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EXPERIMENTAL INVESTIGATION OF THE SPECTRAL EMISSION CHARACTERISTICS OF ARGON-TUNGSTEN AND ARGON-URANIUM INDUCTION HEATED PLASMAS

by Pierre J. Marteney, A. E. Mensing, and N. L. Krascella

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FOREWORD

An exploratory experimental and theoretical investigation of gaseous nuclear rocket technology is being conducted by the United Aircraft Research Laboratories under Contract NASw-847 with the joint AEC-NASA Space Nuclear Propulsion Office. The Technical Supervisor of the Contract for NASA is Captain C. E. Franklin (USAF). Results of portions of the investigation conducted during the period between September 15, 1967 and September 15, 1968 are described in the following five reports (including the present report) which comprise the required eighth Interim Summary Technical Report under the Contract:

1. Kendall, J. S., W. C. Roman, and P. G. Vogt: Initial Radio-Frequency Gas Heating Experiments to Simulate the Thermal Environment in a Nuclear Light Bulb Reactor. United Aircraft Research Laboratories Report G-910091-17, September 1968.

2. Mensing, A. E. and L. R. Boedeker: Theoretical Investigation of R-F Induction Heated Plasmas. United Aircraft Research Laboratories Report G-910091-18, September 1968.

3. Krascella, N. L.: Theoretical Investigation of the Composition and Line Emission Characteristics of Argon-Tungsten and Argon-Uranium Plasmas. United Aircraft Research Laboratories Report G-910092-10, September 1968.

4. Marteney, P. J., A. E. Mensing, and N. L. Krascella: Experimental Investigation of the Spectral Emission Characteristics of Argon-Tungsten and Argon-Uranium Induction Heated Plasmas. United Aircraft Research Laboratories Report G-910092-11, September 1968. (present report)

5. Latham, T. S.: Nuclear Studies of the Nuclear Light Bulb Rocket Engine. United Aircraft Research Laboratories Report G-910375-3, September 1968.

Experimental Investigation of the
Spectral Emission Characteristics of
Argon-Tungsten and Argon-Uranium Induction Heated Plasmas

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Experimental Investigation of the Spectral Emission Characteristics of Argon-Tungsten and Argon-Uranium Induction-Heated Plasmas

SUMMARY

An experimental study was conducted to determine the emission characteristics of gaseous tungsten and uranium located in an rf induction-heated, vortex-stabilized argon discharge. The tungsten and uranium were introduced into the discharge in the form of tungsten hexafluoride or uranium hexafluoride at heavy-atom to argon mass ratios of approximately 1.0×10^{-4} and a total pressure of one atmosphere.

Temperatures in the heavy-atom seeded discharges were determined to be approximately 8500 deg K, and were ascertained by measuring neutral argon atom relative line intensity ratios by the Boltzmann method. Temperatures determined by this method were confirmed by measurements of absolute neutral argon atom line intensities and absolute argon ion continuum intensities.

Spectra were obtained for pure argon, tungsten hexafluoride-argon, and uranium hexafluoride-argon systems in the wavelength region from 1250 Å (0.125 micron) to 100,000 Å (10 micron). The experimental data were reduced to obtain integrated continuum and line intensities over intervals of 100 Å for pure argon. Integrated line intensities were obtained over wavelength intervals of 100 Å for tungsten and uranium after correcting the experimental results for the contribution to total intensity due to argon continuum and lines.

Experimental integrated line intensities over 100 Å wavelength intervals for argon, tungsten and uranium were subsequently compared to similar analytical results calculated for the visible region of the spectrum (2000 Å to 10,000 Å). The correlation between experimental and analytical results for tungsten was generally poor, particularly at wavelengths less than approximately 4000 Å, although fairly good agreement was noted between 4000 Å and 6000 Å. The correlation between experimental and analytical results for uranium is somewhat better than that for tungsten, and is best in the region between approximately 2000 Å and 4000 Å. The agreement between experimental and analytical results for argon is excellent in all wavelength intervals of comparison.

RESULTS

1. Good agreement in the estimates of the temperature of an argon discharge was obtained from the following: relative intensities of ArI lines (8500 deg K), absolute intensities of ArI lines (8450 deg K), and absolute intensity of the argon continuum (8575 deg K).

2. Measured line and continuum radiation of rf-heated argon were in good agreement with calculated values in the wavelength range between 2000 Å and 9000 Å.

3. Measured line radiation in tungsten and uranium contained in an argon discharge were not generally in good agreement with calculated values.

4. The greatest portion of the total energy emitted by tungsten or uranium in an argon discharge occurred as line radiation in the visible spectral region (4000 Å to 7000 Å).

INTRODUCTION

In the gaseous nuclear rocket engine concept currently under investigation at the NASA Lewis Research Center and at United Aircraft Research Laboratories (Refs. 1 and 2), energy generated by nuclear fission in a fuel-containment region is transferred by thermal radiation to a propellant such as hydrogen. The propellant is usually assumed to be seeded with a heavy-atom material such as tungsten to augment the propellant opacity in spectral regions where the propellant would otherwise be transparent. Effective analysis of the radiant energy transfer processes occurring in the rocket engine requires a knowledge of the spectral or mean emission and absorption characteristics of typical fuel, propellant, and seed materials.

A number of analytical and experimental investigations have been conducted at United Aircraft Research Laboratories to assess the spectral and mean emission or absorption characteristics of such materials as hydrogen, uranium, and a variety of possible propellant seeding agents (Refs. 3 through 7). The absorption characteristics of diatomic gases and solid particle seeding materials have been investigated experimentally (Refs. 5 and 6). Analytical estimates have been made to determine the absorption coefficients of hydrogen (Refs. 3 and 4), solid spherical particles of heavy-atom metals (Ref. 7), gaseous heavy-atom metals (Ref. 7), and gaseous uranium (Ref. 4). However, no detailed estimates have been made of emission or absorption characteristics in the bound-bound (line) spectral region of heavy-atom gases or gaseous fuels; these characteristics are difficult to estimate analytically due to the complexity and number of lines in the spectra of heavy-atom elements and the general lack of necessary line emission or absorption data such as energy levels, transition probabilities, and corresponding wavelengths. Even available data, such as contained in Ref. 8, are usually incomplete and generally confined to a spectral region between approximately 2000 Å and 9000 Å. To overcome these deficiencies, an experimental program was formulated with the objectives of (1) investigating the general line emission properties of heavy-atom metals such as tungsten and uranium at high temperatures in the wavelength region between 1250 Å and 100,000 Å (10 microns), and (2) comparing experimental line emission results with emission characteristics calculated in the spectral region between 2000 Å and 9000 Å using data reported in Refs. 8, 9, and 10. The experimental investigation was conducted using an inductively heated argon gas containing tungsten hexafluoride or uranium hexafluoride.

APPARATUS

RF System

The experiments described in this report were conducted using the United Aircraft Research Laboratories 80 kw radio-frequency (rf) induction heater. This facility was constructed in 1962 and was originally employed for induction heating of large-diameter gas vortex flows (i.e., vortexes having diameters of about 8 in. and lengths of about 20 in.). The results of these early tests are reported in Refs. 11 and 12. In 1967, this facility was modified to permit rf power to be coupled efficiently into small gas loads. A schematic diagram of the modified system is shown in Fig. 1. The principal modification consisted of changing the mode of operation of the rf generator from a self-oscillating system to a driven system. A 600 W tunable rf transmitter was used to drive the grid of the 80 kw power amplifier through a tuned coupling network. The output resonator was replaced with an easily modified work coil connected to the output of the power amplifier by means of a tunable π-coupling network. The modifications provided an induction heater that could efficiently add rf power to plasmas having wide ranges of impedances and sizes.

Details of the work coil and vortex chamber in which the plasma was created are shown in Fig. 2. The coil (Fig. 2a), which surrounded the fused silica vortex tube, consisted of 2.5 turns of 3/8-in. OD copper tubing with a mean coil diameter of 4 in. The vortex tube had an ID of 3 in. and an OD of $3\frac{1}{4}$ in. A vortex chamber was formed by water-cooled end walls spaced 6 in. apart (Fig. 2b). The working fluid (argon, or argon with gaseous seed) was injected circumferentially from the top end wall of the vortex chamber through eight 1/16-in. ID injectors. Flow was withdrawn from the vortex chamber through 0.3-in. ID water-cooled thru-flow ports located at the centers of the end walls. The fused silica peripheral wall was cooled by small air jets blowing axially along the outer surface.

The hot argon flowing out of the vortex chamber through the thru-flow ports was cooled to room temperature by passing it over water-cooled copper tubing. The end walls of the vortex chamber were also water cooled. The flow rate and temperature rise of the coolant water were measured and used to determine the power carried away in this manner, i.e., the approximate amount of power deposited in the gas that was not radiated (the convective losses through the peripheral wall were negligible). The powers deposited in work coil and π-coupling network were also determined from measurements of the temperature rises and flow rates of the water passing through these components.

Spectral Apparatus

Spectral intensity measurements, which were taken over an extremely wide range of wavelengths, required several different arrangements of equipment. The principal spectral instrument was a McPherson Model 235 scanning spectrometer/monochromator, used for tests in the ultraviolet and visible spectral ranges. The instrument was mounted on a modified milling table, which afforded motion in three axes, permitting precise adjustment of the spectrometer position with respect to the discharge. The table was also equipped with a drive motor which permitted continuous lateral motion of the entire instrument for chordwise viewing of the discharge.

In order to eliminate atmospheric absorption of the emission from the heated gas in the ultraviolet region of the spectrum, and to circumvent the cut-off of transmission by the vortex tube walls, the apparatus shown in Fig. 3 was used for measurements at wavelengths less than 2500 Å. A fused silica side arm was attached to the vortex tube and was capped with a lithium fluoride window. An extension tube was bolted to the spectrometer entrance slit flange and attached to the side arm with a Veeco vacuum coupling. The entire spectrometer and extension tube were purged with pure argon to eliminate oxygen and water vapor from the spectrometer system; the vortex tube was initially pumped down to a low pressure and was then continuously purged by the test gases. With this arrangement, it was possible to maintain the pressure differential required during initiation of the discharge while maximizing light transmission.

In order to provide estimates of possible absorption due to cold gases surrounding the discharge or contained in the side arm, tungsten hexafluoride was admitted to an evacuated sample chamber at a pressure of 5 mm Hg. The chamber had a length of 10 cm, and was capped with lithium fluoride windows. Depending upon the wavelength of interest, light from a Hanovia hydrogen discharge lamp (for the UV) or a GE DXW coiled-filament tungsten lamp (for the near-UV and visible) passed through the sample cell into the McPherson spectrometer, and the relative intensities transmitted by the cell were determined both with and without sample. The absorption of room temperature WF_6 (for the 10 cm path) was determined to be less than 10 percent between 1200 Å and 2000 Å, and negligible between 2000 Å and 4000 Å. In the visible region, the WF_6 sample in the cell exhibited no coloration, indicating no significant absorption. Similar tests using sulfur hexafluoride, SF_6, likewise indicated less than 10 percent absorption in the region between 1200 Å and 2000 Å, and no detectable absorption between 2000 Å and 8500 Å. Since only molecular spectra would be evidenced in these room temperature gases, it was assumed that the WF_6 and SF_6 samples would also be representative of the UF_6 molecular absorption characteristics, and the effect of absorption by either of the added test gases was deemed negligible.

No tests were conducted to determine absorption by room temperature argon, in view of the widely-held practice of purging optical systems with argon to eliminate other gases which exhibit absorption.

Photoelectric detection in the UV was accomplished primarily using an EMI 9558C phototube. The end window of the phototube was coated with sodium salicylate, which responds with essentially constant quantum efficiency below 3500 Å (Ref. 13). Some tests between 1650 Å and 4500 Å were conducted using an EMI 9558QA phototube, which has a Suprasil window and is sensitive without the sodium salicylate coating. The phototube output was amplified in a signal processor and recorded on a Honeywell Model 1108 Visicorder. Wavelength scanning rates as high as 4000 Å/min were permitted by the high frequency response (up to 1000 Hz) of the Visicorder.

For tests in the visible region of the spectrum, the spectrometer was placed 50 cm from the discharge, the extension tube was removed from the spectrometer, and a short extension tube, having a 0.025 cm x 0.4 cm aperture to limit the field of view, was attached. The aperture restricted the field of view to a region of the discharge having cross sectional dimensions of 0.15 x 0.4 cm. Since the diameter of the discharge was approximately 5 cm, the volume observed by the spectrometer was approximately 0.3 cm^3. Based on the same aperture, the area observed on the discharge subtended a solid angle of 2.4×10^{-4} steradian. A straight-walled vortex tube was used to permit lateral or chordwise scans of the discharge. Lateral scans were conducted at specific wavelengths to observe desired lines or continua. Wavelength scans were conducted on the discharge centerline and at a number of chordal positions. Detection was accomplished between 3500 Å and 8500 Å using the EMI 9885C phototube, which responded directly to plasma radiation.

Tests in the infrared spectral region were conducted using a Perkin-Elmer Model 99 spectrometer equipped with a sodium chloride prism. Although the salt prism does not afford the relatively high resolution of the McPherson Model 235, it does permit coverage of the spectrum from the red end of the visible region to beyond 5 microns in the infrared. The general arrangement of apparatus for tests in the infrared was the same as that used for the UV measurements. A vortex tube equipped with a side arm was connected to an extension tube on the Model 99. Both the Model 99 and the extension tube were purged with argon. Detection was accomplished with a cooled Santa Barbara PbSe detector; the signal was displayed on a Moseley strip chart recorder.

Wavelength calibration of the McPherson Model 235 was accomplished using mercury, sodium, and argon spectral lamps. Calibration of the Model 99 was made possible through the use of bandpass filters and a tungsten strip lamp which furnished a continuous source. Absolute intensity calibration of the Model 235 system above 2500 Å was referred to a GE T24/7 tungsten strip lamp operated at 2470 deg K. Spectral radiance of the strip lamp was taken from Refs. 14 and 15. The constant response of sodium salicylate below 2500 Å (Ref. 13) was used to extend the calibration to the limit of these tests in the UV. Calibration of the Model 99 system to 2.5 microns was also accomplished through use of the strip lamp and cross-checked through the overlap of the PbSe and EMI 9558 spectral detectors in the near infrared. Extension of the PbSe calibration proceeded through use of a Nernst

glower operated at 1500 deg C to give a relative calibration from 2.5 microns to beyond 5 microns, which was then matched to the absolute response at 2.5 microns (the limit of transmission of the window on the strip lamp).

In view of the low level of signal evidenced in the seeded argon spectra at wavelengths approaching 5 microns, it was decided to use a survey method for the region between 5 microns and 10 microns. A radiometer having a thermopile detector responding to radiation between 0.2 and 15 microns was used in conjunction with several cut-off filters transmitting light only above wavelengths of 1.06, 2.0, 2.5, 3.0, 3.5, and 3.83 microns. The known quantity of radiation removed by successive filters permitted estimation of the residual radiation beyond 3.83 microns.

The total radiation of the plasma was measured with a Reeder NSL 6C thermopile. The spectral response of this thermopile with a BaF_2 window is approximately 0.2 to 15.0 microns. Various cut-off filters were inserted in front of the thermopile to determine the radiation in different regions of the spectrum. The transmission characteristics of these filters are shown in Fig. 4. The response of the thermopile with filters was calibrated using an Eppley Laboratory Calibrated Standard of Spectral Irradiance. The calibration range was from 0.22 microns to 2.5 microns.

