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UV spectroradiometric output of an F404 turbojet aircraft engine

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ABSTRACT

Spectroradiometric measurements of the ultraviolet output of a GE F404 aircraft engine were made over the wavelength range of 200 to 320 nm. The tests were conducted at the GE Lynn, Mass. Riverworks facility in the F404 ram cell. The severe environmental conditions associated with the test cell required a special acoustical noise-proof and mechanical shock-proof enclosure for the double monochromator and UV detectors along with special long cabling to the externally located radiometer and automatic data reduction system. The tests successfully provided spectral irradiance measurements of the afterburner over the 225-320 nm wavelength range with a UV-enhanced silicon detector and over the 200-260 nm range with a PMT detector.

1. INTRODUCTION

The GE manufactured F404 aircraft engine is the powerplant of the U.S. Navy's newest aircraft, the F/A-18 carrier based attack fighter. This turbojet engine provides additional thrust for combat maneuvers and carrier takeoffs from an afterburner (the burning of additional fuel "after the burning" in the main or core engine). To improve afterburner lightoff characteristics and provide safeguards against undesired lightoffs, an ultraviolet flame detector is employed. The flame detector uses a proprietary solar blind, UV Geiger-Mueller type sensor manufactured by Armtec Industries.

Unstable operation of the afterburner's gas exit nozzle has been a field complaint. This condition, designated as VEN (variable exhaust nozzle) cycling, is an undesirable operating condition and was assessed to be caused by intermittent flame sensor output. Previous work by the Air Force Aero Propulsion Laboratory[1] reported spectral radiant intensity measurements of aircraft engine fuel for other than actual operating conditions. However, no in-situ spectral data was available for use in the analysis of the intermittent VEN condition. Accordingly, Optronic Laboratories was contacted by GE to determine the relative spectral flux distribution of the afterburner flame through the flame sensor window. Absolute spectral data was of secondary importance. Since irradiance measurements were desired for the worst case conditions, the engine testing was conducted using MIL-F-7024 Grade JP4 and Grade JP5 fuels and simulating the engine operation at high mach number and high inlet temperature. These operating conditions were part of a systematic approach to investigate the cause of the intermittent operation of the engine-mounted ultraviolet flame detector when operating on the engine. A condition not observed during bench acceptance testing.

All spectroradiometric measurements on the afterburner were made at the GE's Lynn, Ma. Riverworks facility in the F404 ram cell during the week of June 13, 1988. The "window", or time available for setting up the instrumentation, calibrating the measurement systems and performing the engine measurements, was one week.

In addition to the relatively short "window", the environmental conditions in the test cell with the engine running was quite severe. The turbulence in the test cell was extremely high and the noise level adjacent to the engine was on the order of 140 db. These severe environmental conditions required a custom, acoustical noise-proof and mechanical shock-proof enclosure to house the sensitive optics portions of the spectroradiometer and filter-radiometer. The enclosure had two one-inch diameter openings with supersil UV transmitting windows over the openings. The openings lined up with the entrance port of the double monochromator and with the filter radiometer's sensor head. The enclosure was approximately 70 x 50 x 40 cm and was lined with a 6 cm thick foam-lead-foam, acoustical absorber.

The flame sensor normally mounts to the outside of the afterburner section of the F404 engine at about 7:30 o'clock aft looking forward (see Figure 1). The doors of the test cell were located on the opposite side of the flame sensor viewing port; thus, the distance from the optics portions of the measurement systems to the externally located electronics and automatic data reduction system was about 35 feet. Accordingly, special 35 foot long, low-noise cables were assembled and rigidly secured to the floor of the test cell. Figure 2 shows the F404 engine installed in the test cell.

2. BACKGROUND

In order to understand the need for the engine spectral testing, one has to understand the operation of the flame detector and its controlling effect on the afterburner nozzle.

A flame detector or "light-off detector" is installed on the modern GE turbojet engines to provide a smooth lightoff for the large quantities of fuel that are delivered to the afterburner in order to generate a large incremental thrust increase for combat maneuvers and short runway and carrier takeoffs. The detector, which consists of a gas filled tube with parallel metal filaments, acts as a closed switch when it senses the ultraviolet wavelengths in the engine's hydrocarbon flame. As the uv-sensitive gas ionizes between the filaments in the presence of uv, the ac voltage impressed on one filament is conducted to the other element and an ac voltage is fed out to the engine control unit circuit to integrate sufficient pulses into a dc voltage to trigger the control logic that a lightoff has occurred. The control unit then allows main afterburner fuel flow to be delivered once a lightoff on pilot flow is detected. During afterburning, the detector must maintain an output signal to the control unit which schedules VEN area for power condition demanded. If the detector output signal is interrupted, the VEN area is reduced. When the signal is reestablished, the VEN area is restored to the original condition. Accordingly, if the detector signal is intermittently interrupted, the VEN will cycle.

The question was: If the detector delivers sufficient signal (a high number of pulses) from the test propane flame during bench acceptance testing, then why does it deliver an insufficient signal (a lower number of pulses) during engine operation?

The uv spectroradiometric engine tests were conducted to determine the ultraviolet content of the afterburner flame when viewed from the side near the flame. Second and third phases of the overall measurement program was to measure the spectral response of the flame detectors (both at ambient and elevated temperatures) and to measure the spectral content of the propane test flame. With all of the above data, the question could then be answered.

3. INSTRUMENTATION

Measurements were made using both a scanning spectroradiometer for determining the relative spectral output of the engine flame and a fixed wavelength, filter-radiometer for determining the absolute irradiance at a specific wavelength and at a known distance from the flame sensor opening in the engine. The use of these two instruments enabled positioning the scanning spectroradiometer relatively near the flame sensor opening. Thus, the signal to noise ratios were sufficient to obtain meaningful relative spectral data. The relative spectral output of the flame could then be normalized to the absolute irradiance as determined with the filter-radiometer.

