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STUDY OF THE SURFACE EMISSIVITY OF TEXTILE
FABRICS AND MATERIALS IN THE 1 TO 15MU RANGE

Mark T. Mason, et al

Block Engineering, Incorporated
Cambridge, Massachusetts

March 1967

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TECHNICAL REPORT
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STUDY OF THE SURFACE EMISSIVITY OF TEXTILE FABRICS AND
MATERIALS IN THE 1 TO 15 μ RANGE

By

Mark Mason and I. Coleman

Block Engineering, Inc.
Cambridge, Massachusetts 02139

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Clothing and Organic Materials Division
U.S. Army Natick Laboratories
Natick, Massachusetts 01760

FOREWORD

Surface emissivity data of textile fabrics are important for many military end uses including studies of comfort, heat stress, heat load in shelters and undercoverings, studies in camouflage against detection systems using infrared radiation, and studies of thermal protective systems, among others.

This study was essentially exploratory in nature to provide general information relative to the properties of typical textile fabrics of varying fiber composition and also guidance as to possible methods of controlling emissivity.

The work covered in this report was performed under Contract DA19-129-AMC-523(N). It was conducted under the leadership of Mr. Myron Block, President of Block Engineering, Inc. The principal participating Block Engineering personnel were Messrs. M. Mason and I. Coleman. The study was initiated under Project 1M643303D547 by Mr. Frank J. Rizzo, who acted as Project Officer, assisted by Mr. A. O. Ramsley, both of the Clothing & Organic Materials Division.

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ABSTRACT

Laboratory measurements of the total and spectral infrared radiation emitted by textile materials, as applicable to the outer layer of a uniform, were made with an interferometer spectrometer. The effects of changes in the environmental parameters of the fabric, such as background temperature, fabric temperature, and humidity, were studied. For this report twelve different fabrics with a diversity of weaves and surface roughnesses were studied. The fifty-five spectra of these fabrics, which are published in this report, cover a wide range of fabric temperature, background temperature, and humidity.

It was found that the weave of the fabric acts as many small blackbody radiators and tends to mask any spectral detail that may be present. Further masking of detail is done by reflected background radiation. It was found that a fluctuation in background temperature, fabric temperature, or humidity caused a change in the spectral characteristics of the fabric.

Spectra of terrain features are presented and are compared to the spectra of the fabrics. It is shown that there is a spectral similarity between the fabric and terrain features because both are subject to spectral masking by background and sample characteristics. In the field, there is inter-reflection between the terrain features and the sample, sky radiance, atmospheric absorption, and reflection from background objects of the fabric, giving a spectrum that is not representative of the sample.

STUDY OF THE SURFACE EMISSIVITY
OF TEXTILE FABRICS AND MATERIALS IN THE 1 TO 15 μ RANGE

I. INTRODUCTION

Under the subject contract, Block Engineering, Inc. obtained measurements of the total and spectral infrared radiation emitted by textile materials as applicable to the outer layer of a uniform and related these measurements to comparable characteristics of the terrain. At the outset of this measurement program, little published information was available on the infrared spectra of fabrics, and it was not known whether sample composition or sample environment was the more relevant parameter affecting differences in observed sample spectra. The first group of measurements obtained on this program were spectra of twelve different dry fabric samples maintained at the 50° to 60°C range in a room environment of 20°C. Subsequently, sample measurements were made under various environmental conditions.

Five of these twelve fabrics were selected for further study of the effects that fabric environment has on the spectra. The effects of controlled variations in temperature, humidity, infrared background, and fabric insulation on the spectra of the five selected fabrics were measured. The major part of this report consists of a description of the apparatus and an interpretation of the data taken according to this plan.

The spectra submitted in this report (Appendix A) were obtained with a Block Model I-4T interferometer and a Block Coadder (coherent information adder). Spectral data were computer-processed, using two specially written programs that are included in Appendix B.

II. THEORETICAL CONSIDERATIONS

A. Infrared Radiation Theory

Atomic and molecular activity is found in every object whose temperature is above that of absolute zero Kelvin (-273.15°C). As a result of this atomic and molecular activity, electromagnetic radiation is emitted from these objects. The wavelength of this radiation extends from gamma

radiation (.003 μ) to beyond the wavelength used in radar (30 cm). The visible region of this electromagnetic spectrum is from about 4000 $\text{\AA}$ (violet light) to about 8000 $\text{\AA}$ (red light). From 8000 $\text{\AA}$ to past 100 microns (1,000,000 $\text{\AA}$) is the region of the electromagnetic spectrum known as the infrared. The region commonly called "near infrared" extends in wavelength from about 1 μ to 25 μ and is the region of interest in this discussion¹.

Certain bodies, known as "black" or "grey" bodies, emit a continuous band of radiation which has its maximum intensity at a particular wavelength depending on the temperature of the body; the lower the temperature, the longer the wavelength of this maximum. For example, a body at room temperature emits maximum intensity radiation at about 9.6 μ , and a source at 900°C has a maximum in the region of 2.4 μ . Fabrics and terrain normally emit as black or grey bodies since they have no discrete spectral emissions.

The ideal emitter and absorber of radiation is a body that absorbs all the radiation incident on it. This is called a blackbody radiator. If such a body were placed in a uniform temperature enclosure, it would come to equilibrium at the temperature of the enclosure and would therefore emit just as much radiation as it absorbs. The radiant power emitted between the wavelengths λ to $(\lambda + d\lambda)$ is given by Planck's distribution law:

$$E_{\lambda} d_{\lambda} = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\exp \frac{c_2}{\lambda T} - 1}$$

h = Planck's constant

c = Velocity of light

c_2 = hc/k when k is Boltzmann's constant.

The curves described by the blackbody equation for several different temperatures are shown in Figure 1. The integral of this equation would be the total emission of the blackbody at a given T ^{2,3}.

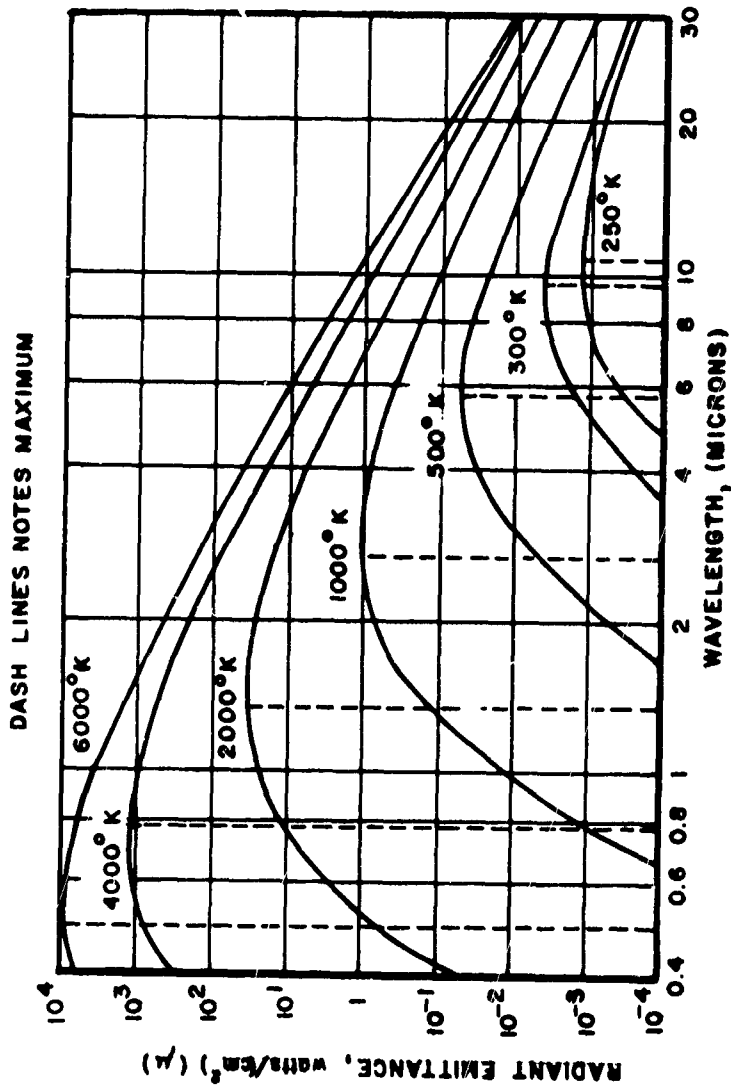


Figure 1: BLACKBODY SPECTRAL EMITTANCE AT VARIOUS TEMPERATURES.

Reference: Jamieson, John A., McFee, Raymond H., Plass, Gilbert N., Grube, Robert H., Richards, Robert G., Infrared Physics and Engineering, McGraw Hill, N.Y. 1963.

The emissivity of the ideal blackbody radiator is taken as 1 at all wavelengths. Then all bodies whose emissivity is less than that of a blackbody would have an emissivity of something less than 1. Such a body is called a grey body. The value for the emissivity of various materials is given below:²

TABLE I

EMISSION OF VARIOUS MATERIALS

<u>Material</u>	<u>Emissivity</u>
Paper	.94
Cotton Cloth	.77
Wool Cloth	.78
Nylon	.85
Sand	.95
Wood	.90 - .92
Bricks	.93

With a properly calibrated spectrometer, it is possible to determine the total emission from an infrared source with emissivity less than 1. In this report, the total emission of various fabrics will be studied with respect to the spectral distribution of radiation for each type of fabric. The measurements made, show that a fabric emits nearly as a blackbody. The small cavities due to the weave of the fabric act as good blackbody radiators, thus explaining why the spectrum of the fabric is very similar to Planck's curve for a blackbody at the same temperature.

B. Theory of Operation and Calibration of Instrument

As the operation of the Block Interferometer Spectrometer is unique when compared to other spectrometers, a discussion of the theory of operation and circuitry of the Block Model I-4T will be given before the calibration procedure so that the calibration and experimentation may be more fully understood.

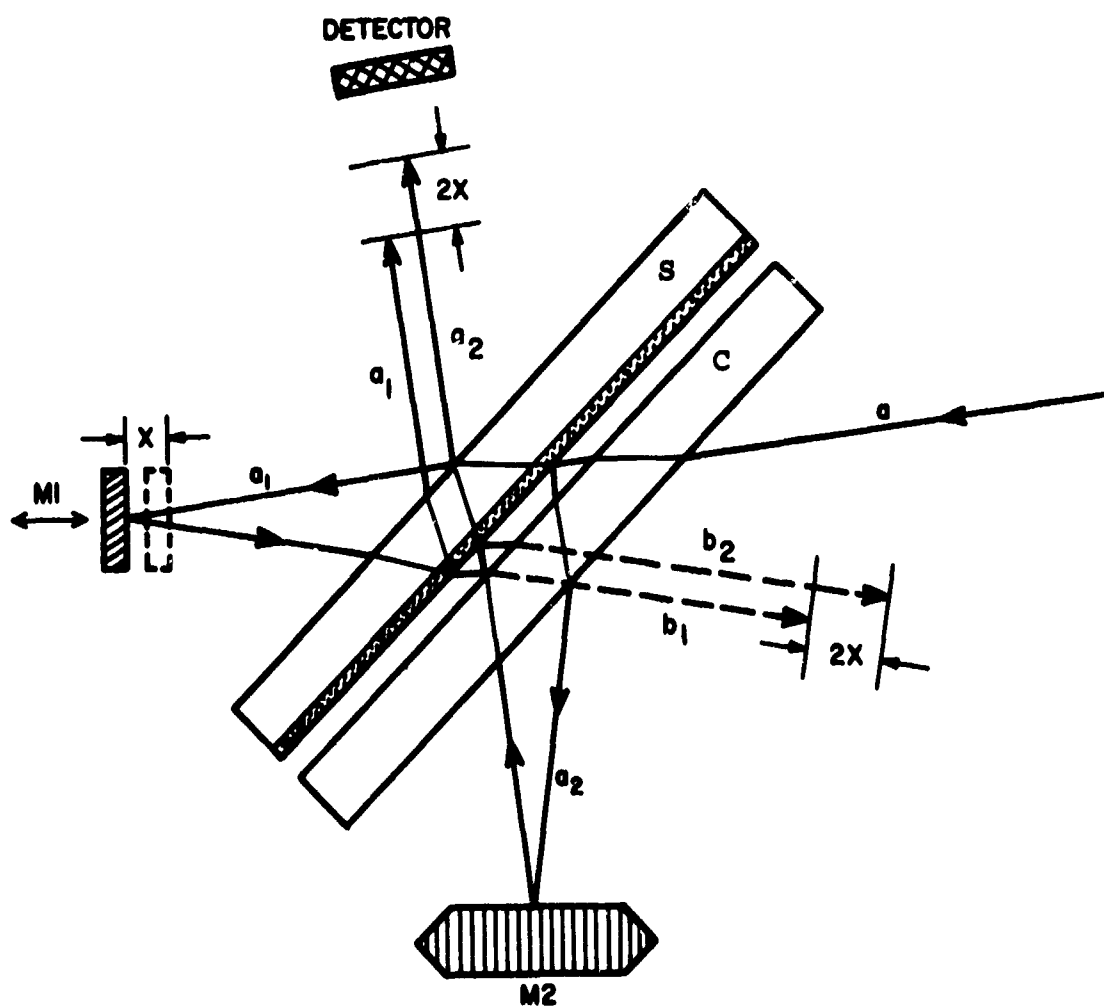
1. Optics: An optical diagram of a Michelson interferometer is given in Figure 2. There are two mirrors, M1 and M2; a beamsplitter plate, S; and a compensator plate, C. Plates S and C are made to the same thickness and of identical material. On its inner surface the beamsplitter plate carries a semi-reflecting coat, shown dotted in the diagram. The planes of the two mirrors and the semi-reflecting coat intersect in one line when the moving element of the transducer is crossing its zero position, i.e., when M1 is at $x = 0$.

Consider a beam such as a entering the interferometer. The ray is divided into two beams, a_1 and a_2 , at the semi-reflecting coat. If beams a_1 and a_2 return to the beamsplitter in phase, they will constructively interfere. That is, their amplitudes will add vectorially, and 50% of the energy (neglecting losses except for the 50% transmission at the beamsplitter) of beam a will appear as beam b_1 . However, if there is a phase difference between the two, caused by unequal paths, there will be partial destructive interference. This interference manifests itself in two ways: (1) it is seen by the detector as a decrease in signal level; and (2) it can be seen in the corresponding increase in amplitude of b_2 , since $b_1 + b_2$ are 180° out of phase with $a_1 + a_2$.

Now the phase of a_1 with respect to that of a_2 can be changed by moving mirror M1. In the interferometer, the mirror corresponding to M1 is attached to a linear actuator. The relationship of the position of M1 to the intensity of $a_1 + a_2$ can be stated as:

$$I = I_0 A (1 + \cos 2\pi vx) \quad (1)$$

where I is the intensity of $a_1 + a_2$, I_0 is the intensity of a, x is the mirror excursion, v is the wave number, and A is the modulation efficiency, a number always less than 0.5. The excursion of M1 is always measured from zero-retardation, the position at which the paths taken by rays a_1 and a_2 are equal. Note that for an excursion of x , the retardation or difference in path lengths of a_1 and a_2 is $2x$. Also note that so long as these rays remain parallel, the wave fronts



**Figure 2: Optical Diagram of a Michelson Interferometer
(Displacement X of M1 Producing Retardation $2X$)**

remain parallel and will interfere, even though they are laterally separated.

In the interferometer, mirror M1 is moved by a transducer (linear actuator) responding to a voltage supplied as a sawtooth wave, so that the mirror travels at constant velocity for most of the scan cycle. This velocity can be defined in terms of a peak-to-peak retardation B, mirror M1 moving from $-B/4$ to $+B/4$ during the constant velocity period, T_B . Thus, we have

$$x(t) = B(t)/2 \quad (2)$$

where x is the instantaneous displacement of mirror M1.

Substituting Equation (2) into Equation (1), the intensity transmitted by the interferometer is given by:

$$I = I_0 A [1 + \cos 2\pi \nu B(t)]. \quad (3)$$

Thus, it is seen that the transmission is periodic and has a frequency ν , which depends upon the wave number of the incident radiation:

$$f_\nu = \nu B/T_B. \quad (4)$$

Equation (4) is derived by considering the number of waves of incident radiation, νB , contained within the retardation distance B. Therefore, the frequency which results when a retardation interval B, scanned at a time T, is $\nu B/T$. This fundamental relationship shows that the output frequencies of the interferometer spectrometer are related one-to-one to the wave number of the input radiation and that B and T_B can be varied to adjust the output frequency and resolution.

2. Electronics: Infrared radiation incident on the Bolometer detector causes a change in the resistance of the active element, or flake, in direct proportion to the intensity of the energy. The detector is biased with a high frequency voltage to

provide a signal suitable for amplification. A low noise preamplifier amplifies the detector signal and provides the low output impedance needed for minimum pick-up in the long inter-connection cable between the optical head and data reduction unit. See Figure 3 for a flow diagram of the circuitry.

The preamplifier is followed by a constant impedance stepped attenuator consisting of a compensated resistance divider. The five attenuation steps, selected by a front panel control, are unity, $1/3$, $1/10$, $1/30$, and $1/100$ of the signal level.

The 3-stage post amplifier has a gain of approximately 400. A feedback loop provides added high frequency stability to the system. The amplifier is designed to render an undistorted signal output of approximately 14 volts peak-to-peak into a load exceeding 100K ohms; maximum output is 20 volts peak-to-peak. Lower impedances are permissible but some dynamic range is sacrificed.

Figure 4 illustrates the mirror drive circuitry. The sweep generator and transducer drive are coupled at the SWEEP LENGTH control on the front panel so, as the sweep length is reduced, the sweep time is also reduced. The sweep time control uses an operational amplifier and a monostable multivibrator. The ramp rise time of the sawtooth waveform is determined by increasing or decreasing the charging rate of a resistance-capacitance network in the feedback loop of the operation amplifier. The linear drive for the mirror transducer is obtained from a low impedance output amplifier. Sweep length, or the physical movement of the mirror, is controlled by varying the transducer drive voltage.

The output from the post-amplifier shown in Figure 2 is modified by a variable bandpass filter. The filter has a roll-off of 12 db per octave on both the high and low side. It is used to reduce the spurious noise entering the analog-to-digital converter.

The Coadder repeatedly samples the filtered output of the interferometer electronics (interferogram) at a rate which is more than twice the maximum frequency present in the signal of interest. The samples are sequentially digitized and stored in the core memory. Each series of samples

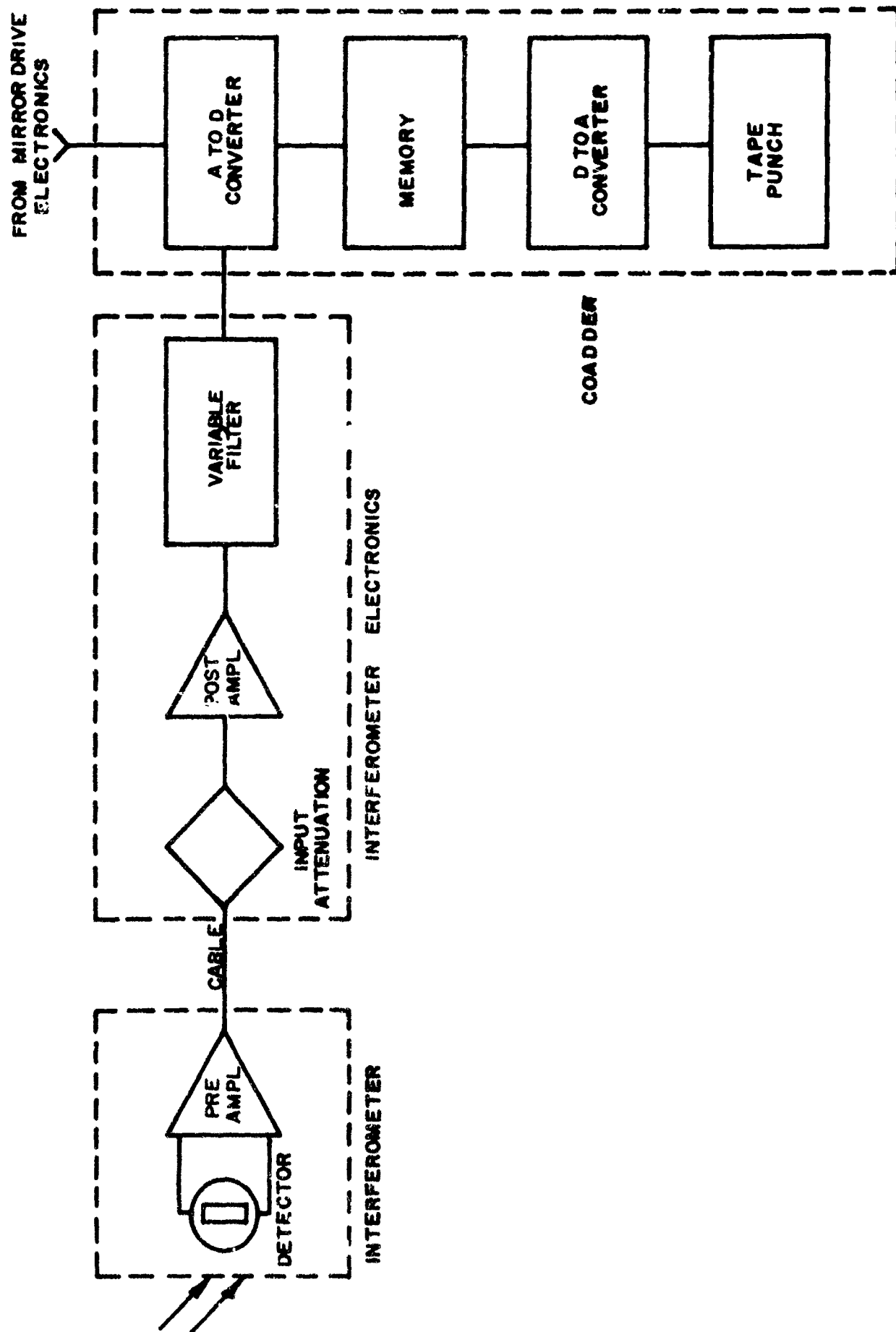


Figure 3: SIGNAL PROCESSING AND DATA REDUCTION ELECTRONICS

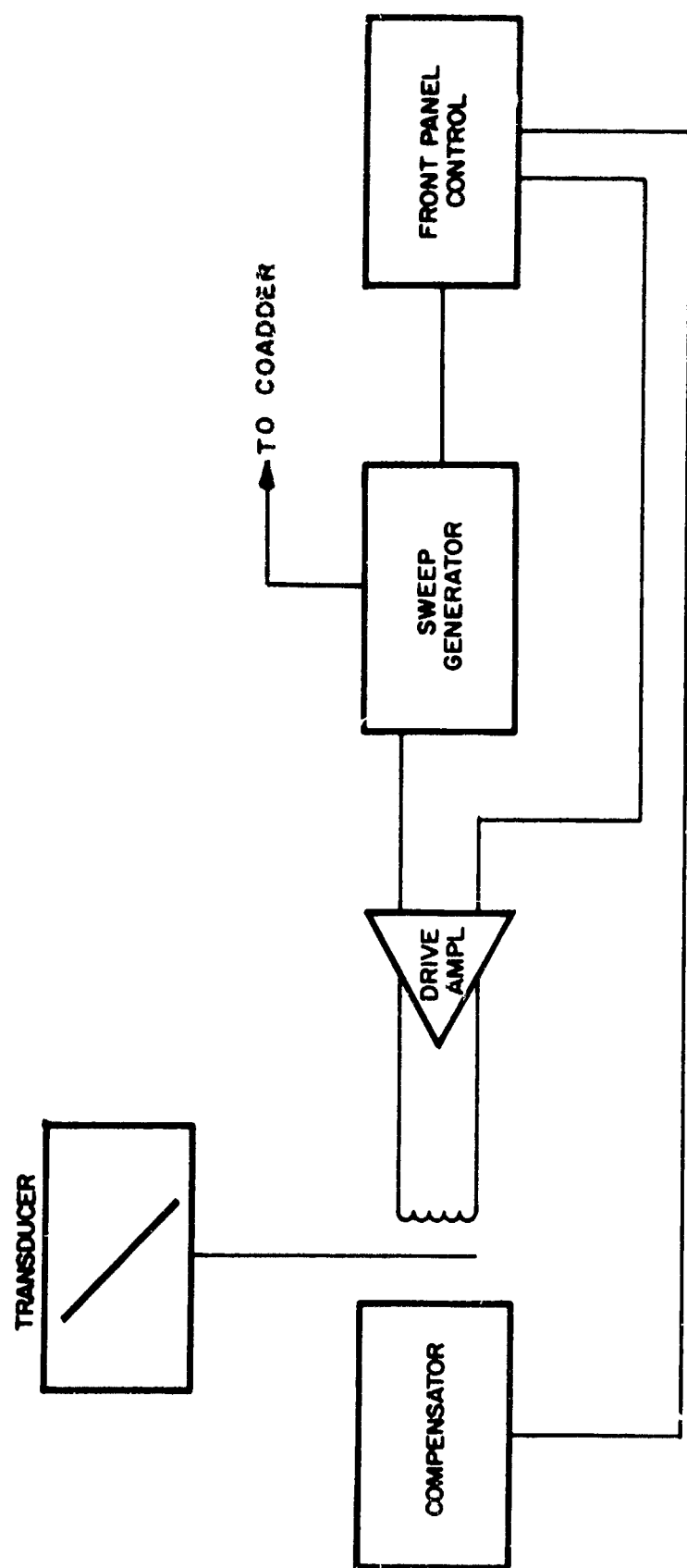


Figure 4: MIRROR DRIVE ELECTRONICS

is initiated by a triggering pulse supplied by the interferogram. Therefore, the samples from successive interferograms correspond precisely in time. Their levels are digitally added in the memory; the coherent signal increases linearly in amplitude with the number of interferograms accumulated.

