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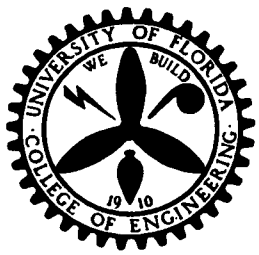

ENGINEERING AND INDUSTRIAL EXPERIMENT STATION

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SPECIAL REPORT

The Emission Coefficient of Uranium Plasmas

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ABSTRACT

The emission coefficient for uranium plasmas (Temperature: 8000°K) has been measured for the wavelength range (200 Å - 6000 Å. The results are compared to theory and other measurements. The absorption coefficient for the same wavelength interval is also given.

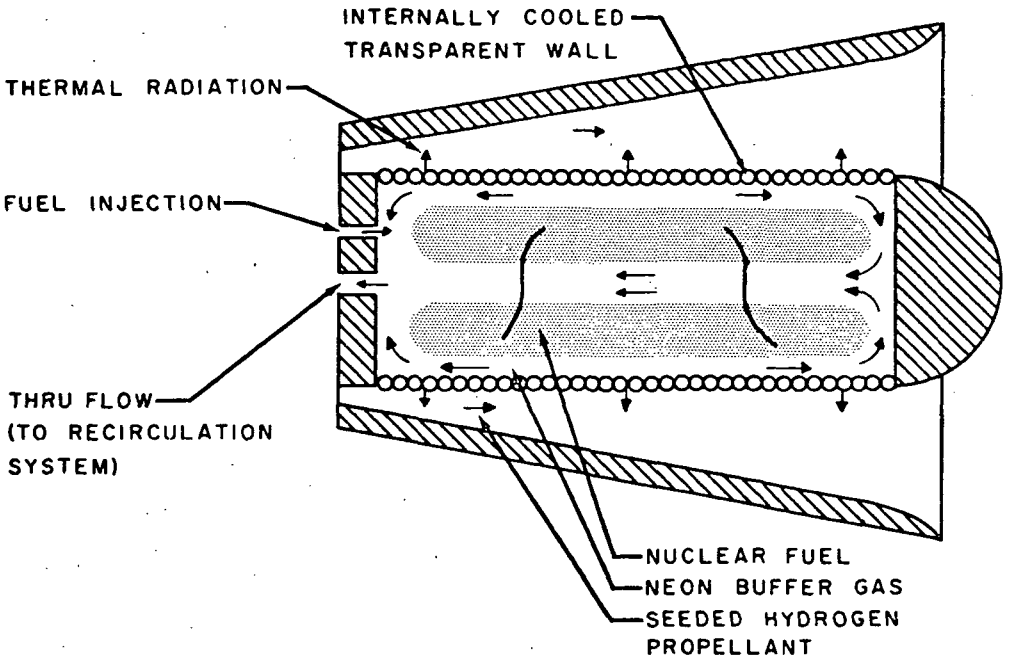
I. Introduction

The knowledge of the emission coefficient of a uranium plasma is required for the design of a plasma core reactor. Examples of such plasma core reactors are shown in Figure 1 and have been discussed extensively in the literature [1,2] and most recently by Thom [3]. Ultimately, both emission and absorption coefficients will be required for any device employing uranium in either vapor or plasma form. This paper describes the results obtained in the 1500 Å - 7500 Å range using a d.c. uranium arc. The results are compared to other experiments [4,5,6] and to theoretical predictions [7,8]. In order to perform this comparison it was necessary to scale all of the literature data to a common particle density. Justification for this scaling is discussed in detail.

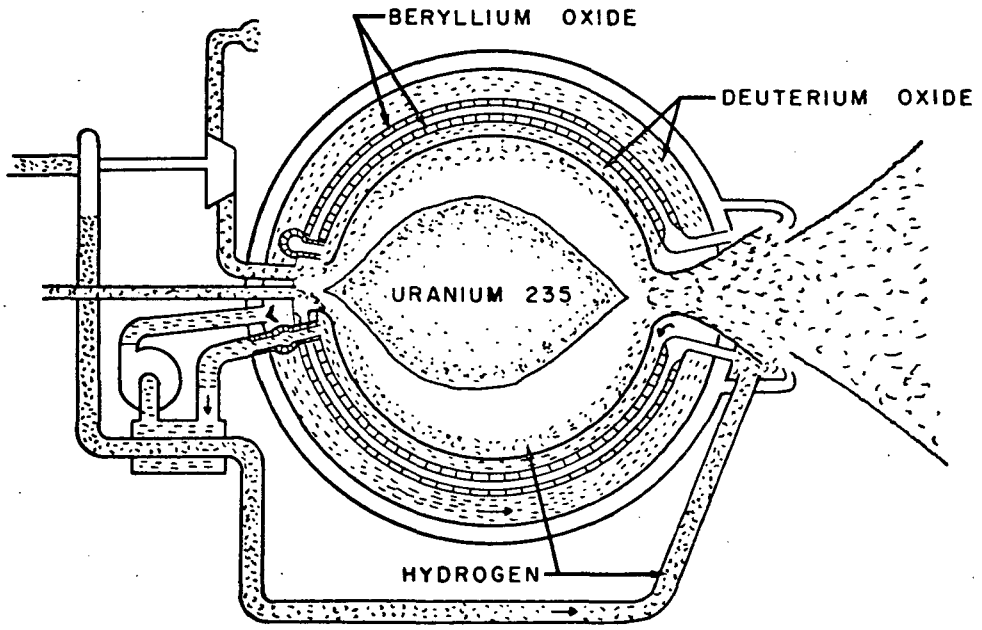
II. Description of Experiment

A detailed description of the experiment and apparatus has been given elsewhere [9], and so only a brief review will be presented here. Figure 2 shows the test cell for generating the uranium plasma. It is a segmented arc with a uranium anode employing a small flow of helium for stabilization. As the arc burns, vaporization of the anode releases uranium into the plasma region. The significant difference in the ionization potentials of uranium and helium (6.4 ev versus 25.4 ev) strongly suggests that the electrical properties of the arc would be determined by properties of the uranium component.

Examination of the arc emission spectrum reveals that the majority of the lines are UII and as well, some of the stronger UI lines are present. A large number of lines are not identifiable at present,