The spectroradiometer consisted of an Optronic Laboratories Model 740A/D Optical Radiation Measurement System (double monochromator option) optimized for measurements in the 200 to 320 nm wavelength region. A system employing a double monochromator for the optical dispersing mechanism was considered essential in order to maintain minimum levels of stray light. The monochromator was equipped with

1200 lines/mm gratings blazed at 250 nm. Under normal laboratory conditions, the wavelength accuracy of the monochromator is ±0.5 nm and the wavelength precision is ±0.1 nm. Stray light levels are less than 0.0001%. Five sets of fixed slits were available for use with the monochromator giving equivalent bandwidths of 0.5, 1, 1.25, 5 and 10 nm. The majority of the measurements were made using the 5 and 10 nm bandpass slits.

An Optronic Laboratories Model 740-1C Automatic Wavelength Drive-Filter Wheel Controller Unit was used to set the wavelength, insert the proper blocking filter and shutter the source via remote control. The Model 740-1C consists of:

1) A stepper motor drive.
2) A high-accuracy, bi-directional optical shaft encoder.
3) An automatic second order blocking filter wheel.
and 4) A control chassis for the wavelength drive electronics.

The stepper motor, optical shaft encoder and blocking filter wheel are located inside the monochromator while the controller is a separate module.

Most of the spectroradiometric measurements were made using a UV-enhanced silicon detector. This detector was chosen because of its ruggedness, high stability, moderate sensitivity, wide dynamic range and good linearity. Supplemental measurements were made using a more sensitive, more fragile photomultiplier detector.

The detector signal was fed into an Optronic Laboratories Model 730A Autoranging Radiometer. Signal levels as low as 10^{-13} amperes could be detected with the Model 730A. Table 1 gives the noise equivalent irradiance (NEI) of the measurement system for 10 nm bandpass slits.

Figure 3 shows a layout of the spectroradiometric measurement system prior to inserting the double monochromator into the special, acoustically and mechanically insulated enclosure. The system, as shown in Figure 3, was calibrated for spectral irradiance response outside of the test chamber. Measurements of the uv output of the engine flame were made with the double monochromator in the insulated enclosure and in the test chamber approximately 6.6 cm from the flame. The Model 730A Radiometer, the controller portion of the Model 740-1C, and the computer/printer were all located outside of the test chamber. The detector and wavelength signals inside the enclosure and chamber were fed to the radiometer and controller via specially fabricated 35 foot long cables.

Detector and wavelength signals from the radiometer and wavelength controller were fed into an IBM PC-AT class computer via the Optronic Laboratories Model 740-410 Interface Card and Cables. Thus, using the standard Optronic Laboratories spectral irradiance and transmittance software packages, the entire system calibration and source measurement process could be computer controlled.

The filter radiometer consisted of a 1 cm^2, UV-enhanced silicon detector with a 1-inch diameter, 254 nm transmitting, narrow bandpass interference filter directly in front of the detector. This detector-filter combination could be mounted in the insulated enclosure directly above the entrance slit of the double monochromator. A 35 foot signal cable was fabricated to relay the detector signal to the Model 730A Autoranging Radiometer. The NEI of the 254 nm radiometer was 5×10^{-13} watts/cm^2 nm.

4. STANDARDS AND CALIBRATION

Two different kinds of spectral irradiance standards were available for calibrating both measurement systems: the tungsten-filament quartz-halogen lamps[2,3] which are calibrated for spectral irradiance over the wavelength range of 250 to 4500 nm and the deuterium arc lamps[4] which are calibrated over the wavelength range of 200 to 400 nm. Both types of standards are traceable to the National Institute of Standards and Technology (NIST). The uncertainty in the tungsten standards varies from about ±3% at 250 nm to ±2% at 350 nm. However, the tungsten standards cannot be used below 250 nm and, due to the very sharp decrease in radiant output in the UV, it is difficult to obtain highly accurate calibrations using the tungsten standards in the 250 to 300 nm region. The uncertainty in the deuterium lamp standards is estimated to be ±6% over the entire 200 to 350 nm wavelength region.

In order to obtain the best calibration possible on the spectroradiometer system and to verify that there was no significant stray light present when using the double monochromator, both the tungsten (Optronic Laboratories Model 220-C) and deuterium (Optronic Laboratories Model UV-40) standards were used to calibrate the spectroradiometer. Since the tungsten and deuterium standards have completely opposite spectral distributions, problems associated with stray light, wavelength accuracy, bandwidth, etc. would be revealed by discrepancies in the spectral irradiance response calibration factors as determined using each standard. Calibrations using both standards were performed in the Radiometry Laboratory at the Optronic Laboratories facility in Orlando, Florida. The agreement between both sets of calibration factors for the spectroradiometer system was within ±3% over the 250 to 350 nm wavelength region.

Since the Model UV-40 deuterium lamp standard of spectral irradiance could be used over the entire region of interest (200 to 320 nm), only the deuterium lamp was used to calibrate the spectroradiometer at the GE facility. This calibration was performed immediately before and after measurements were made on the aircraft engine.

5. MEASUREMENT PROCEDURE

Two approaches were considered when determining how to best mount the instrumentation in the test chamber and which instruments should remain in the chamber. The distance from the viewing area to the exterior of the cell most suitable for remotely operating the measurement system was 35 feet. Accordingly, the choice was:

A) Place only the optics portions of the spectroradiometer and filter-radiometer in the chamber and run 35 foot length detector signal, PMT voltage, shutter and wavelength drive control cables from the measurement viewing area to the measurement control area.