The noise present as the input accumulates, due to its random character, in such a way that the noise power increases linearly with the number of scans. Its root-mean-square (rms) value therefore increases only by the square root of the number of scans. The resultant gain in the coherent signal relative to the noise is thus, $\sqrt{n}$ where n is the number of times the same signal is sampled. For example, if the Co-adder accumulates as few as 16 interferograms, the signal-to-noise ratio will be increased by a factor of four.

The Coadder memory contains 1024 words; a maximum of 1024 sample points may be taken. Each sample is digitized by an 8-bit A-to-D converter that accepts a maximum signal of 9 volts peak-to-peak. Since the capacity of each word in the memory is 16 bits, it is possible to coadd up to 256 interferograms with 9-volt peak-to-peak components. Smaller amplitude interferograms, of course, may be coadded many more times.

C. Calibration

Prior to measurements of fabric emission, three different calibrations were performed on the interferometer. First, the wavelength scale of the instrument was determined. Second, the instrument's effective field-of-view was determined. Third, the spectral responsivity of the instrument was determined over the wavelength region to be used.

1. Wavelength Calibration: The interferometer spectrometer heterodynes the very high electromagnetic frequencies present in the incident radiation down to audio frequencies. If a beam of light of a single frequency, ν , is split and sent over different optical paths and then recombined, the light will constructively or destructively interfere, depending on the difference in path lengths. If this interference is incident on a detector, then the ensuing signal will be a sine function of frequency m , which is directly proportional to the frequency of incident radiation, ν .

The ratio M/ν equals a constant, K , for every point throughout the spectrum. For this calibration, the instrument viewed a known temperature blackbody source, with a 1-mil-thick sheet of polystyrene between the source and the entrance aperture. The resulting spectrum is that of a blackbody with the polystyrene absorption lines present, as shown in Figure 5.

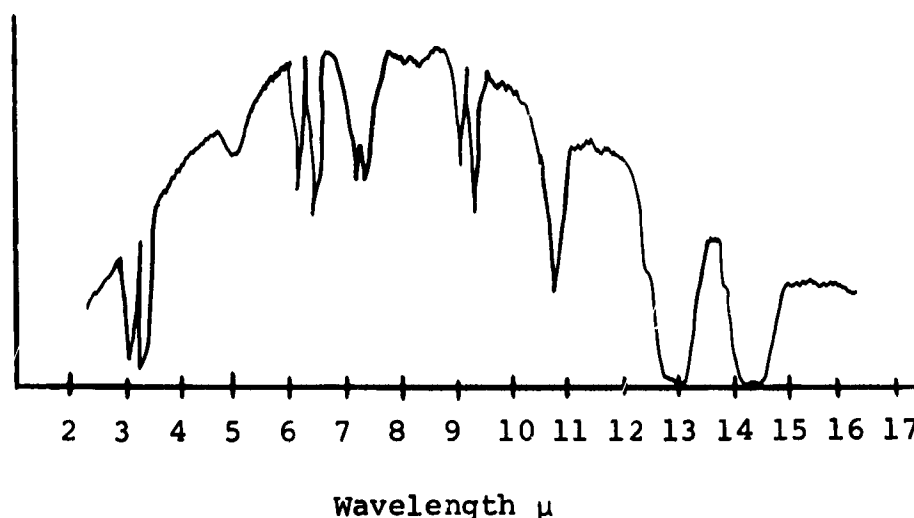


Figure 5: Absorption Spectrum 1 mil. Thick Polystyrene

The absorption lines of polystyrene are well identified,⁵ i.e., their exact wavelengths are known and from them the calculation of M/ν can be carried out. The value K determined by this method is accurate to $\pm 5 \text{ cm}^{-1}$, while the instrument has a resolution of 60 cm^{-1} .

The pertinent equation relating audio frequency to wavelength is

$$f = B/T\lambda.$$

f = audio frequency in cps.

B = optical retardation in microns.

T = sweep time in seconds.

λ = wavelength in microns.

The equation can be written as

$$f\lambda = \frac{B}{T}.$$

Since B and T are constant for any given series of measurements, $f\lambda$ must also be constant.

a. Field of View: The effective field of view of the instrument was determined by having the instrument view a chopped collimated source. The optical head was placed on a vernier rotary table capable of controlled movement along both horizontal and vertical axes. The chopped source was viewed and the output recorded for every degree from zero output on one side of the field to zero output on the other side. This was done for both the horizontal and vertical axes, and then plotted as output versus position. The points where the roll-off on either side of center position is reduced by 6 db are marked and the area between is considered to be the effective field-of-view, since the 6 db points are considered to be the half-power points in a uniformly varying field of view, and to describe the effective response of the instrument.

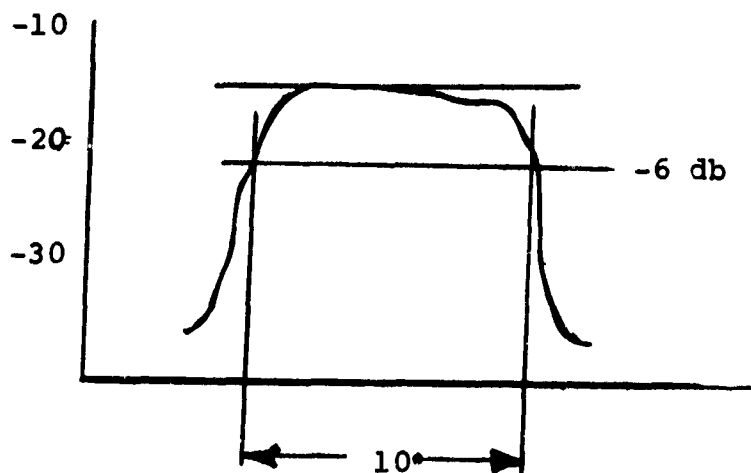


Figure 6: Horizontal Scan Field of View

3. Instrument Responsivity: The responsivity of the interferometer was obtained by focussing it on a blackbody cone and measuring the spectra of the blackbody at a large number of temperatures, both higher and lower than the temperature of the detector. The temperature of the blackbody cone was monitored by thermocouples located on its aluminum surface. Figure 7 portrays the arrangement used. The spectral responsivity of the system is calculated from the formula

$$R_e = \frac{V_\lambda}{Ns_\lambda = Nd_\lambda}$$

where:

V_λ = measured voltage at wavelength λ

Ns_λ = blackbody radiance at wavelength λ

Nd_λ = detector radiance at wavelength λ

The final R_e is determined by a least mean square fit using values determined for the different source temperatures. The spectral responsivity curve for the spectrometer is shown in Figure 8.

The computed responsivity of the instrument as a function of wavelength was used as one of the inputs to computer Program B, which corrected the spectra to read out in absolute radiance versus wavelength. The spectrum for each fabric sample is the absolute power spectrum of that sample for the environmental conditions under which the measurements were made.

III. EXPERIMENTAL PREPARATIONS AND PROCEDURES

A. Experimental Procedure

The experimental arrangement used for spectral measurements of the fabric samples is illustrated schematically in Figure 9. The equipment used consisted of the following:

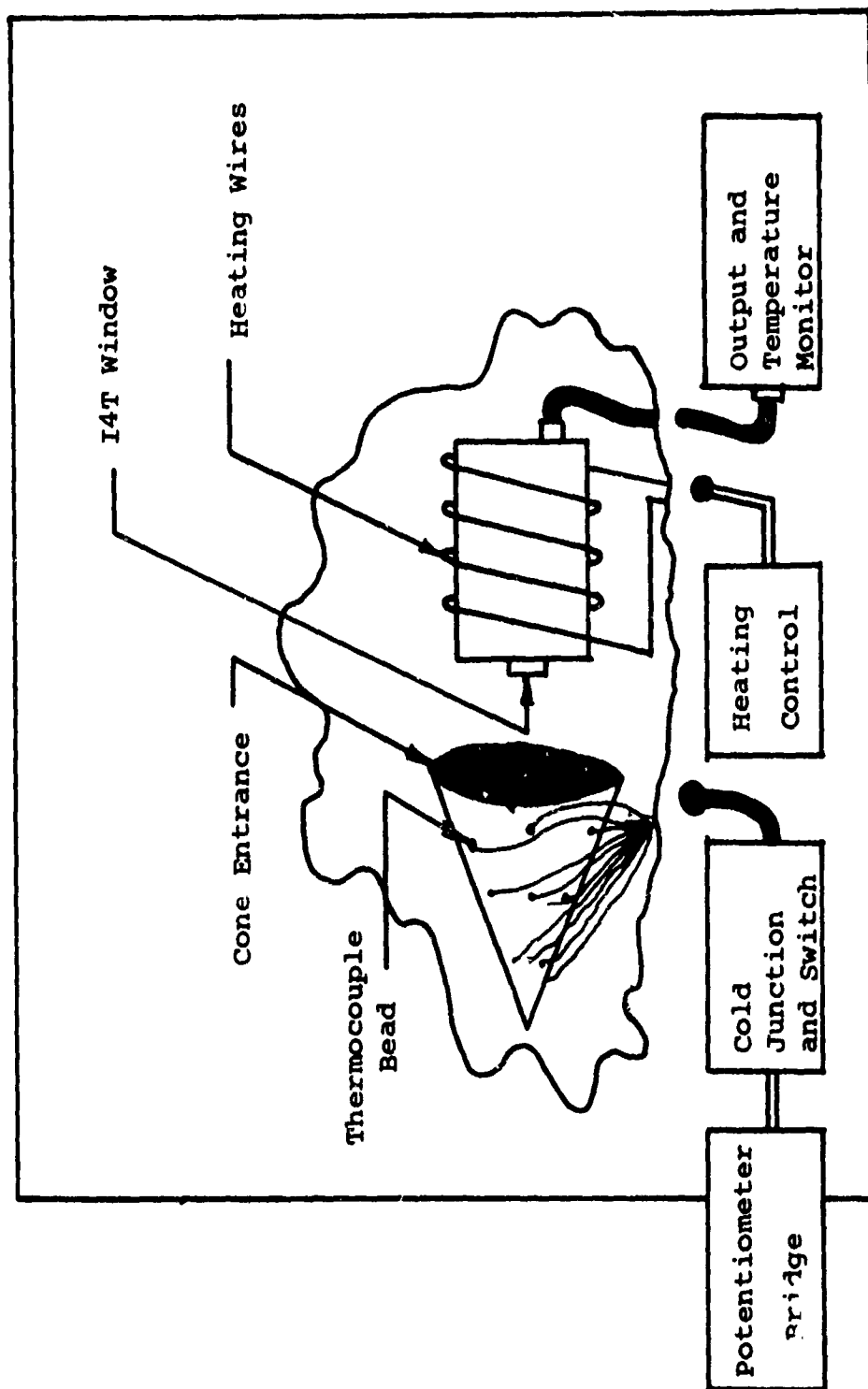


Figure 7: Setup for Response Measurements

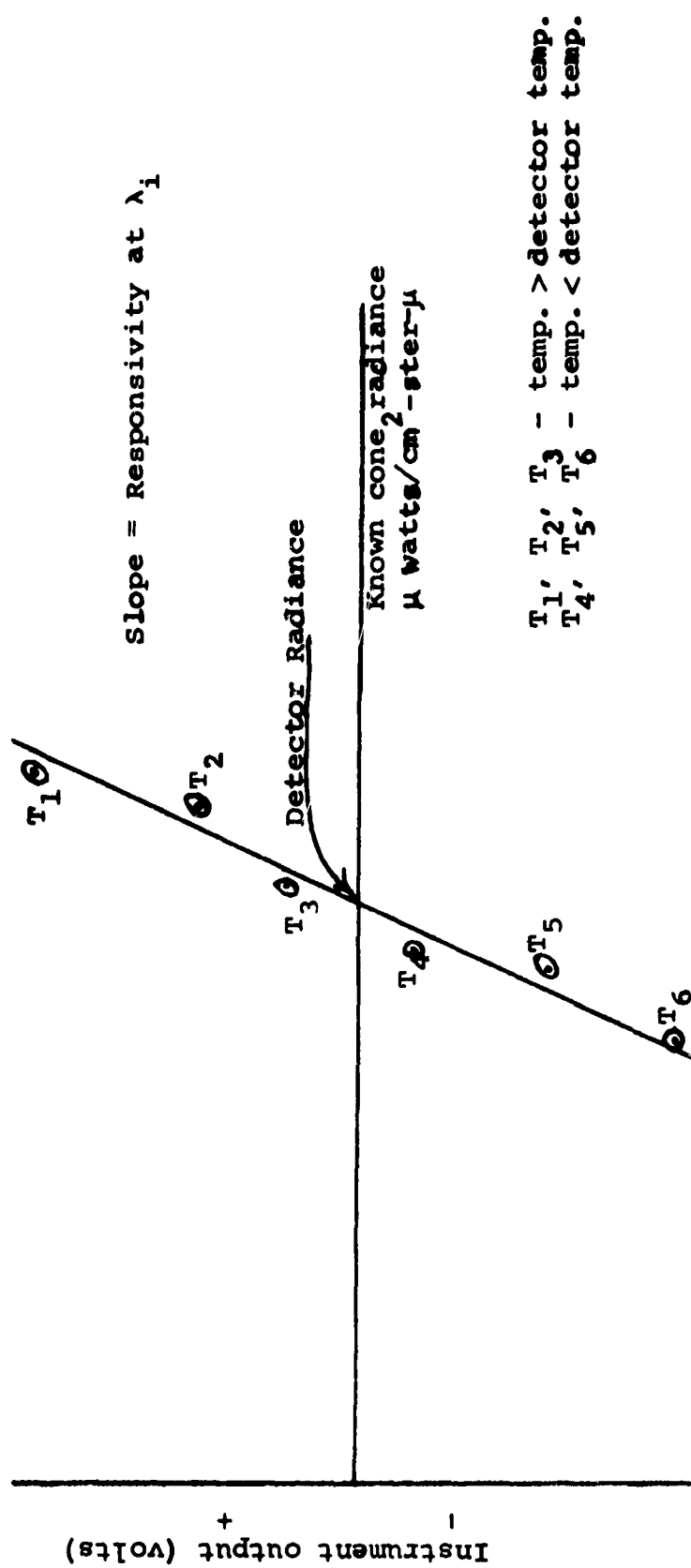


Figure 3: Responsivity Calibration

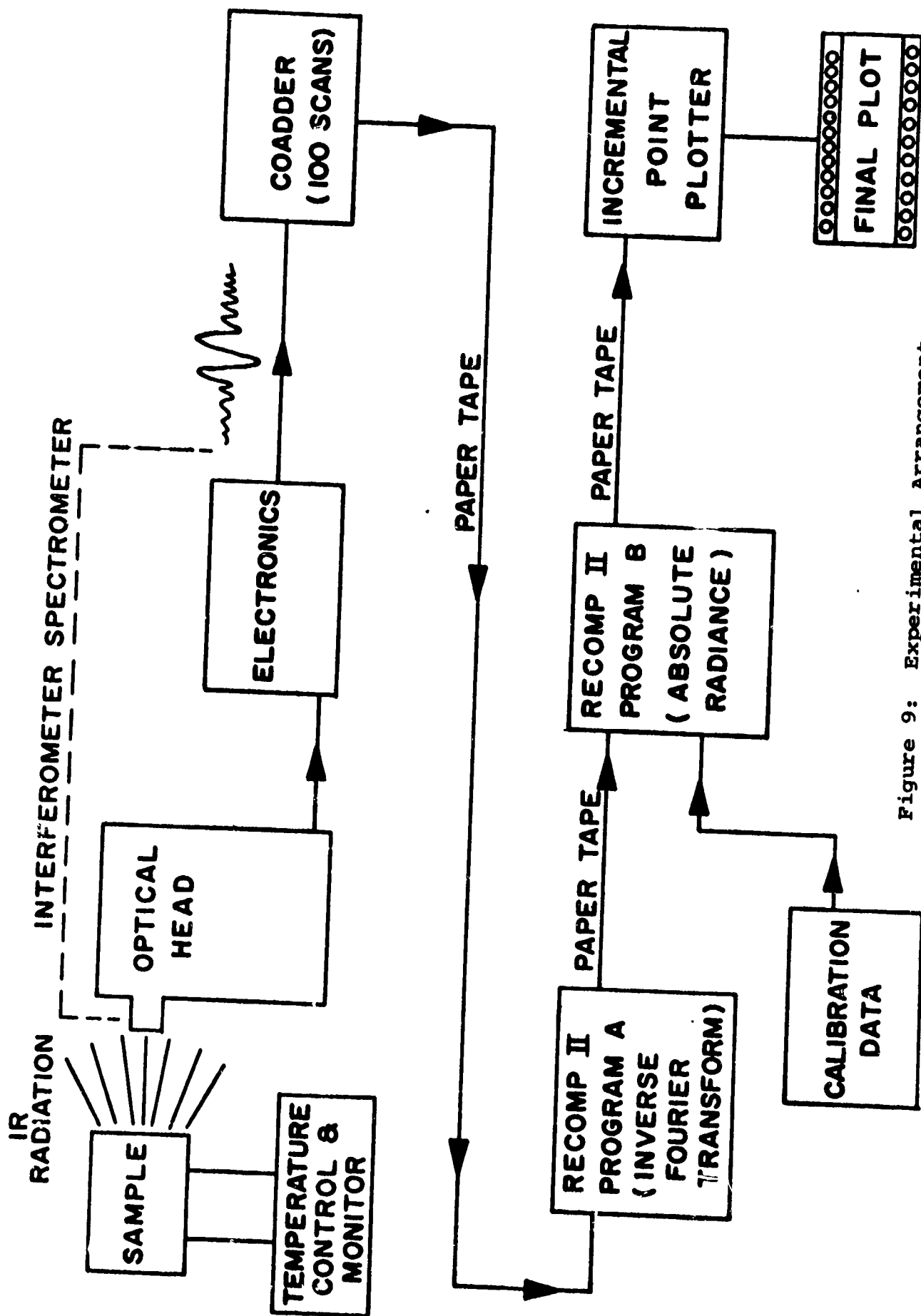


Figure 9: Experimental Arrangement

1. Cold Box
2. Hotplate with fabric sample attached
3. Temperature monitoring and controlling unit
4. Interferometer spectrometer
 - a. Optical head
 - b. Electronics console
5. Time averaging computer unit (Coadder)
6. Digital paper-tape punch unit

The first set of measurements made revealed that observations of samples in a room environment at ambient temperatures obscured any change in emission, thereby blurring any spectral detail in the reduced data. To reduce the effects of a fluctuating background and spurious emission, a "cold box" was constructed. The box consisted of a large thermal mass of copper, a reservoir for dry ice or other coolant, a hotplate for heating samples, a window for the instrument, and temperature-monitoring thermistor beads. Figure 10 shows the construction of the cold box.

If the cold box is used at room temperature, the large thermal mass prevents any fluctuation in temperature. If the box is used with dry ice, then the temperature of the background is lowered to a level that makes background emission negligible. The box is constructed in such a manner as to allow the sample to be heated while the background is at -70°C .

B. Data Processing

For each sample, enough scans were coadded to give an 8-volt peak-to-peak interferogram (see Theory of Operation). The resulting enhanced interferograms were punched on paper tape for computer processing.