a) CONCEPT OF NUCLEAR LIGHT BULB ENGINE



b) COAXIAL-FLOW GAS-CORE NUCLEAR ROCKET

FIGURE 1

PLASMA REACTOR ENGINE CONCEPTS

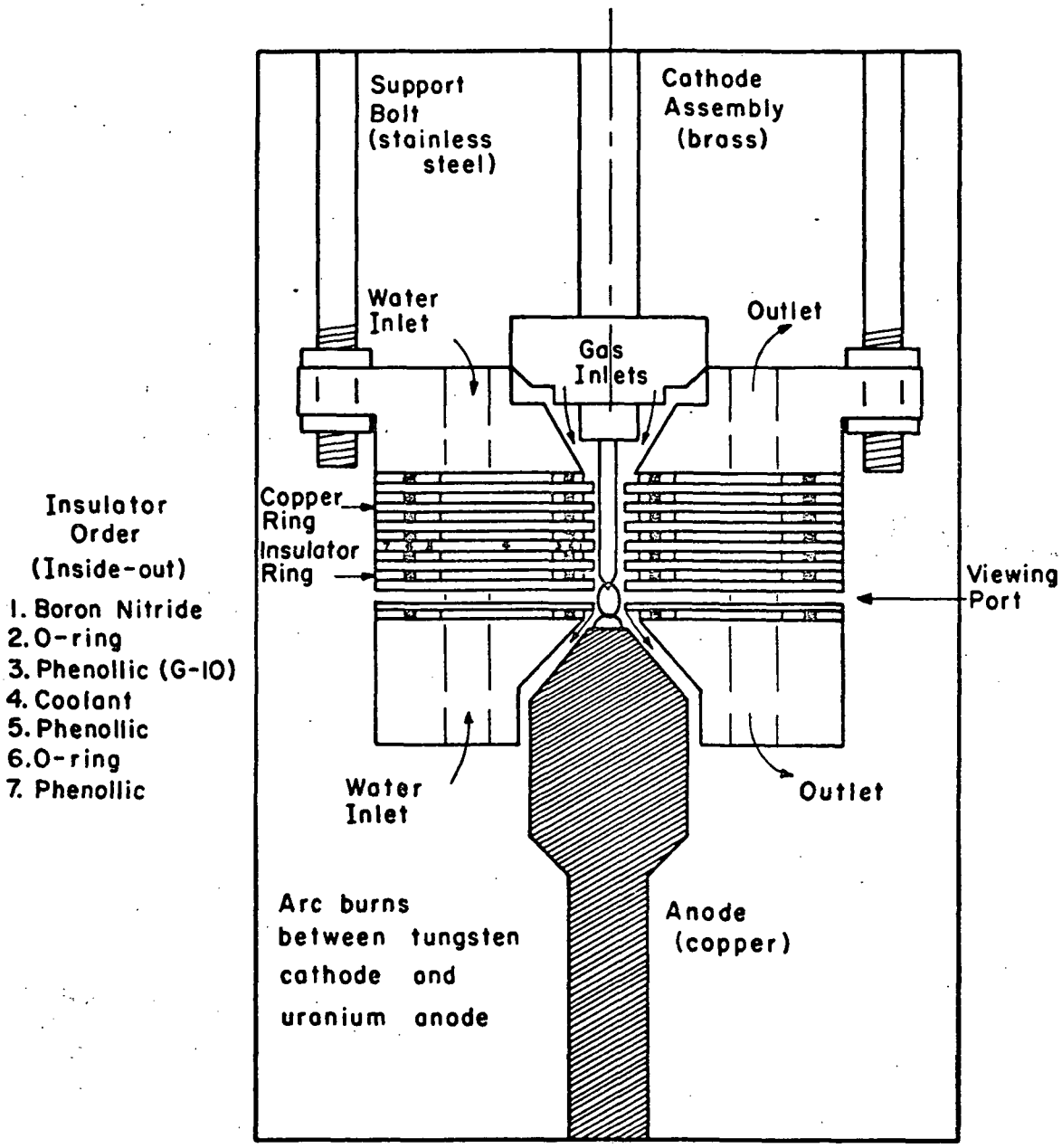


FIGURE 2

URANIUM ARC DEVICE

however it is likely these are UIII lines. These observations indicate that the plasma obtained in the device is a nearly fully ionized uranium plasma. The absence of He I and He II lines coroborates the assertion that helium does not participate in the conduction mechanism of the arc and consequently is not a part of the arc plasma formed, i.e., a uranium plasma is obtained rather than a helium or helium-uranium plasma.

Figure 3 shows the optical system used for data acquisition. A 3/4 m McPherson scanning spectrometer was used and the photomultiplier signal was digitized and fed into a magnetic core memory (1024 channels) of a Fabri-Tek signal averager. However, as the signal to noise ratio of the raw data was sufficiently high, it was not necessary to use the averaging feature of this instrument. The pattern appearing on all reported data is not noise but line structure, which was verified by repeated scanning.

A sodium solicilate phosphor was used to measure the vacuum-u.v. region of the spectrum. The photomultiplier-sodium solicilate combination was calibrated with a standard tungsten ribbon and a deuterium lamp [10,11]. These references provided calibration over the entire range of the spectrum reported in this paper.

III. Results

Measurement of particle densities and temperatures of the above uranium arc plasma have been reported earlier [12]. The accuracy achieved in the temperature measurement is believed to be 20% or better. Similar accuracies were reported by the other authors referred to previously. Hence the substantial disagreement between the individual results

