperature deduced from the profile corresponding to 2 μsec is 30,000°K.

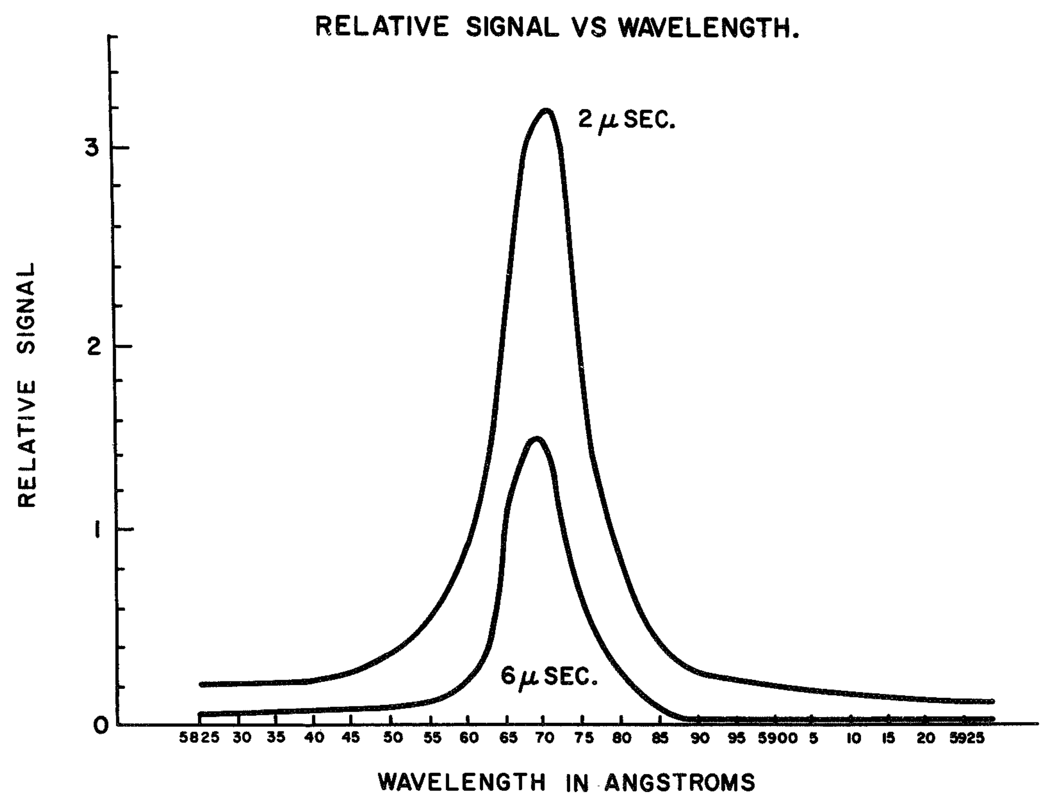

Figure 5.- Profiles of HeI 5876Å line

Similar profiles and temperature determinations were made for each instant of time during the discharge. After the line profile had been determined, as indicated in Figure 5, the temperature was determined from three shots. The slit width and monochromator dial were set so that all of the light from the spectral line was measured on the first shot. Additional discharges were taken with the monochromator set 50Å each side of the line. These two measurements were averaged to obtain the background continuum intensity.

Most of the error in this temperature measurement technique was due to the slit width settings. Much greater accuracy would be obtained using three exit slits with three P.M. detectors, since the temperature would be obtained with a single discharge of the electrical system.

The HeI(5876Å) line can also be used with the HeII(4686Å) line (ref. 2) to measure electron temperatures between 40,000°K and 70,000°K as indicated in Figure 1. The profile of the HeII(4686Å) line is shown in Figure 6. This profile was obtained by firing many discharges of the capacitor through the arc and plotting