Two computer programs were used for the processing of the data. (The processing is schematically diagramed in

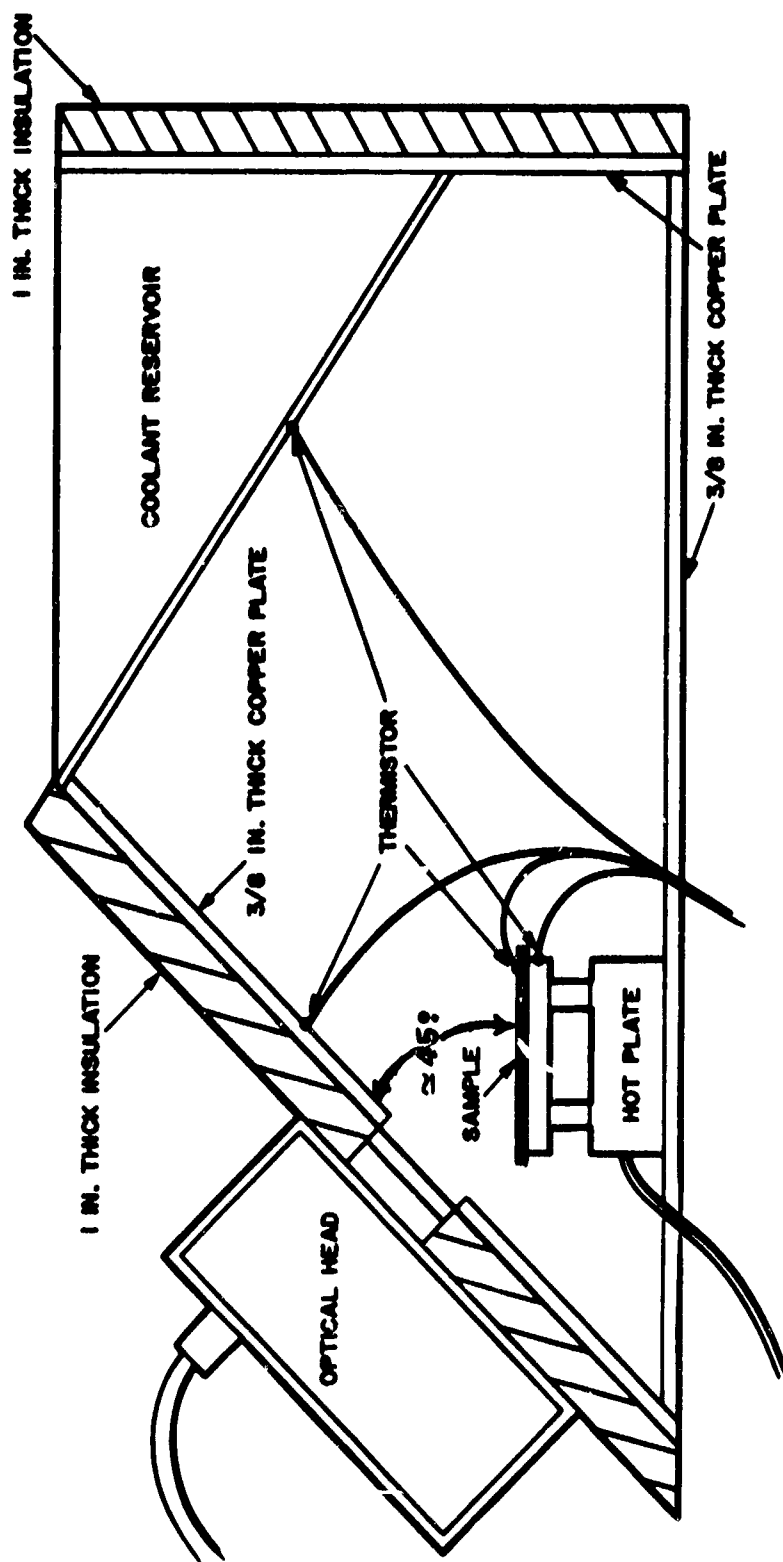


Figure 10: COLD BOX CONSTRUCTION

Figure 3.) The interferogram on paper tape was first processed by Program A, which computed the inverse Fourier transform of the interferogram. The inverse Fourier transform is, in fact, the spectrum of the source uncorrected for the instrument's response function. The output of Program A is also a paper tape.

The output of Program A was processed by Program B, which has an additional input of calibration constants. Program B computes the absolute radiance spectrum of the source corrected for the instrument function and has an output of a paper tape which is used as an input to the incremental point plotter.

An incremental point plotter having an accuracy of 0.01 inch was used to plot the power spectrum of each source on a linear-linear plot. This plot, together with the enclosed blackbody overlay, defines the emissions of the materials in the sense of the fabrics' efficiencies as heat radiators; both also define any identifying spectral structure which may be present due to the composition of the material.

Two basic computer programs were used to process the test data. (See Appendix B for complete programs). Program A converts the interferograms into the raw spectra by taking the inverse Fourier transform of the interferograms. Program B corrects the raw spectra for the instrument function yielding absolute power spectra.

Program A computes a spectrum from an interferogram by taking the real part of the Fourier integral of the interferogram signal as a function of time. That is:

$$A(m) = \text{Real Part} \int_{-\tau}^{\tau} I(t) e^{-2\pi i m t} dt$$

$A(m)$ = intensity of source as a function of audio frequency, m

τ = one-half the sweep time

$I(t)$ = the interferogram signal as a function of time

m = audio frequency ($m = Kv$ where v = wave number of incident radiation)

The spectrum produced by Program A is uncorrected for the instrument function and is linear in audio frequency, m , hence, it is also linear in wave number.

Program B uses as inputs the uncorrected spectra computed by Program A (punched on paper tape), and the previously determined calibration information for the instrument.

The responsivity of the instrument as a function of audio frequency, m , is defined:

$$Re_m = \frac{A(m)}{|N_s - N_d|_m}$$

N_s = radiance of the blackbody source

N_d = radiance of the detector

$A(m)$ = the response of the instrument

N_s and N_d were computed by measuring the temperatures of the source and detector, and $A(m)$ was directly measured. From these values, the responsivity, Re , as a function of m was determined.

For the first group of sample spectra, the detector is cooler than the source and its temperature is recorded. Hence, the absolute radiance is calculated by Program B, using the following relationship:

$$(N_s)_m = \frac{A(m)}{Re_m} + (N_d)_m$$

Program B also converts the audio frequency to its corresponding wavelength, λ , in microns by the relationship

$$\lambda = \frac{K}{m} .$$

The output of Program B is a punched paper tape which contains the radiance of the source as a function of wavelength. The plot has a linear-vertical scale in micro-watt/cm²-ster- μ versus a linear-horizontal scale in microns.

IV. RESULTS

A. Experimental Results

The first group (Group I) of emission measurements was obtained from fabric samples maintained at temperatures in the 50°C to 60°C range. Table II lists the fabrics which were tested in a 20°C dry room environment, without use of the "cold box" and shows the sample temperature during measurement.

TABLE II
FABRIC TYPES

<u>Spectrum</u>	<u>Fabric</u>	<u>Temperature (°C)</u>
1	Cotton Towel, reactive dye	51
2	Cotton towel, reactive dye	51
3	Cotton towel, reactive dye	51
4	Cotton towel, reactive dye	52
5	Wool/nylon shirting, 16 oz; 0154-58	58
6	Wool/nylon shirting, 16 oz; 0154-58	58
7	Wool/nylon shirting, 16 oz; 0154-58	58
8	Wool/nylon shirting, 16 oz; 0154-58	60

Table II - Fabric Types Continued

<u>Spectrum</u>	<u>Fabric</u>	<u>Temperature (°C)</u>
9	Fiber 6-sateen, 8.5 oz., OG-106, 37 VEE-1545A	59
10	Fiber 6-sateen, 8.5 oz., OG-106, 37 VEE-1545A	58
11	Fiber 6-sateen, 8.5 oz., OG-106, 37 VEE-1545A	60
12	Wool flannel, OG-108, vat dyed	57
13	Wool flannel, OG-108, vat dyed	58
14	Wool flannel, OG-108, vat dyed	56
15	Nylon oxford acid dyes	60
16	Nylon oxford acid dyes	59
17	Nylon ballistic cloth, OG-106 (std)	57
18	Nylon ballistic cloth, OG-106 (std)	57
19	Nomex twill, VEE-166-2A	56
20	Nomex twill, VEE-166-2A	58
21	Wool serge, 18 oz. 85-0717	58
22	Wool serge, 18 oz. 85-0717	55
23	Wool serge, 18 oz. 85-0717	57
24	Cotton sateen, 9 oz., RBP topped, OG-107 w/Permell	59
25	Cotton sateen, 9 oz., RBP topped, OG-107 w/Permell	56
26	Nylon oxford, acid metallized	59
27	Nylon oxford, acid metallized	60
28	Nomex, 5419, 8.9 oz. duck, coated on 1 side	58
29	Nomex, corduroy, aluminized	56

From these fabrics, the following four were selected for study in the second part of the program:

1. Nylon, oxford, acid metallized
2. Nomex, twill Vee-166-2A
3. Wool serge, 18 oz. 85-0717
4. Fiber 6-sateen, 8.5 oz. OG-106, 37 Vee-1545A

In addition, cotton poplin, 4 oz. OG107, vat was added at the suggestion of the Project Officer. These fabrics were placed in the "cold box" and the effects of variation of the following parameters on the spectra were measured.

A. Temperature

1. 20°C
2. -40°C
3. 60°C

B. Humidity

1. Low humidity
2. High humidity

C. Infrared Background

D. Insulation-Effect on Spectrum

The reduced spectra for these samples are presented as groups II through VII. The following is an outline of the procedure for recording each group.

GROUP II - Cloth Surface and Ambient 20°C - The "cold box" was used with the interior slightly below room temperature (20°C). Each of the material samples was placed in the box, allowed to reach equilibrium with the interior of the box, and then the spectrum was recorded.

GROUP III - Cloth Surface and Ambient -44°C - The cold box coolant reservoir was filled with dry ice and the temperature was allowed to reach equilibrium. The temperature of the walls of the box, the sample holder, and the sample was -44°C. The spectra show that there was very little total emission from the sample at this temperature.

GROUP IV - Cloth Surface 20°C Ambient (background) -44°C - With the walls still at -44°C, the temperature of the sample and sample holder was raised to 20°C. There was negligible emission from the background at this temperature, and any spectral detail would be real.

GROUP V - Cloth Surface 60°C Ambient -40°C - The temperature of each material sample was allowed to reach +60°C and its spectrum was recorded.

GROUP VI - Cloth Surface 60°C Ambient 13°C - Variation of Humidity - The floor of the "cold box" was lined with damp absorbent material. Using a humidity gauge that was placed in the chamber, the humidity was recorded and the spectral information was gathered at several different relative humidities.

GROUP VII - Hotplate 65°C Ambient -40°C - Fabric Insulated - The hotplate was heated to 65°C. Five-eighths of an inch of foam insulation was placed between the cloth surface and the hotplate. Each material was left in this condition for 25 minutes before the spectrum was recorded.

By using the enclosed blackbody overlay with the resultant spectra, the emission spectrum of each fabric can be compared to the emission spectrum of the blackbody at the sample temperature, thus indicating the fabric emissivity.

B. Sources of Error

The radiation reaching the detector of the instrument from the source is actually the superposition of radiated and reflected radiation from many sources. Figure 11 shows the phenomena quite graphically: radiation is emitted from the source; scattered and absorbed by the atmosphere; mixed with radiation emitted and reflected from background objects; modified by the transmission characteristics of the windows, lenses, beamsplitters in the instrument; further mixed with emitted radiation from the inner surfaces of the instrument; and finally, altered by the instrument and the interpretation of the reduced data⁶. In the case of the measurements made for this report, all the sources of error due to the instrumentation were corrected by a computer program. Therefore, only the background characteristics are of concern. There

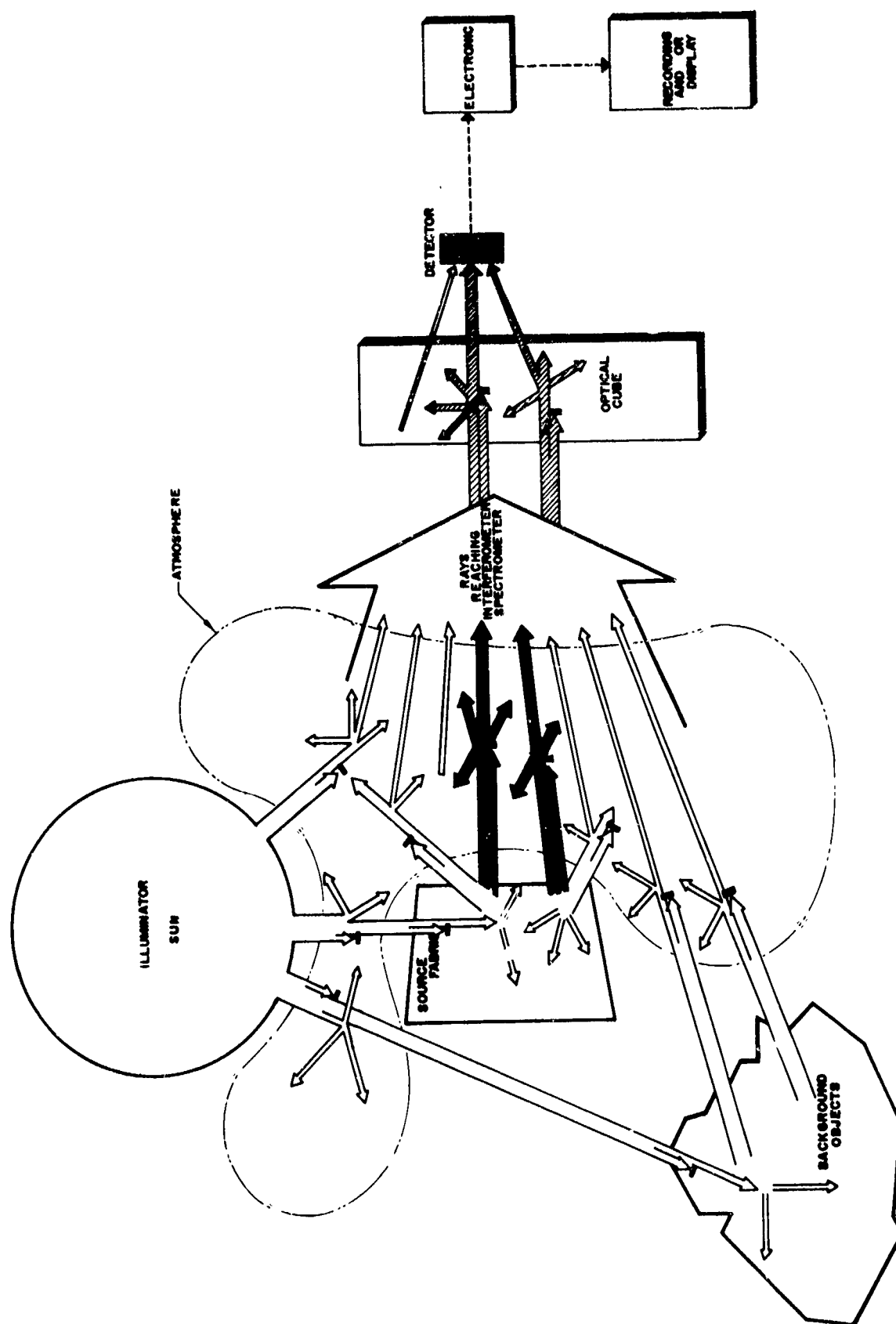


Figure 11: THE EFFECTS OF BACKGROUND AND ATMOSPHERE ON RADIOMETRIC MEASUREMENTS

are two means of working with background interference: one is to eliminate it as much as possible, and the other is to understand it and let it be a factor in interpreting the data. Both of these methods are used in this report.

For example, if the background is cooled so that it radiates considerably less than the source of interest, then the radiation and reflection due to the background is lessened, making more accurate measurements possible. Figure 12 illustrates this effect more fully. In the description of the experimental procedure, the construction of a "cold box" is detailed. This box is used for the reduction of background radiation. Much of the data used in this report were taken inside the chamber.

For analysis of the data, it was important for the temperature of the source, fabric, background, and instrument to be known exactly, for an error of a few degrees in source or instrument temperature can significantly change the total emission characteristics of the reduced spectrum. This error occurs when the parameters of the experiment are put into the computer.

C. Terrain Features

Terrain features are defined as all objects other than the source of interest that contribute to the radiant flux reaching the instrument. This includes earth, grass, trees, water, sky, clouds, and atmosphere. The spectra of certain terrain features were taken by Block Engineering independently of this study. These terrain features were sand and dirt, trees, a river, and a brick building.

Sand and dirt have a high emissivity and, due to their granular nature, act as good blackbody radiators. A fabric sample at the same temperature as sand and dirt would have about the same spectral characteristics, and the total emissivity from each would be equal. The spectrum of a group of trees shows structure at 10.8μ and 11.5μ . Aside from this, there is nothing to differentiate the spectrum of trees from the spectrum of a fabric sample. The spectrum taken of a river shows mostly radiation reflecting from other sources, and could be called a continuum. The spectrum of a building shows structure at 6μ , 7μ , and 12μ . This spectrum is also a composite of reflected and emitted

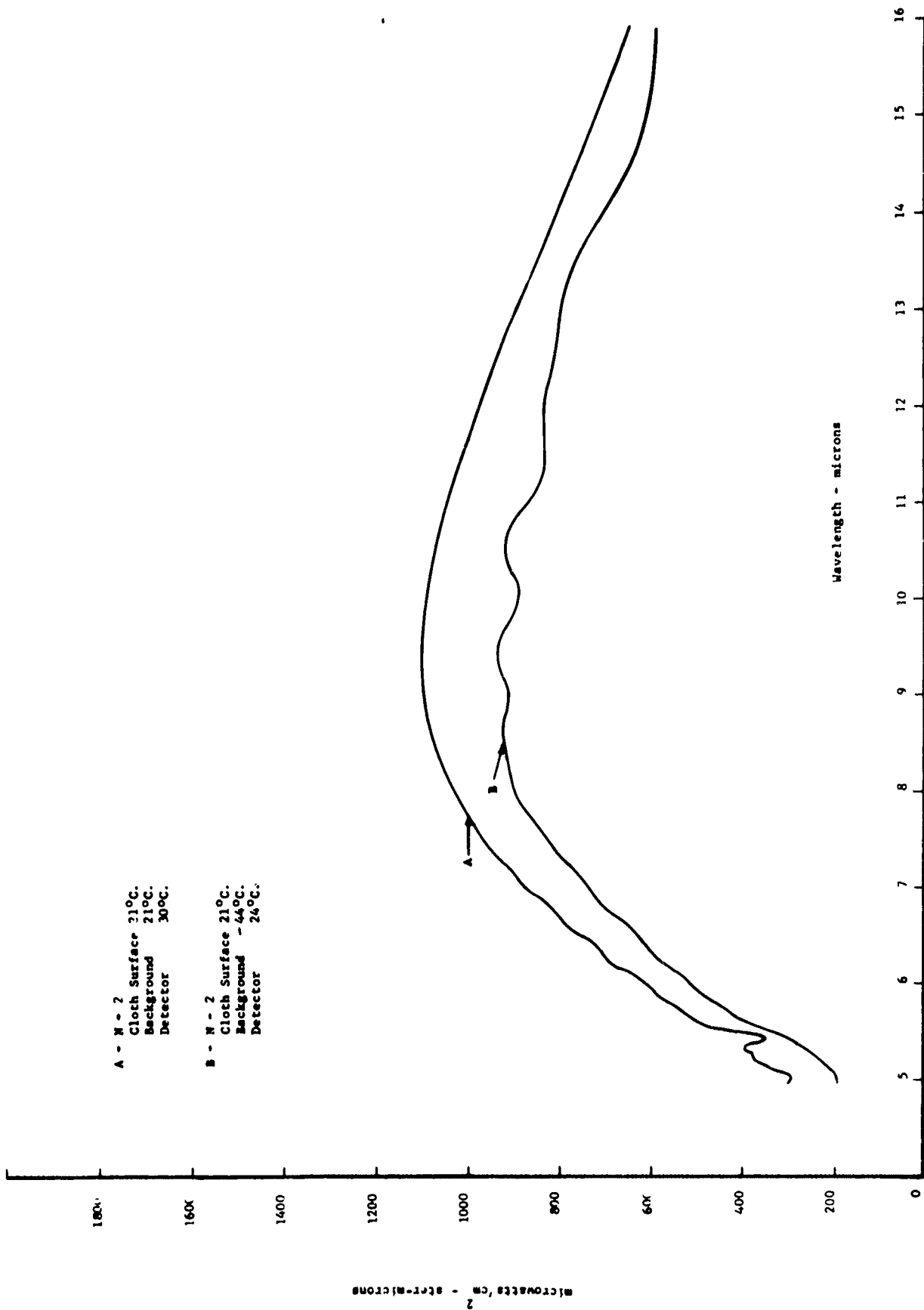


Figure 12: Effects of Spurious Selection

radiation, and differs very little from the other terrain features.

In Section V, (Conclusions), the effect of background feature reflection and radiation on the source is discussed and related to the fabric spectra. This spurious reflection and radiation causes the same spectral masking and blending of terrain features as it does of the fabric samples, so that terrain measurements made in the field will vary with changing ambient conditions. A change in the ambient temperature, cloud cover, or sun position may all change the spectral characteristics of the source.

With measurements made, either in the field or in the laboratory, it is almost certain that a portion of the optical path will be exposed to the air. The atmosphere absorbs and scatters radiation from the source. Figure 13 shows the transmission of a 1000-foot path through the atmosphere.³ However, in measurements for this report, the main concern would be the H₂O and CO₂ absorption bands at 2.7 , 4.2 , and 6.5 , due to the relatively short path lengths of air experienced in the experiment.

The same parameters that affect the total emission measurements of fabrics would affect total emission of terrain features.