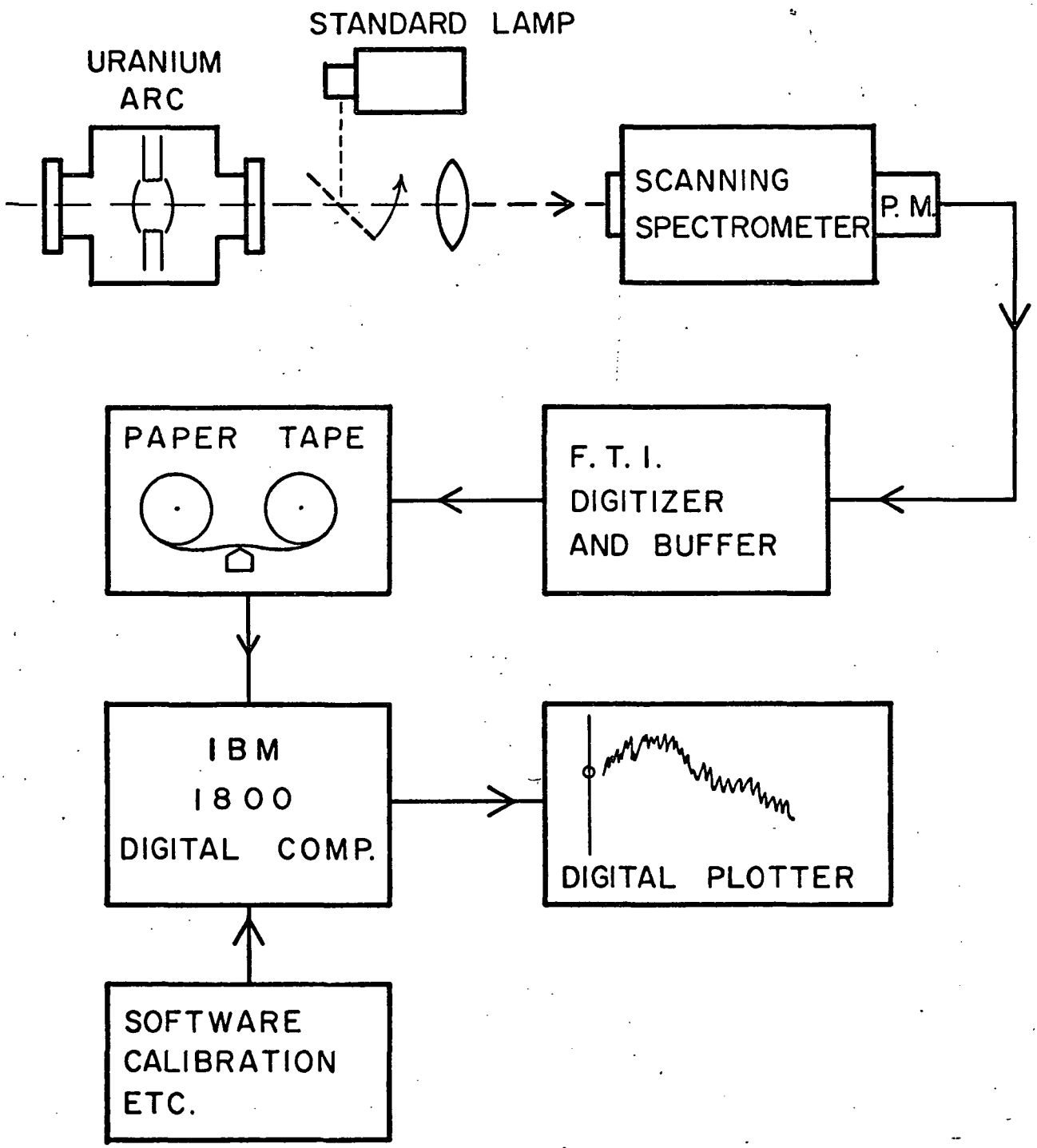


FIGURE 3

DATA ACQUISITION SYSTEM

(several orders of magnitude in certain wavelength regions) cannot be attributed to the limited precision of the temperature measurement. Similar comments can be made regarding the density measurements. Even a poor knowledge of particle density cannot explain differences of several orders of magnitude. Therefore the discrepancies must be caused by differences in the experimental system.

Figure 4 shows the results for the emission coefficient of the above arc for the wavelength region 1,000 - 2,000 Å. The relevant parameters of the plasma are the temperature, the partial pressure of uranium, and the arc diameter and these were respectively 8,000 °K, 1×10^{-2} atm, and 1 cm. These operating conditions were selected to conform with the anticipated temperature conditions of 8,000 - 10,000 °K at the interface between the edge of the plasma core of the reactor and the surrounding cooling medium (see Figure 1).

The emission coefficient as plotted in Figure 4 is defined as the energy emitted by a unit volume of plasma per sec, per unit wavelength interval, per unit solid angle (i.e., erg/(sec-cm^3-Å-ster). For a plasma in LTE (local thermodynamic equilibrium) such as this one the emission and absorption coefficients are related by Kirchhoff's Law

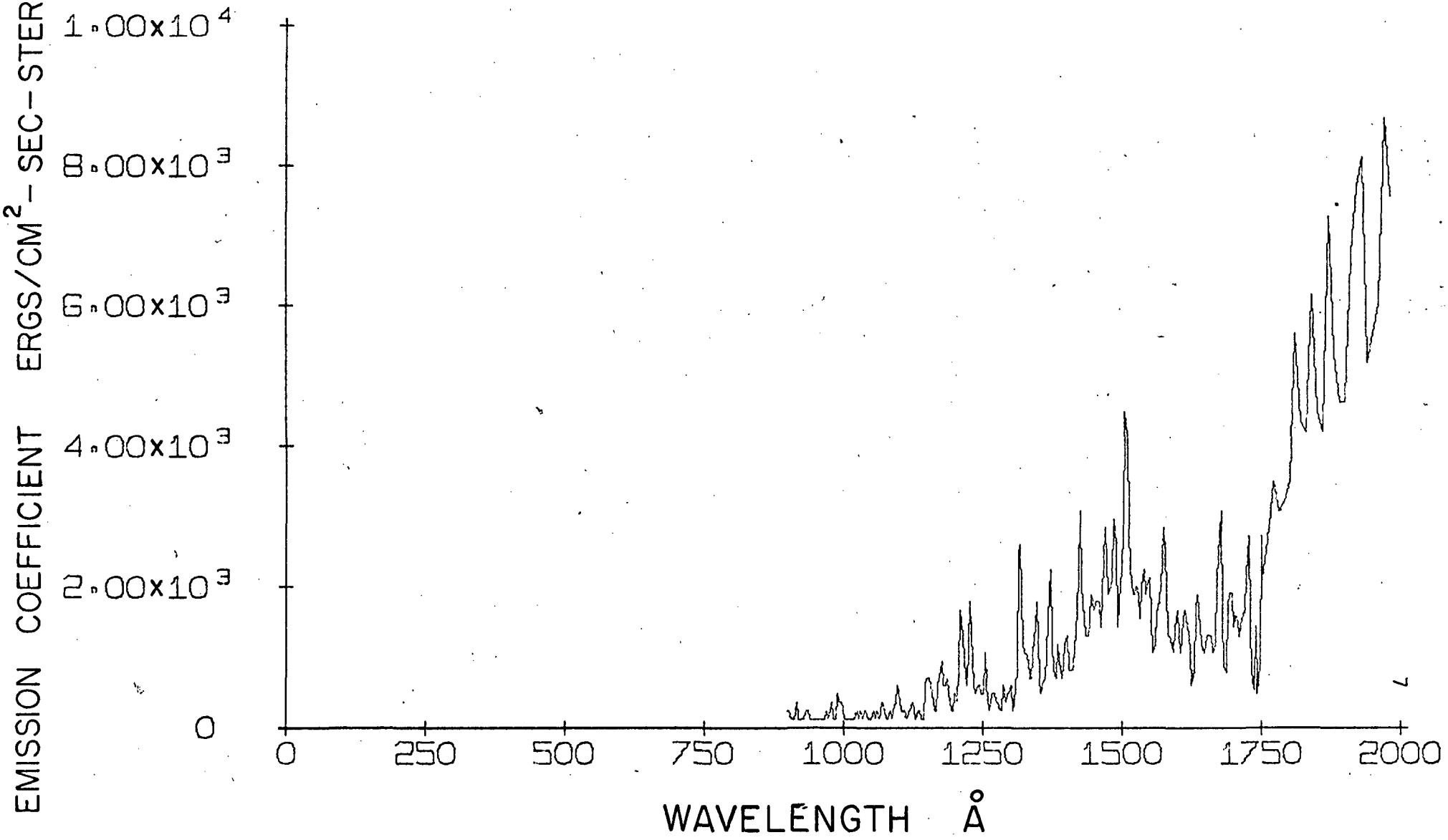
$$\varepsilon_\lambda = K_\lambda B_\lambda$$

where K_λ is the absorption coefficient (units of cm^{-1}), B_λ is the Planck function. Since the temperature is known the absorption coefficient can be obtained by dividing the values of Figure 4 by B_λ(8,000°K).

The wavelength region covered in Figure 4 is especially critical for the Nuclear Light Bulb concept (Figure 1). Clearly this is so

FIGURE 4

MEASURED EMISSION COEFFICIENT OF URANIUM FOR WAVELENGTH REGION 1000-2000 Å



because the radiative power has to penetrate a quartz envelope. There is indeed a moderate emission in the 1,000 - 2,000 Å wavelength region--apparently overlapping line structure. Kelly [13] lists for this wavelength region the following strong uranium lines: 990 Å, 1112 Å, 1575 Å, 1579 Å, 1586 Å, 1832 Å, 1981 Å, 1985 Å. The 1981 - 1985 Å cluster is indeed the strongest one in the spectrum, while 1575-1579-1586 Å cluster which is given the highest intensity in the catalog is only of moderate strength in the present experiment. An explanation for this may be found in the fact that excitation conditions were significantly different in the two experiments. Further, the 990 Å line is present only with an apparently low intensity. However, this result is almost certainly due to fact that the LiF window (required for all U.V. measurements) has significant absorption at this wavelength. The majority of other strong uranium lines listed in the catalog can be located in Figure 4.