B) Place the entire spectroradiometric and filter-radiometric systems in the measurement viewing area and run 35 foot cables to the computer in the measurement control area.

Option A was chosen since the special 35 foot computer cables were still in the fabrication process and since the cables necessary to execute option A were available and had been checked out under normal laboratory conditions.

The instrumentation was initially set up on tables adjacent to the large entrance doors of the test cell. The gratings were installed in the monochromator and a wavelength calibration was performed on the monochromator.

The measurement sequence was as follows:

1) The spectral transmittances of the three supersil quartz windows were measured over the wavelength range of 200 to 350 nm. These measurements were made using the spectroradiometer and a deuterium arc lamp for the source. NOTE: Two of the supersil windows were for the spectroradiometer and filter-radiometer openings in the insulated enclosure and the third supersil window covers the opening in the afterburner section of the engine.

2) The Model 740A/D spectroradiometer system was calibrated for spectral irradiance response using the Model UV-40 ultraviolet irradiance standard. The measurement parameters were as follows:

   Wavelength range..........200 to 320 nm
   Wavelength interval.......5 nm
   Half bandwidth............10 nm
   Detector..................UV-enhanced silicon
   Distance..................30 cm

3) The Model 730A filter-radiometer was then calibrated for

response at 254 nm using the Model UV-40 ultraviolet irradiance standard. The radiometer-irradiance standard distance was 30 cm.

4) The double monochromator and filter-radiometer were installed in the insulated enclosure. The enclosure was positioned 6.6 cm from the engine viewport window. The engine was turned on and spectral measurements of the afterburner emission were made over the wavelength range of 230-320 nm for the following engine operating conditions:

Minimum Afterburner	T=90F
Maximum Afterburner	T=90F
Minimum Afterburner	T=150F
Maximum Afterburner	T=150F

5) The engine was turned off and the enclosure was repositioned such that the filter-radiometer was 36.8 cm from the engine viewport window. The spectral irradiance at 254 nm of the afterburner was measured for the conditions given in 5.4.

6) The engine was turned off and the fuel was switched to JP-5. Without changing the filter-radiometer position, the spectral irradiance of the engine with the JP-5 fuel was measured for the following engine operating conditions:

Minimum Afterburner	RAM	T1=150F
Maximum Afterburner	RAM	T1=150F
Minimum Afterburner	No RAM	T1=90F
Maximum Afterburner	No RAM	T1=90F

7) The engine was turned off and the spectroradiometer and filter-radiometer were removed from the enclosure. Both systems were recalibrated for spectral irradiance response in the same manner as described above in 2.2 and 2.3.

8) The spectroradiometer and filter-radiometer were reinstalled in the insulated enclosure and the enclosure was repositioned 6.6 cm from the engine viewport window. Spectral measurements were then made with the engine operating on the JP-5 fuel over the wavelength range of 230-320 nm.

9) In order to obtain additional spectral data at the shorter wavelengths, the UV-enhanced silicon detector was removed and a more sensitive, more fragile photomultiplier detector was inserted at the exit port of the double monochromator. Measurements were then made of the spectral emission of the engine afterburner over the wavelength range of 200-250 nm when using the JP-5 fuel. For these measurements, the bandwidth of the monochromator was set to 5 nm. The engine parameters were:

Minimum Afterburner	No RAM	T1=90-100F
Maximum Afterburner	No RAM	T1=90-100F

10) The engine was turner off and the double monochromator (with PMT) was removed from the enclosure and the system was calibrated for spectral irradiance response over the wavelength range of 200-250 nm.

6. RESULTS

The relative spectral distribution of the engine afterburner was measured with the spectroradiometer positioned 6.6 cm from the viewport window. Absolute measurements of spectral irradiance were made at 36.8 cm from the engine viewport window using the 254 nm filter-radiometer. The relative spectral values were normalized to the absolute value at 254 nm in order to obtain the spectral irradiance values at 36.8 cm. However, the effect of the supersil windows over the engine viewport window and over the openings of the insulated enclosure had to be taken into consideration. Accordingly, the spectral data was corrected by the window transmittances as determined in section 5.1 (see Table 2).

Figures 4 and 5 give plots of spectral irradiance for the engine afterburner for the different operating conditions when operating on the JP-4 and JP-5 fuels respectively.

In addition to the spectral distribution of the afterburner, the spectral radiant intensity (watts/ster nm) and spectral radiant flux per unit area (watts/cm^2) incident on a flame sensor was also of interest. From a knowledge of the spectral irradiance at 36.8 cm, the spectral radiant intensity was computed. The assumption was made that the radiating source was indeed a lambertian emitter i.e., that the radiant intensity per unit area in any direction varied as the cosine of the angle between that direction and the normal to the source.

The distance from the flame or one inch opening in the afterburner to the position where the flame sensor is normally located (viewport window) is 1.5 inches. The spectral irradiance at the viewport window was computed from a knowledge of the spectral radiant intensity and the area of the source using the relationship:

$$E = \pi L r^2 / (d^2 + r^2) \qquad (1)$$

where, E = spectral irradiance at viewport window (watt/cm^2)
L = spectral radiance of source (watts/ster cm^2 nm)
d = distance (cm)
r = radius of source (cm)

NOTE: Spectral radiance of source is equivalent to spectral radiant intensity per unit area.

Figures 6 and 7 give the radiant flux per unit area incident on the viewport window for the different operating conditions when operating on the JP-4 and JP-5 fuels respectively.