V. CONCLUSIONS

Owing to the number of spectra taken, and the wide variety of conditions under which they were taken during the course of these tests, it is felt that the data presented here are conclusive. There are two basic physical reasons for the lack of spectral detail in these measurements. The first reason is that the small variations in the weave of the cloth act as blackbody radiators, thus masking spectral detail. Second, the observation of the samples in a room environment gave rise to spurious reflection of radiation from walls, ceiling, light, etc. Kirchoff's law states:

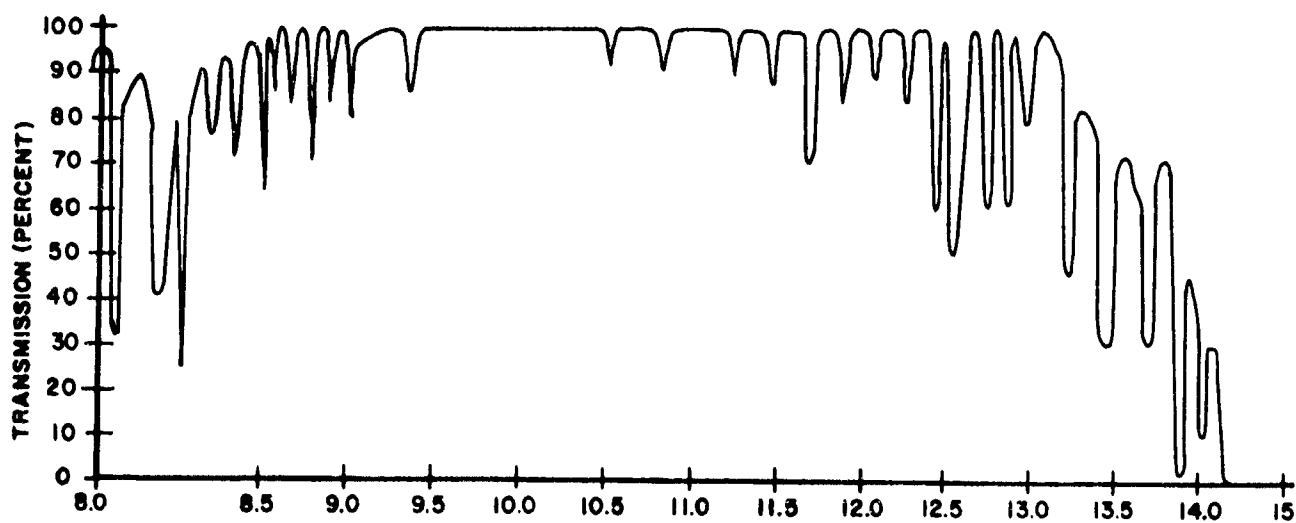
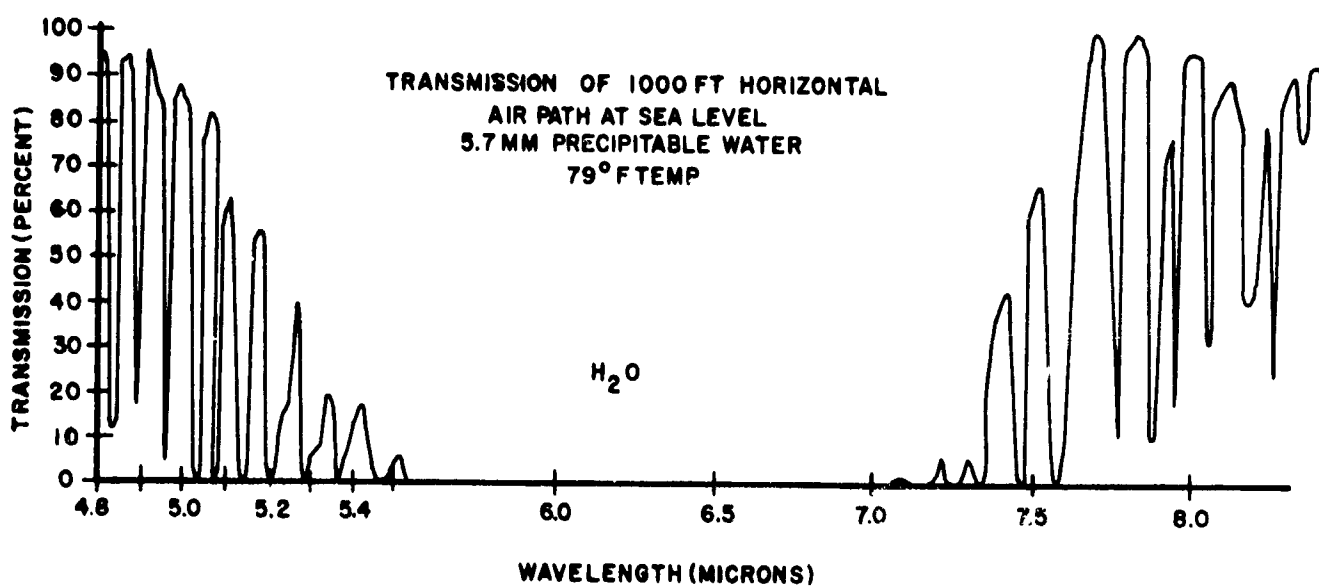
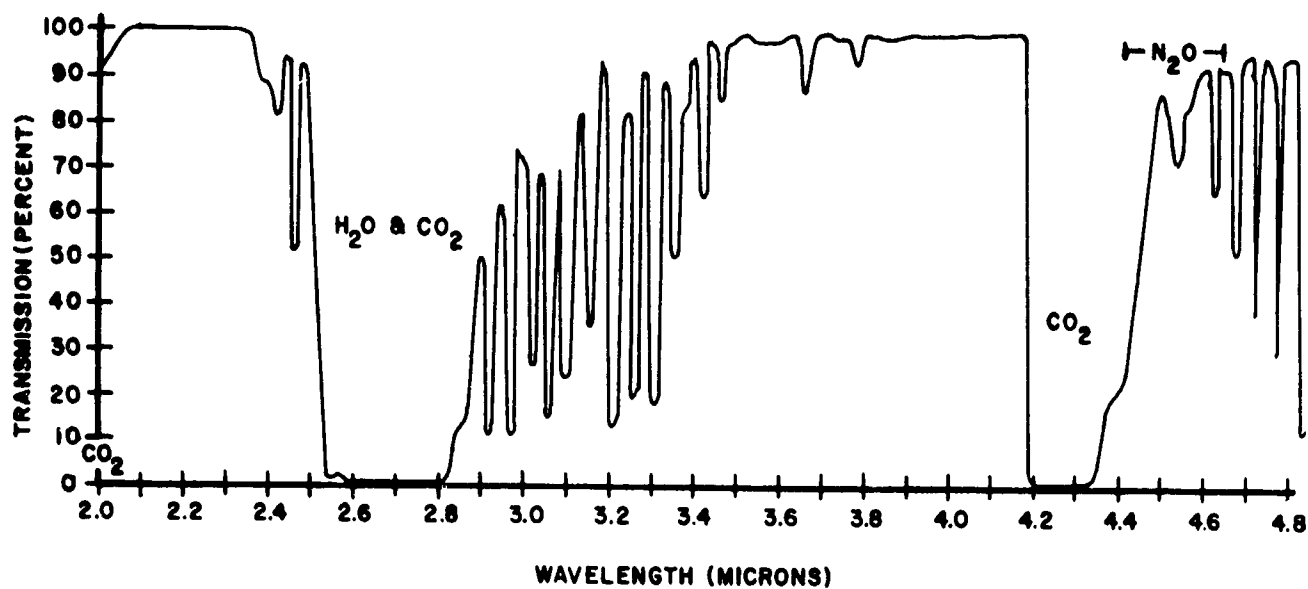


Figure 13: WAVELENGTH (MICRONS)
SPECTRAL TRANSMISSION OF THE ATMOSPHERE

$$\epsilon + \tau + \rho = 1$$

where ϵ = emissivity

τ = transmissivity = 0

ρ = reflectivity

Since the sum of emissivity and reflectivity equals a constant (1) a rise in reflectivity means a corresponding decrease in emissivity⁸. The use of the cold box largely eliminates spurious emission and reflection.

Figure 21 shows two superimposed spectra of the same fabric at the same temperature. The only difference in the two measurements is that the background of A was at room (and sample) temperature while the background of B was at -44°C . The difference in the maximum heights of A and B is the reduction in reflection resulting from cooling the background. It can also be seen that certain detail appearing in spectrum B is almost totally masked in spectrum A. This increase in reflectivity, brought about by the sample being at the same temperature as the surroundings, is the largest deterrent to taking significant spectra in the field. To show that the amount of spectral detail is an ambient condition dependent phenomenon, consider the following.

On a clear day, the radiant emittance from the sky has the spectral distribution as shown in Figure 14 below⁹.

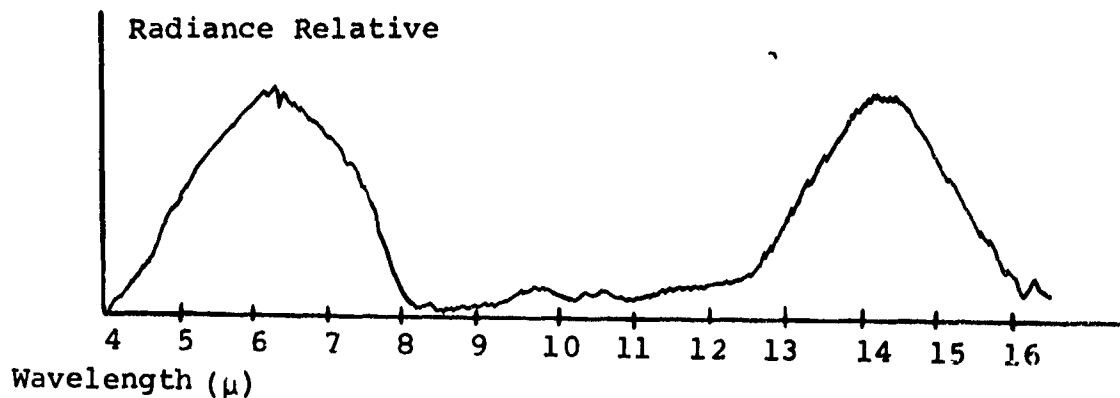


Figure 14: Radiance of Clear Sky

If a sample were observed under clear sky conditions, the 8μ to 12.5μ region of its spectrum would show very little reflected radiation, and largely true sample spectrum; however, on an overcast day, the sky spectrum has the shape⁹ shown in Figure 15.

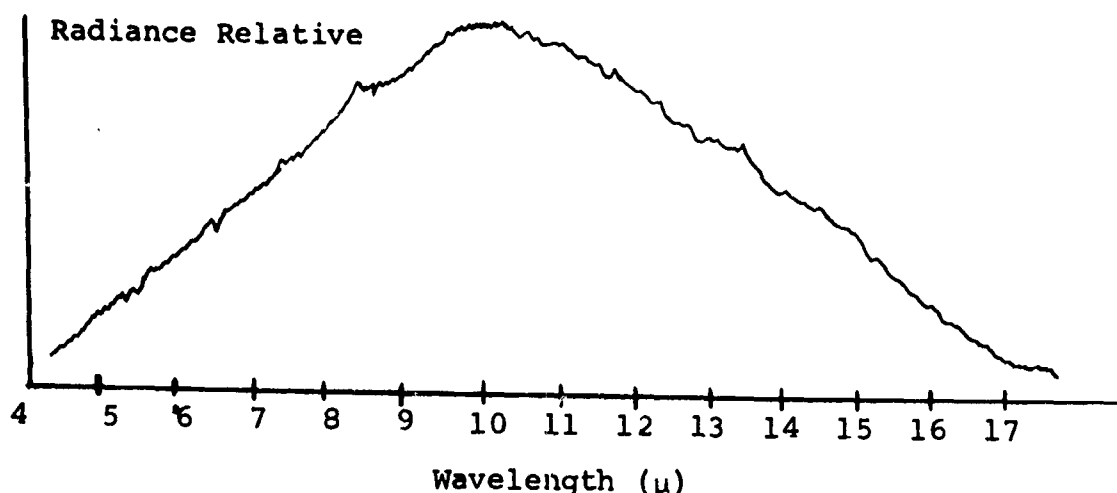


Figure 15: Radiance of Cloudy Sky

It can be seen that the emission in the 8μ to 12μ portion of the spectrum is much greater, and hence, the radiance reflected by the sample would be greater in this region, giving a false total emission measurement. Add to this effect the reflected radiance from trees, grass, water, and rocks and it can be seen that the resultant spectrum could be an ambiguous representation of the sample.

The spectra taken under conditions of varying humidity show that the change in humidity affects the spectrum much less than changing the background. For significant path lengths between the source and the instrument, the water-absorption bands would increase in strength with an increase in humidity, but the other portions of the spectrum would remain unchanged.

The spectra taken with insulation placed between the hotplate and the sample show that the radiance from the cloth surface is less when insulation is present than when insulation is absent. It can be concluded that the rate of radiation exchange between the hotplate and the cloth surface is slower through insulation than it is when the cloth and hotplate are in direct contact. The spectrum of the insulated cloth cannot be distinguished from the spectrum of cloth at room temperature.

VI. RECOMMENDATIONS FOR FURTHER WORK

The data presented in this report comprise a fairly rigorous measurement program directed towards the determination of the complete emission characteristics of fabric samples under laboratory conditions. It is concluded that terrain features and ambient conditions have a very large effect on any measurements taken under field conditions. Therefore, it will be difficult to correlate laboratory emission studies to field conditions because of the many variables involved. More work in the total emission of fabrics should now be performed in a field environment, and a better understanding of the exact difference between the emission of fabrics and the emission of terrain may be derived. Such work could lead to the development of fabrics, methods of treating fabrics, or methods of utilizing fabrics so that fabrics cannot be differentiated from background features. It is further recommended that no further laboratory work be undertaken. Field measurements should be the next extension of this work.

V.1 REFERENCES

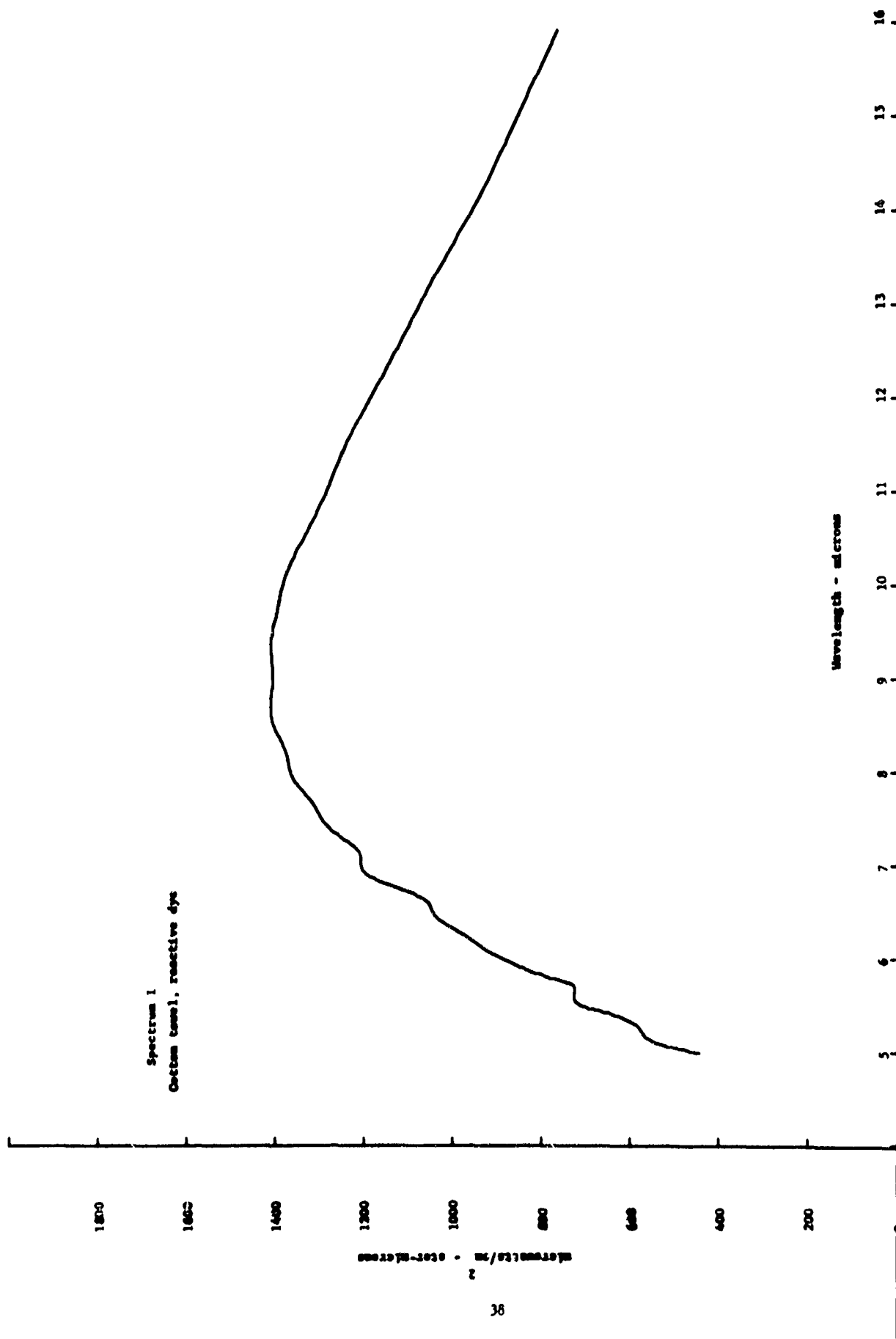
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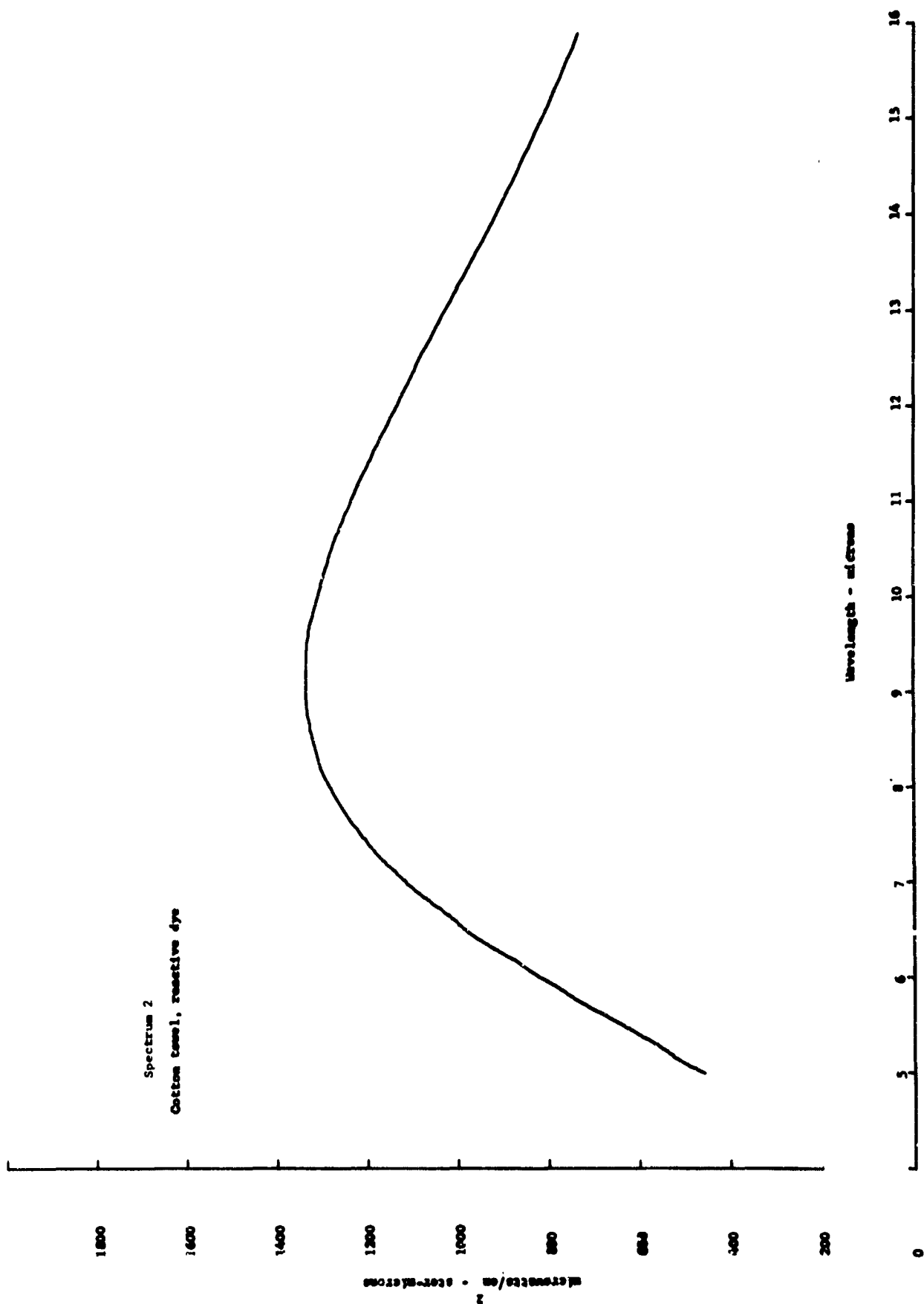
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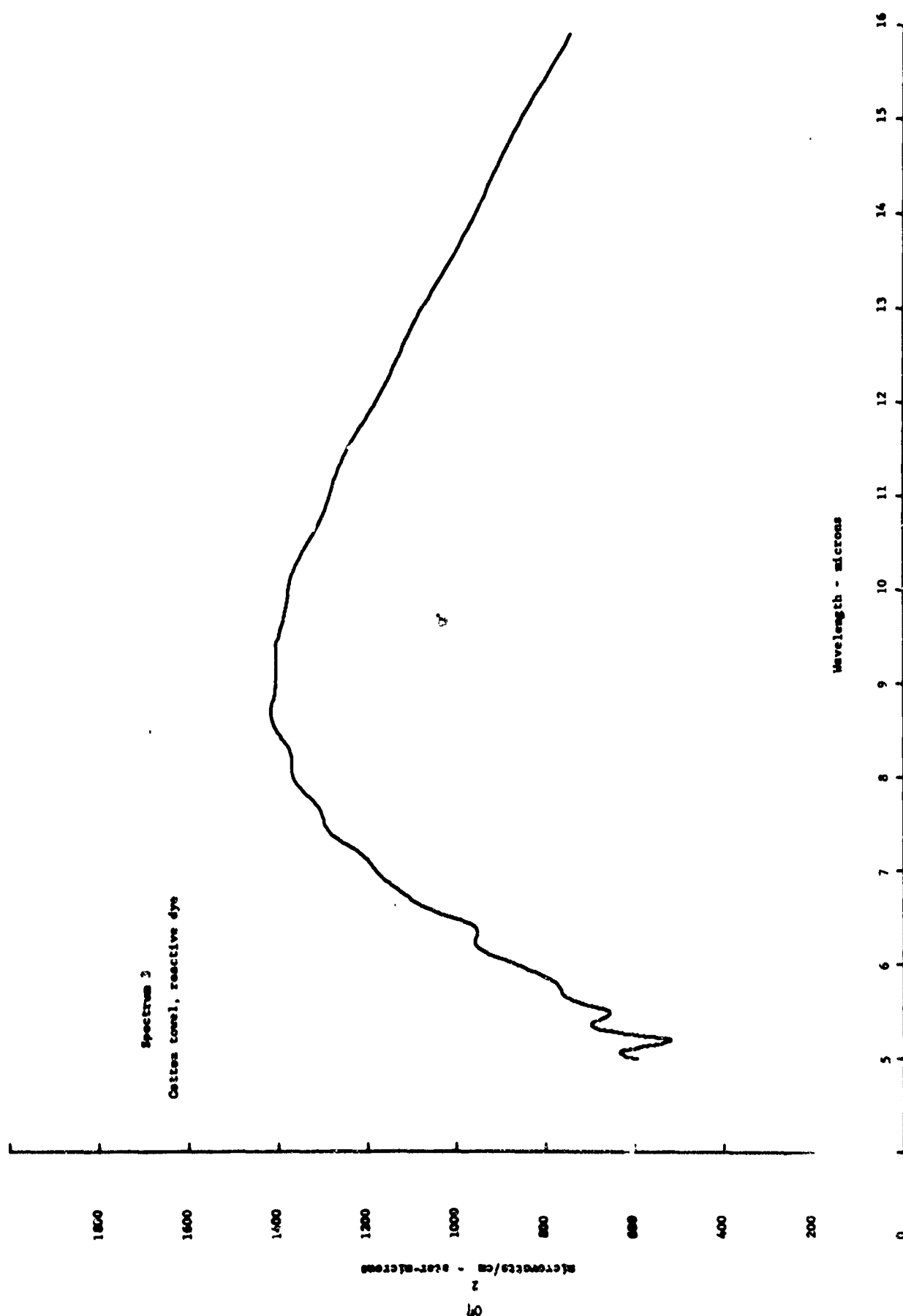
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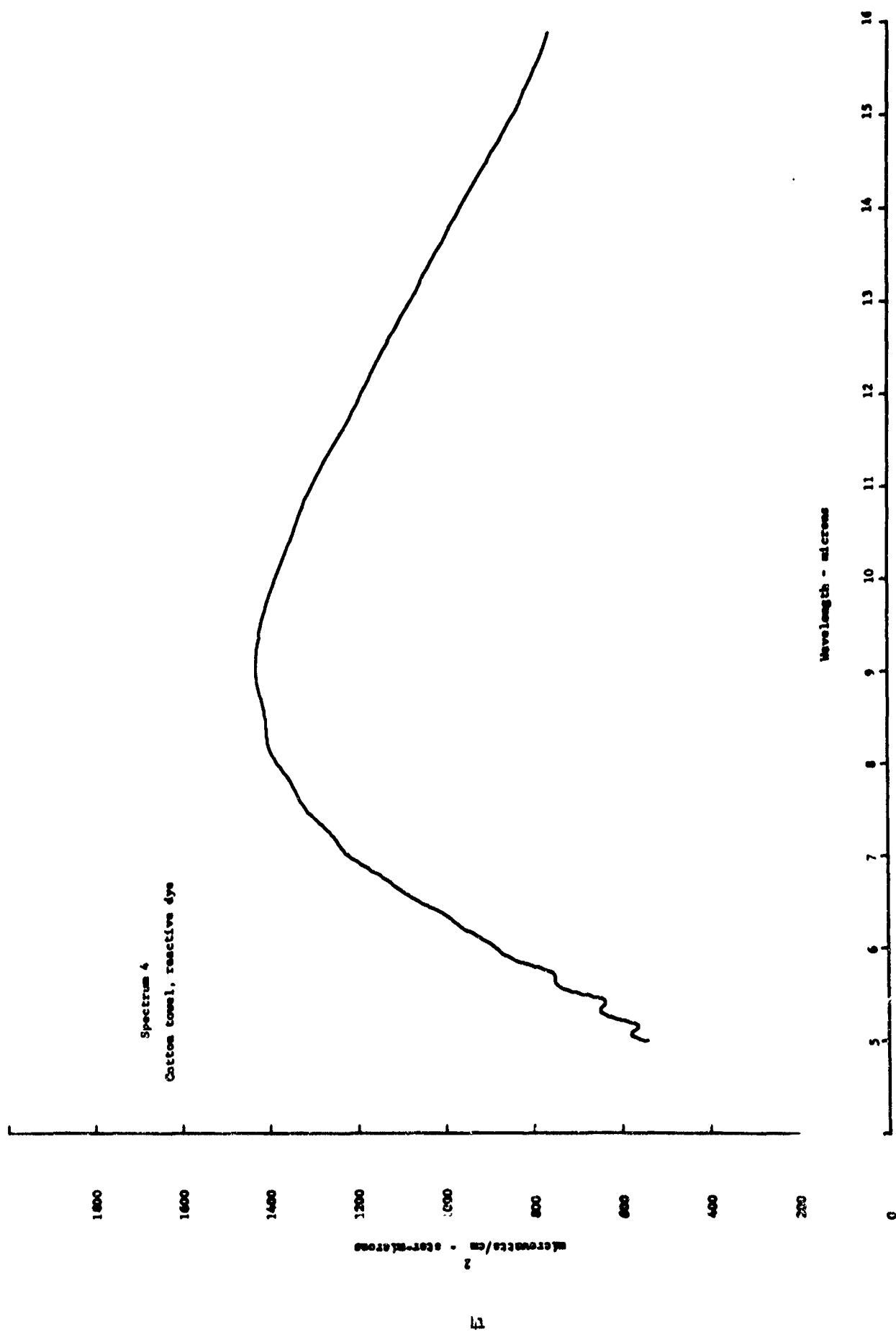
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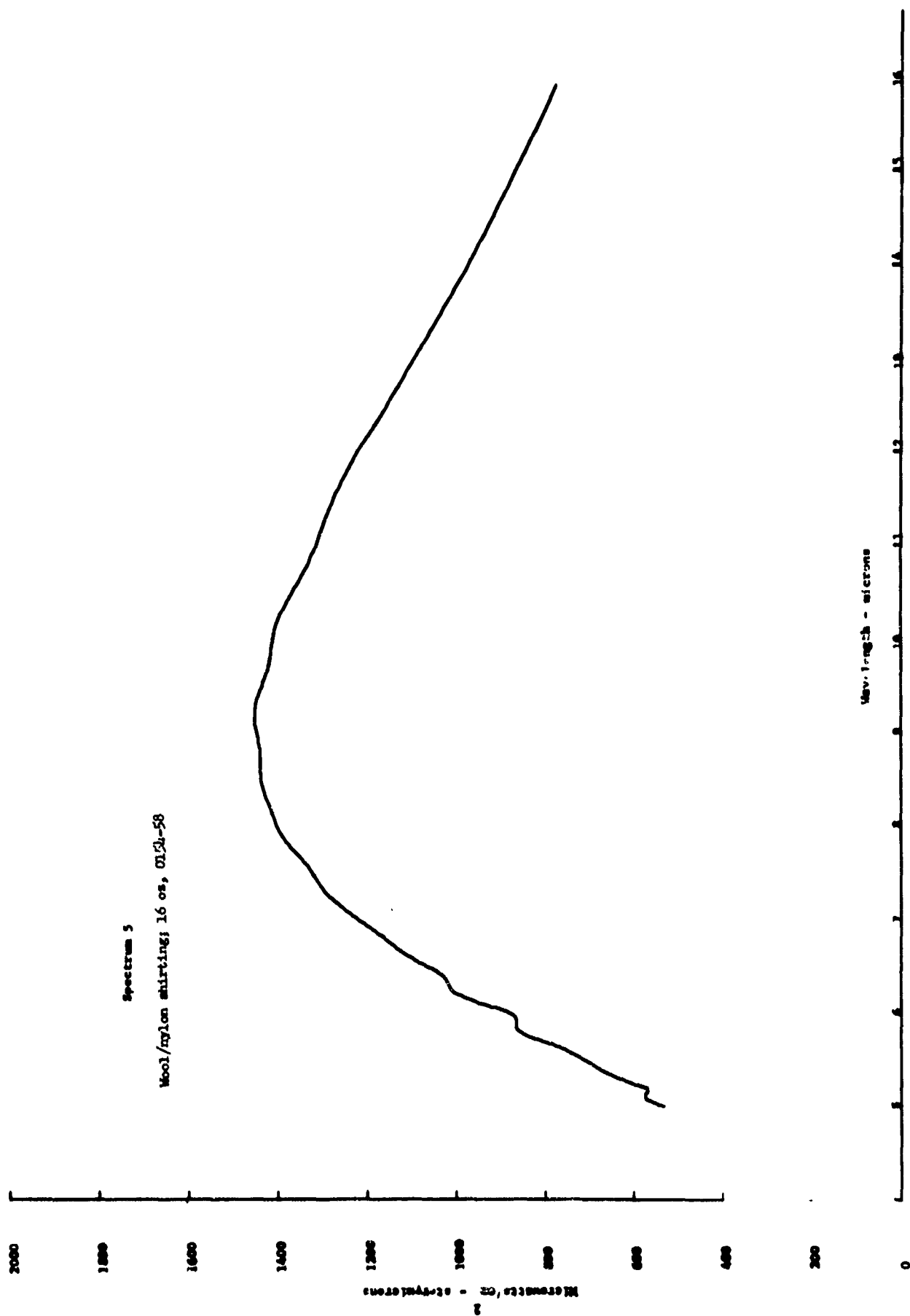
GROUP I SPECTRA