Figure 5 shows the results for the wavelength region between 2,000 Å - 4,000 Å. On this figure most of the known UII lines and some of the stronger UI lines can be identified. A large number of other unidentifiable lines have tentatively been considered to be UIII lines.

Figure 6 shows a comparison of the present measurements (total pressure of 5 atm) with measurements reported by us earlier [14]. Note that the line structure of this figure refers to new measurements, while the dashed lines refer to the previous measurements. The earlier measurements were taken two years ago with a prison spectrograph while the present data was gathered with a grating spectrograph. The slight deviation in the two sets of data at 5 atm can be explained by the fact that

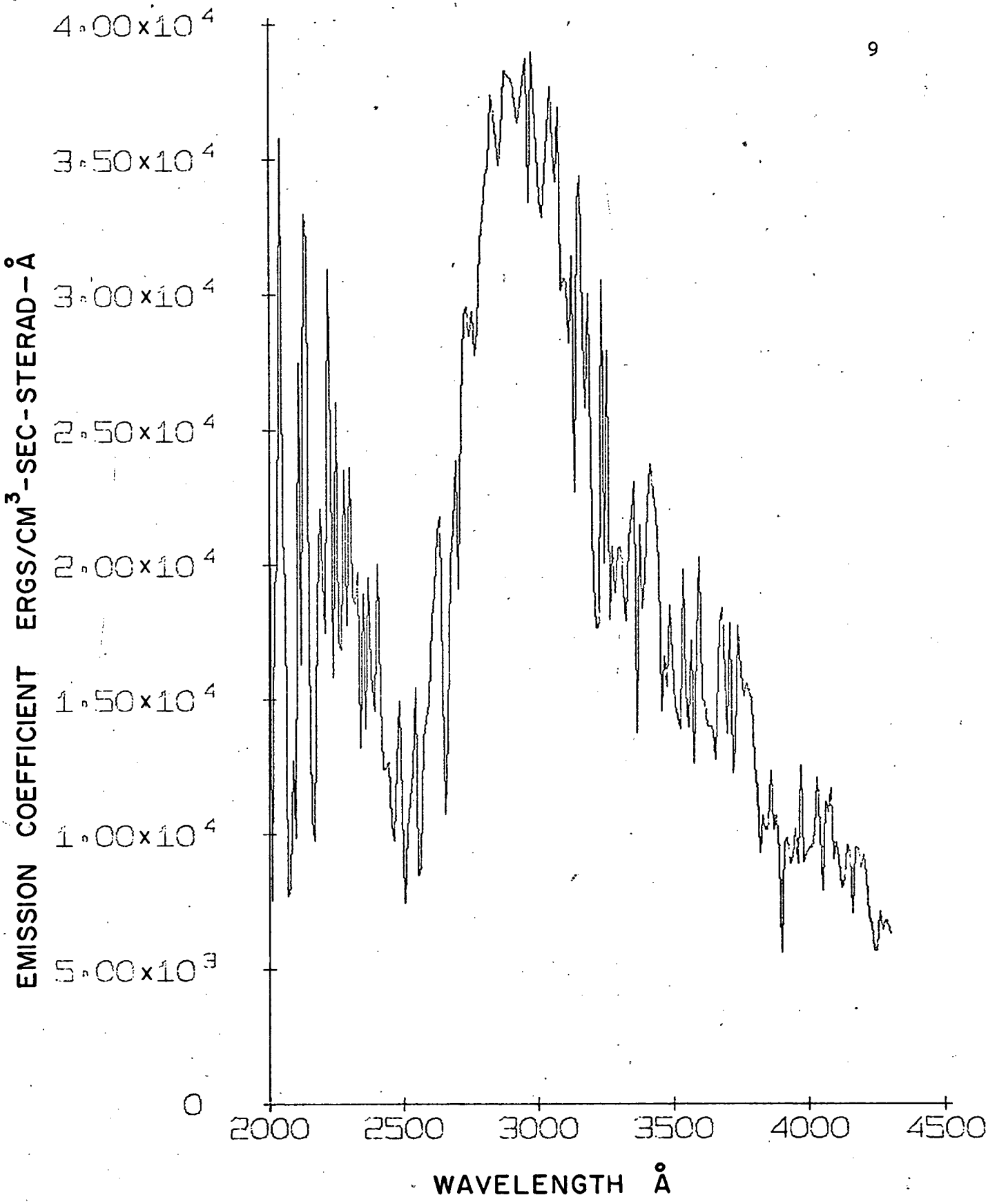


FIGURE 5

MEASURED EMISSION COEFFICIENT OF URANIUM FOR WAVELENGTH REGION 2000-4000 Å

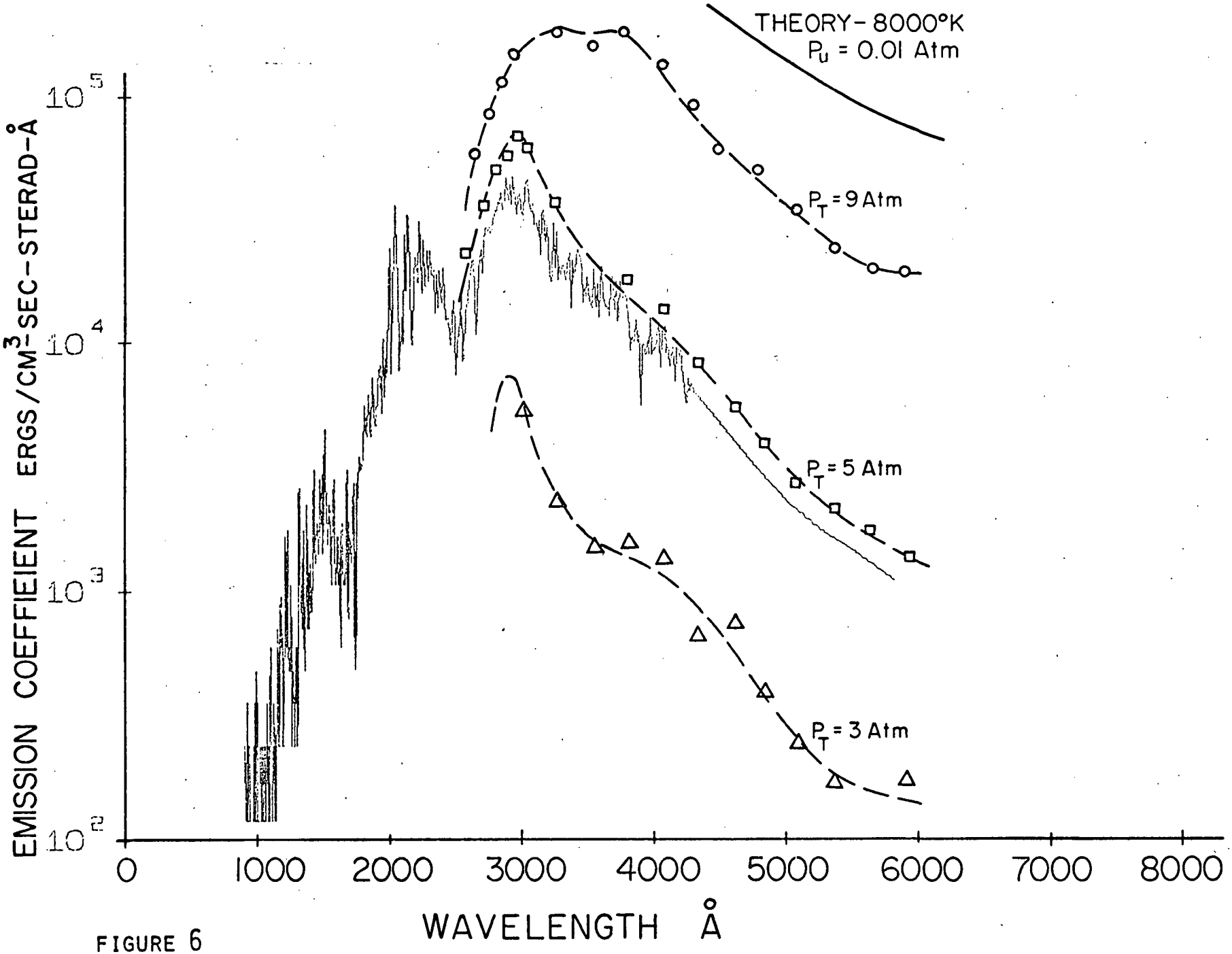


FIGURE 6

COMPARISON OF PRESENT MEASUREMENTS WITH EARLIER MEASUREMENTS

our present diagnostic equipment is significantly more sophisticated and accurate than the equipment available to us two years ago.

IV. Discussion of Results

Figure 7 gives a compilation of the results shown in Figures 4 and 5. The emission coefficient as predicted by the theory of Parks et al. [7] is plotted in this figure as well. In addition to this, the Planck-function for a temperature of 8,000 °K is plotted. Since the Planck-function is measured in ergs/(sec-cm^2-sterad-Å) a different ordinate-scale is required, as is indicated in Figure 7. As the graph is semi-logrithmic, Kirchhoff's relation has the interesting consequence that the