7. SUMMARY

The agreement in the calibration scans for the spectroradiometer and the radiometer periodically throughout the course of the measurements indicates that the system was not adversely effected by the severe environmental conditions present in the test chamber. Repeated wavelength calibration checks using the Hg arc lamp showed less then a 0.3 nm change in wavelength. Since the bandpass was either 5 or 10 nm during the course of the measurements, a shift of 0.3 nm is not significant. The repeatability in the spectral irradiance response was on the order of ±3 percent. This was considered more than adequate for non-laboratory conditions.

Repeated scans on the spectral output of the afterburner for the same operating conditions varied from 2 to 15%. This variation, however, was not attributed to the performance of the measurement systems, but to the inherent instability in the emission of the afterburner.

As mentioned previously, determining the spectral distribution of the afterburner emission was the first of three phases of the overall measurement program. The successful completion of the first phase was followed by the spectroradiometric output measurements on various sources used to bench test the flame sensors and by the actual measurement of the spectral responsivity of the flame sensors at ambient and elevated temperatures. A paper describing the subsequent phases of the program is in progress.

8. REFERENCES

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2. R. Stair, W.E. Schneider, and J.K. Jackson, A New Standard of Spectral Irradiance, Appl. Opt. 2, 1151-1154 (1963).
3. R.D. Sanders and J.B. Shumaker, The 1973 NBS Scale of Spectral Irradiance, National Bureau of Standards (U.S.) Tech Note 594-13 (Apr. 1977).
4. R.D. Saunders, W.R. Ott, and J.M. Bridges, Spectral irradiance standard for the ultraviolet: the deuterium lamp, Applied Optics Vol. 17, No. 4, pp. 593-600 (Feb. 1978).

Table 1

Noise Equivalent Spectral Irradiance
of
Spectroradiometer System

Wavelength (nm)	NEI ($Watt/cm^2$ nm)
200	4.5×10^{-11}
220	6.0×10^{-12}
240	2.1×10^{-12}
260	2.2×10^{-12}
280	2.7×10^{-12}
300	2.6×10^{-12}
320	2.4×10^{-12}

HBW: 10 nm
Gratings: 1200 g/mm, 250 nm Blaze
Detector: UV-enhanced silicon

Table 2

Spectral Transmittance
of
Supersil Windows

Wavelength (nm)	Engine Viewport Window (%)	Spectroradiometer Window (%)	Filter-Radiometer Window (%)
200	86.399	86.059	81.707
210	87.500	87.634	84.005
220	88.813	88.875	86.313
230	89.828	90.214	88.074
240	90.293	90.691	89.016
250	90.906	91.140	89.678
260	91.732	91.732	90.423
270	92.019	92.070	90.834
280	91.941	91.941	91.026
290	91.822	91.822	90.954
300	92.217	92.147	91.383
310	92.357	92.277	91.553
320	92.523	90.304	92.112