Operating Procedure

A gas discharge was initiated by evacuating the vortex chamber to several millimeters of mercury absolute pressure and establishing a low-pressure glow discharge with the rf field. The pressure, argon flow and rf power were then increased simultaneously until the desired operating condition was established. The standard operating conditions employed in the tests described in this report are listed in Table I. A photograph of an unseeded argon discharge at the standard conditions is shown in Fig. 2c. This discharge was confined well away from the peripheral wall (a distance of approximately 15 mm existed between the edge of the discharge and the wall). Thus, tests could be conducted for long periods with negligible heating of the tube.

To measure the spectral emission of heavy metal vapors, it was first necessary to develop an injection method that would provide a uniform heavy metal flow rate that was reproducible and steady for periods up to several minutes. After several unsuccessful attempts to inject submicron tungsten particles directly into the plasma, it was decided to inject the metals as gaseous fluorides, i.e., as WF_6 and UF_6. The vapor pressure curves of WF_6 and UF_6 are presented in Fig. 5 (Refs. 16 and 17). Attempts to inject the heavy-atom gases directly into the plasma were unsuccessful because of the large disturbance created by injection and an apparent non-uniform distribution of the vapor within the plasma. The technique that proved most successful was to premix the WF_6 and UF_6 with the argon working fluid well upstream of the eight injector ducts (Fig. 2b). Of the techniques that were attempted, this technique probably provided the most uniform distribution of metal vapor within the plasma.

During the initial series of tests, WF_6 was flowed directly from its container through a small flowmeter and metering valve into the argon flow duct. It was necessary to heat the WF_6 container and flowmeter to about 45 deg C to insure adequate pressure for steady flow. However, at the extremely small flow rates of WF_6 used, the accuracy and reproducibility of the flow setting were very poor. No reliable way was found to calibrate the flowmeter for highly reactive WF_6 at the extremely small flow rates employed. A more reliable method, used in later tests, involved evacuation of a container having a volume of approximately $1\frac{1}{2}$ cu ft, and then filling the container to a vapor pressure of 5 mm Hg abs. The vapor pressure was fixed by placing the WF_6 or UF_6 container in a cold sink at the temperature corresponding to a vapor pressure of 5 mm Hg, i.e., -56 deg C for WF_6 and -12 deg C for UF_6 (see Fig. 5). The container was subsequently pressurized to 100 psig with argon. The argon/fluoride mixture was flowed through a flowmeter and then pre-mixed with the main argon flow.

DATA REDUCTION

Reduction of Spectral Data

Typical emission spectra for seeded and unseeded argon are shown in Figs. 6 and 7. Figure 6 is a comparison of the argon and argon/WF_6 spectra in the vicinity of 4300 Å. Figure 7 is a comparison of the same argon spectrum with that of argon/UF_6. The spectra illustrate the relative magnitudes of line and continuum radiation in this wavelength region. It should be noted that the continuum radiation is a maximum at wavelengths between approximately 4200 Å and 4300 Å, and decreases slowly with increasing or decreasing wavelength. However, because of the much greater line intensity of the ArI red lines near 8000 Å, the relative continuum contribution decreases very rapidly toward the near infrared. The argon continuum contribution in both seeded and unseeded argon was taken to be that intensity, measured from the zero reference level, above which only line radiation was evidenced. This assumes that the addition of the seed to the argon discharge increased the total argon radiation (by increasing temperature), as is apparent from Figs. 6 and 7, without introducing significant continuum radiation from the seed species. The validity of this assumption is discussed further in the section on Temperature Determination. The areas corresponding to line and continuum radiation were determined with a planimeter for wavelength intervals of 100 Å. The areas were compared to the area found under the reference lamp curve, which is also shown on the figures, in order to determine absolute intensities. Selected individual ArI line areas were measured for use in temperature determination.

The breadth of lines shown in Figs. 6 and 7 was due primarily to instrumental effects. The true half-width of the lines at half-height was estimated to be approximately 0.2 Å for spectra obtained with the McPherson instrument (1200 Å to 8500 Å). The resolution of the Model 99 is such that individual lines could not be resolved at wavelengths above 8000 Å (0.8 microns); therefore, no estimate could be made of the line contours in the infrared.

The relatively large total line width due to instrumental effects was in part responsible for failure to resolve many of the lines tabulated in Ref. 8. Weaker lines thus appeared in the experimental spectra to be nearly submerged into the continuum. However, this investigation represents the first observation of a number of tungsten and uranium lines in the UV. The number of individual distinguishable lines attributable to additives in the spectral region 1200 Å to 2500 Å was 23 for tungsten and 18 for uranium. The distribution for tungsten was: 1200 Å to 1500 Å -4, 1500 Å to 2000 Å - 9, and 2000 Å to 2500 Å - 10. In the case of uranium, the distribution was: 1200 Å to 1500 Å - 6, 1500 Å to 2000 Å - 9, and 2000 Å to 2500 Å - 3.

Temperature Determination

The determination of the temperature of a radiating system may be based on the radiation of lines or continuum. The intensity of a single line in a system of N_o radiators may be expressed as (Refs. 18 to 21)

$$I_L = 1.58 \times 10^{-24} \frac{gA}{Q\lambda} N_o e^{-E_n/kT} \quad \text{WATTS/CM}^3\text{ SR} \tag{1}$$

where g is the degeneracy of an upper level having energy E_n, A is the transition probability in sec^{-1}, Q is the partition function, λ is the wavelength in Ångstrom units, k is the Boltzmann constant, and T is the temperature.

In Eq. (1) the functional dependence of the intensity of a particular spectral line on temperature is contained in the composition term, N_o, as well as in the exponential. Thus, for Ar at temperatures near 8000 deg K, where the composition of neutral argon (ArI) changes very little with temperature (Ref. 22), the exponential term defines the temperature dependence, and the intensities of ArI spectral lines increase very rapidly with increasing temperature. The dependence of the intensities of the ArI 4158 Å and 4300 Å lines on temperature is shown in Fig. 8. However, for tungsten in this temperature range, the fraction of neutral tungsten (WI) decreases markedly with temperature, damping the effect of the exponential; thus the intensities of WI lines are very weak functions of temperature, as shown in Fig. 9. Therefore, intensity measurements of ArI lines in this temperature range provide very good indications of temperature, while intensity measurements of WI lines do not.

Some improvement in determining temperature from intensity measurements of spectral lines such as the WI lines discussed above can be achieved using an atomic Boltzmann plot, in which log $(I\lambda/gA)$ is plotted versus E_n for a number of lines; the slope of the line best fitting the data is related to the temperature through the following equation, which develops from Eq. (1):

$$\text{LOG}_{10} \left[I\lambda/gA\right] = \text{LOG}_{10}\, C - E_n/kT \tag{2}$$

The constant (C) in Eq. (2) contains the term N_o/Q and constant numerical terms. The slope of the line is thus independent of species density. If E_n and kT are both expressed in eV, a convenient expression for the temperature as indicated by the Boltzmann plot is

$$T\ (\text{DEG K}) = -5040/\text{SLOPE} \tag{3}$$

A second basic characteristic of radiating systems is the intensity of continuum radiation (Refs. 22 through 26), which may be expressed as

$$I_C = 5.41 \times 10^{-46}\ \bar{g}\ Z_{EFF}^2\ N_e N_+ / T_e^{1/2}\ \text{WATTS/CM}^3\ \text{SR} \qquad (4)$$

per unit frequency interval. N_e and N_+ are the electron and ion density, respectively, T_e is the electron temperature, Z_{eff} is the effective charge per ion, and $\bar{g}$ is the Gaunt factor, having a value of approximately 2.3 for argon near 4300 Å (Ref. 22). The strong dependence on temperature of the argon continuum at 4300 Å is shown in Fig. 10. The continuum emission of tungsten or uranium can be neglected in the seeded argon system considered here; the very low values of N_+ or N_{++} in either case would require Gaunt factors several orders of magnitude greater than the predicted value of nearly unity (Ref. 27) for any appreciable continuum to appear.

EXPERIMENTAL RESULTS

Temperature of the Discharge

In view of the sensitivity of the intensity of argon radiation to temperature (Figs. 8 and 10), the argon spectrum afforded the best means of characterizing the temperature of the plasma. In order to determine the temperature profiles in both seeded and unseeded discharges, chordwise scans of the discharge were conducted to obtain the chordal intensity profile of many argon lines. As many as 17 neutral argon atom (ArI) lines were observed during a single test. (No ArII lines were evident.) The left and right half-intensity profiles were folded together and averaged, and an Abel inversion procedure was employed to determine radial intensity profiles from the chordal intensity profiles (Ref. 28).

A typical chordal intensity profile and the resulting radial (inverted) intensity profile are shown in Fig. 11. The calculated dependence of intensity on temperature (Fig. 8) was then used in conjunction with the radial intensity to establish the radial temperature profile shown in Fig. 12. Also shown on Fig. 12 is the chordal average temperature at the midplane of the discharge, determined by constructing a Boltzmann plot of chordal intensities measured at the midplane position. The Boltzmann plot is shown in Fig. 13. This is a valid procedure for obtaining the chordal average temperature as long as the gas composition, reflected by the term N_0 in Eq. (1), remains relatively constant across the discharge. As noted previously, this is the case for ArI at temperatures around 8000 deg K. Other indications of the chordal average argon temperature at the midplane are shown on Figs. 8 and 10; the temperature based on absolute line radiation is approximately 8450 deg K, while that based on absolute continuum radiation at 4300 Å is approximately 8575 deg K.

The temperature profile of seeded argon was also determined using Boltzmann plots of chordal intensities of ArI lines and was found to be essentially the same as for unseeded argon within the precision of the method. Absolute measurements of average centerline intensity for line and continuum emission indicated that seeding the argon with WF_6 resulted in a temperature increase of about 100 deg K, while seeding argon with UF_6 resulted in a temperature increase of about 150 deg K.

In order to ascertain any departures from local thermodynamic equilibrium between the seed gas and the argon, it was intended to follow the procedure outlined above to determine the temperatures of the tungsten or uranium gas using metal vapor line radiation. However, several obstacles existed: (1) the WI lines have a very weak dependence on temperature so that intensity profiles of these lines are not reliable for temperature estimates, (2) the intensities of the few classified WII lines, which are more strongly temperature dependent than those of WI, were not sufficiently strong relative to background or sufficiently isolated to

provide reliable indications of temperature, and (3) too few clearly defined, strong WI or WII lines were available to construct an accurate Boltzmann plot. Therefore, any temperature specification based on tungsten radiation would have limited accuracy.

The same situation prevails in the case of uranium, in which more lines are tabulated (Ref. 8), but fewer strong lines are found than in tungsten. In uranium, considerable overlapping of adjacent lines prevails; any temperature based on uranium line radiation would also be suspect.

Integrated Line and Continuum Intensities

The integrated continuum emission in wavelength intervals of 100 Å for argon, argon/WF_6 and argon/UF_6 between wavelengths of 1200 Å and 8500 Å are shown in Fig. 14. The variation of emission with wavelength is similar in all three cases, and is representative of the argon continuum. It should be noted that there is a greater change in continuum emission upon the addition of UF_6 to the argon than occurs upon addition of WF_6 to the argon. By inspection of spectral regions where little line intensity from either tungsten or uranium could be expected, based on the data of Ref. 8, it was estimated that the increases in continuum emission from argon upon additional WF_6 or UF_6 were 30 percent and 40 percent, respectively, although the total continuum changes between 1200 Å and 8500 Å were 43 percent and 58 percent, respectively. The changes in argon continuum radiation upon addition of seed gas are due to changes in the discharge characteristics such as diameter or temperature. If the increases in argon continuum emission are attributed entirely to temperature changes, the increases in temperatures are approximately 100 deg K and 150 deg K for WF_6 and UF_6 addition, respectively. In spectral regions where line radiation from seeds is known to exist, additional increases in apparent total continuum radiation are attributable to the presence of weak, unresolved lines in the tungsten and uranium spectra.

The results of the radiometric measurements are shown in Fig. 15. The percentages of total radiation falling into the spectral regions defined by the filters are: 2200 Å to 3000 Å - 3%, 3000 Å to 7000 Å - 20%, 7000 Å to 10000 Å (1 micron) - 50%, and 1 micron to 2.5 microns - 27%. The percentages are changed slightly upon addition of WF_6 or UF_6 to the argon, but the near IR (which contains the strongest lines of argon) includes the largest total intensity.

The results of total emission measurements are shown in Fig. 16. The large contribution of the strong lines of ArI near 8000 Å is clearly evident. The largest net changes in emission due to WF_6 or UF_6 addition occur in the same wavelength interval as that in which continuum changes are greatest, namely 4000 Å to 6000 Å. Percentage increases in total radiation at wavelengths of 1200 Å to 8500 Å associated with addition of WF_6 and UF_6 were 25 percent and 70 percent, respectively; these results are in general agreement with the values determined radiometrically (see Fig. 15).

A comparison of the line and continuum radiation from argon is given in Fig. 17. The total line intensity, 0.19 W/cm^3-sr is approximately 21 percent larger than that of the continuum intensity (0.14 W/cm^3-sr). It should be noted that at wavelengths below approximately 7000 Å, continuum radiation predominates, and except for several 100 Å intervals, is greater than the line emission by factors of 2 to 4. As is the case in any line/continuum spectrum, however, some lines appear to become submerged in the background, and a larger line/continuum intensity ratio should be assumed to exist.

The line radiation due to tungsten is shown in Fig. 18. In obtaining this intensity distribution, the argon line and continuum areas were increased by 30 percent and then subtracted from the total intensity due to tungsten and argon. It should be noted that a small quantity of emission, 0.05 W/cm^3-sr, is attributable to tungsten line radiation.

A similar procedure was followed with the uranium spectrum using the argon line and continuum data enhanced by 40 percent. The resulting uranium line intensity is 0.15 W/cm^3-sr, and is shown in Fig. 19.

Total emission spectra between 0.7 microns and 5 microns are shown in Fig. 20. Very little difference was noted in the spectral profiles of the argon, Ar/WF_6, or Ar/UF_6 systems, although slightly more radiation was emitted in the case of Ar/WF_6. The known argon lines between 1.0 and 1.5 microns (Ref. 29) were not resolved by the spectrometer, but the presence of the lines is shown by the added radiation in that region.

Comparison of Experimental Results with Calculated Intensities

Comparisons of the line emission data with calculated values (Ref. 30) are shown in Figs. 21 through 23. Figure 21 shows a comparison between experimental and calculated line intensities in argon. The experimentally determined integrated line intensities agree well with calculated integrated line intensities, being 0.28 and 0.34 W/cm^3-sr, respectively. A temperature adjustment of approximately 75 deg K, which is within the precision of the methods used, would be sufficient to bring the experimental and calculated line intensities into complete agreement. Furthermore, experimentally and analytically determined spectral distributions of integrated line intensity are in good agreement.

A comparison of experimental and calculated line intensities for tungsten is shown in Fig. 22. The experimental total line intensity is much lower than that predicted analytically, although the correspondence between calculated and experimental values of integrated line intensity per 100 Å is very good at wavelengths longer than 4000 Å. The data are in poorer agreement in the near infrared; here small errors in estimation of ArI line enhancement result in large errors in the

W line intensities. Best estimates of W line intensities are found in spectral regions where the line intensities of interest are a significant part of the total emission.

A final comparison is given in Fig. 23, in which the experimental and calculated results for uranium are shown. The experimental total line intensity is somewhat smaller than the calculated intensity, 0.13 vs 0.19 W/cm^3-sr, respectively, although good agreement exists in specific 100 Å intervals near 4000 Å.