vertical distance between any measured or computed emission coefficient value and the Planck-function gives the absorption coefficient in 1/cm. Points falling above the Planck function curve have an absorption coefficient >1 cm^{-1}, while points located below the Planck function correspond to absorption coefficients <1 cm^{-1}. Finally, emission points intersecting the Planck function have absorption coefficient equal to 1 cm^{-1}.

For the case of a geometrical plasma sheath thickness of 1 cm, (the situation for the measurements reported herein) the Planck function also marks the approximate dividing line between the optically thick and optically thin regimes. Figure 7 shows that the uranium arc was optically thin over the entire range of interest.

The experimental curve exhibits three distinct peaks, two of which are predicted by theory, hence the shape of the curve is predicted reasonably well by the theory. As far as the absolute value of the emission coefficient is concerned however, there is disagreement.

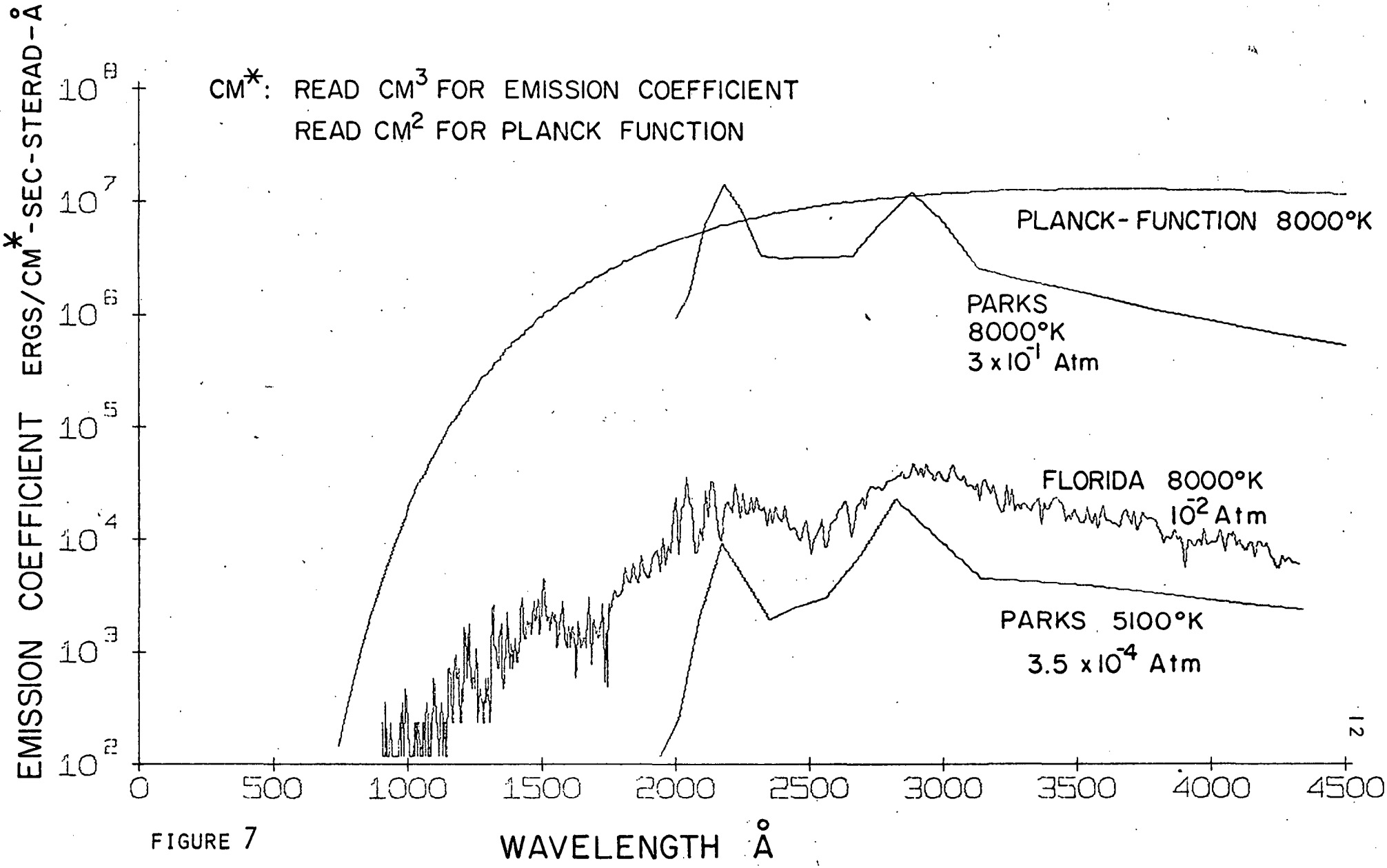


FIGURE 7

COMPARISON OF MEASUREMENTS WITH THEORY

Unfortunately, numerical values of Parks' theory for 8,000°K and 10^{-2} atm are not available. Therefore the conditions most closely approximating our values available were plotted in Figure 7. The conclusion is that the theoretical values are up to one order of magnitude higher than the experimental values. If one considers the complexity of the uranium atom and its ions together with the poor knowledge of basic atomic constants for uranium one can say that the theory performs much better than could reasonably be expected.