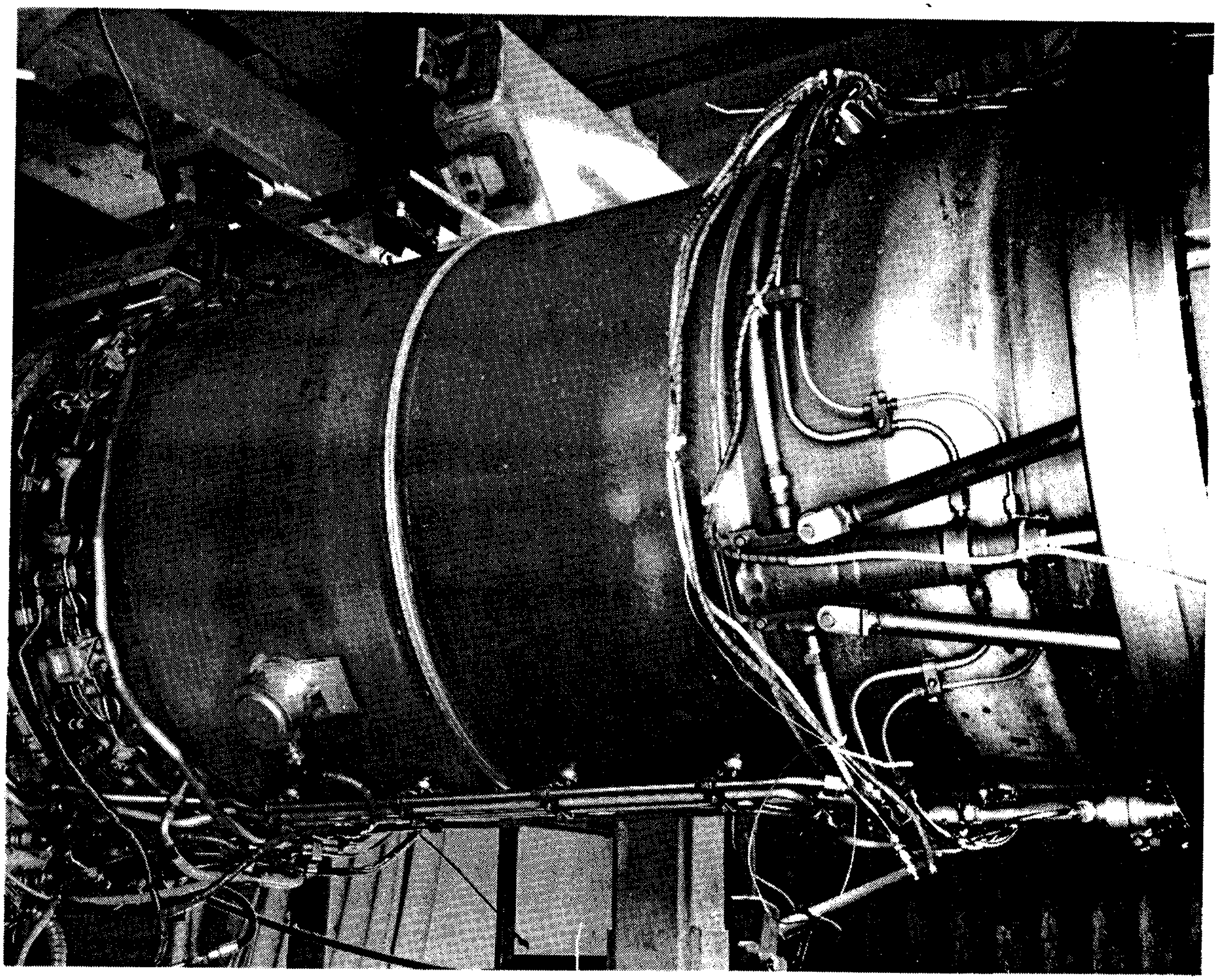

Figure 1. Afterburner Section with Flame Sensor

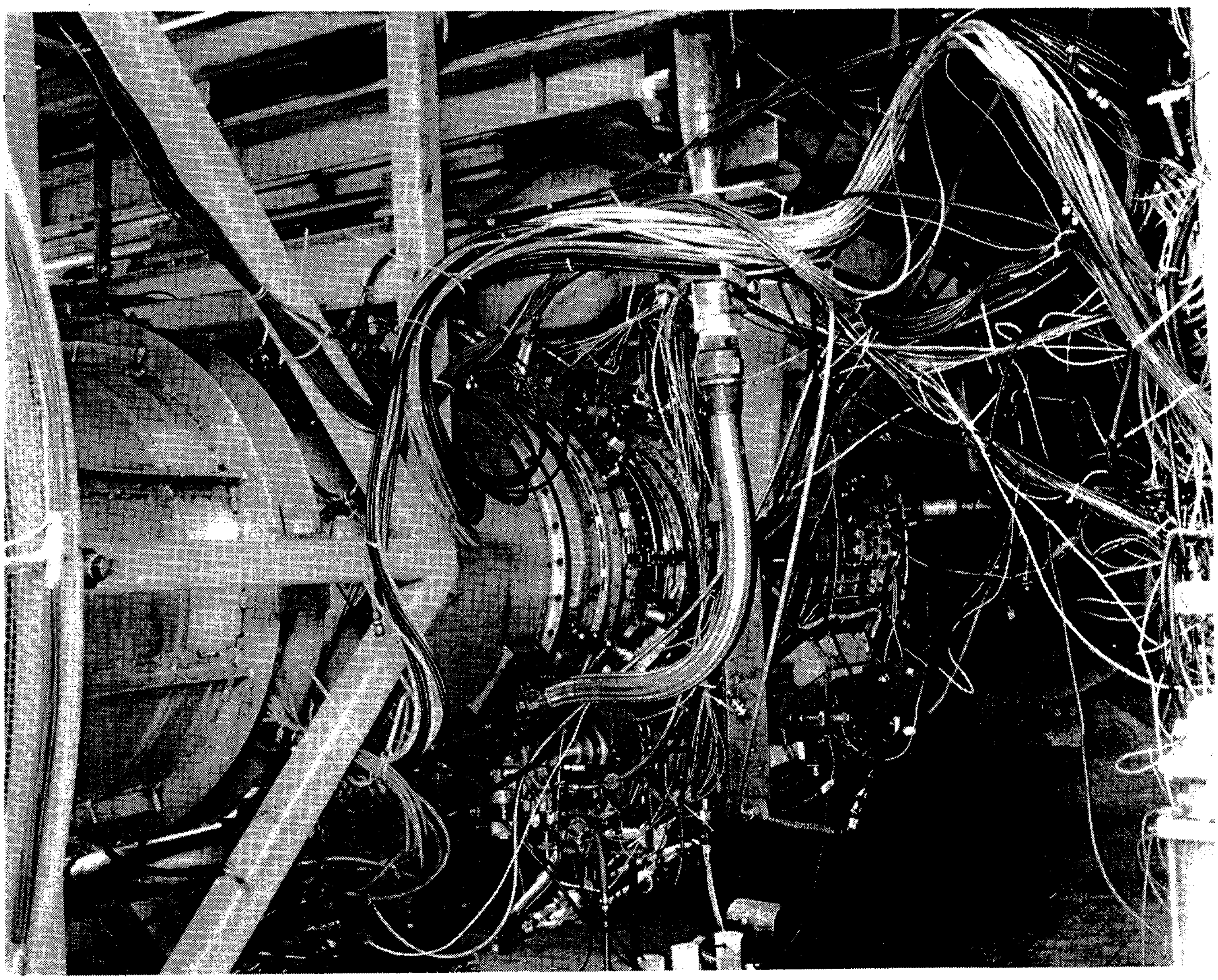

Figure 2. F404 Engine in Test Cell

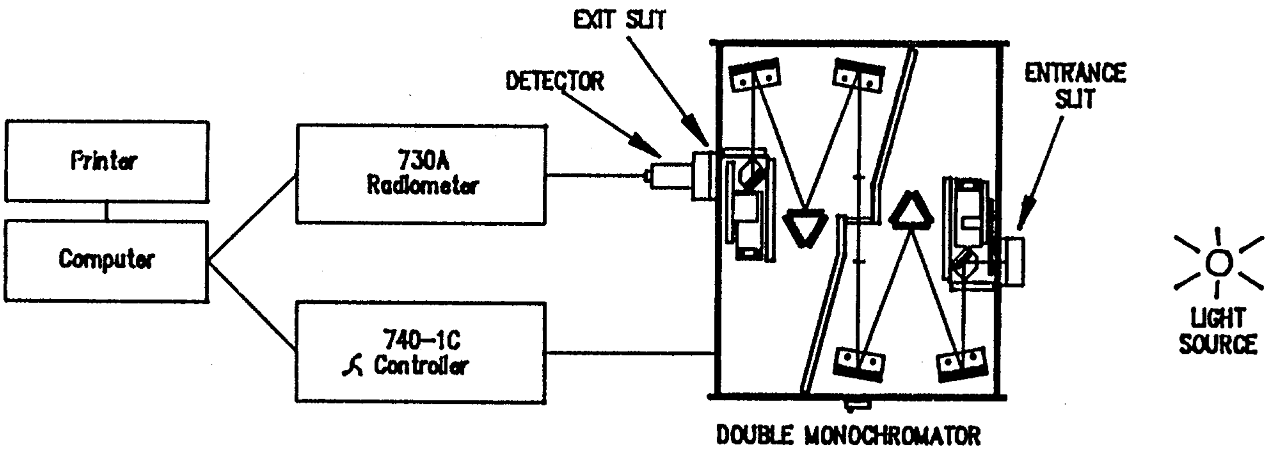

Figure 3. Automated Optical Radiation Measurement System - Double Monochromator Option