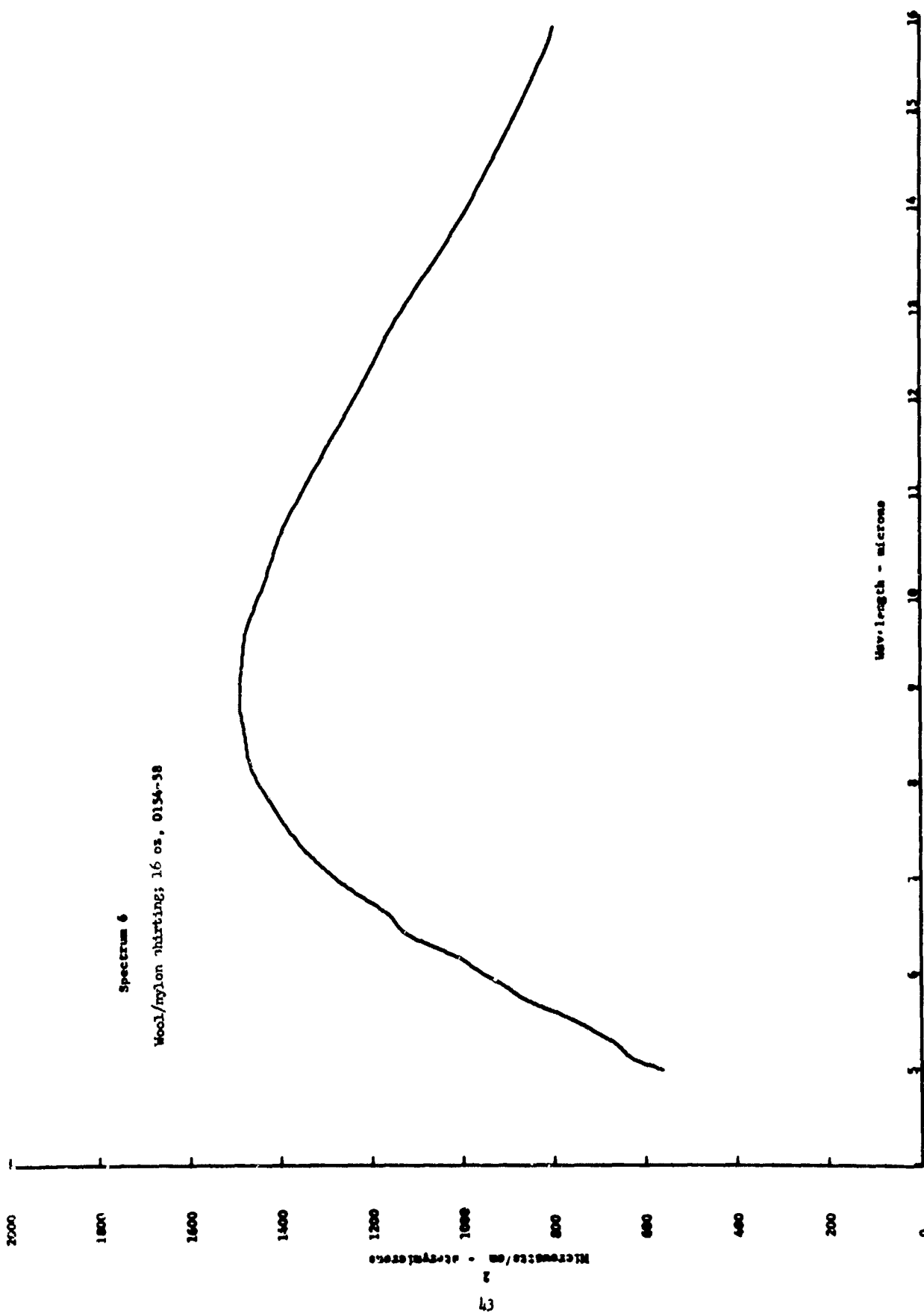


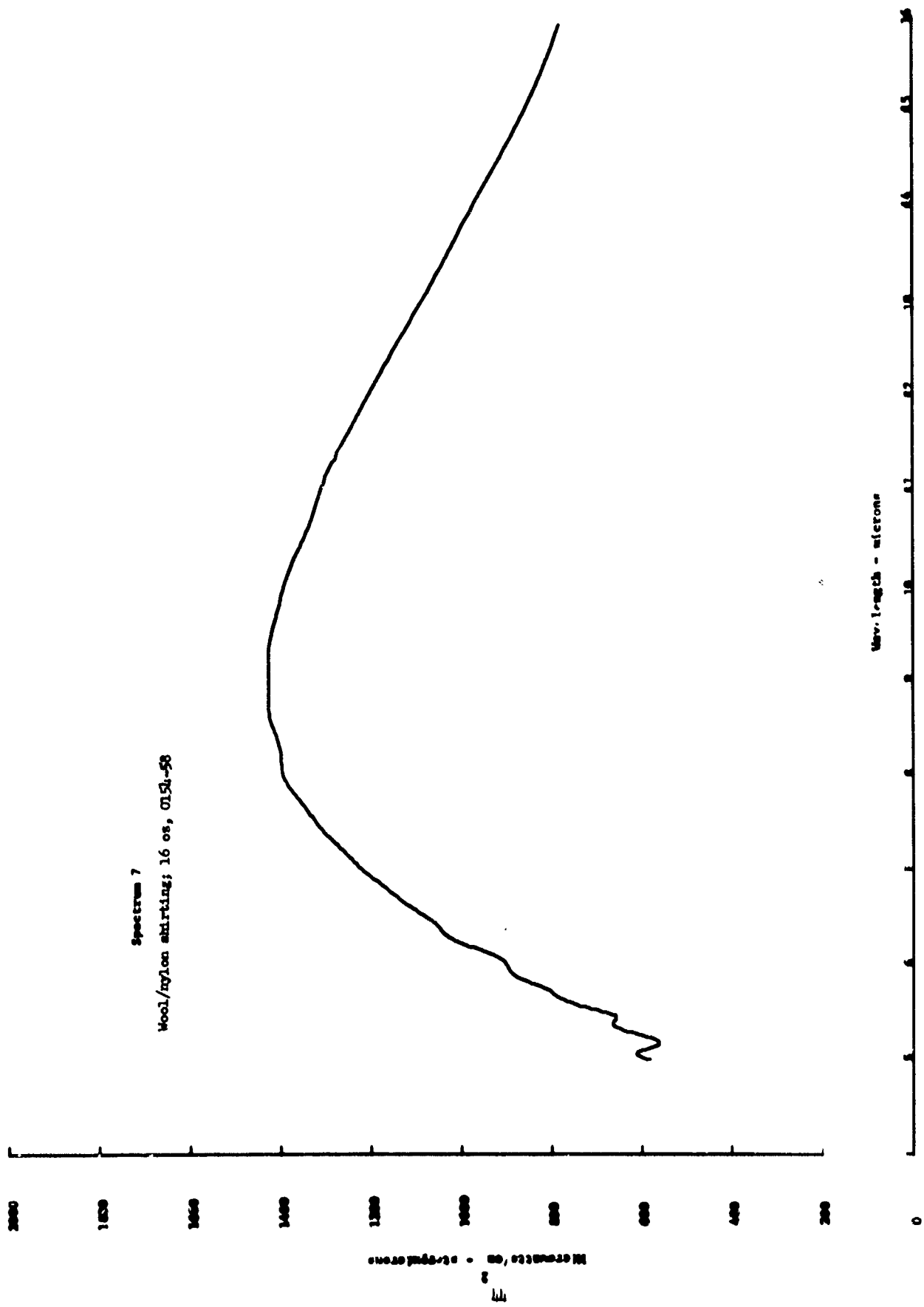




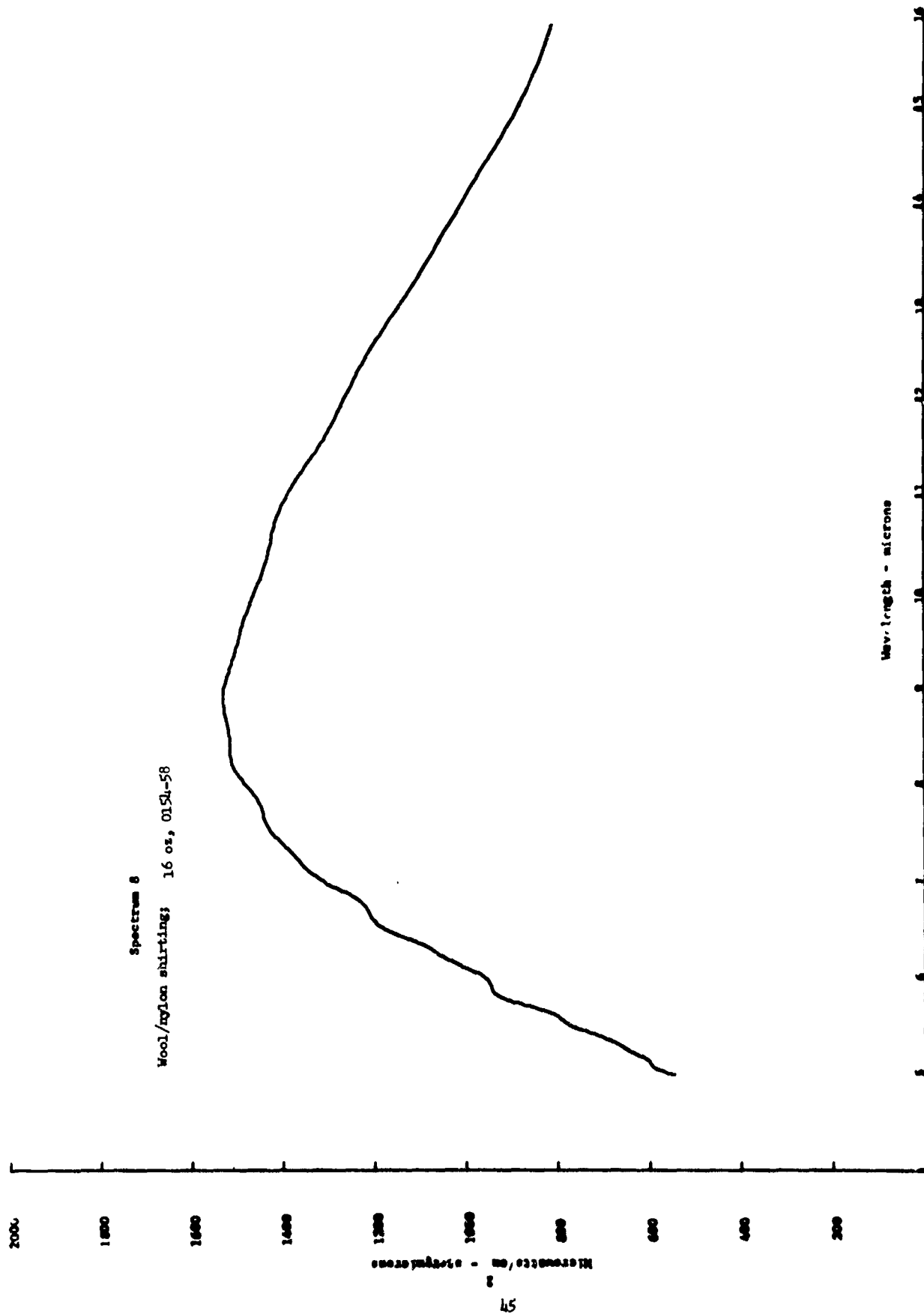




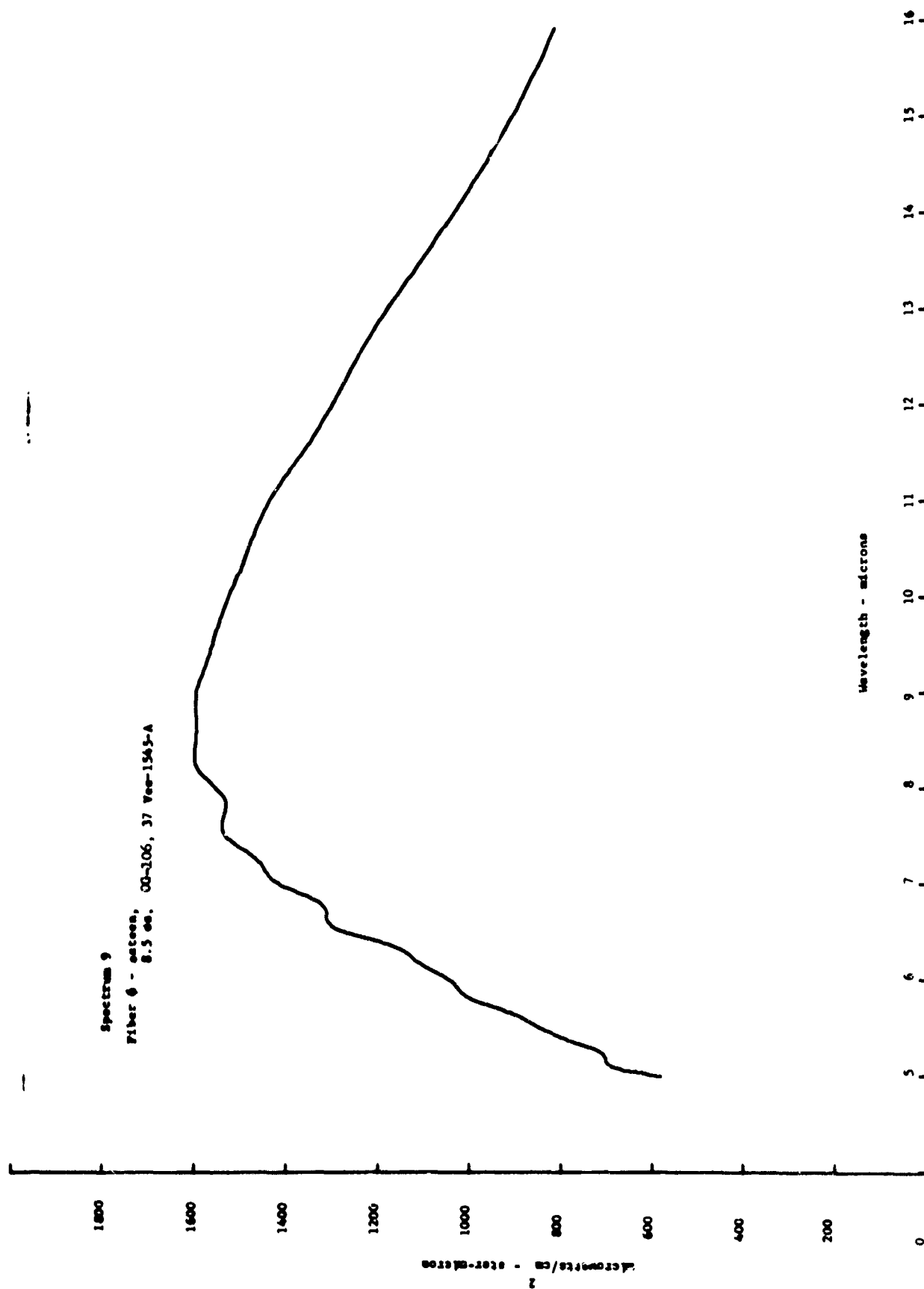


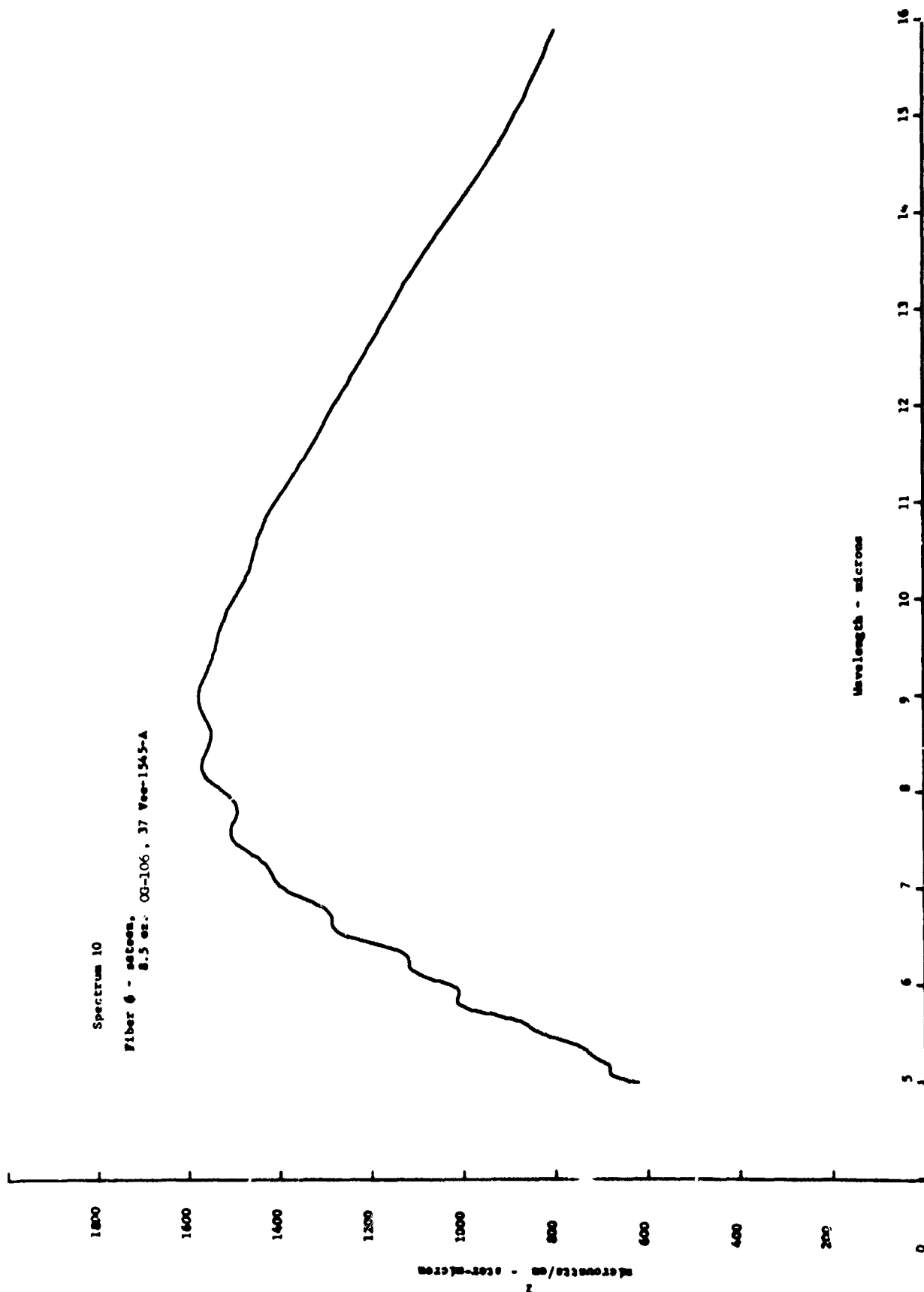


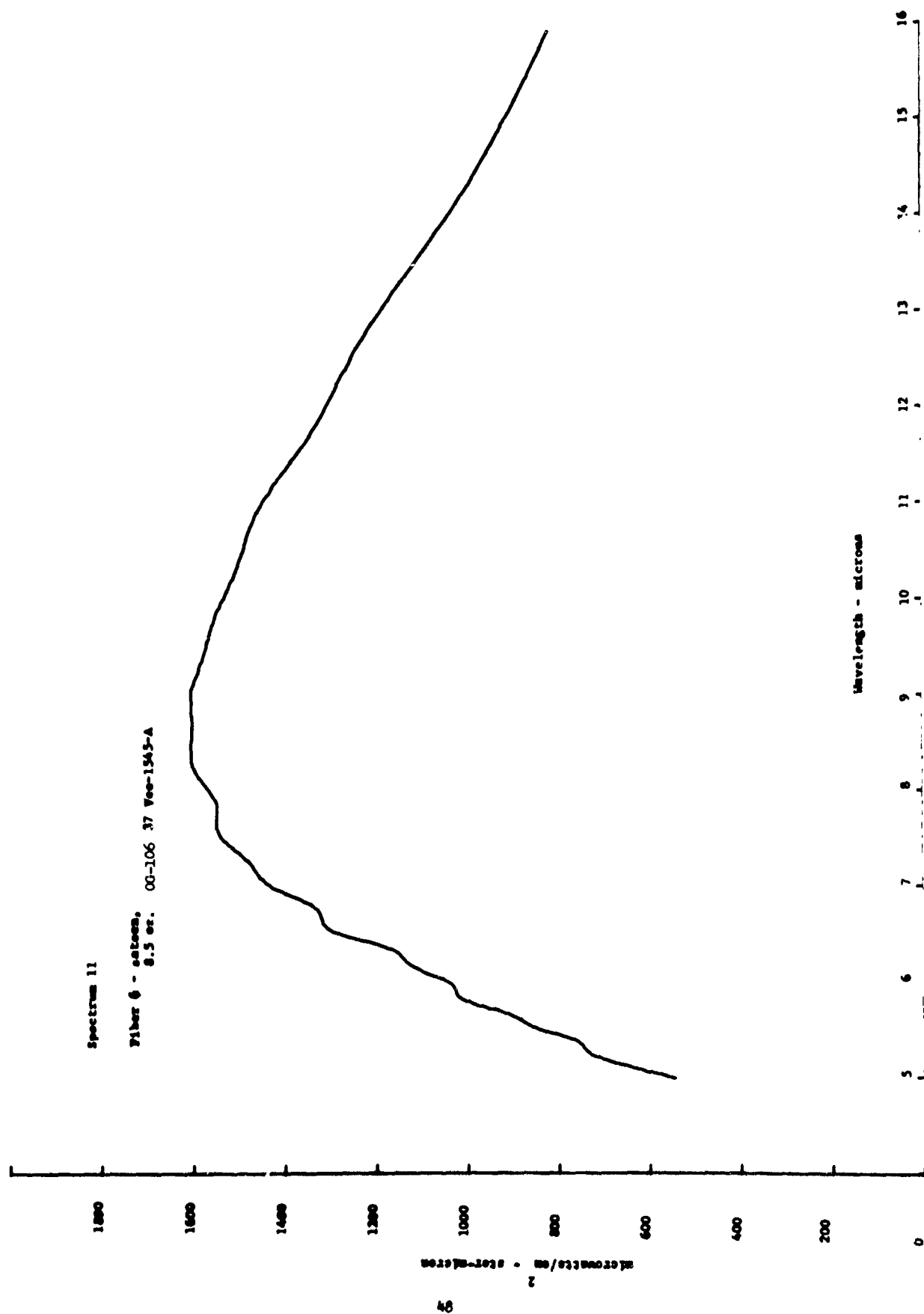
Wool/nylon shirting; 16 oz, 0154-58