Figure 8 shows a compilation of other measurements reported in the literature [4,5,6,7]. Again the theoretical predictions by Parks et al. and modification performed by Patch are added for comparison. The measurements of both Marteney and Miller were taken using UF_6 rather than metallic uranium. The Planck-function for 8,000 °K is also plotted in the same way as described above.

Obviously the conditions under which the different experiments were performed were so different, that no agreement in absolute value of the emission coefficient can be expected. However the shape of the curve for the emission coefficient could be expected to agree at least to some degree. The shape obtained from the metallic uranium experiment agrees with the theoretical curves quite well, while clearly the shape of the emission curves from the UF_6 experiments bear little resemblance to the theoretical curves. An indication of the effect of adding a foreign gas to the plasma can be obtained from Figure 6. Increasing the helium pressure widens the peak at 3,000 Å and spreads the radiation towards longer wavelength at the expense of the relative height of the peak. In Figure 9 the measurements reported by Marteney are superimposed

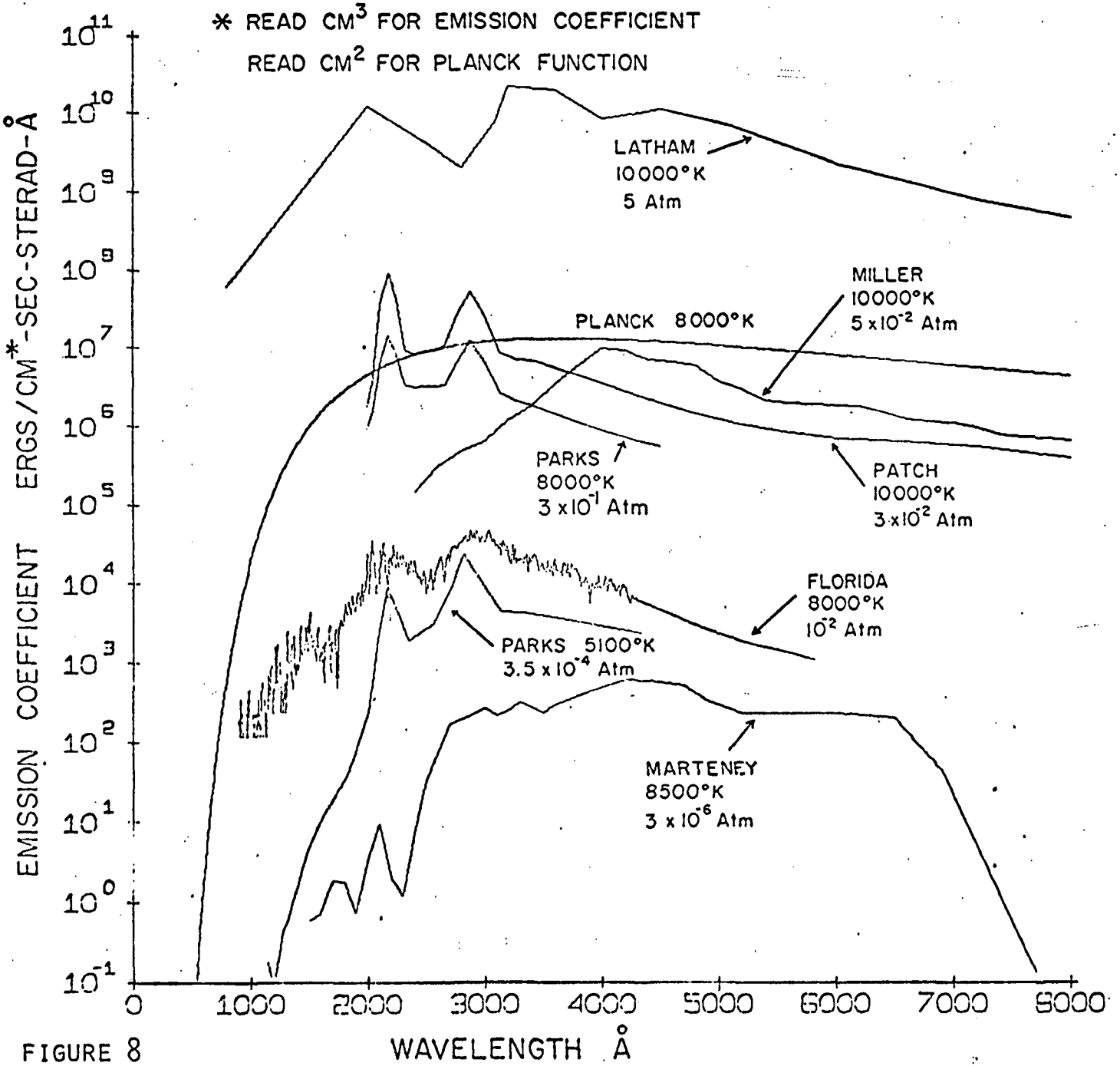


FIGURE 8

COMPILATION OF DATA REPORTED IN THE LITERATURE

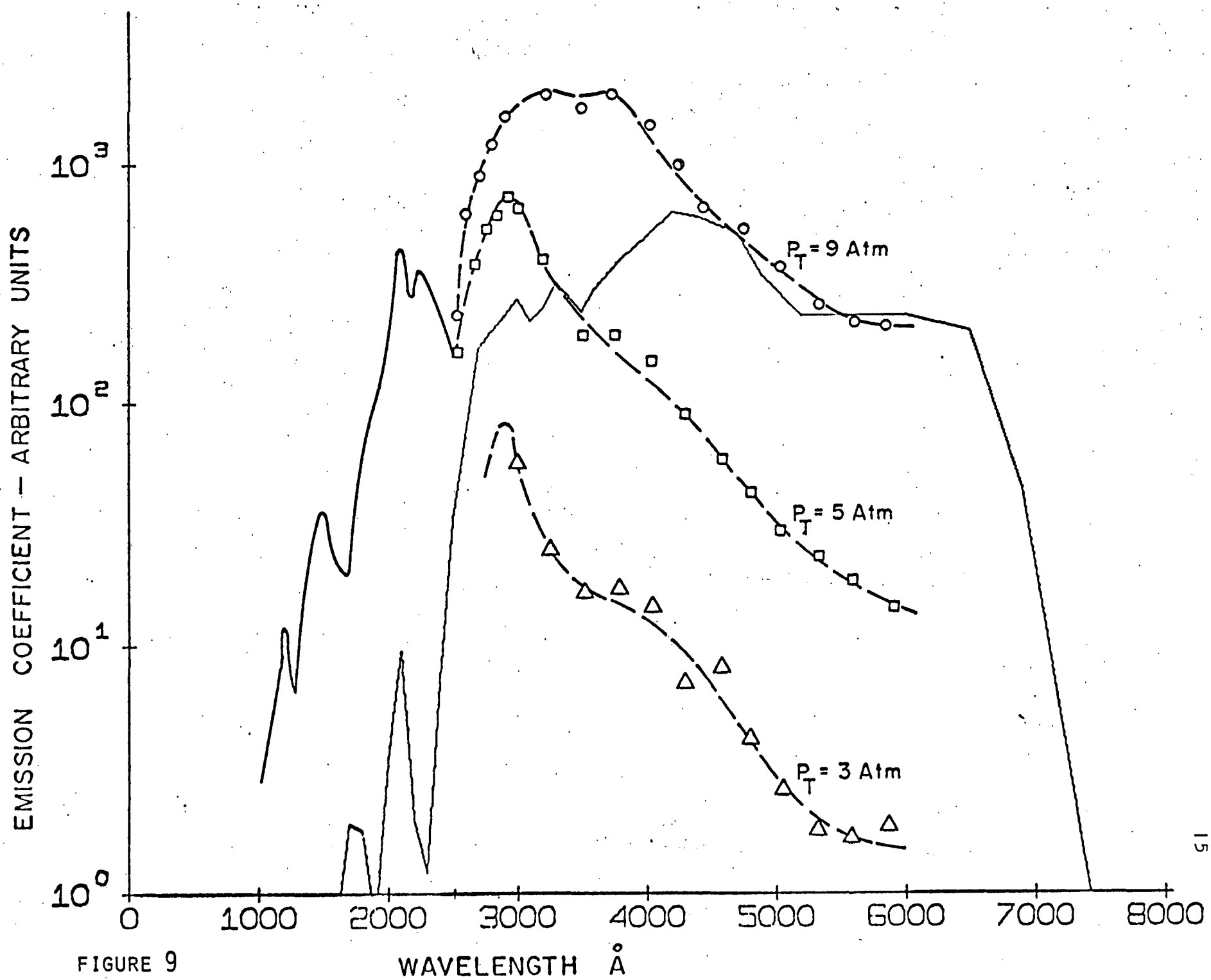


FIGURE 9

COMPARISON OF PRESENT MEASUREMENTS WITH MARTENEY'S MEASUREMENTS

on the measurements reported in Figure 6. Indeed the 3,000 Å peak is eroded away and the radiation is spread towards longer wavelength. It is plausible to attribute this to the influence of argon and expecially UF_6 as an additive gas. The peaks around 2,000 Å and 1,500 Å are not disturbed by this effect, probably due to lack of energy levels in the disturbing gas in the energy region which is responsible for these transitions.

An attempt was made to compare all of the measurements shown in Figure 8 on a common basis. Since all of these measurements fall in the optically region (i.e., assuming a sheath thickness of 1 cm or less) it appeared reasonable to make the assumption that the energy emitted is proportional to the number of emitting particles. With this assumption it is then possible to use the perfect gas law, $P = nkT$ (with P = pressure, n = particle density, k is Boltzmann's constant and T is the temperature) to scale all experimental data to a common temperature and density. This