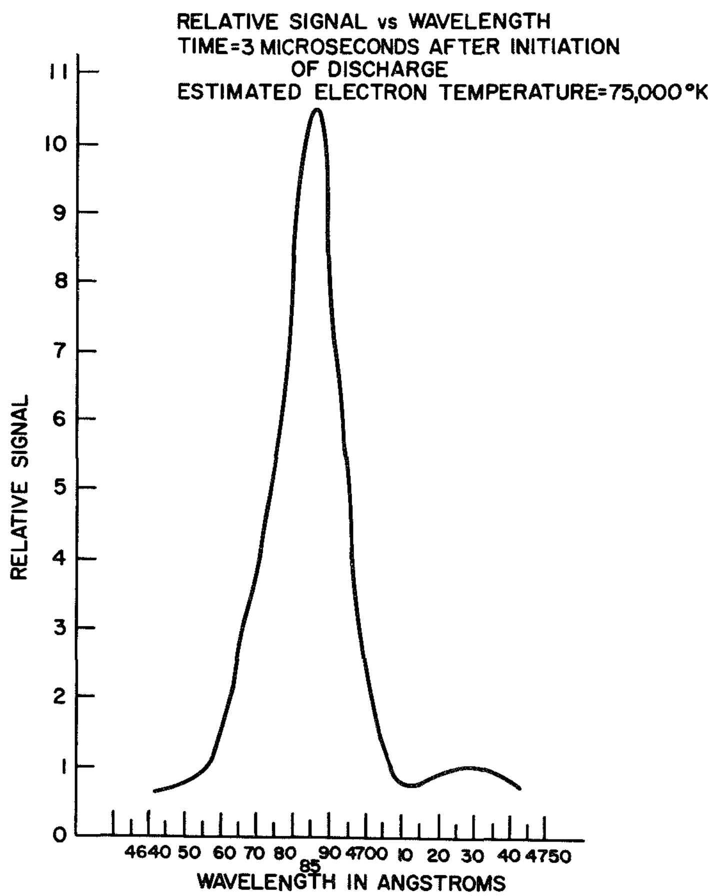

Figure 6.- Profile of 4686Å line

the measured intensities for a delay of 3 μsec after the initiation of the discharge. A damping resistor was placed in series with the electrical discharge to overdamp it. The HeII(4686Å) spectral line was used with the HeI(5876Å) line to measure temperatures of 40,000°K - 70,000°K. It was also used for line-to-background continuum (ref. 2) to measure temperatures between 70,000°K and 500,000°K as indicated in Figure 1.

Figure 7 shows an example of such a measurement. In this case, the temperature increased very rapidly during initial current flow to a temperature above $5x10^5$°K. After 0.5 microsecond, the plasma source cooled to a temperature of about $5x10^5$°K, and after 3 microseconds it cooled to $7x10^4$°K, as indicated in Figure 7. This result illustrates the need for several temperature measurement techniques to study transient plasmas, both for higher and lower temperatures.

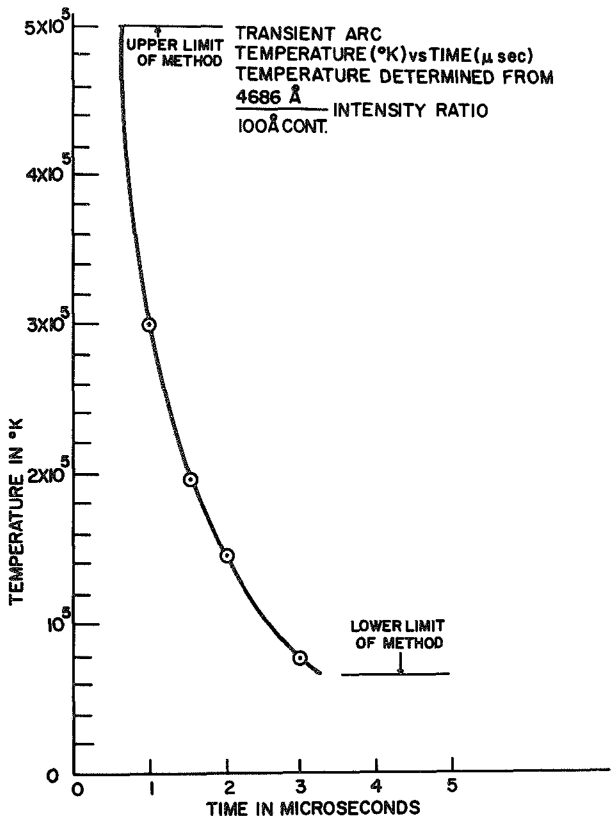

Figure 7.- Te vs time measured by HeII 4686Å/cont.

Profiles of the HeI(4921Å) and HeI(4713Å) lines are shown in Figure 8. These two spectral lines were used to measure temperatures between 10eV and 100eV (Fig. 1) by the intensity ratio of the two spectral lines at 4921Å and 4713Å. The profiles of