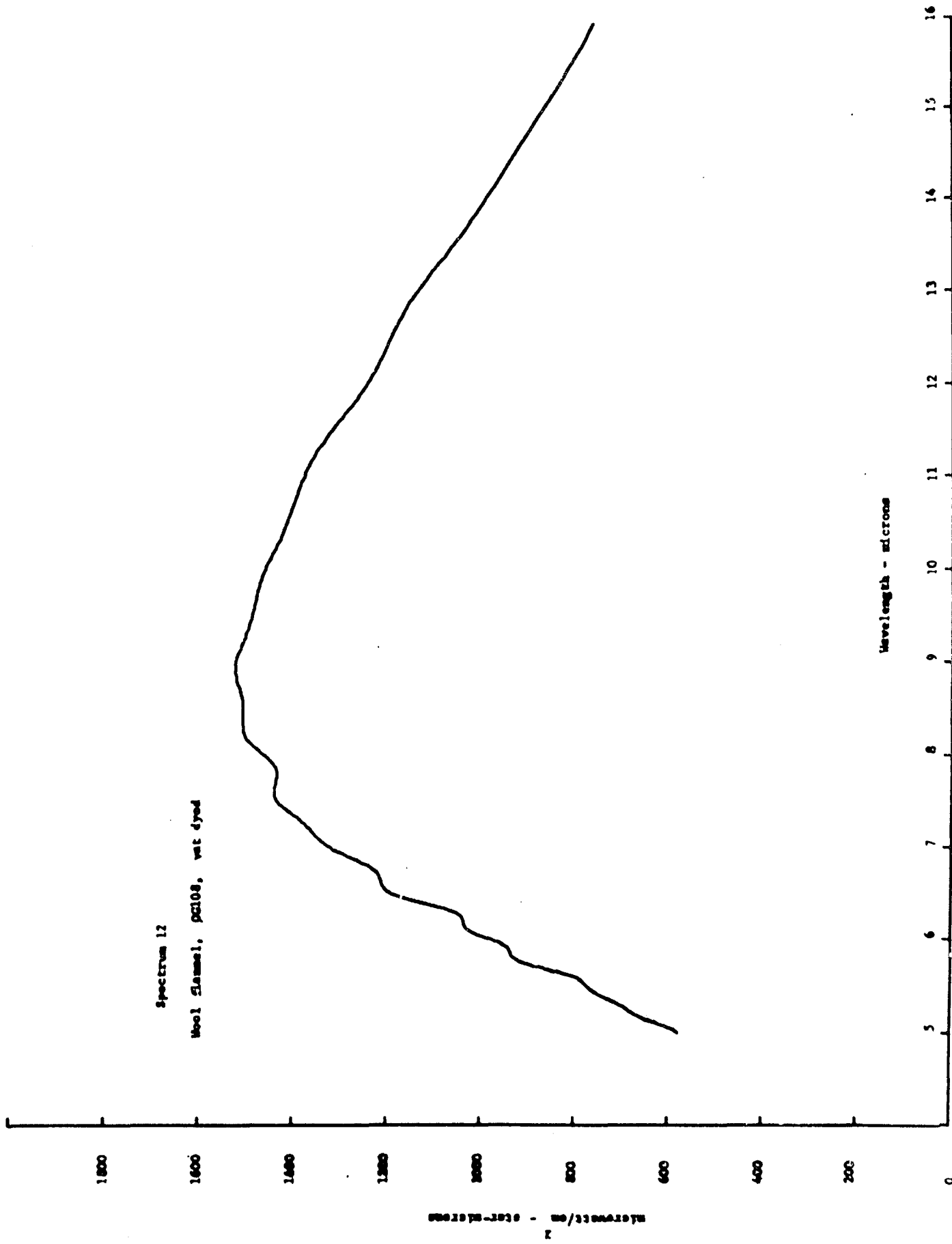


Spectrum 9
Fiber 6 - anticon,
8.5 ea. QD-106, 37 Ver-1545-A

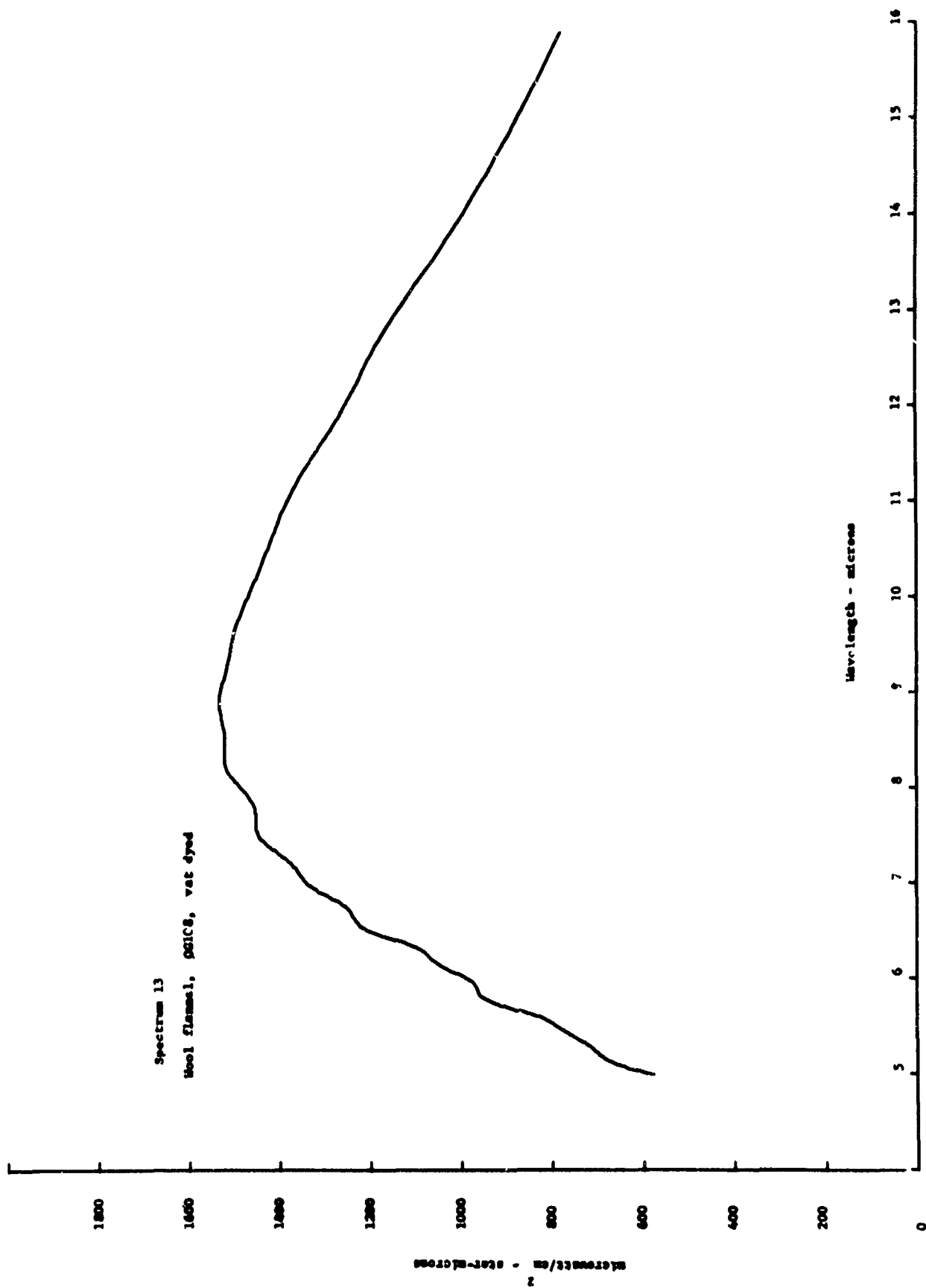


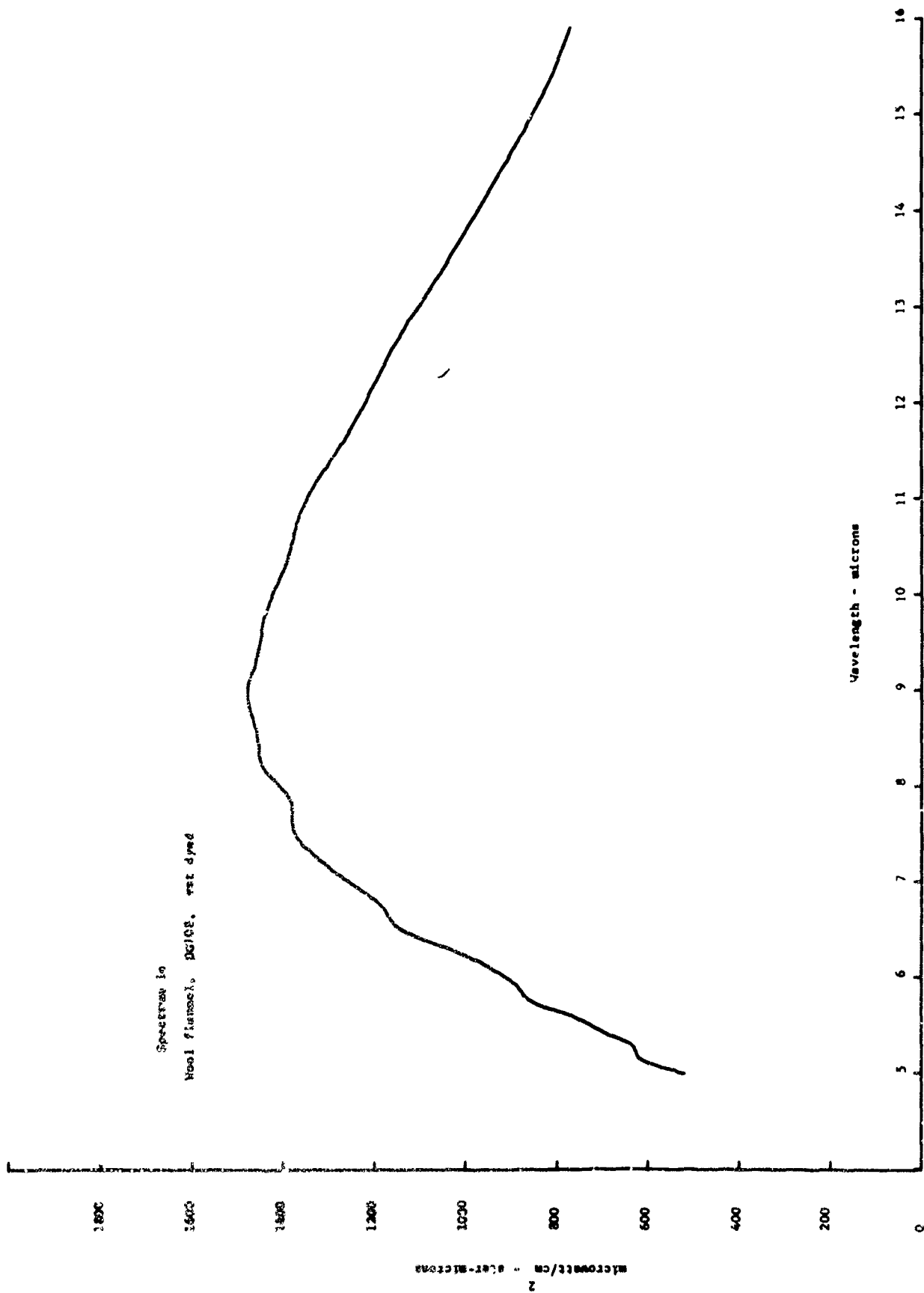


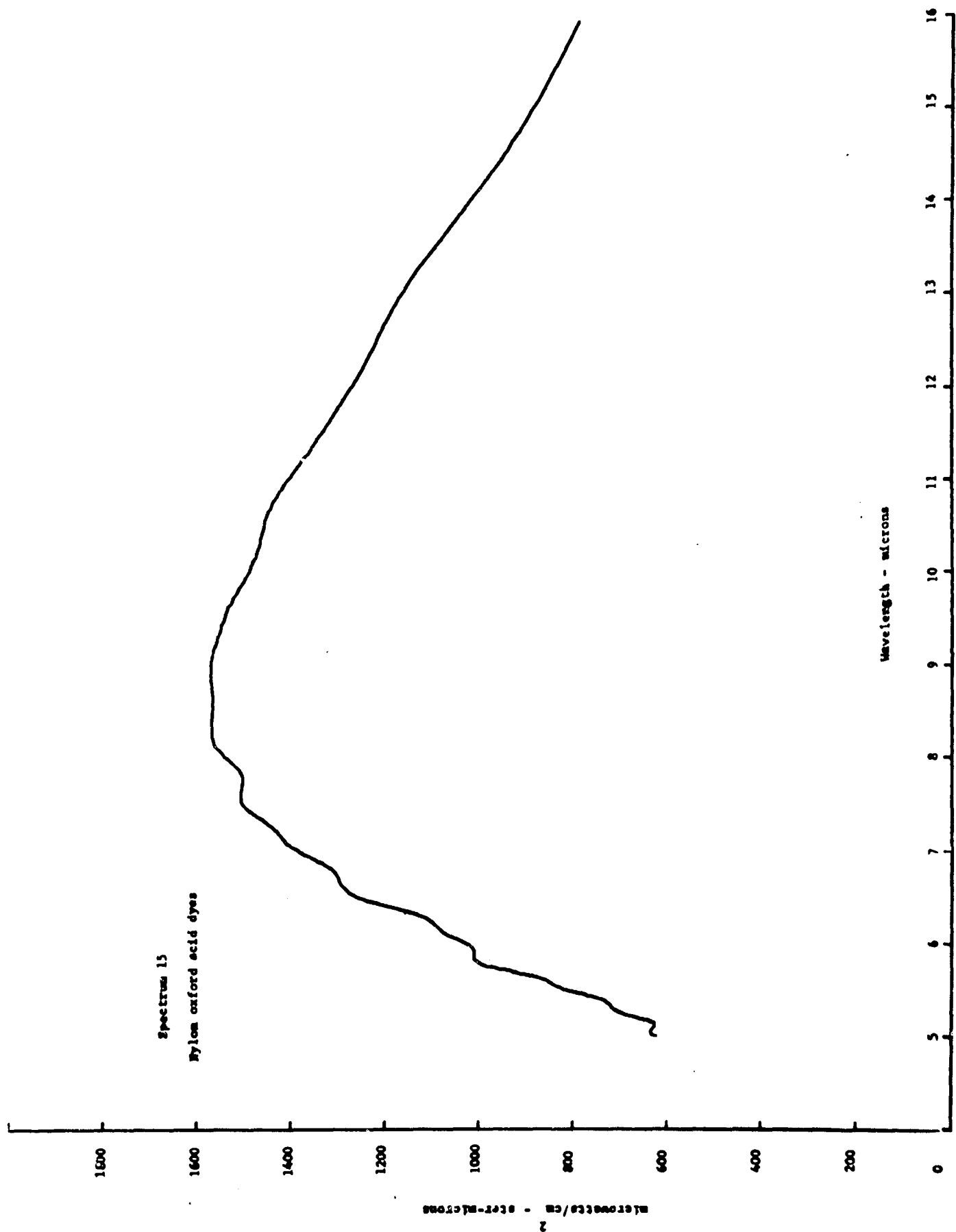


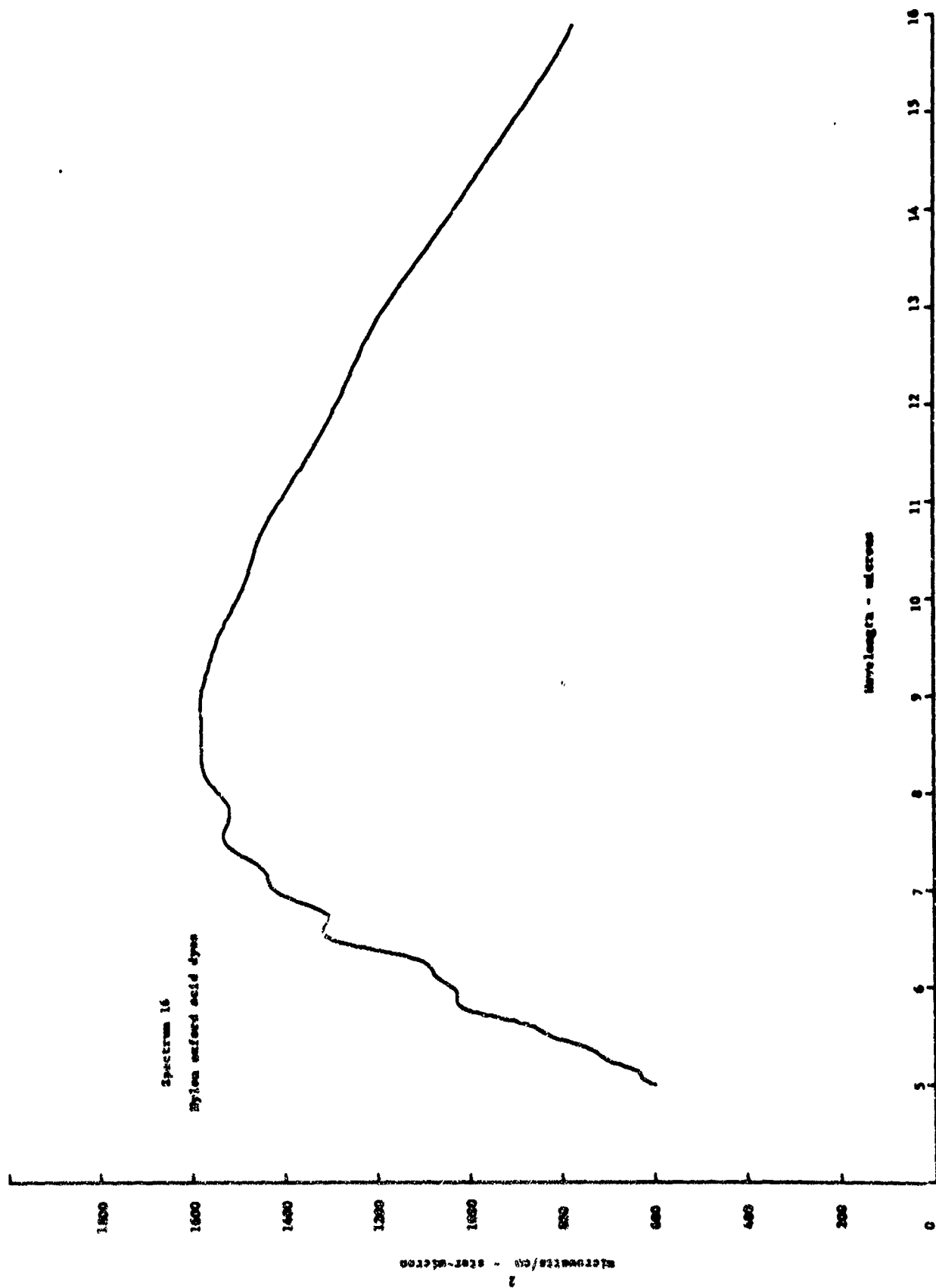