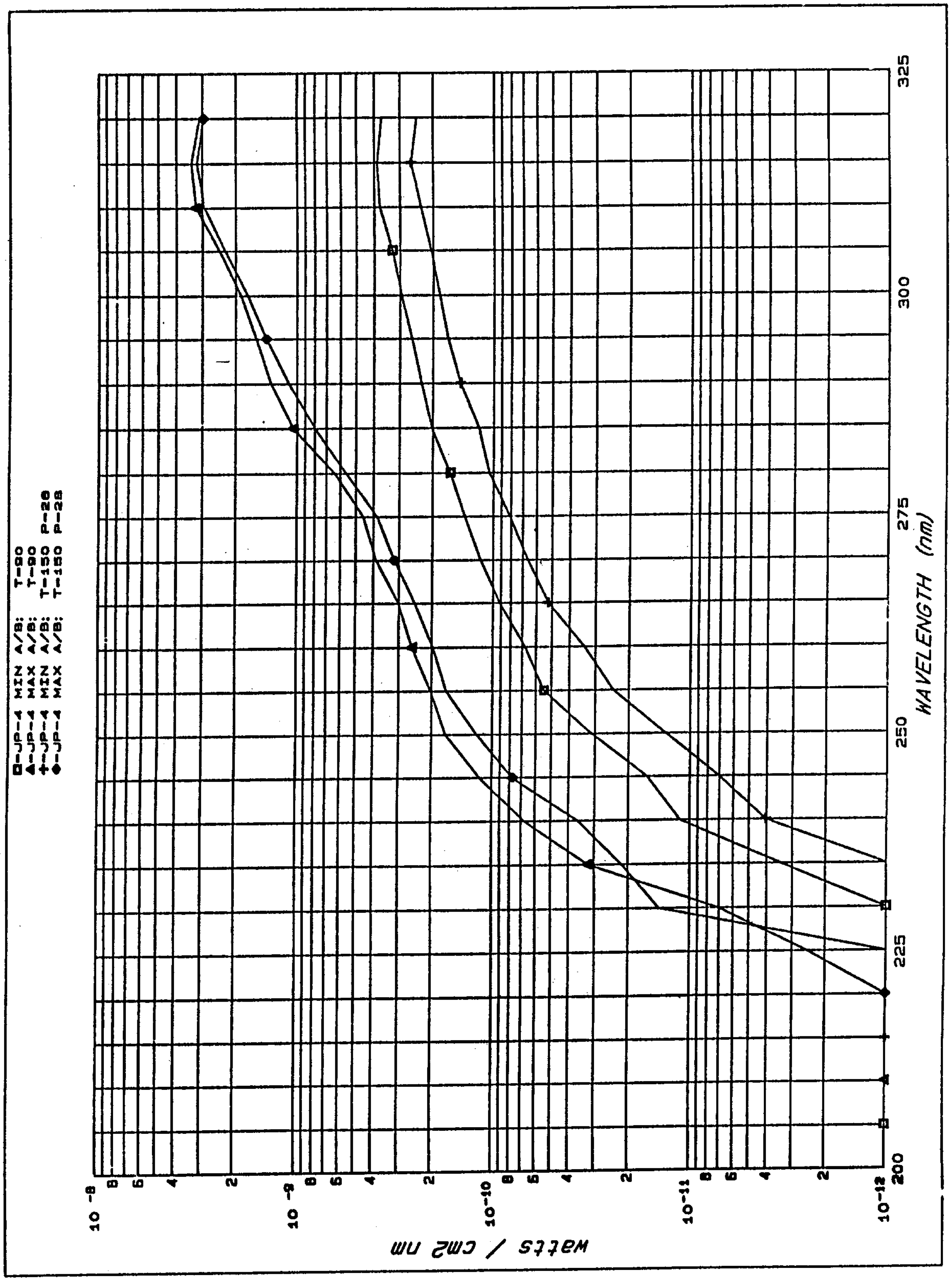

Figure 4. Spectral Irradiance of Afterburner with JP-4 Fuel

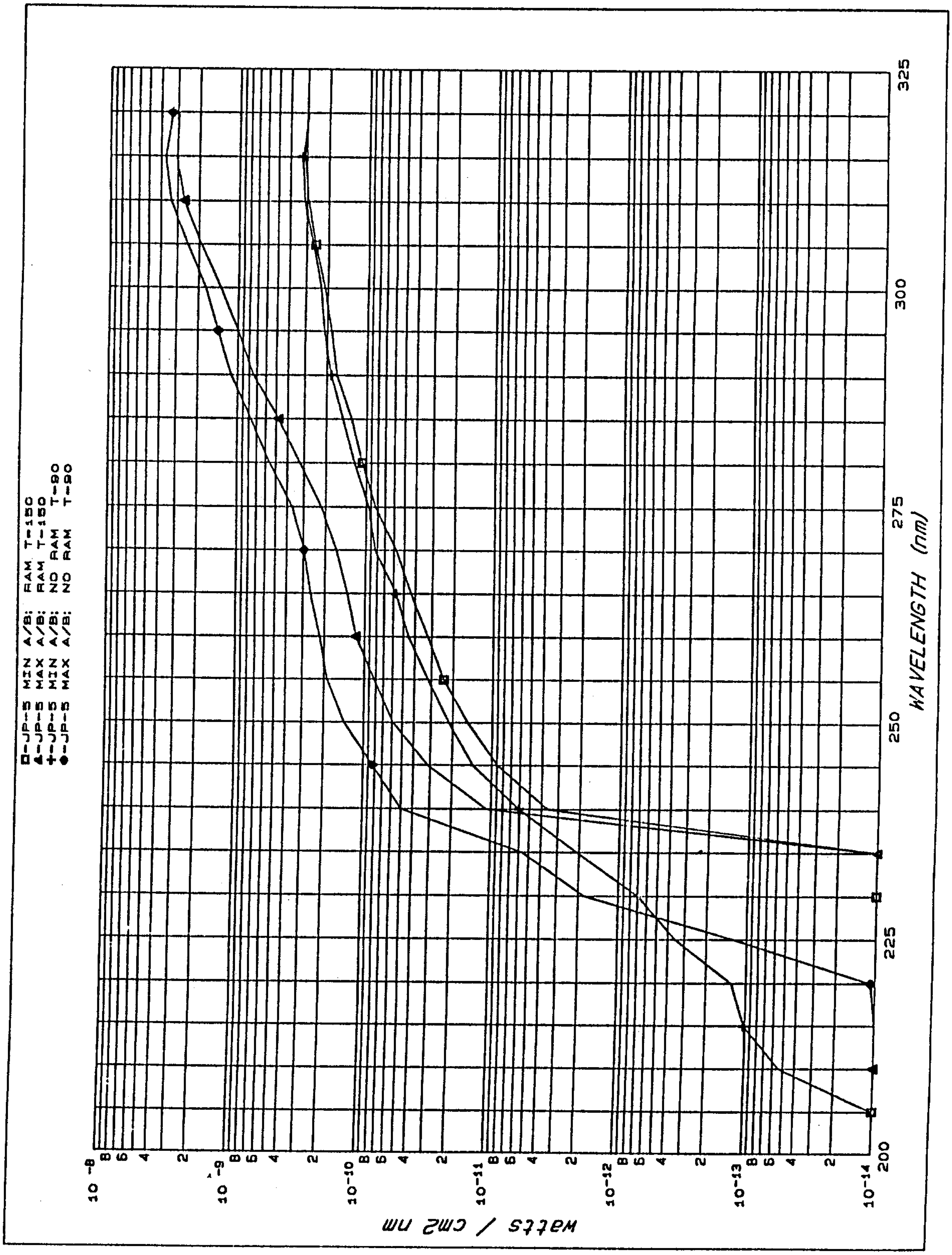