was done and all data were scaled to a temperature of 8,000°K and a pressure of 1 atm. It should be noted that the pressure scaling applied only to the partial pressure of uranium of the plasma. The cover gas pressure was ignored (despite the facts demonstrated in Figures 6 and 9) simply because there is no satisfactory procedure to compensate for this effect. The temperature scaling was undertaken with the sole objective of achieving a common uranium particle density. The strong exponential dependence of emission upon temperature could possibly have been compensated for with moderate success. However, since only Miller's measurements were taken at significantly different temperatures, and there was a 10,000°K theoretical curve available (see

Figure 8) it appeared unwarranted to perform this calculation. Further, the temperature effect can be easily seen without computation in Figure 8.

Figure 10 shows this comparison for all measurements reduced to a particle density corresponding to 1 atm uranium pressure at 8,000°K. The theoretical curve of Parks however corresponds to 1/3 atm and 8,000 °K, which is the closest one available. Our measurements agree with Parks' predictions reasonably well--that is, within a factor of 3 from 3,000 - 4,000 Å, within a factor of 6 over 4,000 - 6,000 Å, and within a factor of 10 at the two peaks. Marteney's measurements agree with ours from 1,500 Å to about 2,200 Å. Unfortunately Miller's measurements do not extend into U.V. below 2,500 Å. However in this region they agree with Marteney's, the theory, and within reason with ours. Therefore it is reasonable to claim that the emission coefficient of uranium is now known from 1,200 Å - 2,200 Å.

Marteney's and Miller's measurements agree from about 3,000 - 6,000 Å in Figure 10. However if the correction for the exponential temperature effect would have been made they would not agree. They disagree with our measurement by at least 3 orders of magnitude in this wavelength range. It should be born in mind however, that both experiments imply optical thickness for a sheath of 1 cm or more at 1 atm in this wavelength range, so that the extrapolation upon which Figure 10 is based--the optically thin assumption--is no longer valid.

Substantial absorption would scatter the radiation into other wavelength ranges and would smooth out the curves so they would obtain a shape resembling the Planck function even more. Our explanation for the