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LIST OF SYMBOLS

A	Absolute transition probability, sec^{-1}
ArI	Neutral argon atom
C	Constant in Boltzmann equation. See Eq. (2)
E_n	Energy of upper level of spectral transition, eV
eV	Electron volt
g	Statistical weight of level E_n, dimensionless
$\bar{g}$	Gaunt factor, dimensionless
I	Spectral intensity, arbitrary units
I_C	Intensity of continuum, W/cm^3-sr
I_L	Intensity of line, W/cm^3-sr
I_r	Radial intensity, arbitrary units
I_x	Chordal intensity, arbitrary units
$I_C,\Delta\lambda$	Continuum intensity in interval $\Delta\lambda$, W/cm^3-sr
$I_L,\Delta\lambda$	Line intensity in interval $\Delta\lambda$, W/cm^3-sr
$I_T,\Delta\lambda$	Total intensity in interval $\Delta\lambda$, W/cm^3-sr
$I(\lambda)$	Transmitted intensity at wavelength λ, arbitrary units
$I_o(\lambda)$	Incident intensity at wavelength λ, arbitrary units
k	Boltzmann constant, 1.38×10^{-16} erg/deg K
N_e	Number of electrons, cm^{-3}
N_o	Number of radiators in specific ionization state, cm^{-3}
N_+	Number of singly ionized atoms, cm^{-3}
N_{++}	Number of doubly ionized atoms, cm^{-3}

LIST OF SYMBOLS
(cont'd)

Q	Partition function, dimensionless
r	Radius, in. or cm
r_D	Radius of discharge, in. or cm
sr	Steradian
SF_6	Sulfur hexafluoride
T	Temperature of gas, deg K or eV
T_e	Temperature of electrons, deg K or eV
UI	Neutral uranium atom
UF_6	Uranium hexafluoride
WI	Neutral tungsten atom
WF_6	Tungsten hexafluoride
x	Chordal distance, in. or cm
Z_{eff}	Effective charge on ion
λ	Wavelength Å or micron
$\Delta\lambda$	Wavelength interval, Å or micron

TABLE I

STANDARD FLOW CONDITIONS AND CORRESPONDING R-F AND POWER CONDITIONS

See Fig. 2 for Details of Vortex Tube Geometry

Standard Flow Conditions	
Primary Gas	Argon
Injection Flow Rate	4.5×10^{-3} lb/sec
Injection Velocity	220 ft/sec
Total Pressure at Vortex Centerline	1.0 atm
Percent Thru-Flow	100%
Percent Axial Bypass Flow	0%
Seeded Gases	WF_6 and UF_6
Injection Flow Rate of WF_6	0.70×10^{-6} lb/sec
Partial Pressure of WF_6	2.1×10^{-5} atm
Mass Ratio of WF_6/Argon	1.6×10^{-4}
Injection Flow Rate of UF_6	0.85×10^{-6} lb/sec
Partial Pressure of UF_6	2.1×10^{-5} atm
Mass Ratio of UF_6/Argon	1.9×10^{-4}
R-F and Power Conditions	
R-F Driving Frequency	7.25 mHz
Inductance of Work Coil	1.2×10^{-6} Henry
Power Deposition - Argon Only	
D-C Plate Voltage	4500 v
D-C Plate Current	4.5 amp

TABLE I (Cont'd)

D-C Plate Power	20.3 kw
Peak Voltage across Coil	8000 v
Power in Work Coil	0.65 kw
Power Deposited in Gas Exiting from Vortex Chamber	7.6 kw
Power Radiated	0.9 kw
Power Deposition - Argon and WF_6 or UF_6:	
D-C Plate Voltage	5000 v
D-C Plate Current	4.5 amp
D-C Plate Power	22.5 kw
Peak Voltage across Coil	8700 v
Power in Work Coil	0.90 kw
Power Deposited in Gas Exiting from Vortex Chamber	7.6 kw
Power Radiated	1.4 kw

Note: Additional power deposited in gas is conducted through 3-in. ID fused silica tube and removed by air jets blowing axially along tube wall. The power removed by these air jets was not measured, but was estimated to be about 0.5 kw.

SCHEMATIC DIAGRAM OF UARL 80-KW R-F INDUCTION HEATER

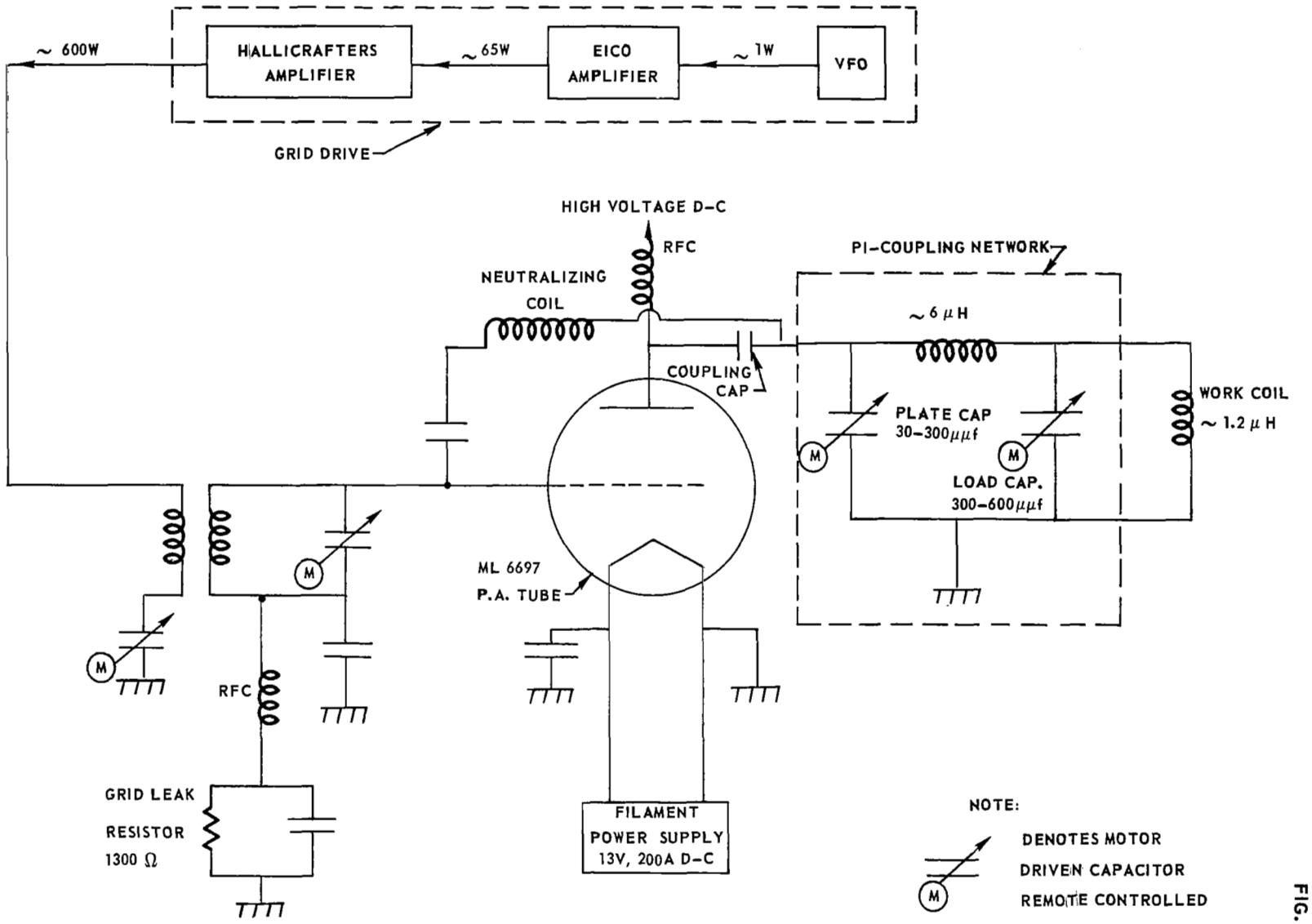
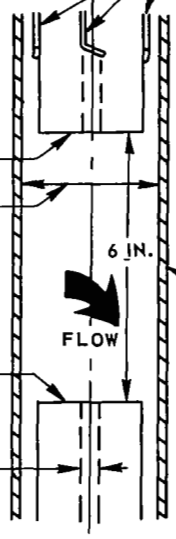


FIG. 1

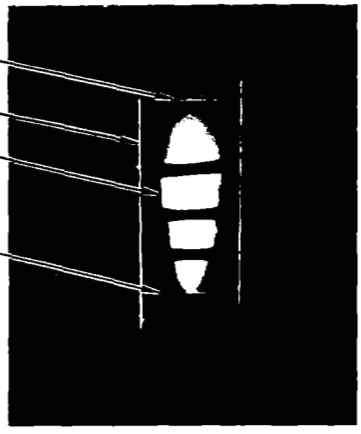
3 IN. (76 MM)–ID VORTEX CHAMBER EMPLOYED IN TESTS IN 80–KW R–F INDUCTION HEATER

a) PHOTOGRAPH OF VORTEX TUBE AND WORK COIL

b) SKETCH OF VORTEX TUBE

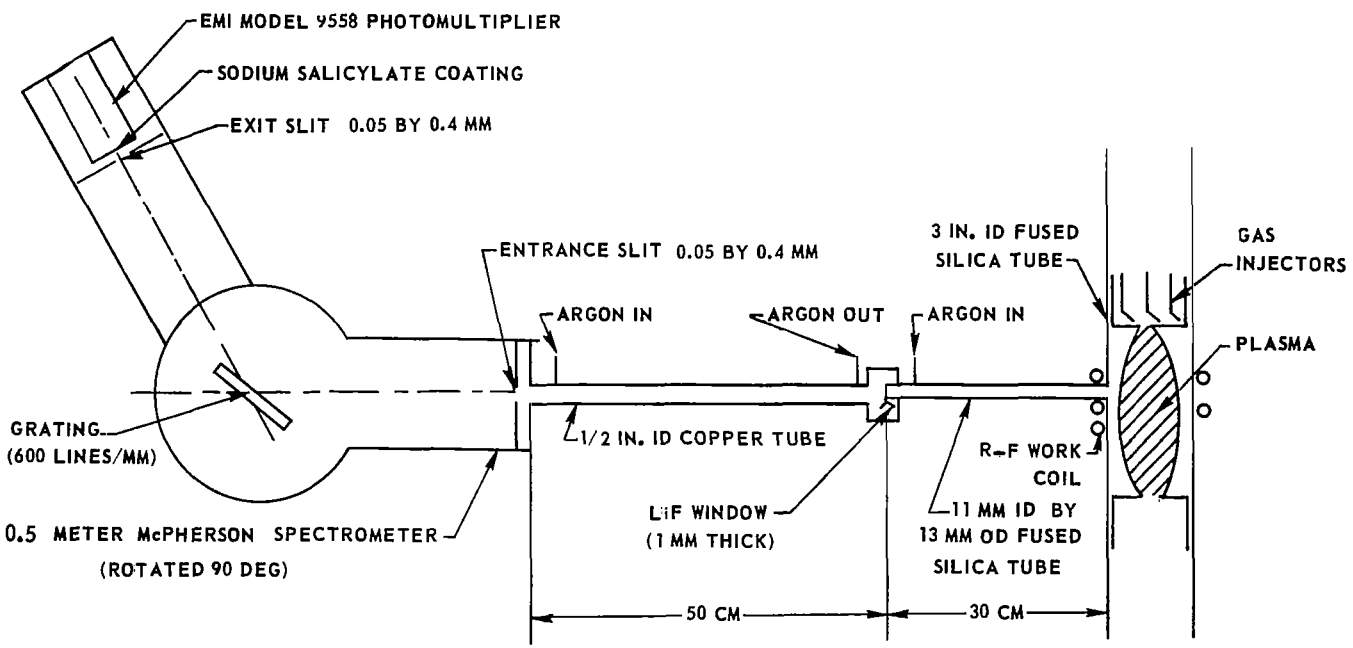


c) PHOTOGRAPH OF ARGON DISCHARGE



SKETCH OF OPTICAL SYSTEM FOR MEASUREMENT OF EMISSION SPECTRA AT WAVELENGTHS LESS THAN 2500 Å

(NOT TO SCALE)



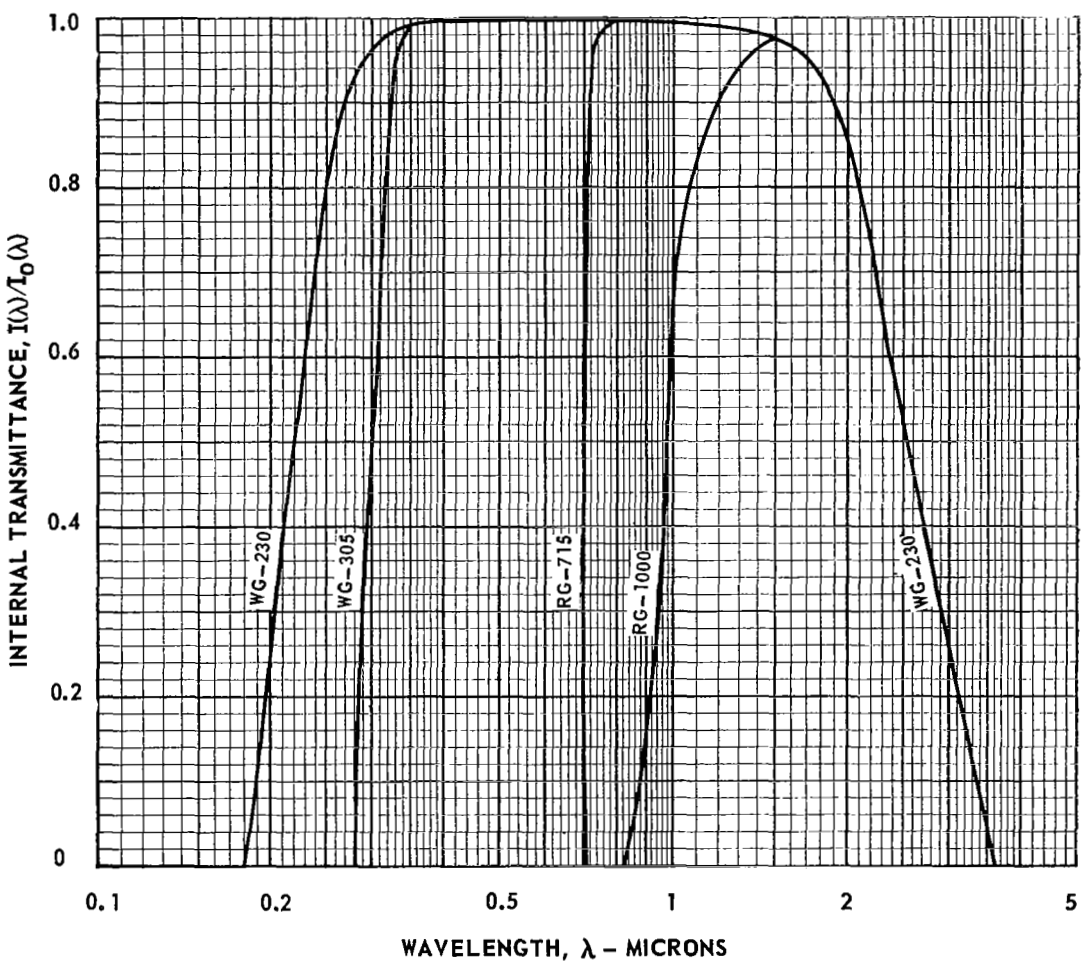
NOTES: MODIFICATION OF APPARATUS FOR OTHER SPECTRAL REGIONS ARE DESCRIBED IN TEXT