Figure 5. Spectral Irradiance of Afterburner with JP-5 Fuel

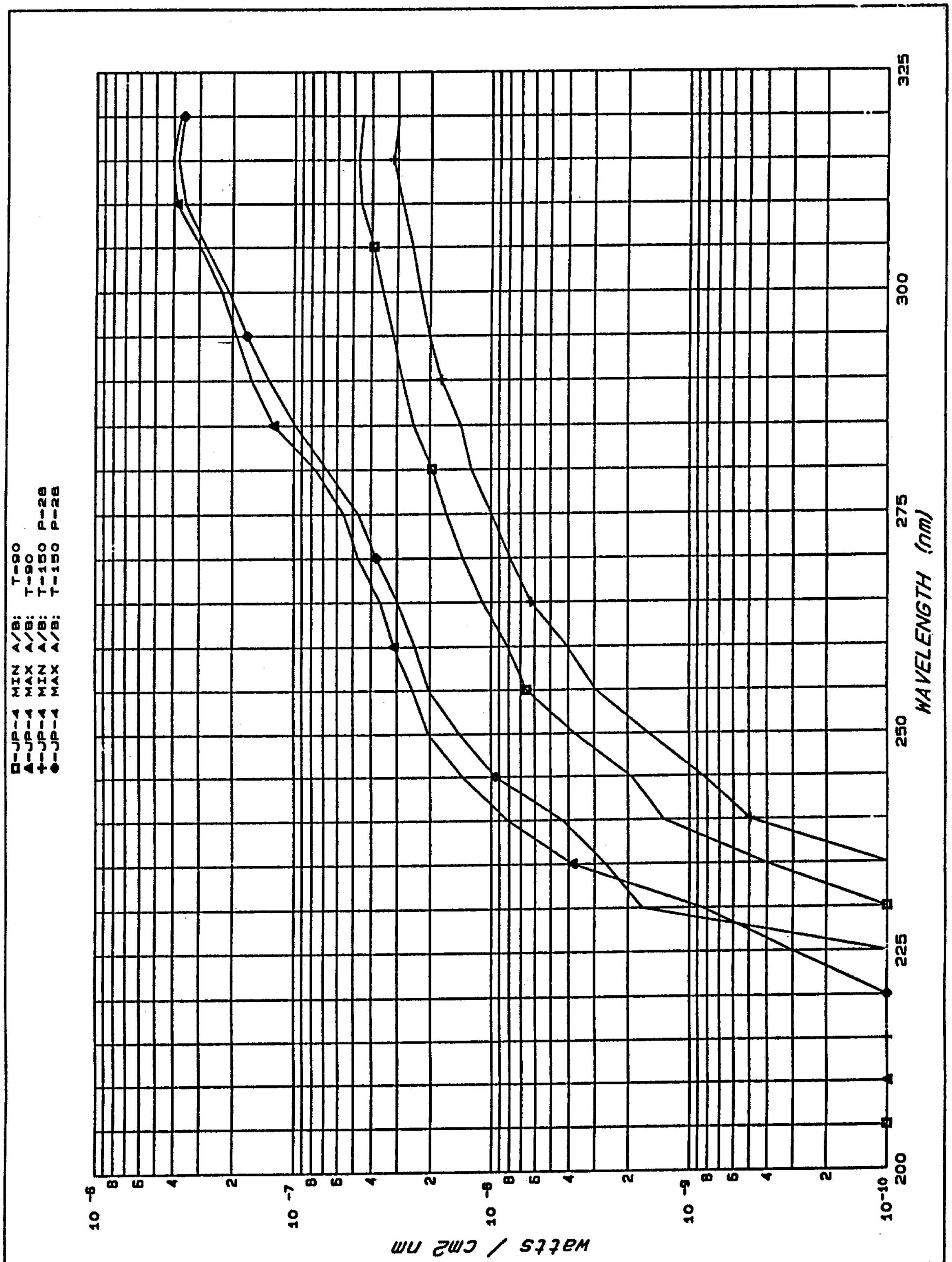

Figure 6. Spectral Flux per Unit Area Incident of