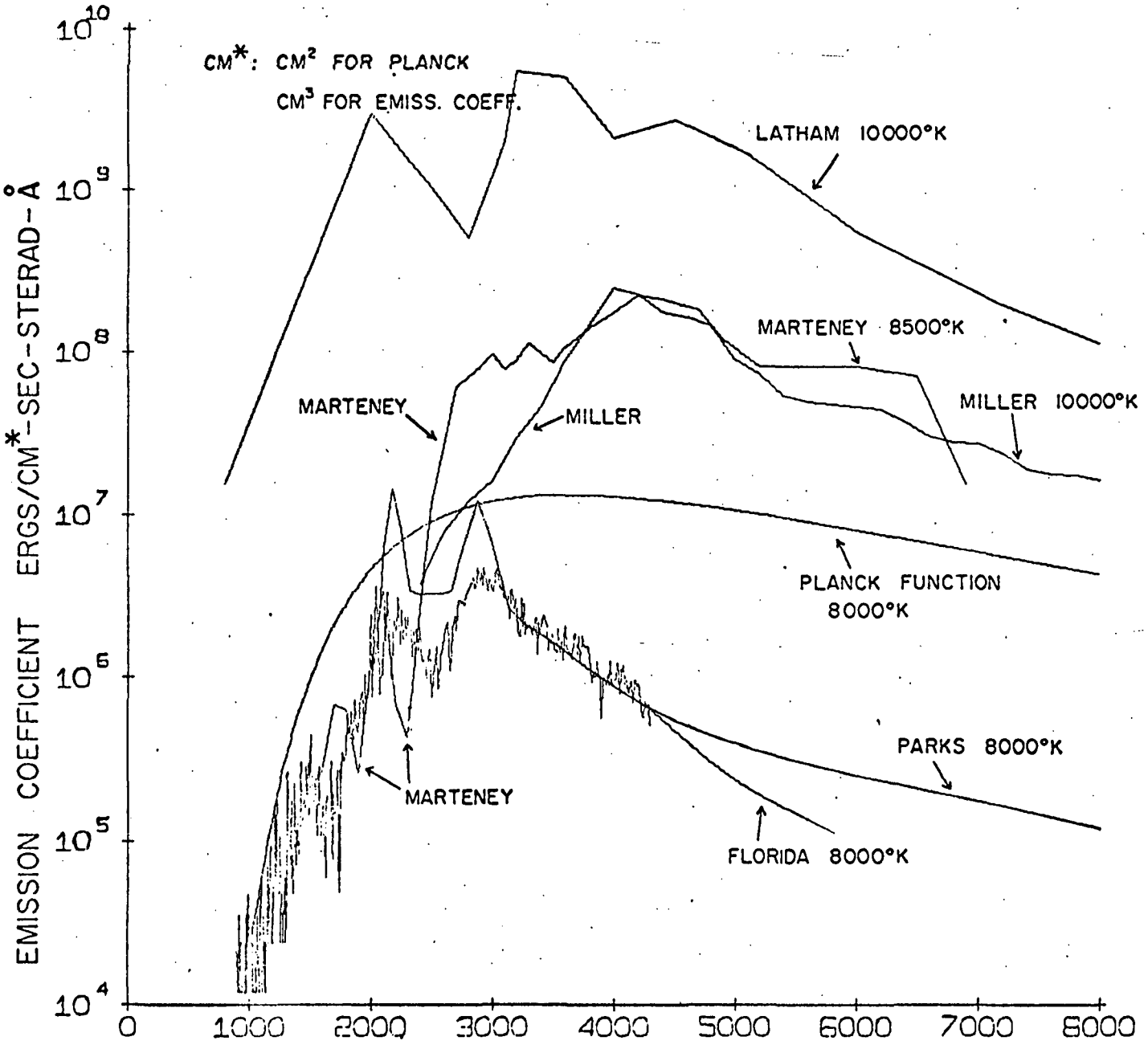


FIGURE 10

MEASUREMENTS REPORTED IN LITERATURE REDUCED TO COMMON PARTICLE DENSITY (1ATM, 8000°K)

unexpectedly large absorption in this wavelength range is, that this is caused by the cover gases, especially UF_6.

Figure 11 finally presents the absorption coefficients of all measurements as computed from the emission coefficient using Kirchhoff's law (with the exception of Miller's data, where originally the obsorption coefficient was given and the emission coefficient was computed for Figure 10). Note that Figure 11 has to be compared with Figure 8 instead of Figure 10, because the condition given in Figure 8 applies as well for Figure 11. Further, it should be pointed out that the information presented in Figure 11 has been displayed earlier in this paper. The repetition of these data was included only for convenience, in its original unscaled form.

Conclusions

The emission coefficient of a uranium plasma at 8,000°K and pressures lower than 1 atm is determined for the 1,200 - 2,000 Å region while disagreement exists for longer wavelengths. We recommend using Parks' theory or our measurements for 3,000 Å and longer. The peaks at 2,000 and 3.000 Å are probably exaggerated in Parks' theory and we recommend using our values for the 3,000 Å peak. Further, since there is agreement between Marteney's values and our own values at 2,000 Å, it is clear that these values should be definitely used in future calculations.

Therefore the edge condition of a plasma core reactor can now be designed with increased confidence. However it should be pointed out that all values presented in Figure 9 apply for non-fissioning plasmas, i.e., thermally excited plasmas. A fission fragment excited plasma

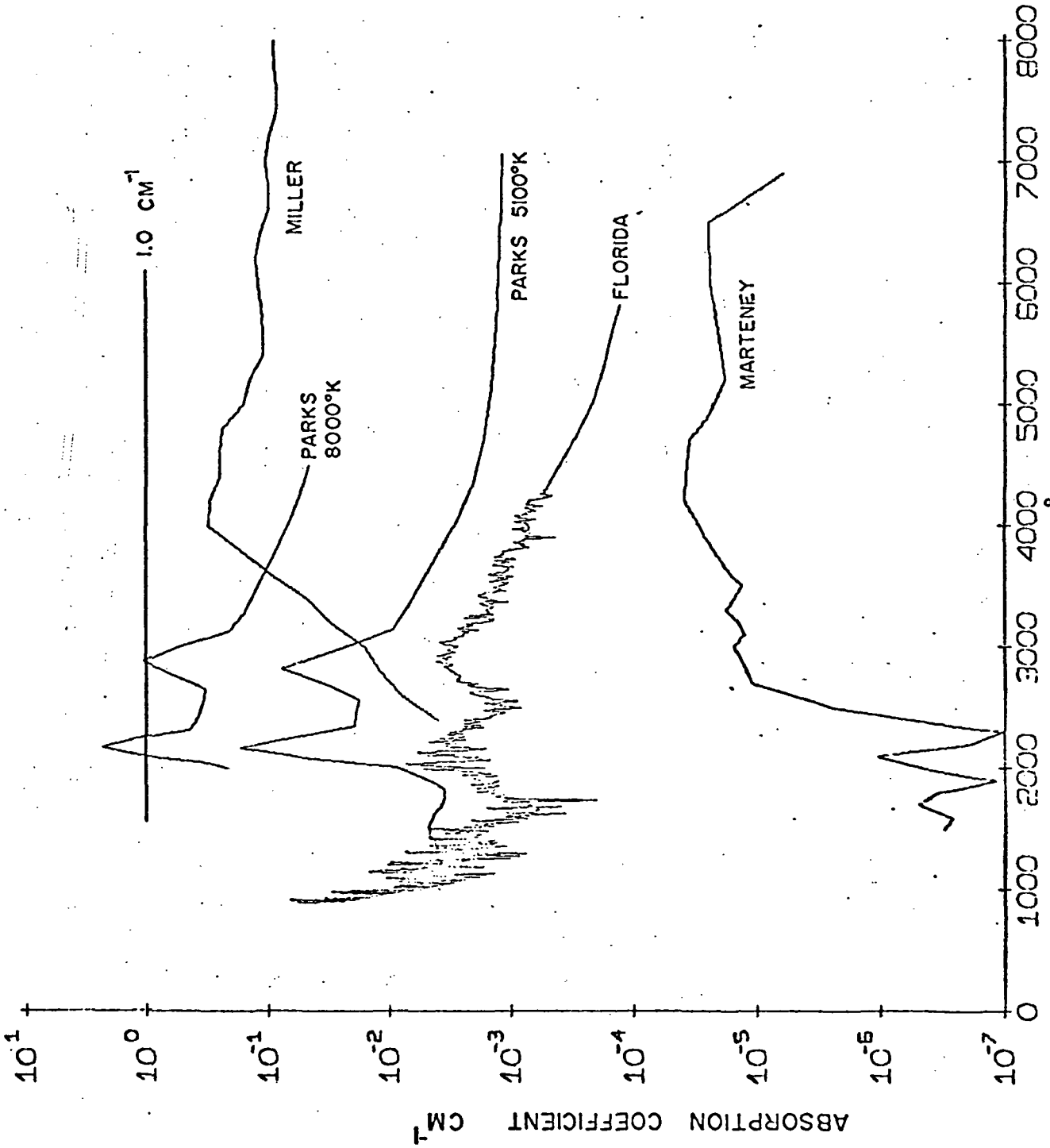


FIGURE 11 ABSORPTION COEFFICIENT OF URANIUM

might have a significantly different emission coefficient. A "plasma temperature" might be hard to define and therefore in principle no disagreement with the presented measurements could be claimed. For practical purposes however, since the edge of the uranium plasma region is also the highest neutron flux region, the emission coefficient of a fissioning plasma still needs to be measured.

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