FIG. 3

FIG. 4

TRANSMISSION CHARACTERISTICS OF FILTERS USED FOR TOTAL RADIATION MEASUREMENTS

FILTER THICKNESS = 2 MM



VARIATIONS OF THE VAPOR PRESSURES OF TUNGSTEN HEXAFLUORIDE AND URANIUM HEXAFLUORIDE WITH TEMPERATURE

WF_6 DATA FROM REF. 3 UF_6 DATA FROM REF. 4

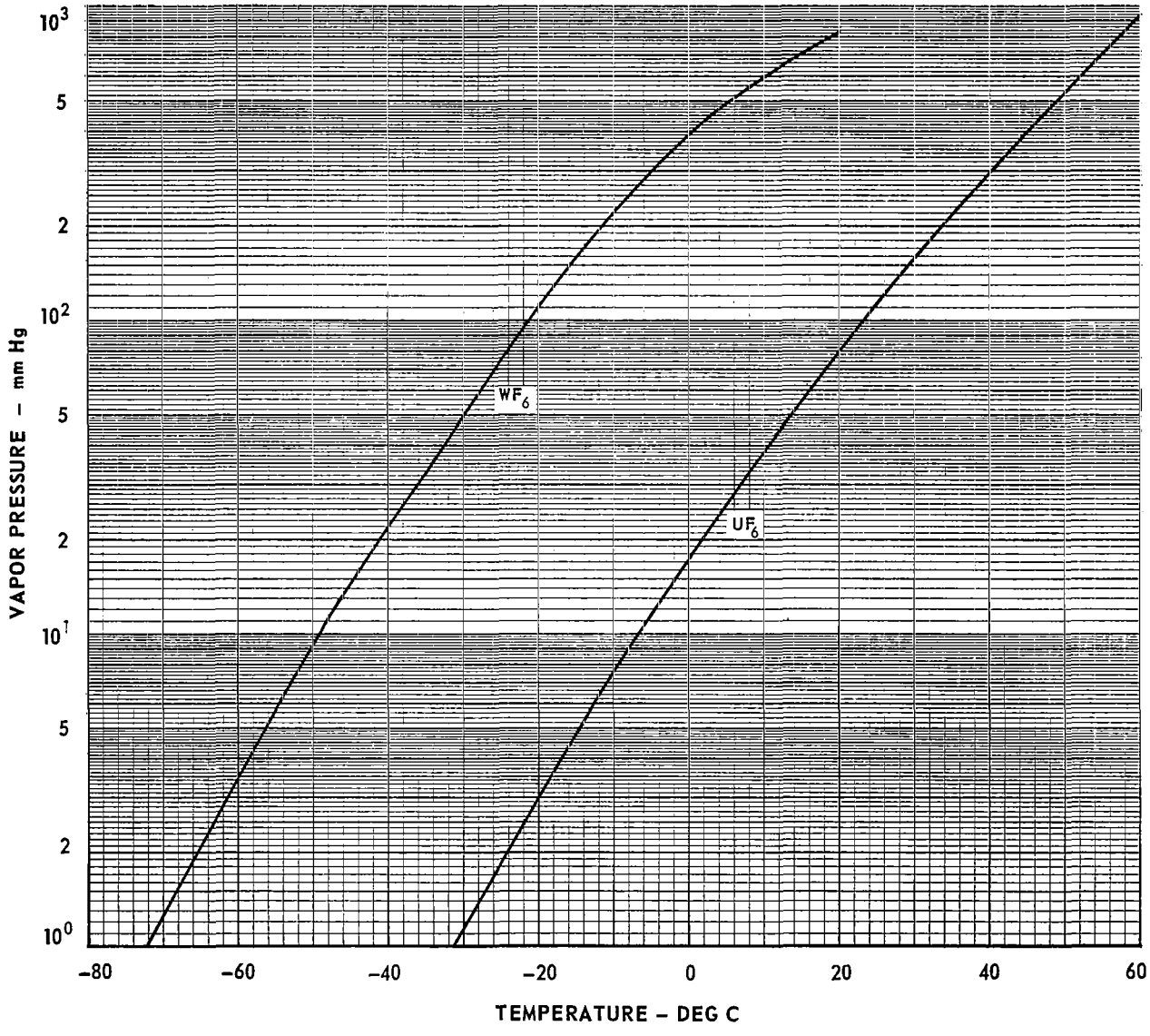


FIG. 5

COMPARISON OF EMISSION SPECTRA OF RF- HEATED ARGON/WF_6 MIXTURE AT APPROXIMATELY 4300 Å

SEE TABLE I FOR FLOW CONDITIONS

DATA TAKEN ON CENTERLINE OF DISCHARGE

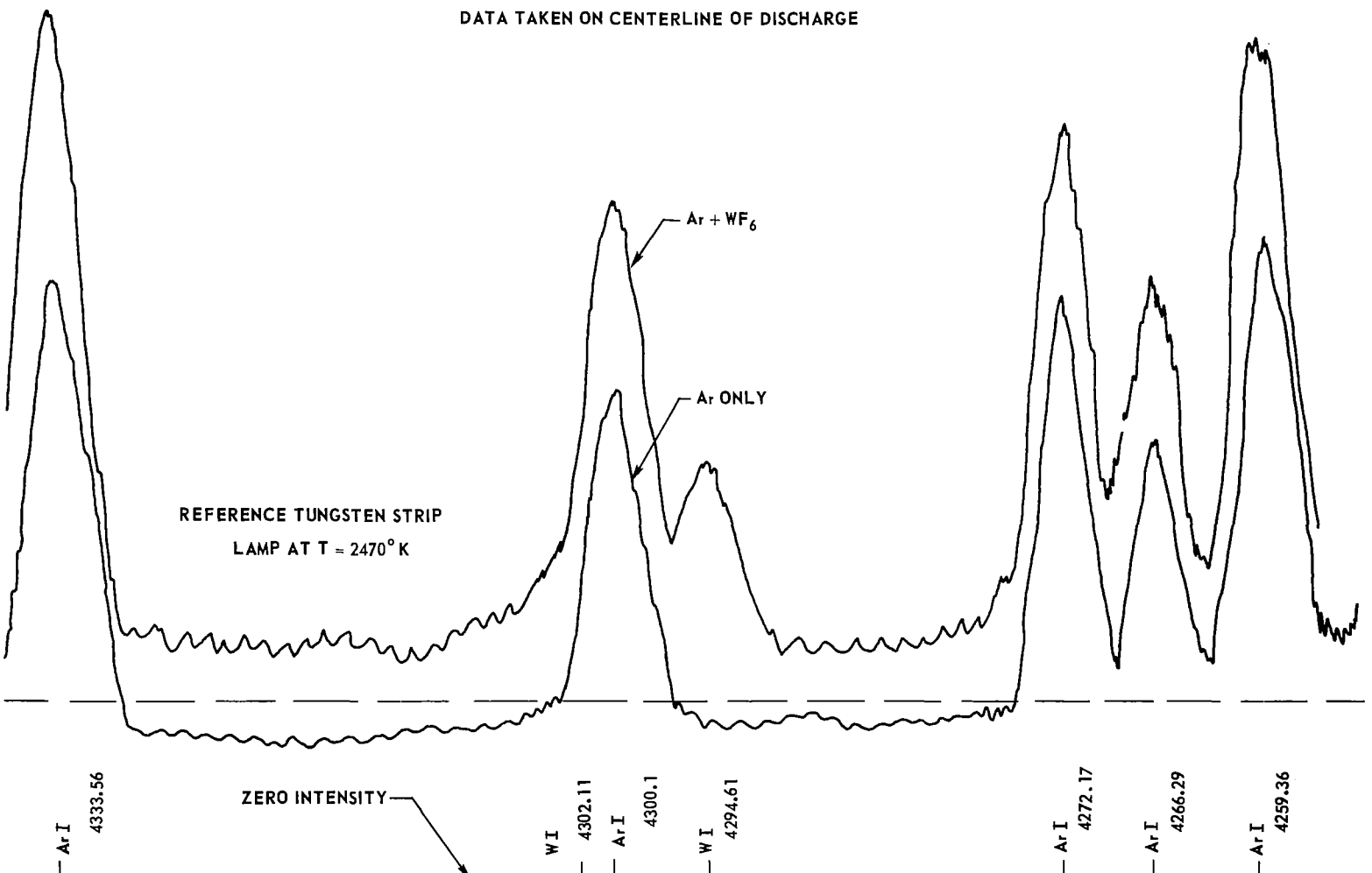


FIG. 6

COMPARISON OF EMISSION SPECTRA OF RF-HEATED ARGON/UF_6 MIXTURE AT APPROXIMATELY 4300 Å

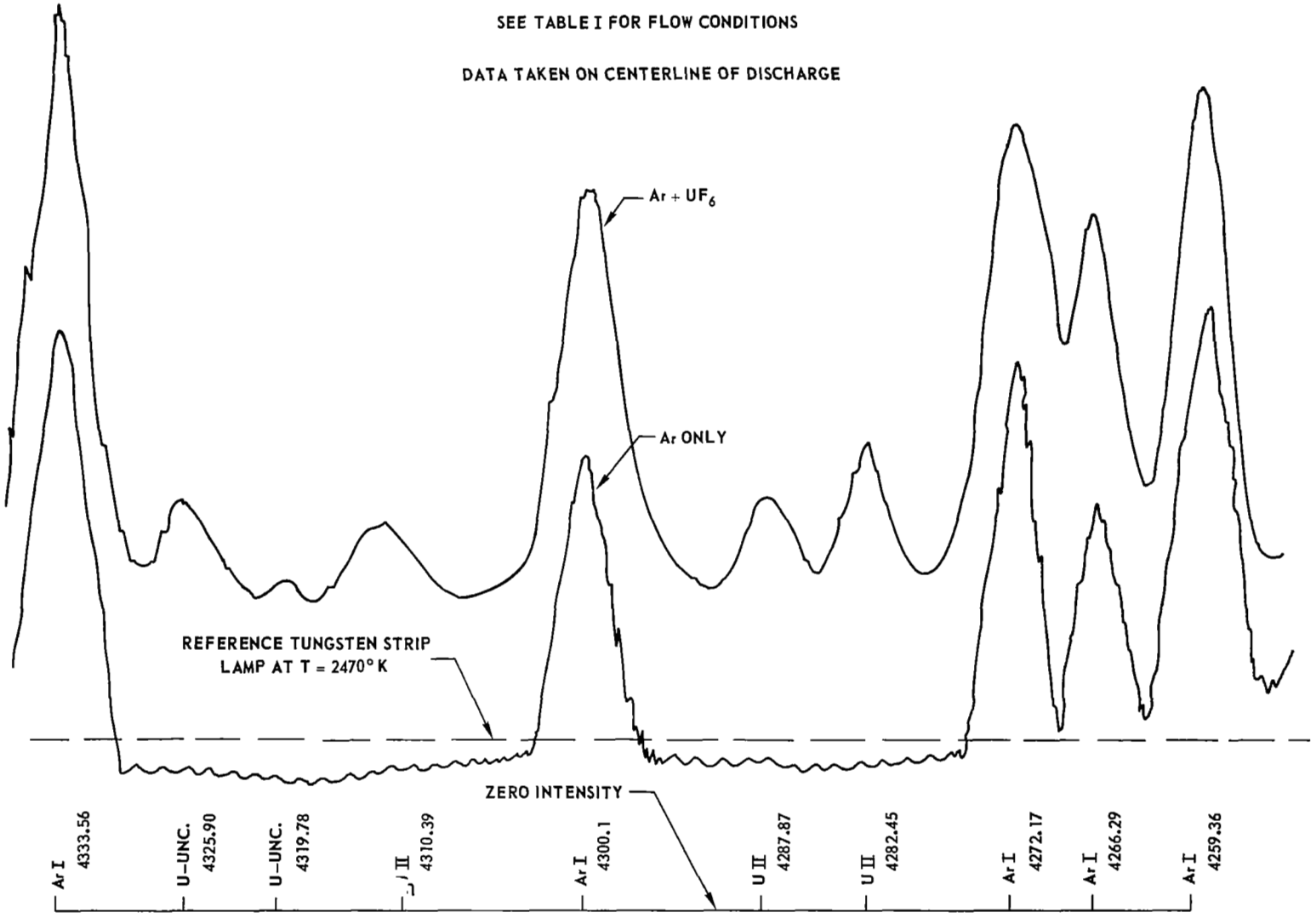


FIG. 7

FIG. 8

CALCULATED VARIATION WITH TEMPERATURE OF INTENSITY OF ARGON I LINES AT 4158 Å AND 4300 Å AT A PRESSURE OF 1 ATM

SEE TEXT FOR DETAILS OF CALCULATION

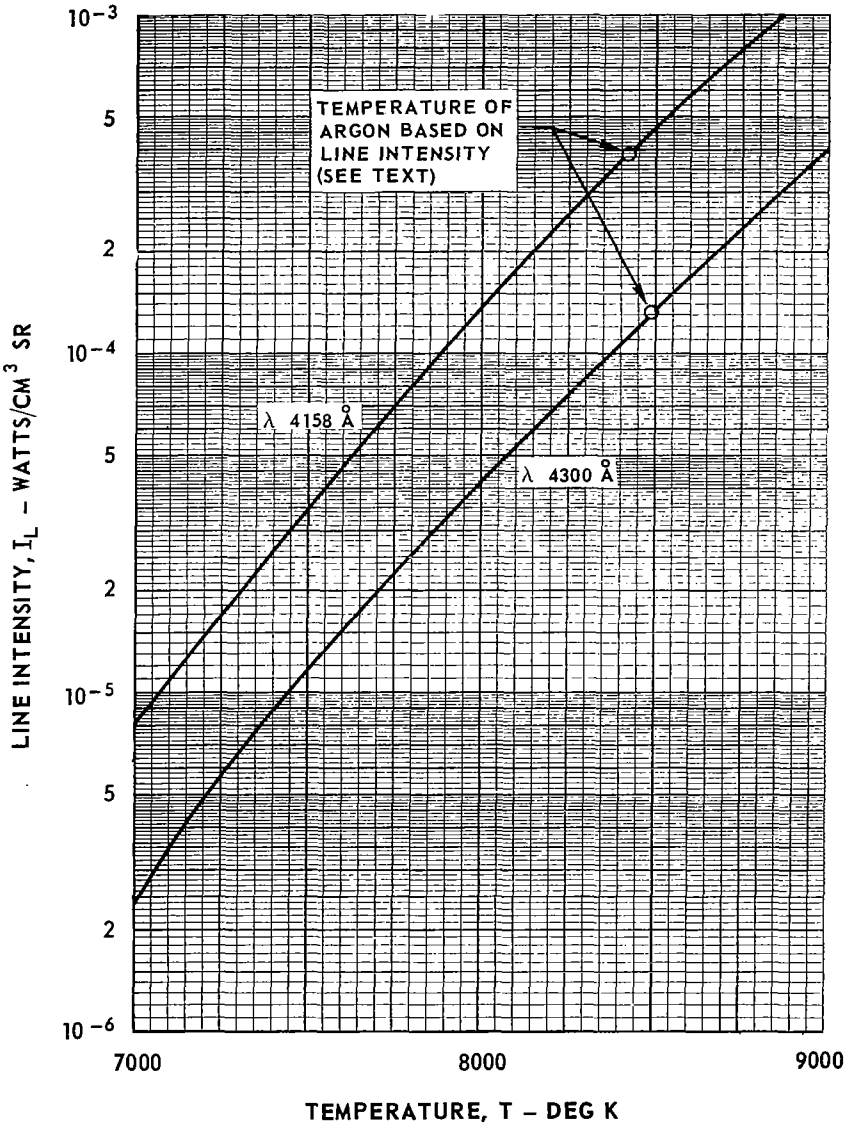


FIG. 9

CALCULATED VARIATION WITH TEMPERATURE OF LINE INTENSITY OF THREE TUNGSTEN I LINES IN ARGON/WF_6 MIXTURES FOR WF_6 PARTIAL PRESSURE OF 1.34×10^{-4} ATM