Flame Sensor with JP-4 Fuel

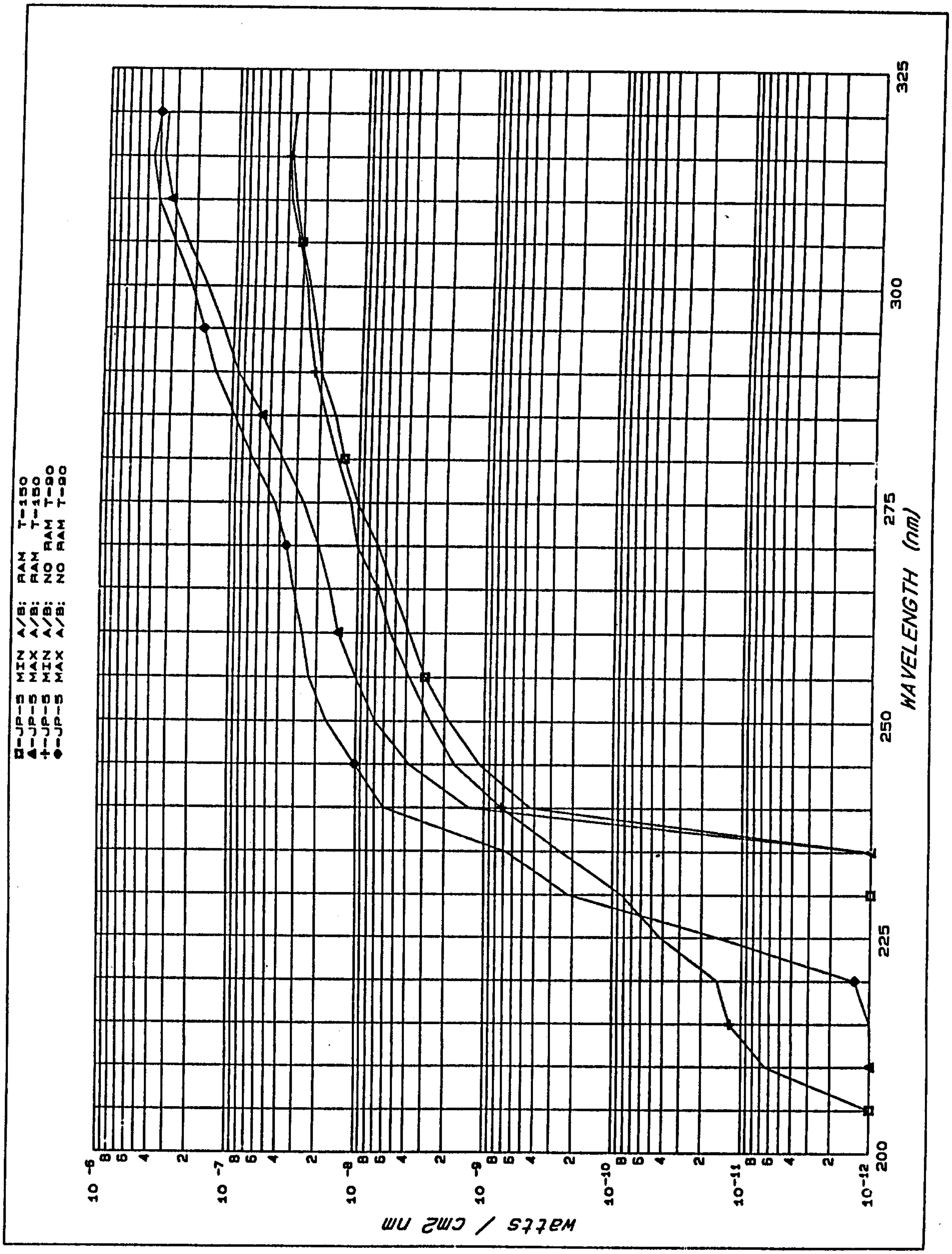

Figure 7. Spectral Flux per Unit Area Incident of Flame Sensor with JP-5 Fuel