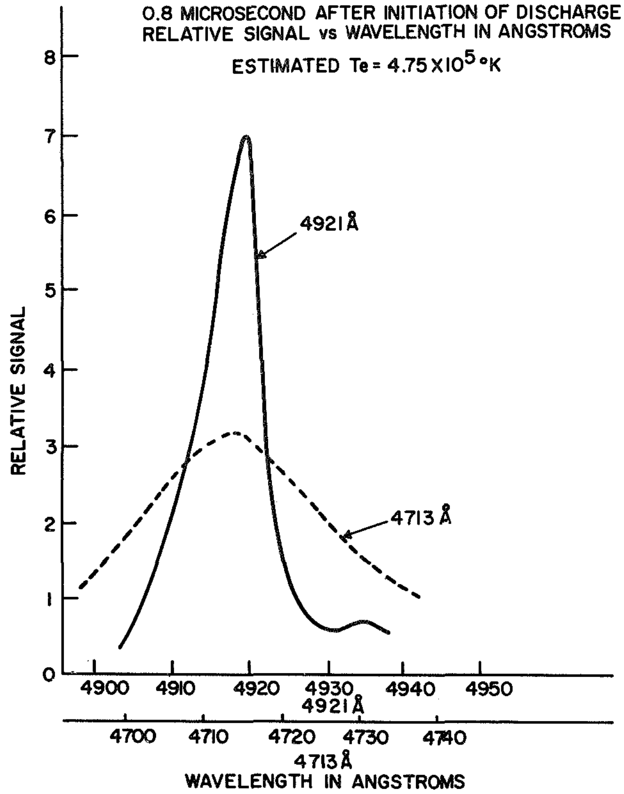

Figure 8.- Profiles of 4921Å and 4713Å lines

these lines were obtained using a double exit slit arrangement on the spectrograph. By firing multiple discharges of the capacitor through the arc, the two line profiles shown, were obtained. Figure 8 indicates that a wide slit (50Å) is necessary to monitor the total radiation from the 4713Å line, while the 4921Å line is narrower (30Å). The principle error in measuring temperatures by the 4921Å to 4713Å line intensity ratio technique is the setting of the exit slit widths.

Figure 9 shows the results of measuring the temperature of helium in the transient arc, using the 4921Å to 4713Å line intensity ratio technique. The discharge circuit was undamped. Continuous temperature measurements were obtained between 10eV and 50eV for a time interval of 1.2 microseconds.

The spectroscopic temperature measurement techniques shown in Figure 1, overlap in temperature between 10eV (116,000°K) and 43eV (500,000°K). This permits a comparison of temperatures, measured by two different techniques, in this temperature region. Such a comparison is given in Table I. Comparisons are made for temperature measurement by two techniques: (1) Intensity ratio 4921Å to 4713Å and (2) intensity ratio 4686Å to 100Å continuum. The temperatures from separate shots are compared for 1.5 μsec

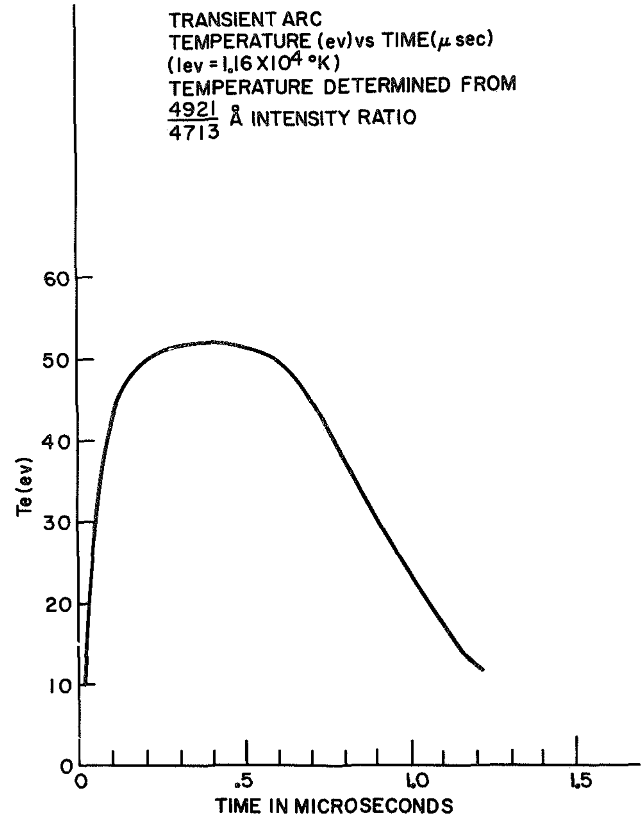

Figure 9.- Te vs time measured by $\frac{4921}{4731}$ Å ratio

TABLE I.- COMPARISON OF TEMPERATURE MEASURED BY VARIOUS TECHNIQUES

Temperature Measurement Technique	Experimental Conditions	Time After Initiation of Discharge	Measured Temperature °K
Intensity ratio of 4921Å and 4713Å He Spectral Lines	700 torr He	1.5 μsec 2.0 μsec	163,000 177,000
Intensity ratio of 4686Å line to 100Å continuum		1.5 μsec 2.0 μsec	195,000 145,000

and 2.0 μsec after initiation of current flow. At 1.5 μsec, the temperature measured by 4686Å line-to-100Å continuum is higher by 20 percent; at 2 μsec, it is lower by 18 percent. Part of the difference in measured temperatures is due to non-reproducibility of the transient arc from shot-to-shot. The other important

error is that of setting exit slit widths and wavelength positions. The width of a spectral line is determined by several factors. One of them, stark-broadening, depends upon the electron density. In these experiments no measurements of electron density were made.

Using the measurement techniques described in this report, an accuracy of 50-100 percent is estimated. An improved temperature measuring instrument would be a 12-channel polychrometer from which the line profiles, electron density, and electron temperature could be determined as a function of time on a single shot with an estimated accuracy of 20 percent or better.

CONCLUSIONS

The systematic study of spectroscopic techniques for measuring the temperature of helium in the range of 1.2eV to 100eV indicates that with careful design an instrument having an accuracy of 20 percent can be constructed. In this study an accuracy of 50-100 percent was obtained.

A transient arc source with temperatures exceeding 100eV was developed. As a future study, it would be profitable to measure the temperature and density of helium in the transient arc source by the Thomson scattering of coherent light.

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