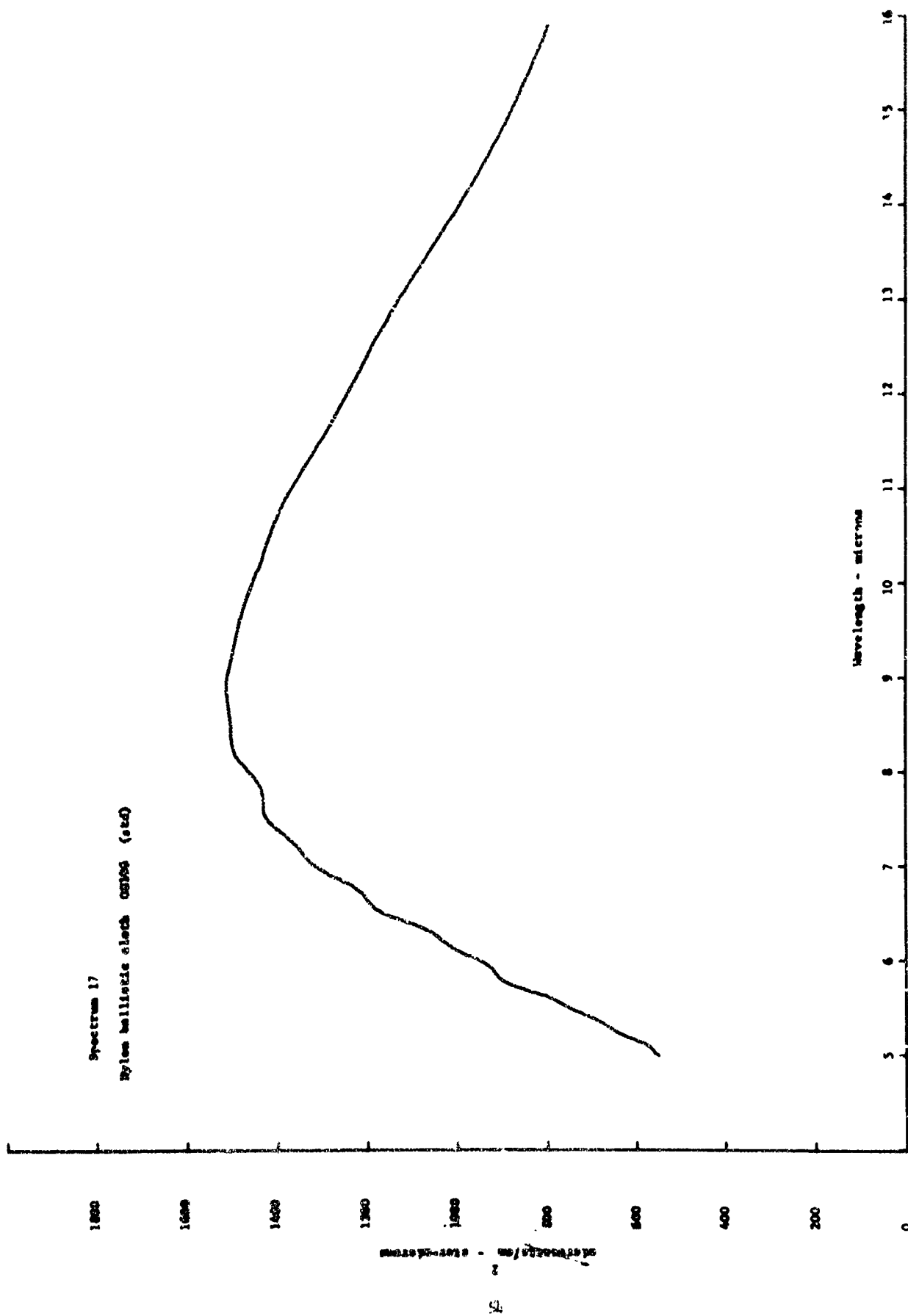
Spectrum 12
Wool flannel, DC108, wet dyed



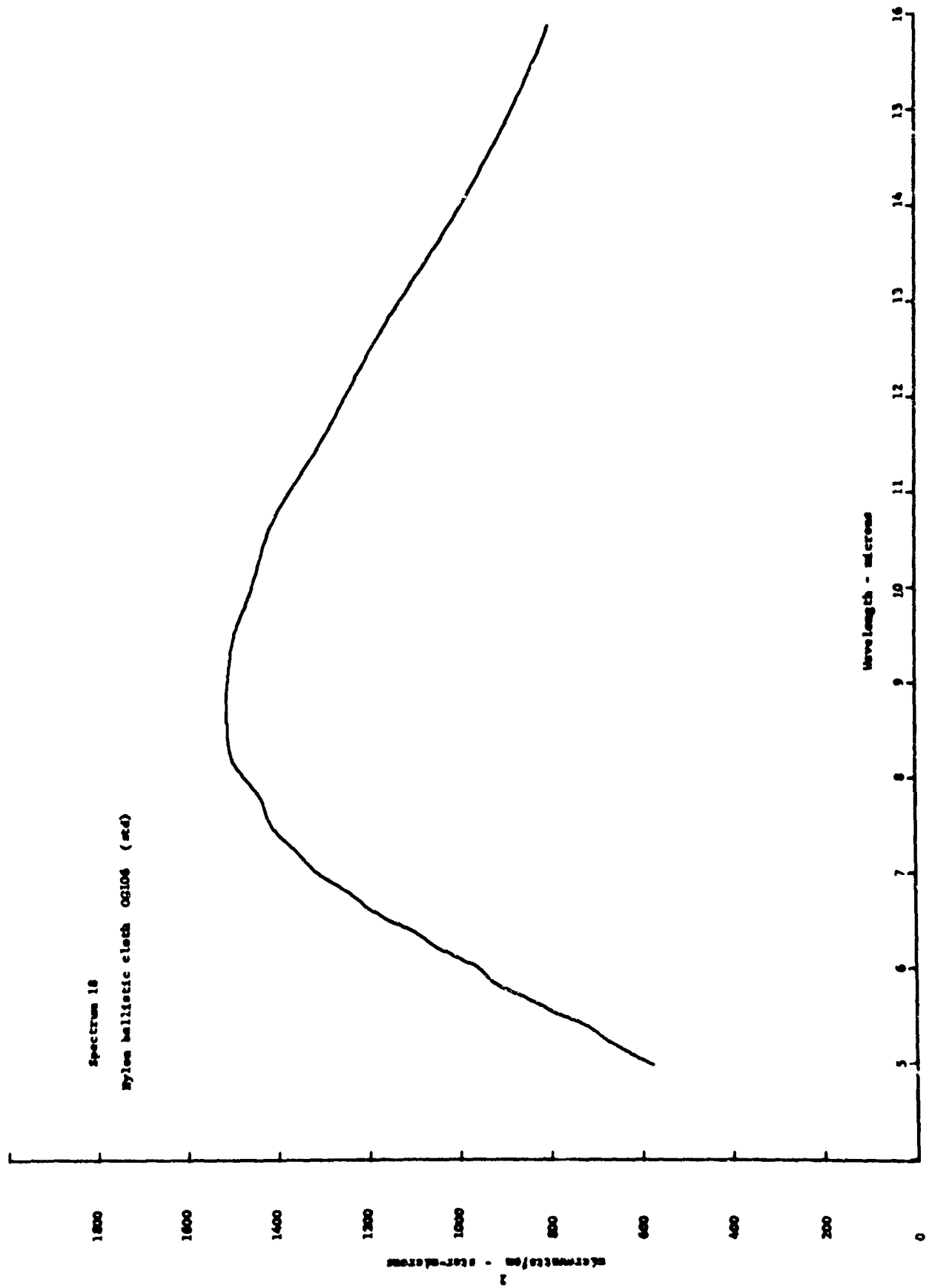




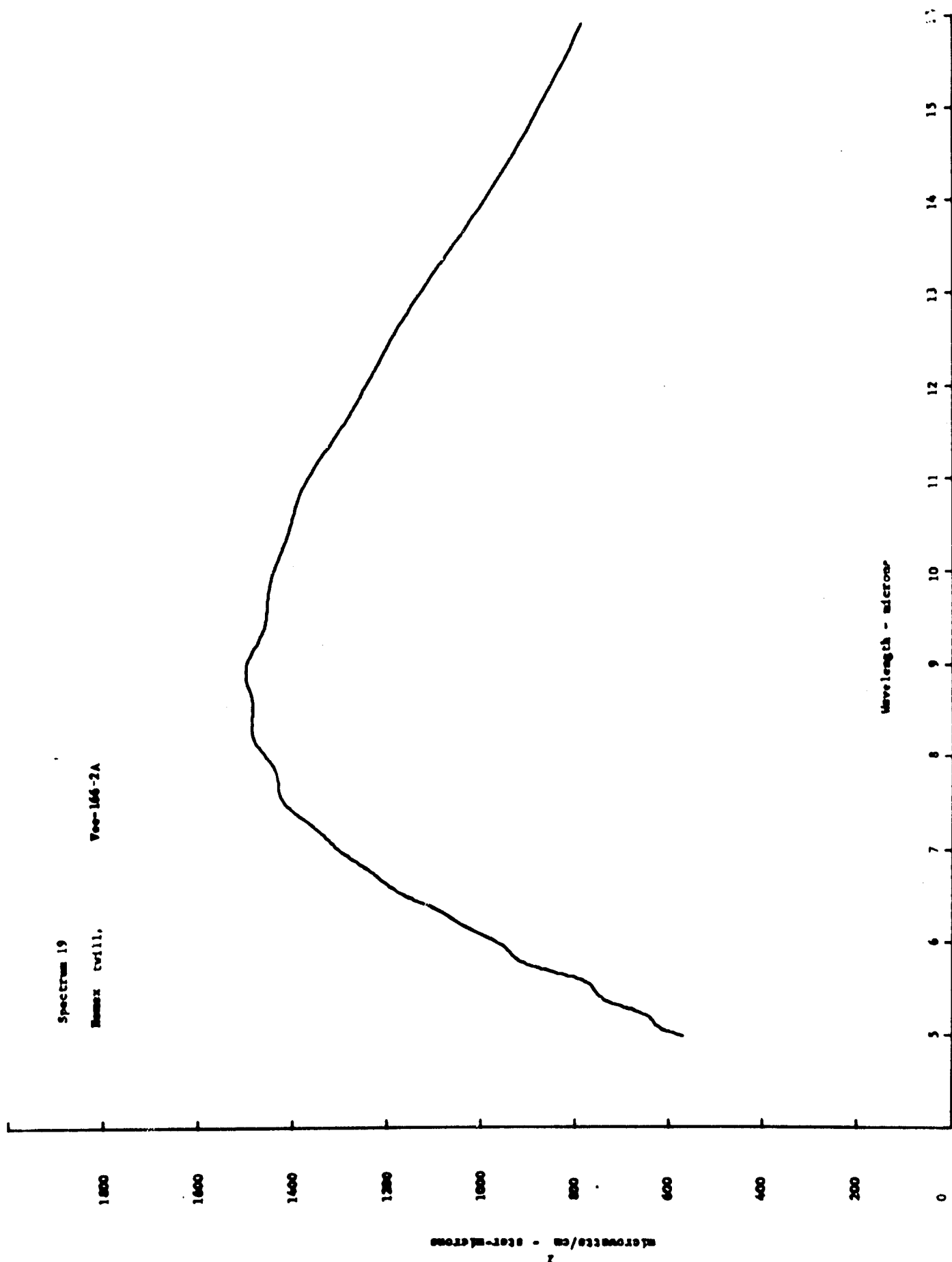


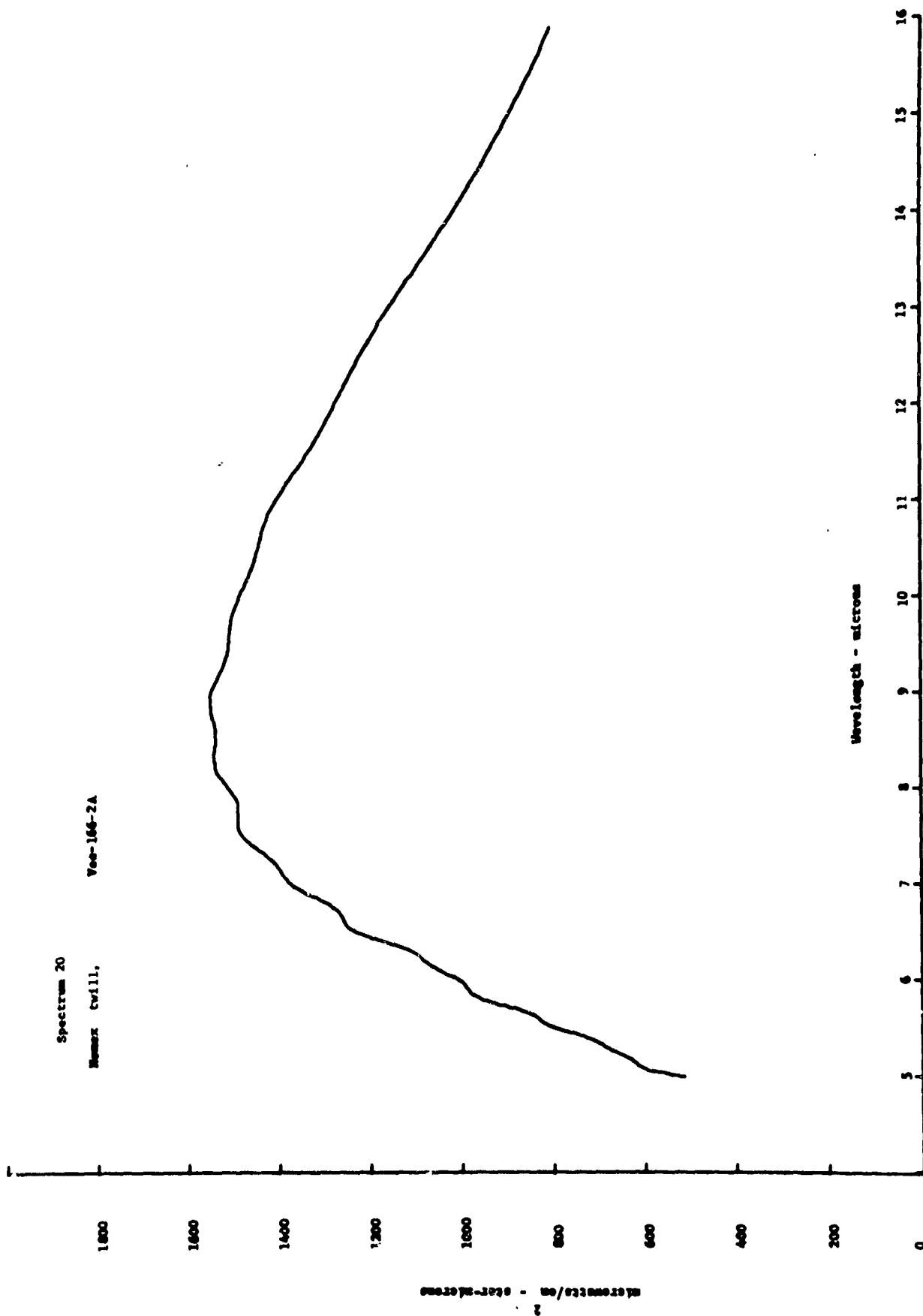


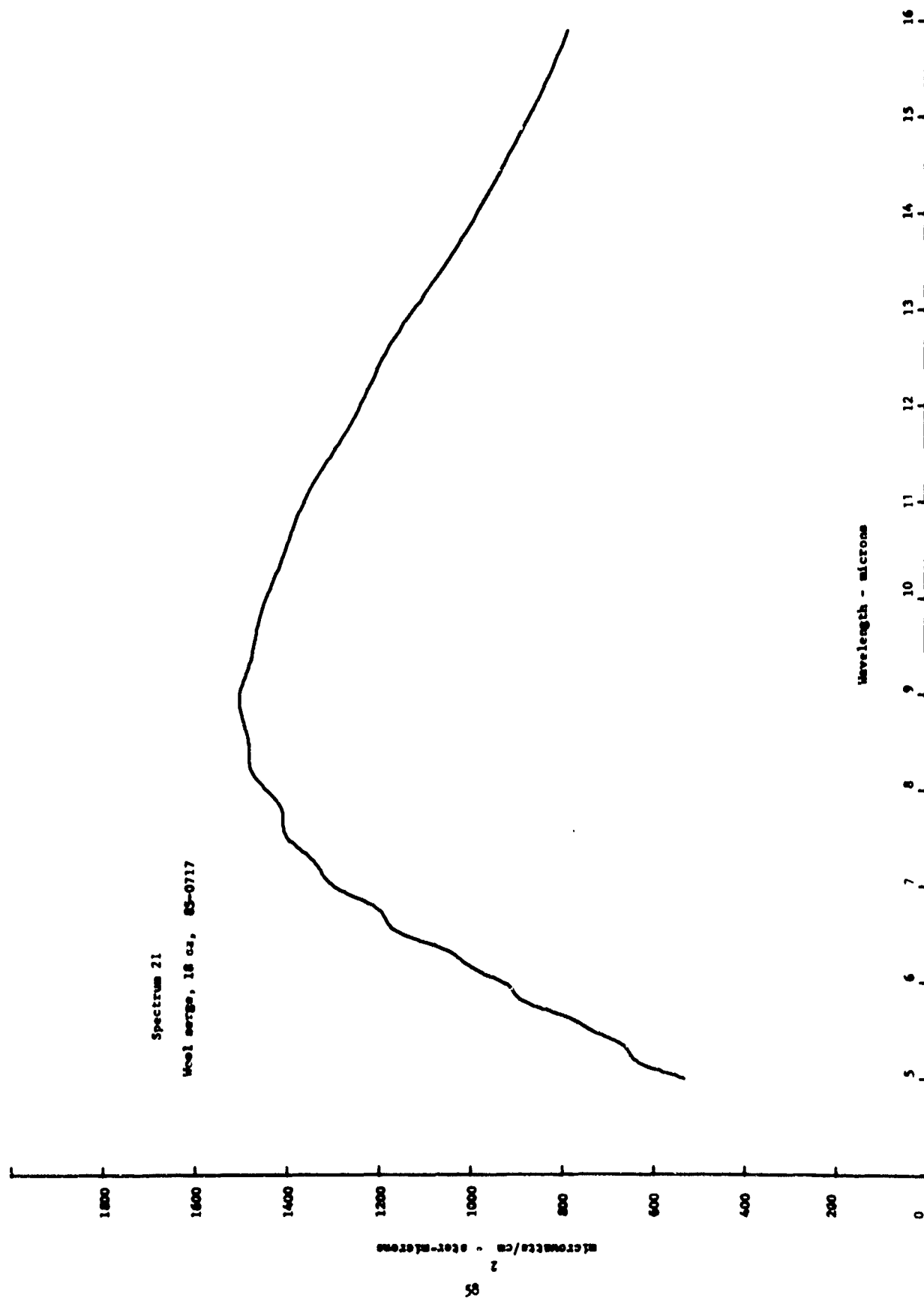
Spectrum 18
Nylon ballistics cloth 00106 (md)