SEE TEXT FOR DETAILS OF CALCULATION

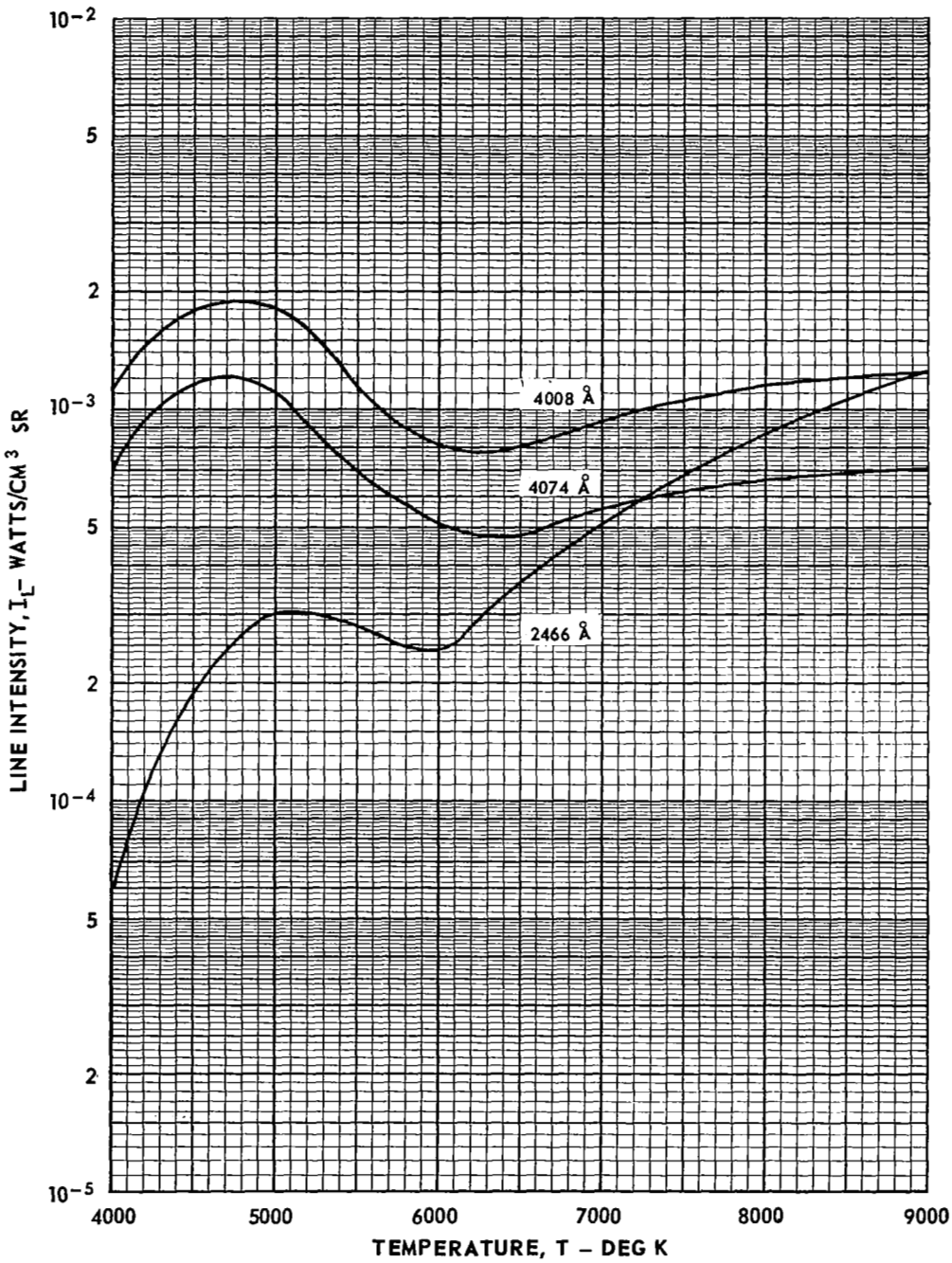


FIG. 10

CALCULATED VARIATION WITH TEMPERATURE OF THE TOTAL ARGON CONTINUUM EMISSION BETWEEN 4200 Å AND 4300 Å AT A PRESSURE OF 1 ATM

SEE TEXT FOR DETAILS OF CALCULATION

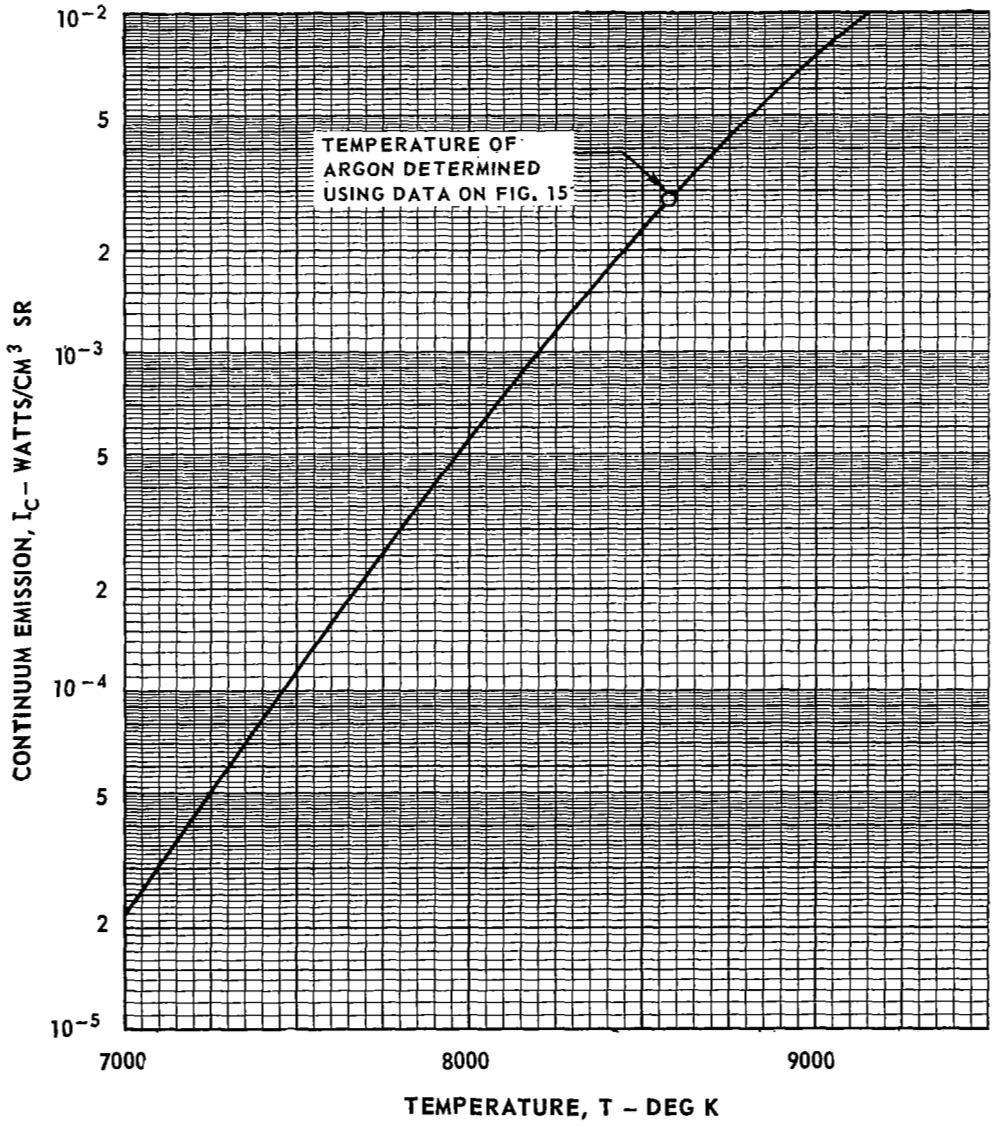


FIG. 11

TYPICAL CHORDAL AND RADIAL VARIATIONS IN INTENSITY OF 4158 Å ArI LINE IN AN UNSEEDED ARGON DISCHARGE

SEE TABLE I FOR FLOW CONDITIONS

○ LEFT HALF

□ RIGHT HALF

$_D$ = RADIUS OF DISCHARGE (55 mm = 2.15 IN.)

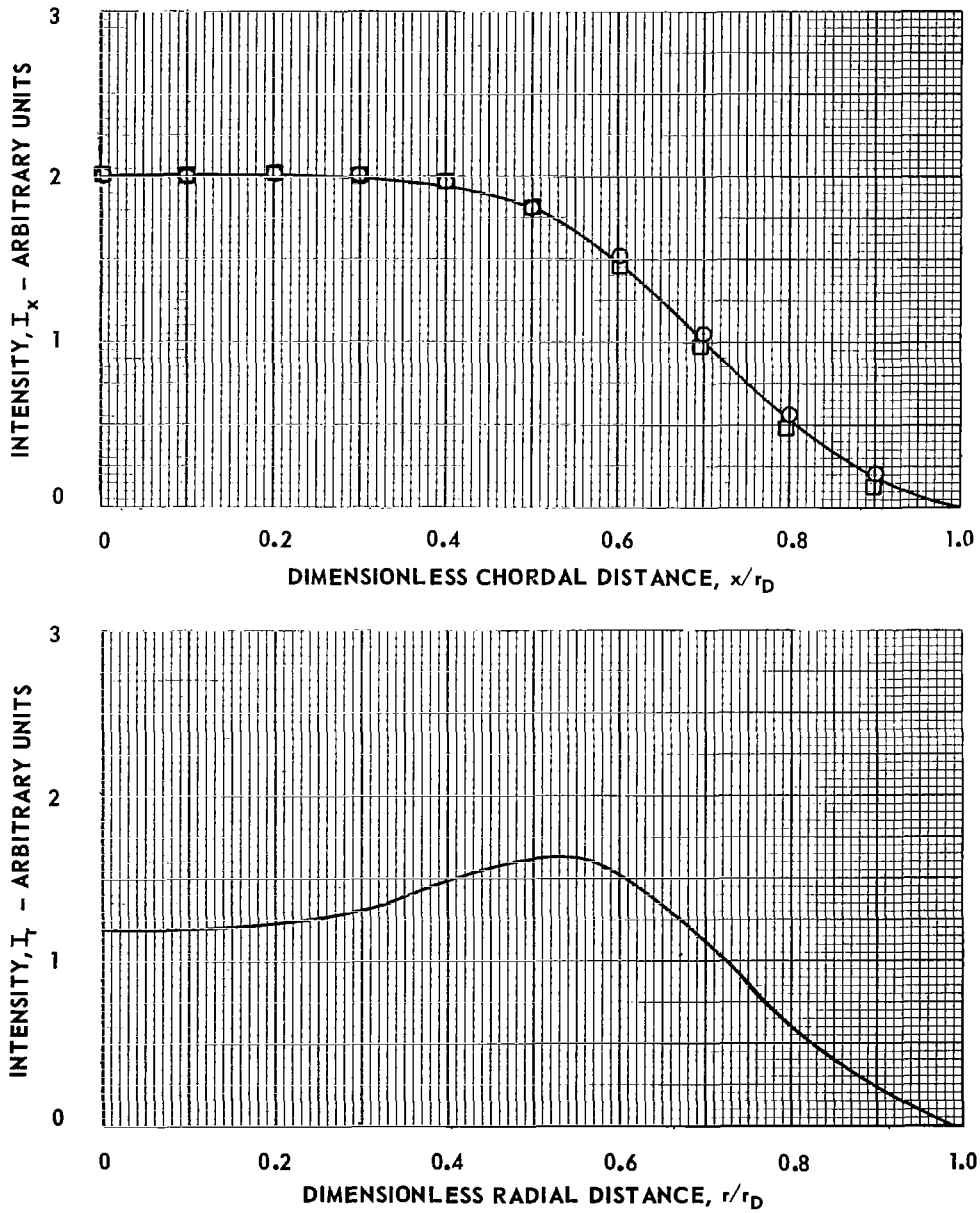


FIG. 12

RADIAL AND CHORDAL VARIATIONS IN TEMPERATURE IN AN UNSEEDED ARGON DISCHARGE

SEE TABLE I FOR FLOW CONDITIONS

r_D = RADIUS OF DISCHARGE (55 mm = 2.15 IN.)

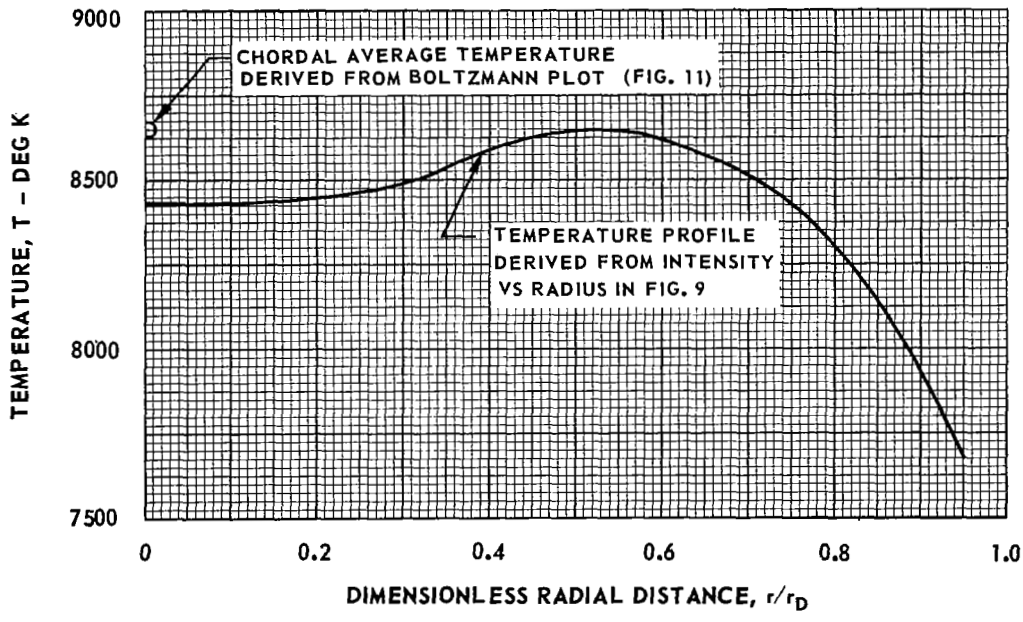


FIG. 13

ATOMIC BOLTZMANN PLOT FOR UNSEEDED ARGON DISCHARGE USING CHORDAL INTENSITIES OF ARGON I LINES ON CENTERLINE OF DISCHARGE

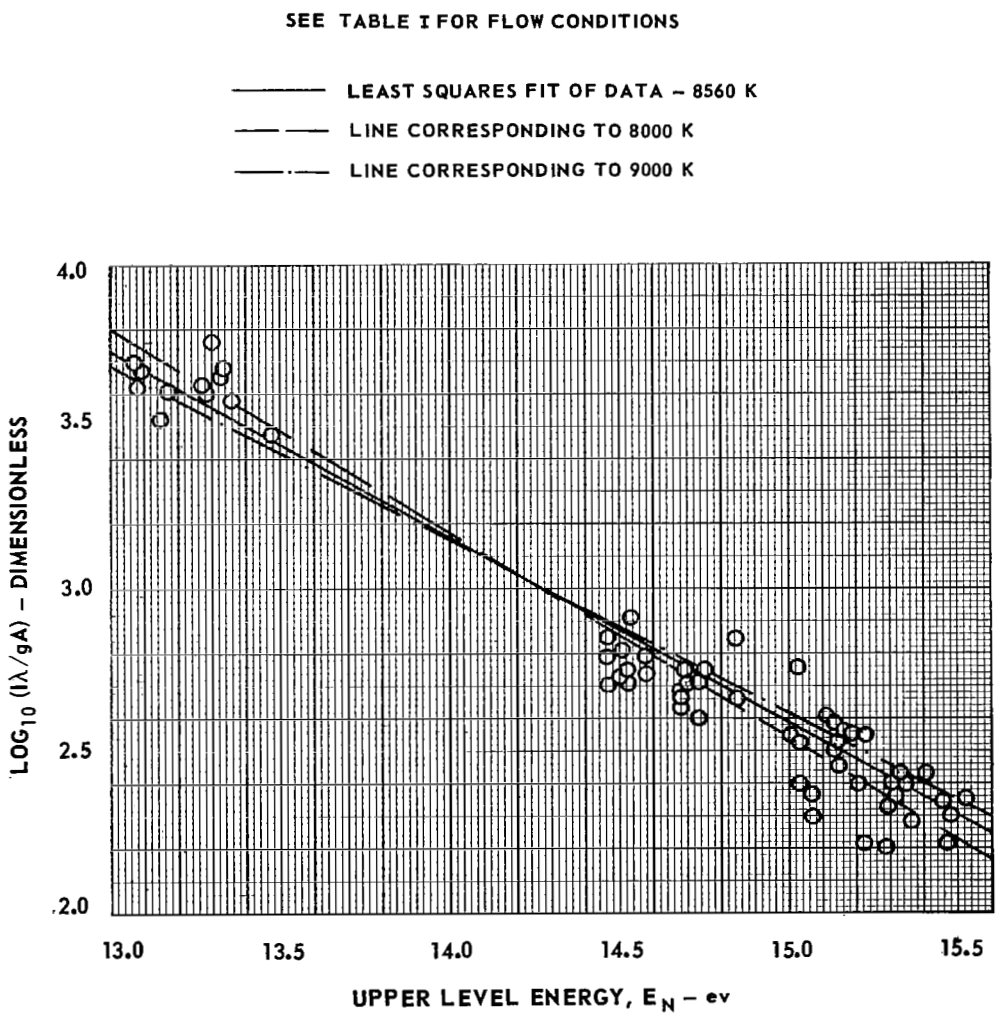


FIG. 14

INTEGRATED CONTINUUM EMISSION PER 100 Å INTERVAL FROM RF-HEATED ARGON, AR/WF_6, AND AR/UF_6 MIXTURES BETWEEN 1200 Å AND 8500 Å

SEE TABLE I FOR FLOW CONDITIONS

TOTAL CONTINUUM EMMISSION FOR λ = 1200 Å TO 8500 Å: ARGON – 0.14 WATTS/CM^3 SR

AR/WF_6 – 0.20 WATTS/CM^3 SR

AR/UF_6 – 0.22 WATTS/CM^3 SR

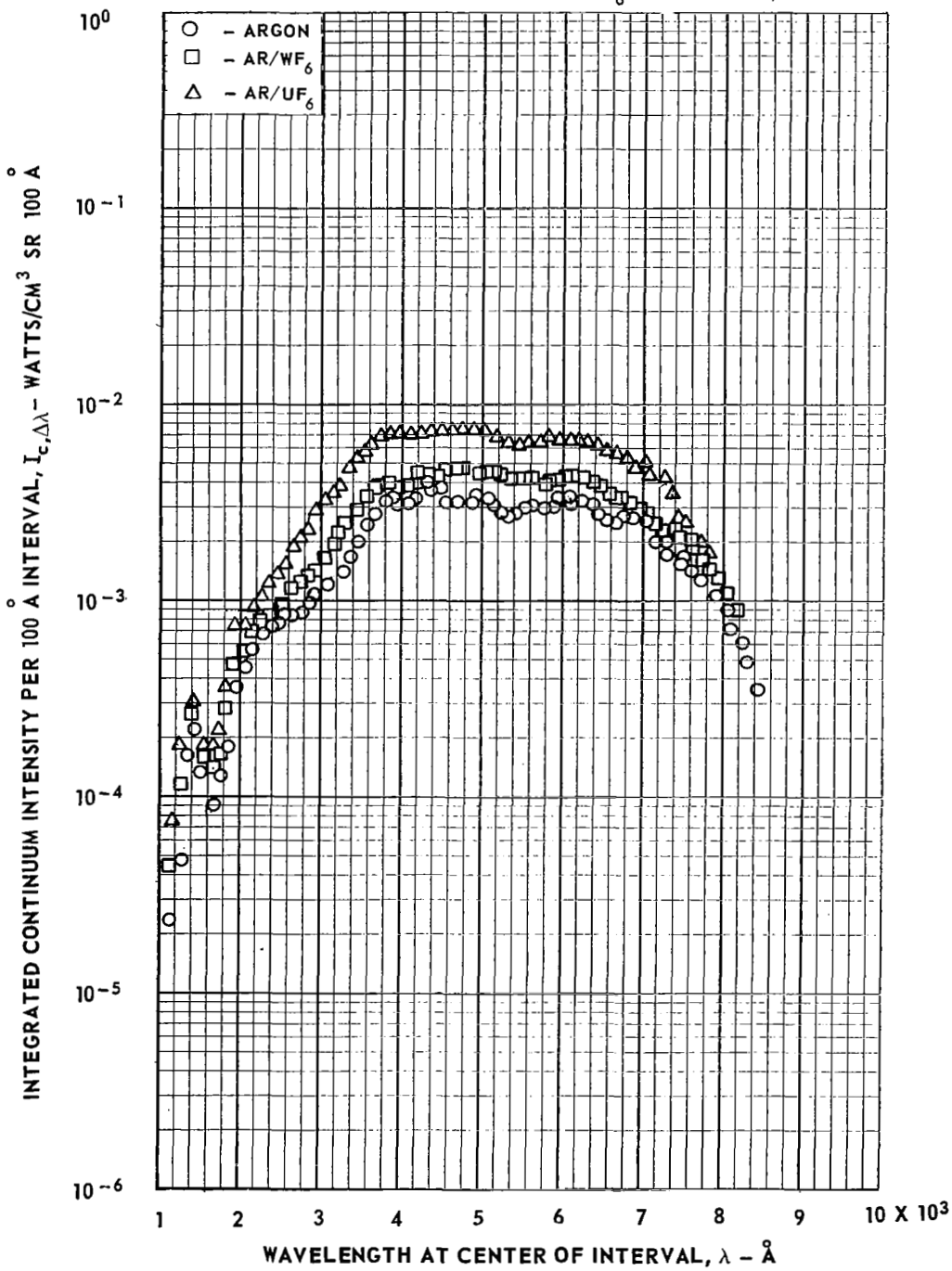


FIG. 15

POWER RADIATED FROM UNSEEDED, TUNGSTEN-SEEDED, AND URANIUM-SEEDED ARGON PLASMAS

SEE TABLE I FOR FLOW CONDITIONS

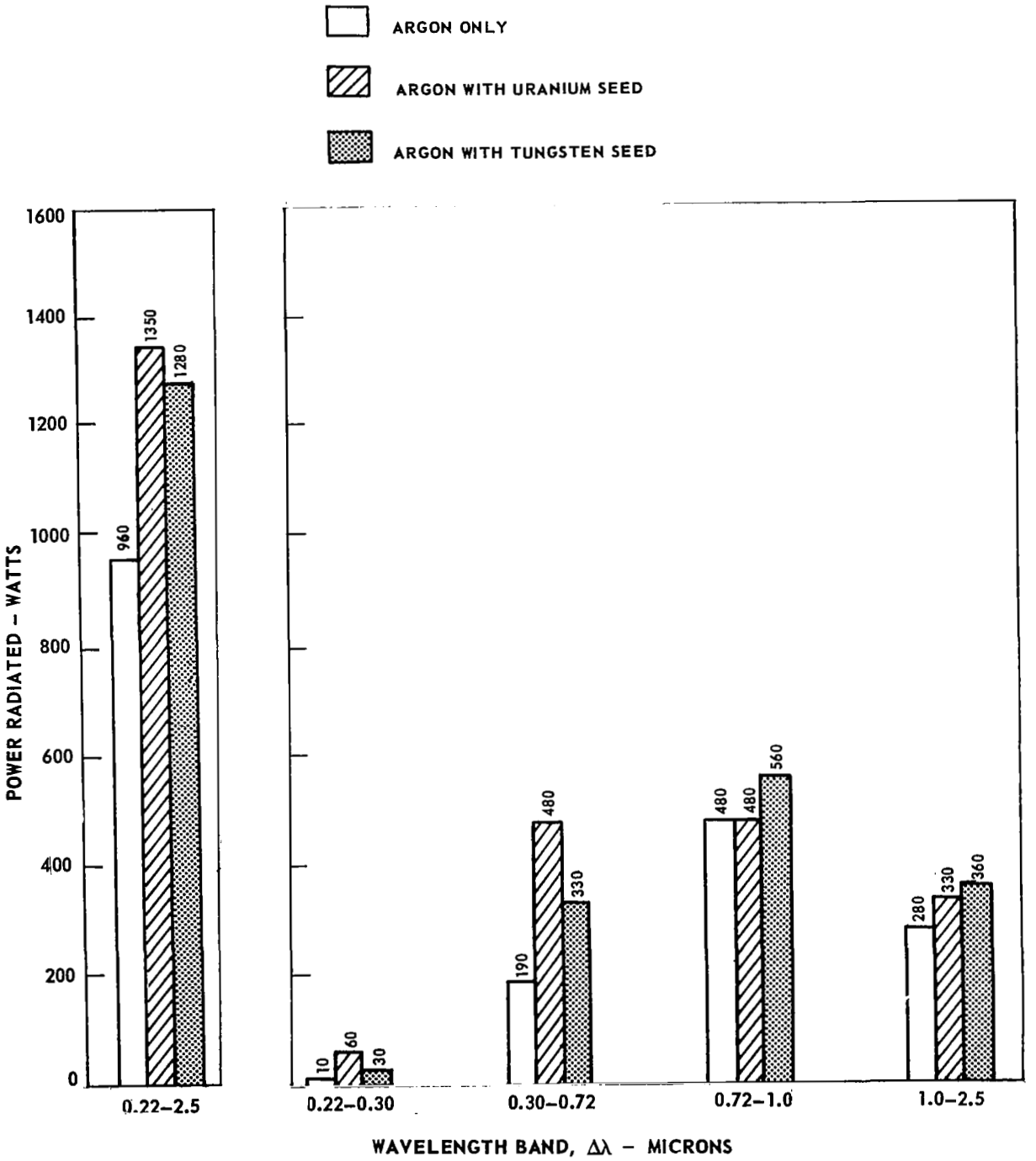


FIG. 16

COMPARISON OF THE INTEGRATED TOTAL EMISSION PER 100 Å INTERVAL OF RF-HEATED ARGON, AR/WF_6, AND AR/UF_6 MIXTURES BETWEEN 1200 Å AND 8500 Å

SEE TABLE I FOR FLOW CONDITIONS

TOTAL INTENSITIES FOR λ = 1200 Å TO 8500 Å : ARGON = 0.34 WATTS/CM^3 SR
AR/WF_6 = 0.43 WATTS/CM^3 SR
AR/UF_6 = 0.58 WATTS/CM^3 SR

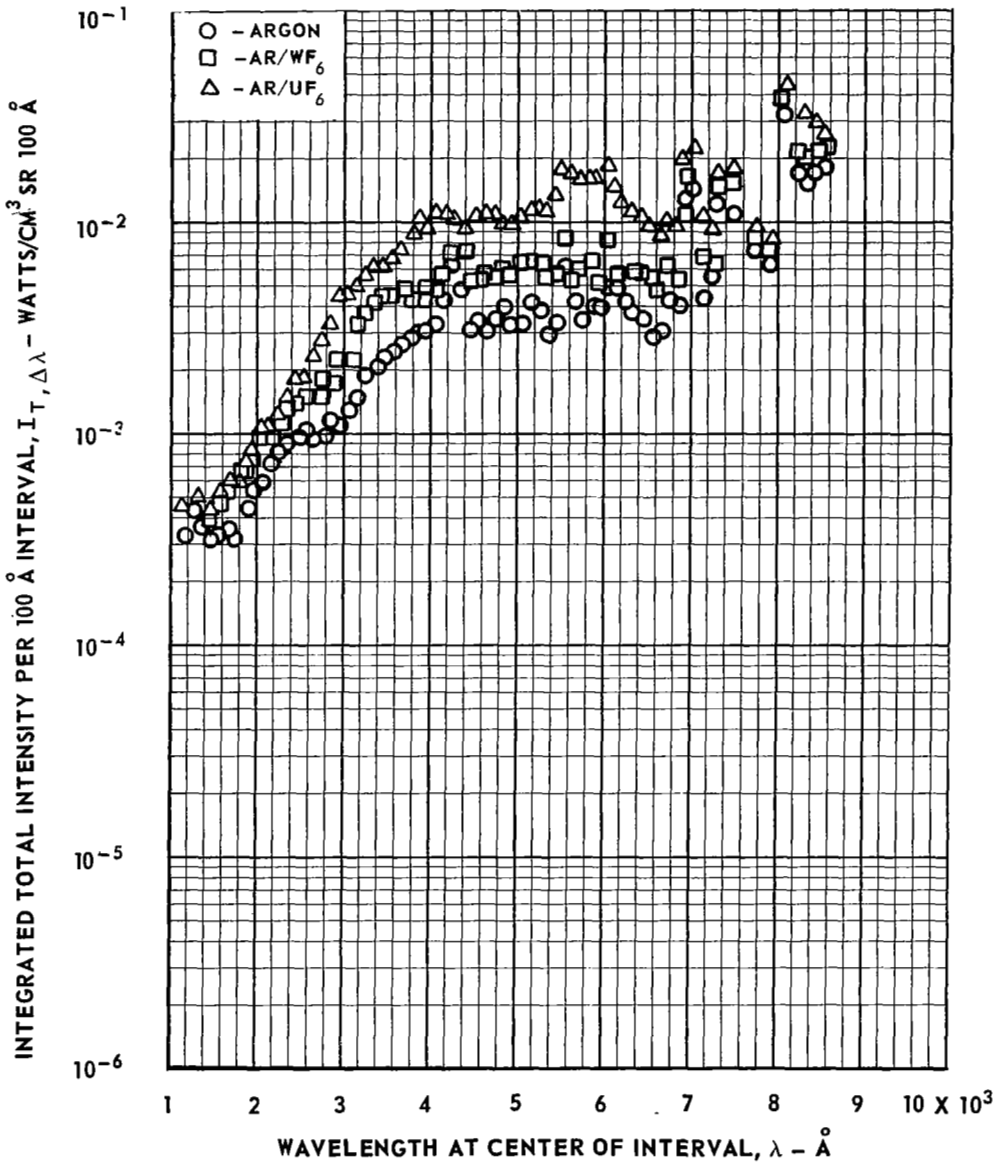


FIG. 17

COMPARISON OF THE INTEGRATED LINE AND CONTINUUM INTENSITIES PER 100 Å INTERVAL FOR RF-HEATED ARGON BETWEEN 1200 Å AND 8500 Å

SEE TABLE I FOR FLOW CONDITIONS

LINE RADIATION FOR λ = 1200 Å TO 8500 Å = 0.19 WATTS/CM^3 SR

CONTINUUM RADIATION FOR λ = 1200 Å TO 8500 Å = 0.14 WATTS/CM^3 SR

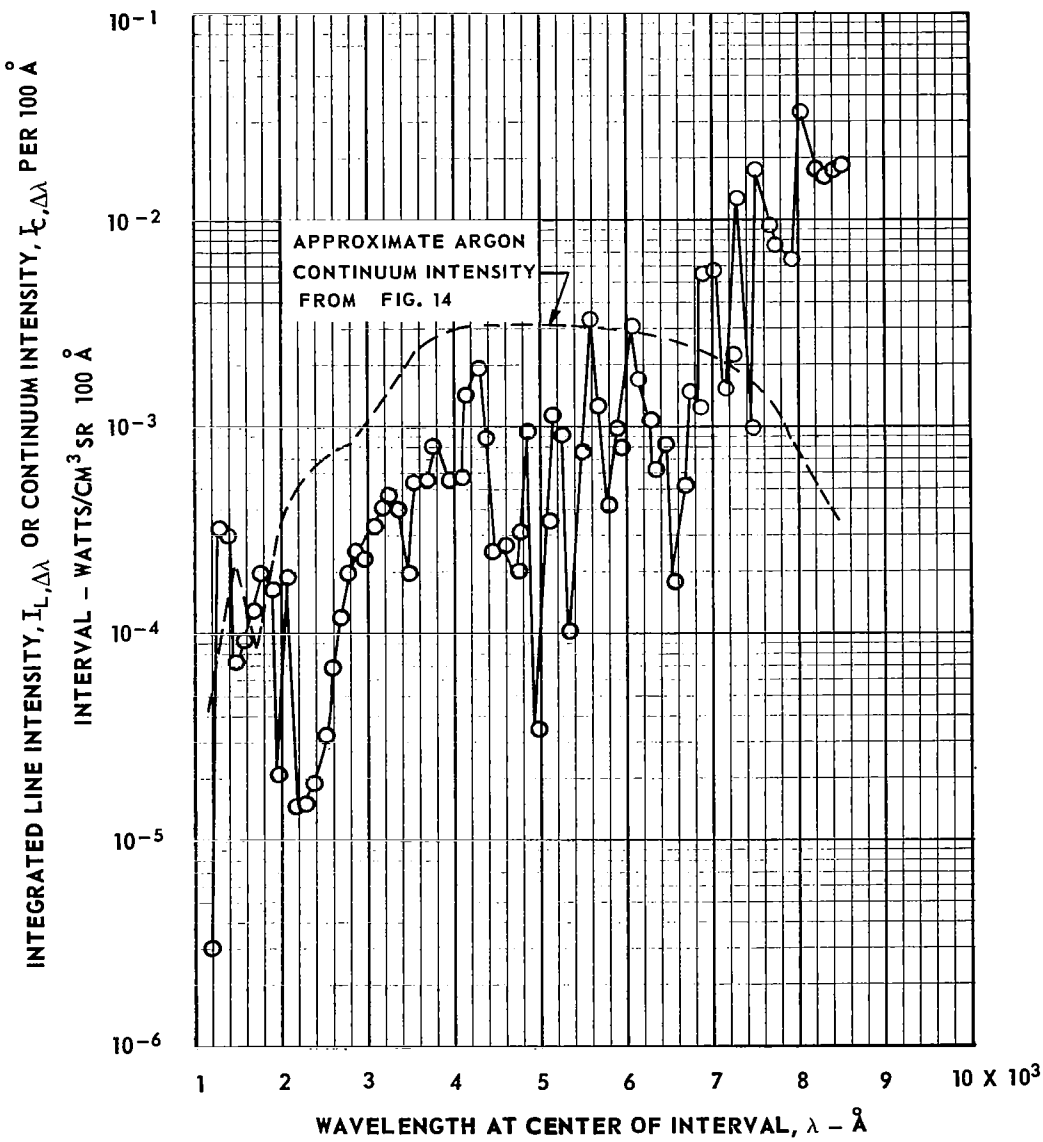


FIG. 18

INTEGRATED LINE INTENSITY PER 100 Å INTERVAL FOR TUNGSTEN LINES IN RF-HEATED AR/WF_6 MIXTURE BETWEEN 1200 Å AND 8500 Å

SEE TABLE I FOR FLOW CONDITIONS

NOTE: CONTRIBUTION OF TUNGSTEN CONTINUUM TO TOTAL RADIATION ASSUMED NEGLIGIBLE (SEE TEXT FOR DETAILS)

TOTAL LINE INTENSITY FOR λ = 1200 Å TO 8500 Å = 0.05 WATTS/CM^3 SR

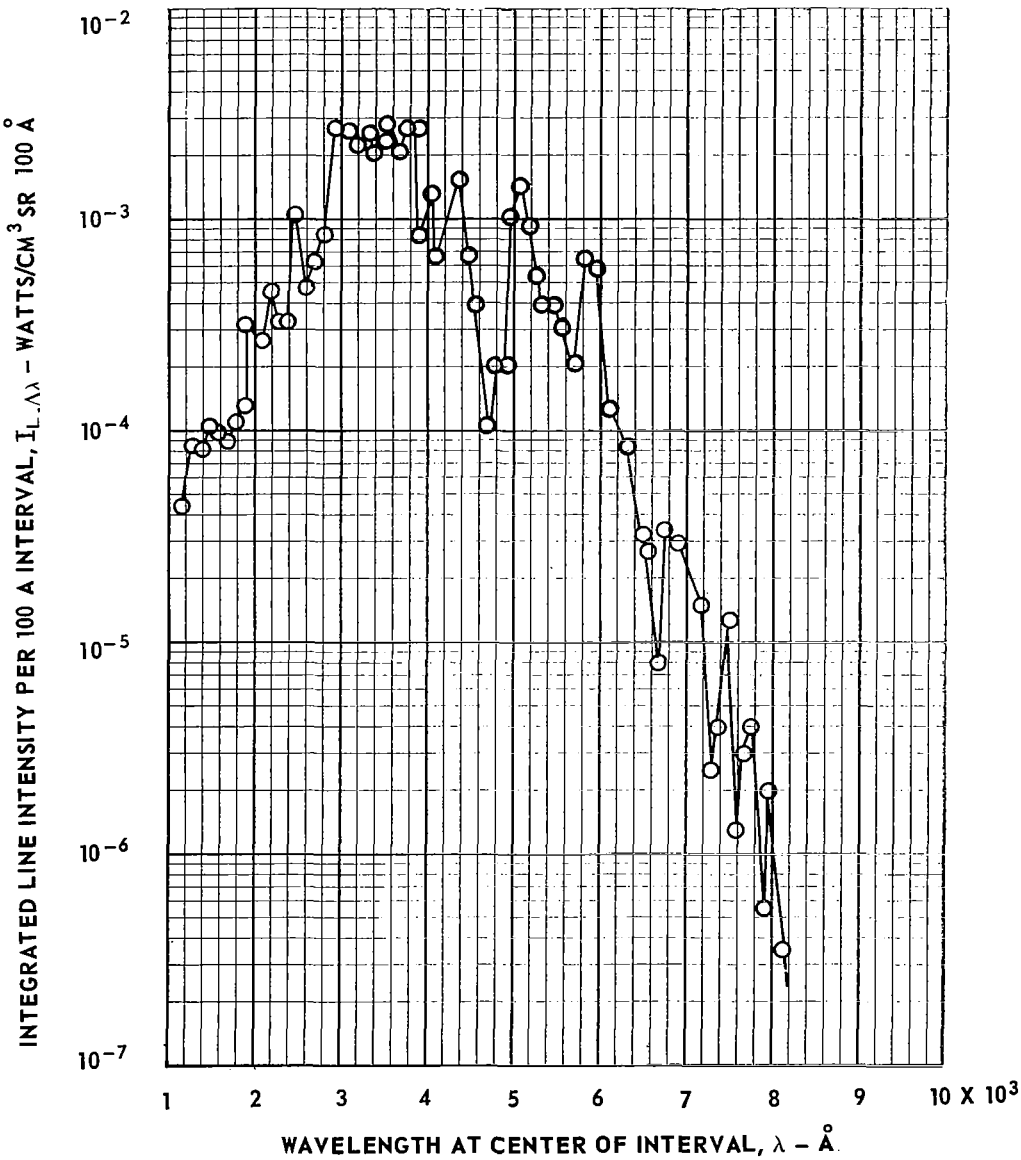


FIG. 19

INTEGRATED LINE INTENSITY PER 100 Å INTERVAL FOR URANIUM LINES IN RF-HEATED AR/UF_6 MIXTURE BETWEEN 1200 Å AND 7500 Å

SEE TABLE I FOR FLOW CONDITIONS

NOTE: CONTRIBUTION OF URANIUM CONTINUUM TO TOTAL RADIATION ASSUMED NEGLIGIBLE (SEE TEXT FOR DETAILS)

TOTAL LINE RADIATION FOR λ = 1200 TO 8500 Å = 0.15 WATTS/CM^3 SR

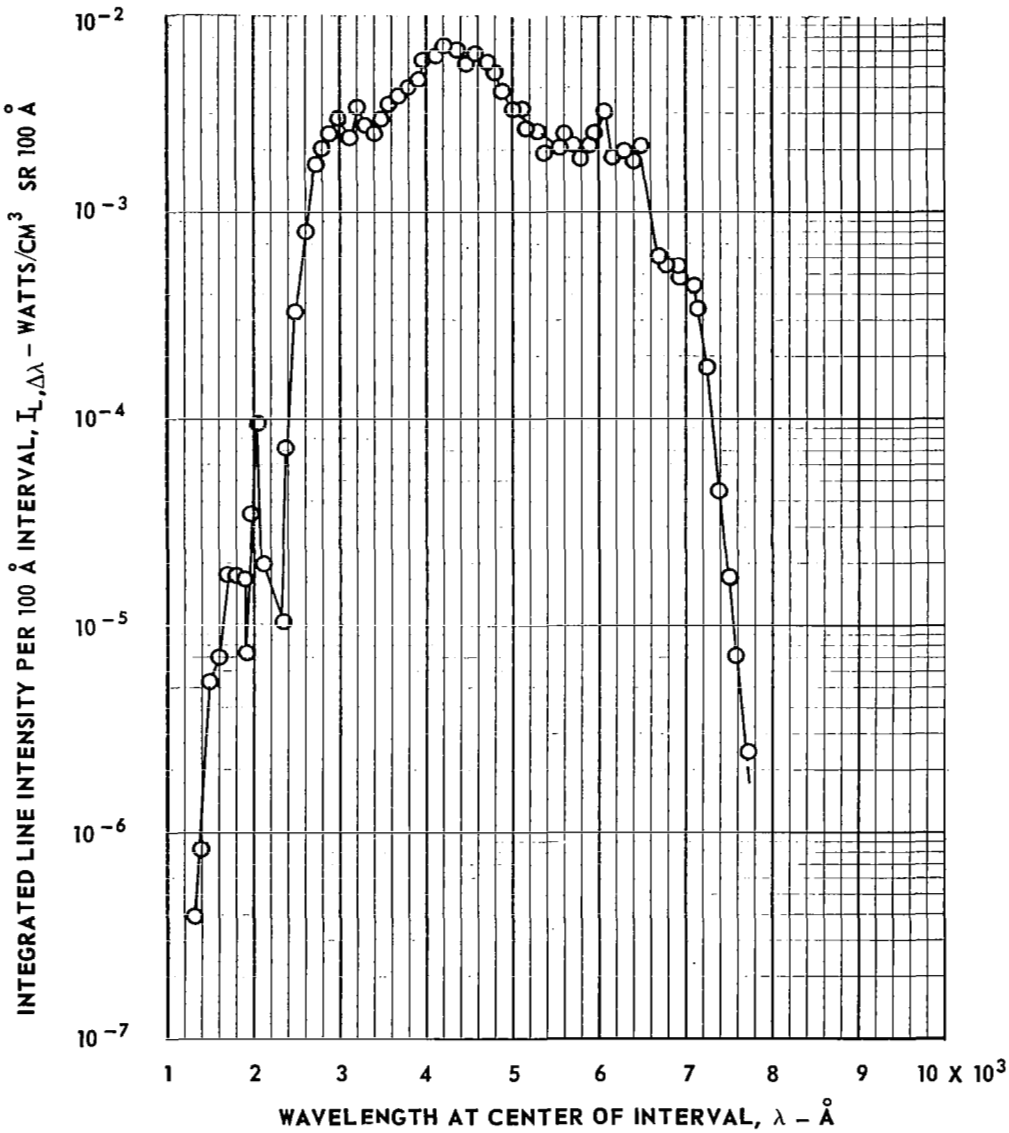


FIG. 20

TOTAL SPECTRAL EMISSION OF RF-HEATED ARGON, ARGON/WF_6 AND ARGON/UF_6 MIXTURES PER 100 Å INTERVAL BETWEEN 0.75 MICRONS AND 10 MICRONS

TOTAL EMISSION FOR $\lambda = \mu$ TO 10 μ: ARGON – 0.11 WATTS/CM^3 SR 0.1 μ

AR/WF_6 – 0.15 WATTS/CM^3 SR 0.1 μ

AR/UF_6 – 0.13 WATTS/CM^3 SR 01 μ

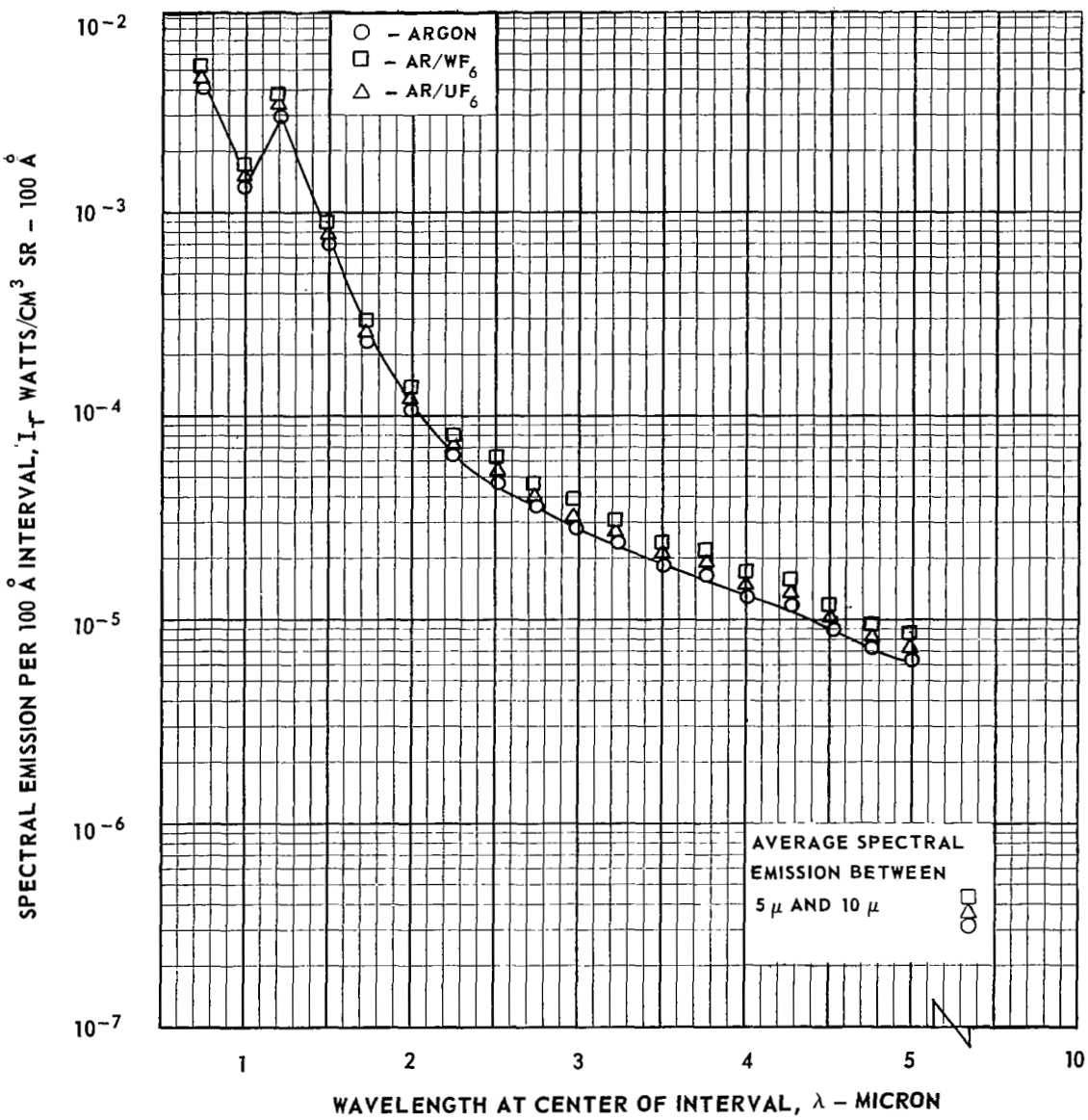


FIG. 21

COMPARISON OF CALCULATED AND EXPERIMENTAL INTEGRATED LINE INTENSITIES PER 100 Å INTERVAL FOR ARGON LINES IN HEATED, UNSEEDED ARGON

SEE TABLE I FOR FLOW CONDITIONS
CALCULATED DATA TAKEN FROM REF. 30
TOTAL LINE RADIATION: EXPERIMENTAL (1200 Å TO 8500 Å) – 0.34 WATTS/CM^3 SR
EXPERIMENTAL (3500 Å TO 8500 Å) – 0.34 WATTS/CM^3 SR
CALCULATED (3500 Å TO 8500 Å) – 0.28 WATTS/CM^3 SR

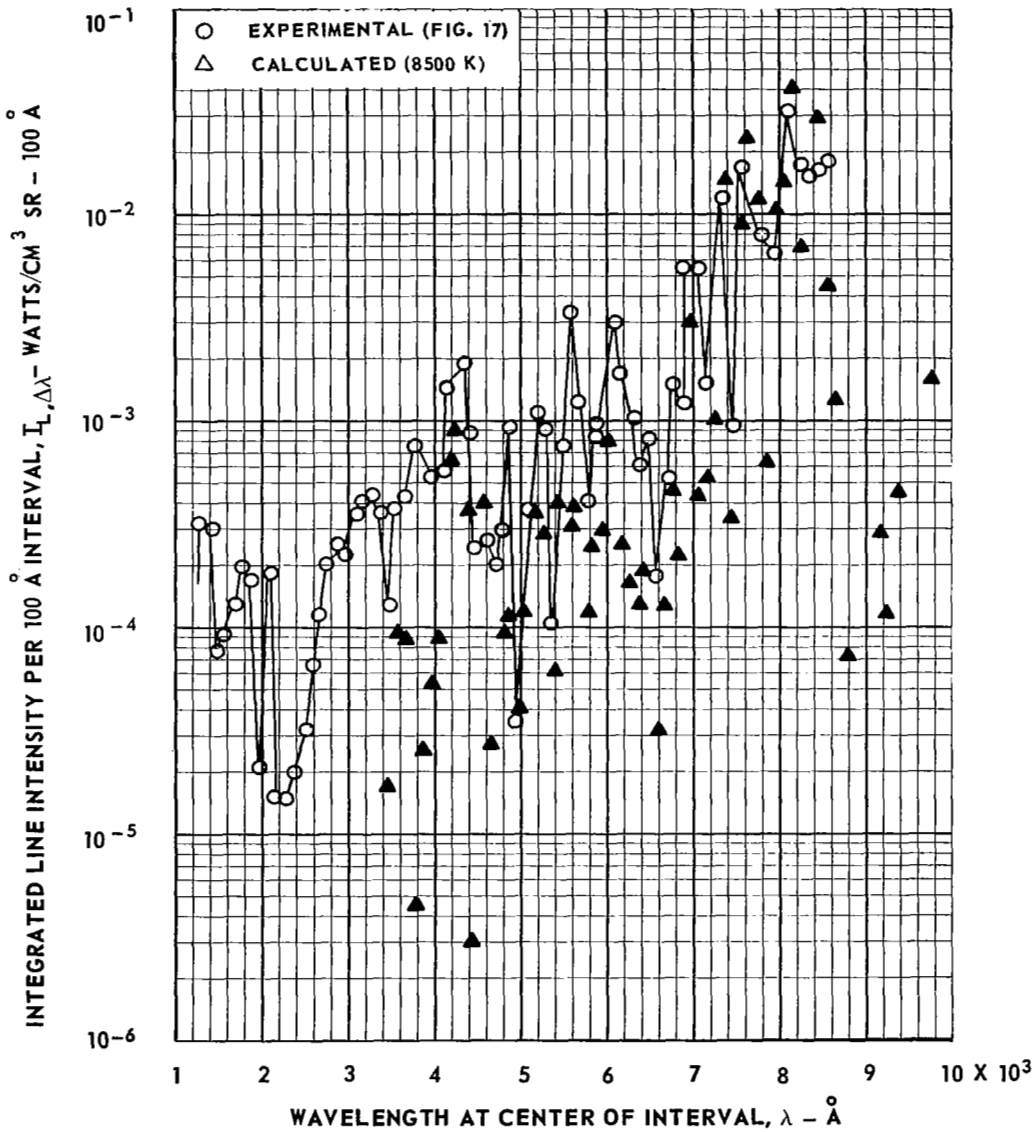


FIG. 22

COMPARISON OF CALCULATED AND EXPERIMENTAL INTEGRATED LINE INTENSITY PER 100 Å INTERVAL FOR TUNGSTEN IN HEATED AR/WF_6 MIXTURE

SEE TABLE I FOR FLOW CONDITIONS
CALCULATED DATA TAKEN FROM REF. 30
NOTE: THEORETICAL PREDICTION BASED ON TUNGSTEN MASS FRACTION OF 10^{-4}
TOTAL LINE INTENSITY: EXPERIMENTAL (1200 Å TO 8000 Å)– 0.05 WATTS/CM^3 SR
CALCULATED (1700Å- 8500 Å)– 1.94 WATTS/CM^3 SR
EXPERIMENTAL (1700Å – 8000 Å)– 0.05 WATTS/CM^3 SR

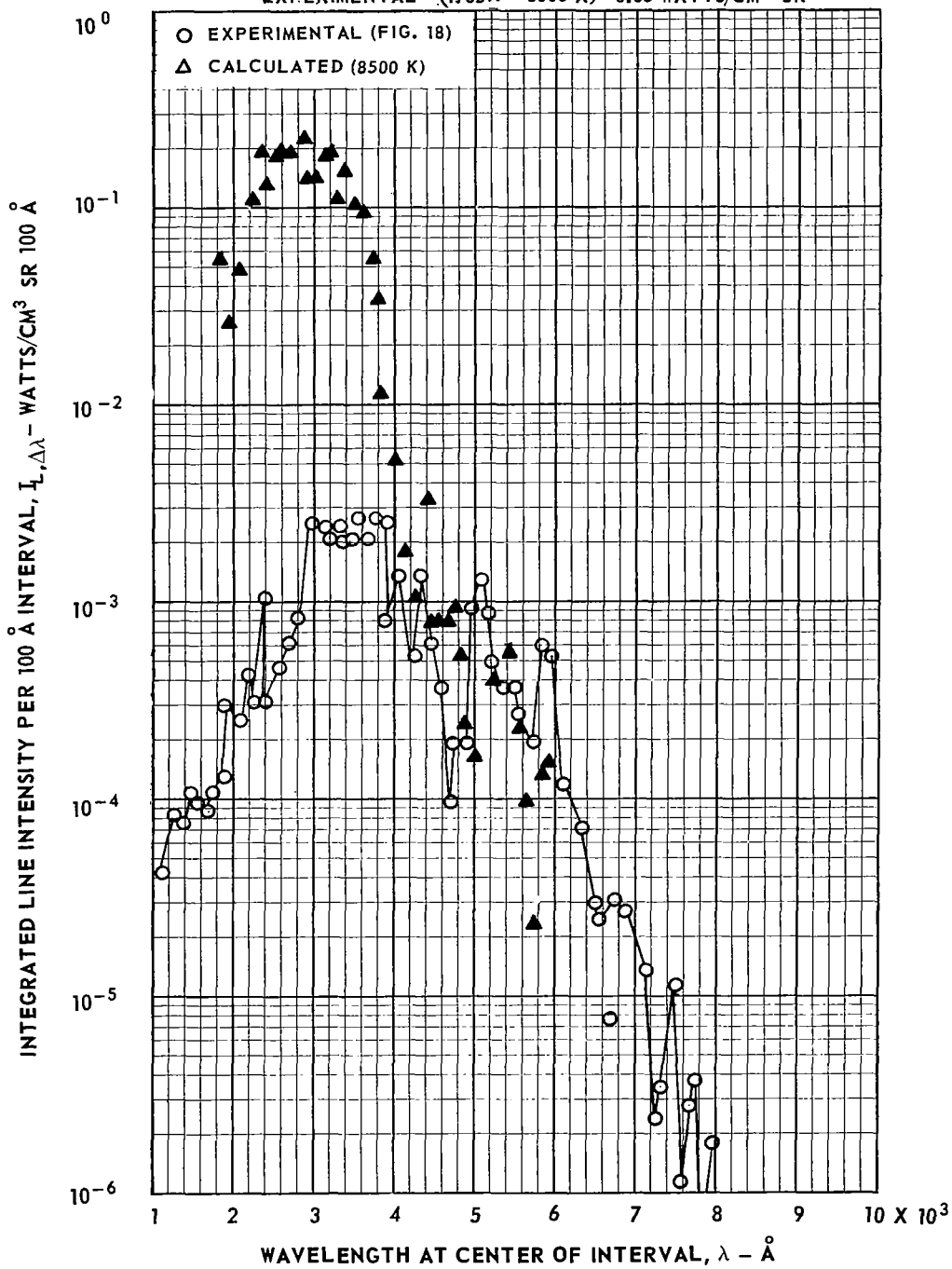


FIG. 23

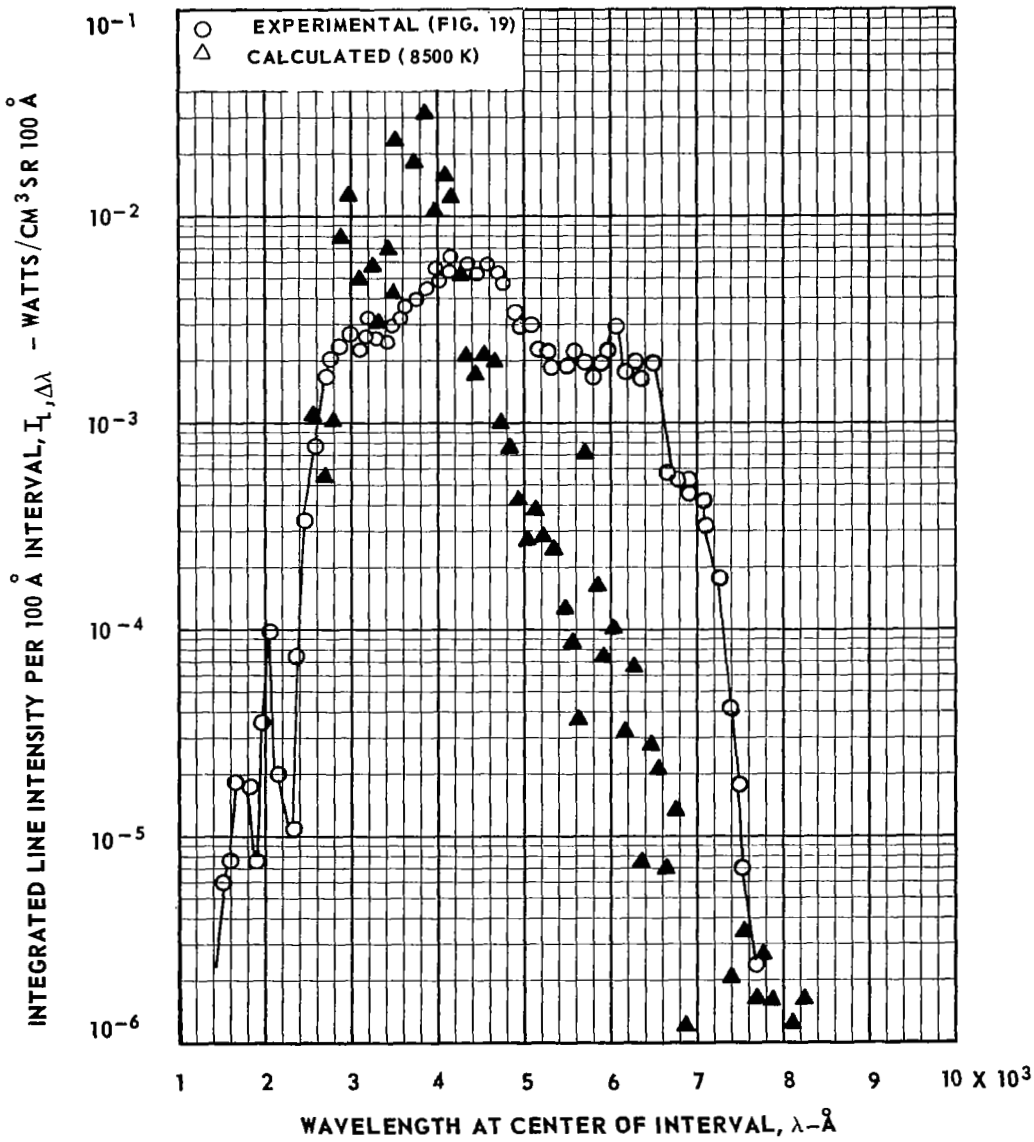
COMPARISON OF CALCULATED AND EXPERIMENTAL INTEGRATED LINE INTENSITY PER 100 Å INTERVAL FOR URANIUM IN HEATED AR/UF_6 MIXTURE

SEE TABLE I FOR FLOW CONDITIONS

CALCULATED DATA TAKEN FROM REF. 30

NOTE: THEORETICAL PREDICTION BASED ON URANIUM MASS FRACTION OF 10^{-4}

TOTAL LINE RADIATION: EXPERIMENTAL (1200 Å TO 7500 Å) –0.13 WATTS/CM^3 SR

EXPERIMENTAL (2200 Å TO 7500 Å) –0.13 WATTS/CM^3 SR

CALCULATED (2200 Å TO 7500 Å) –0.19 WATTS/CM^3 SR