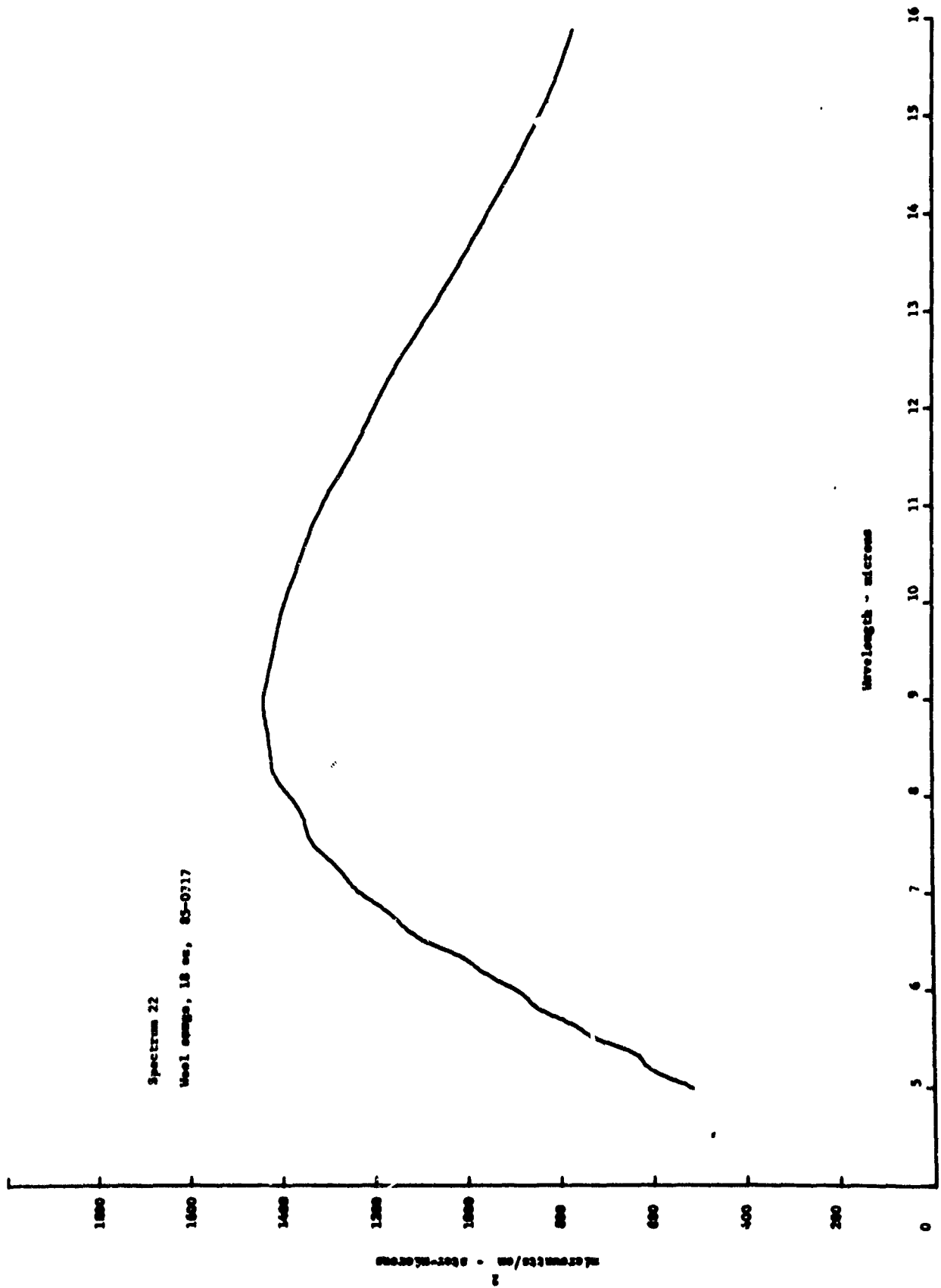


Spectrum 19
Rumex crill.
Vee-166-2A

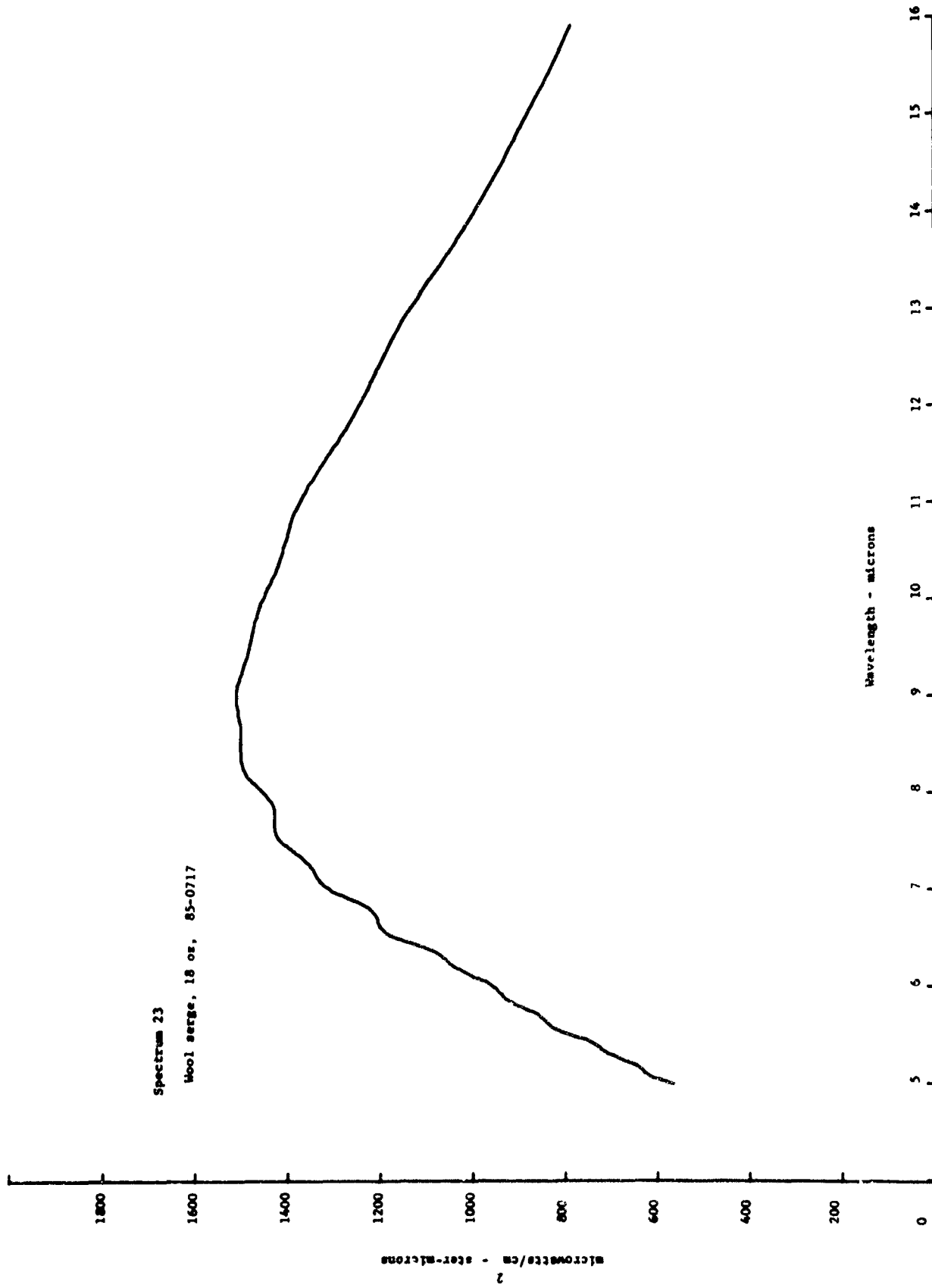


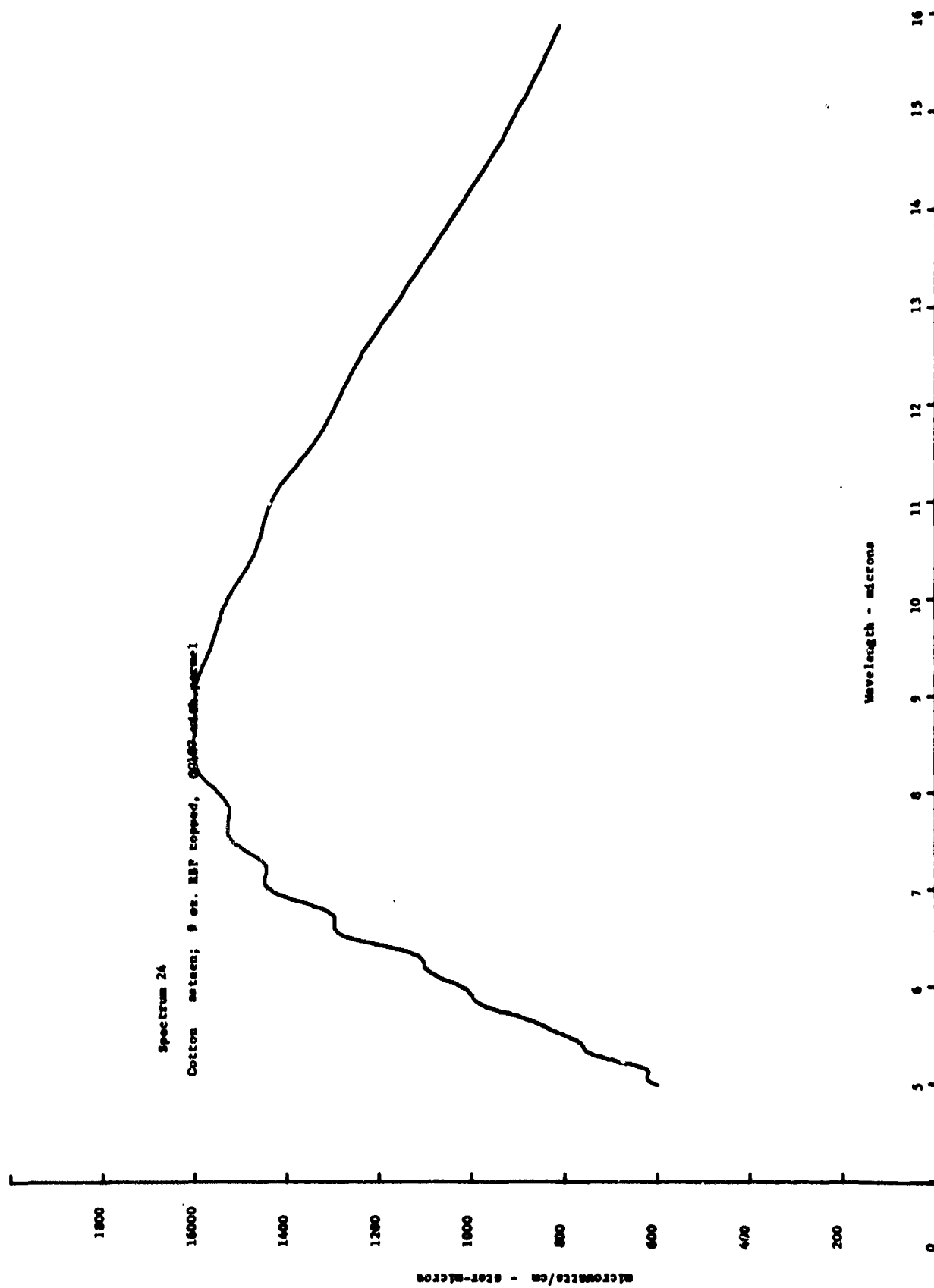


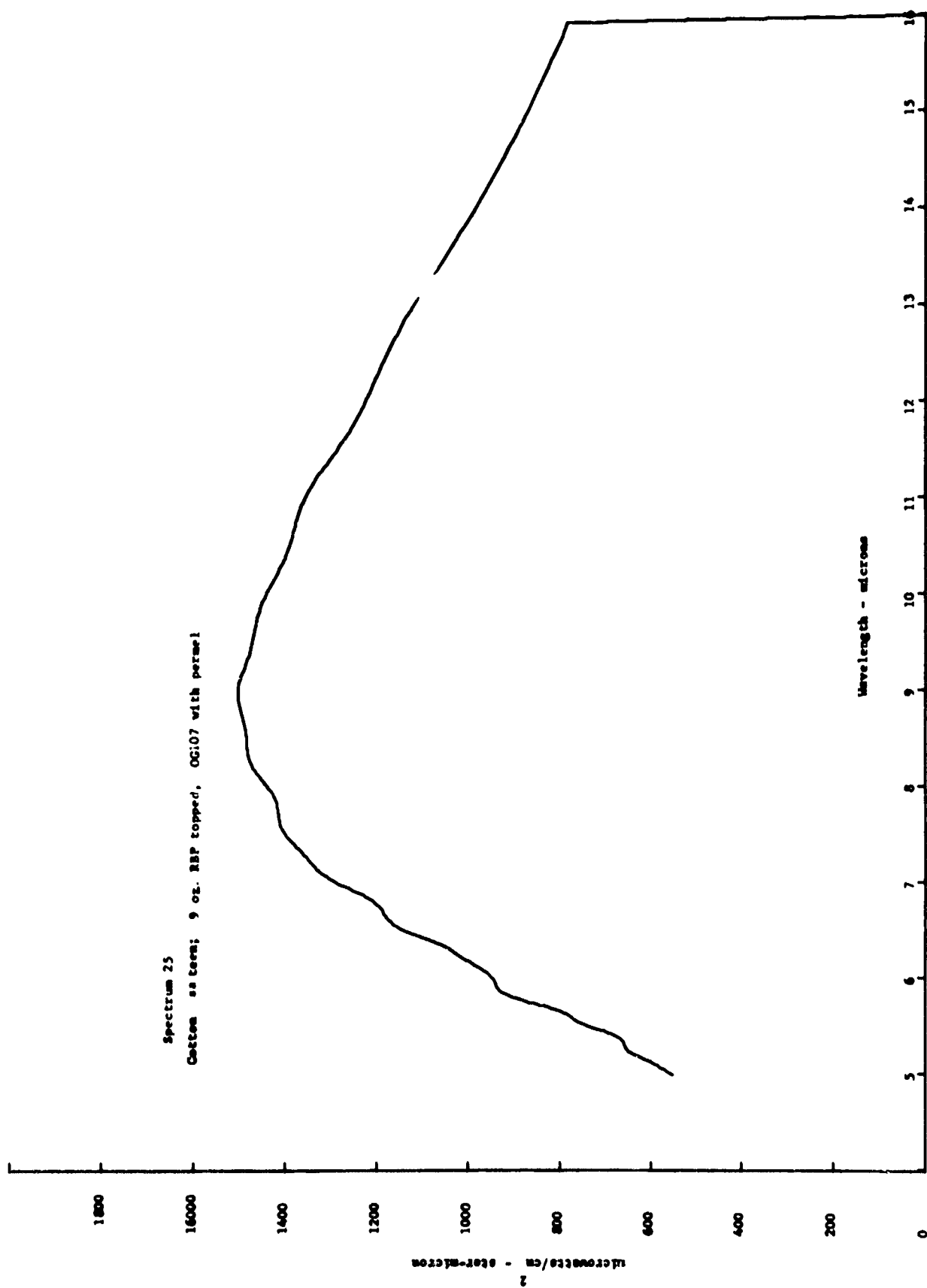


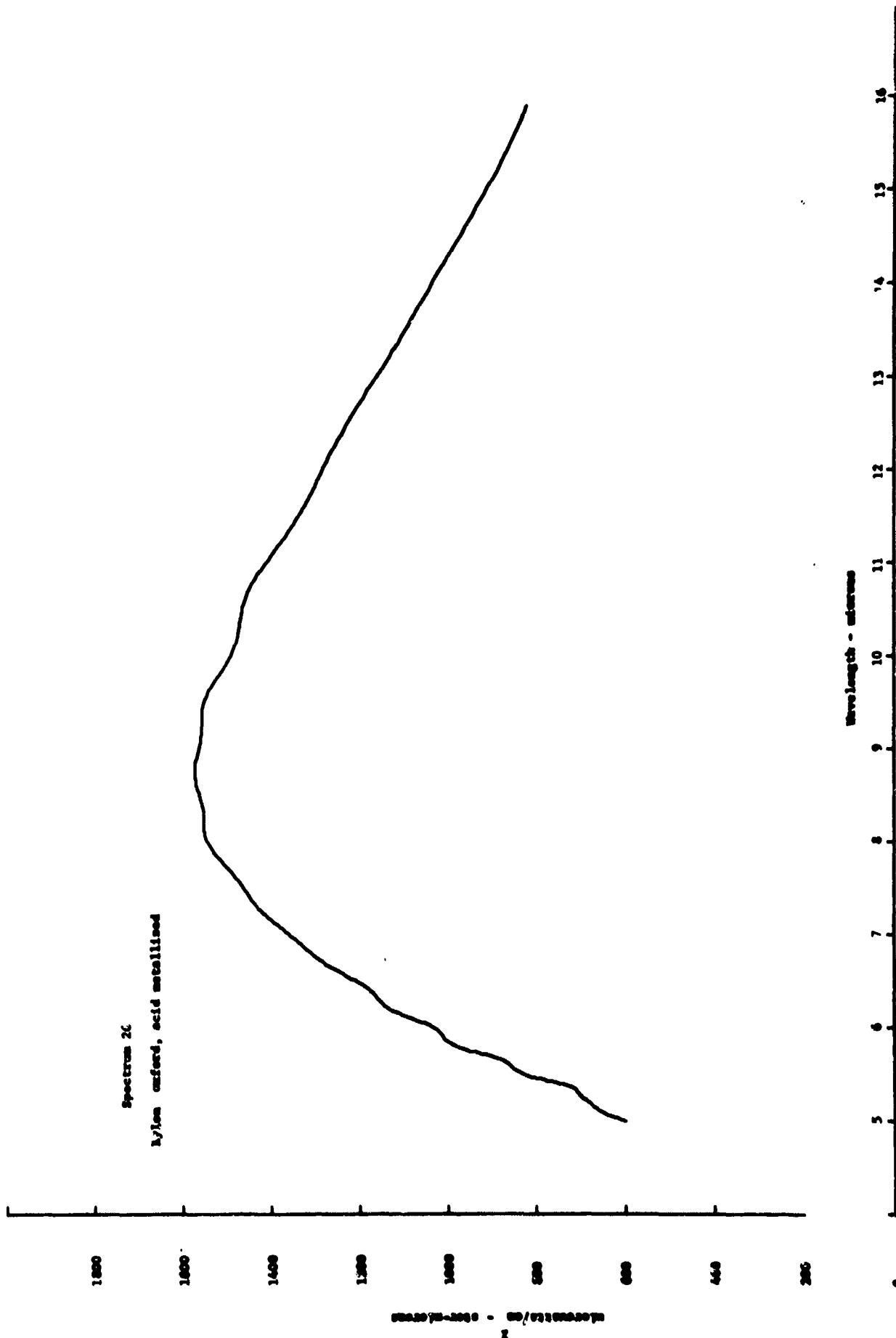


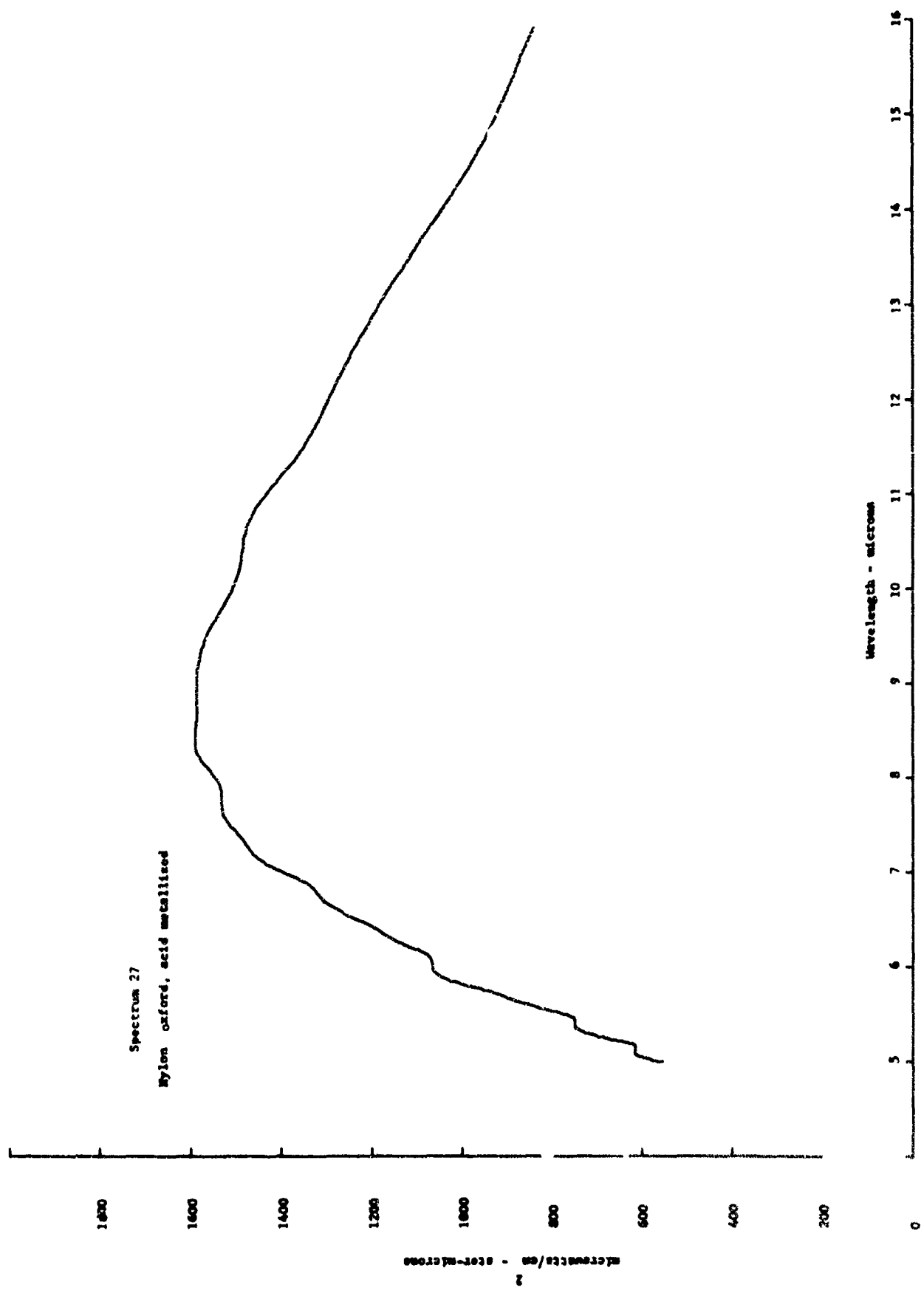
Spectrum 22
Wool sample, 18 cm, 85-0717

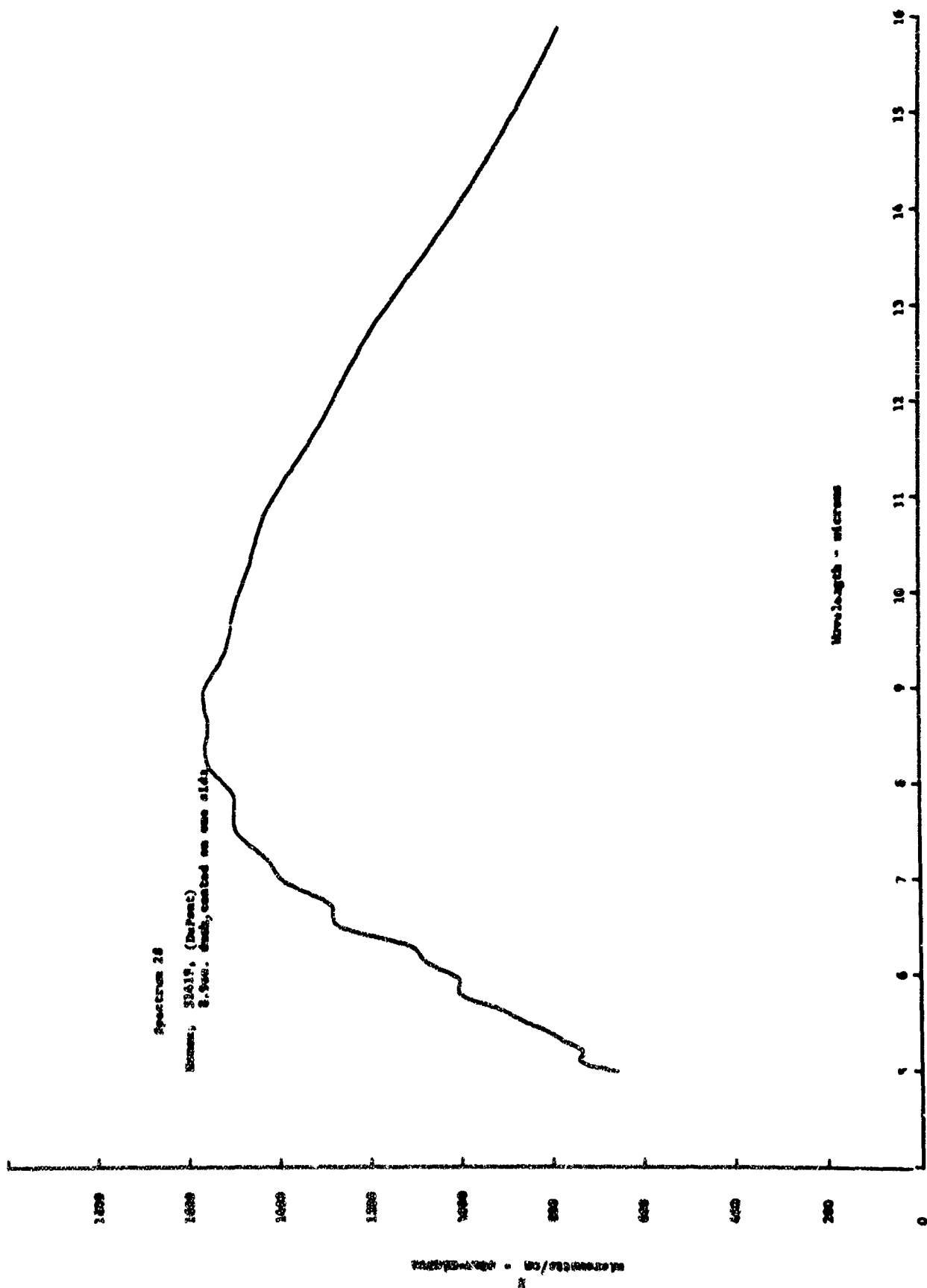


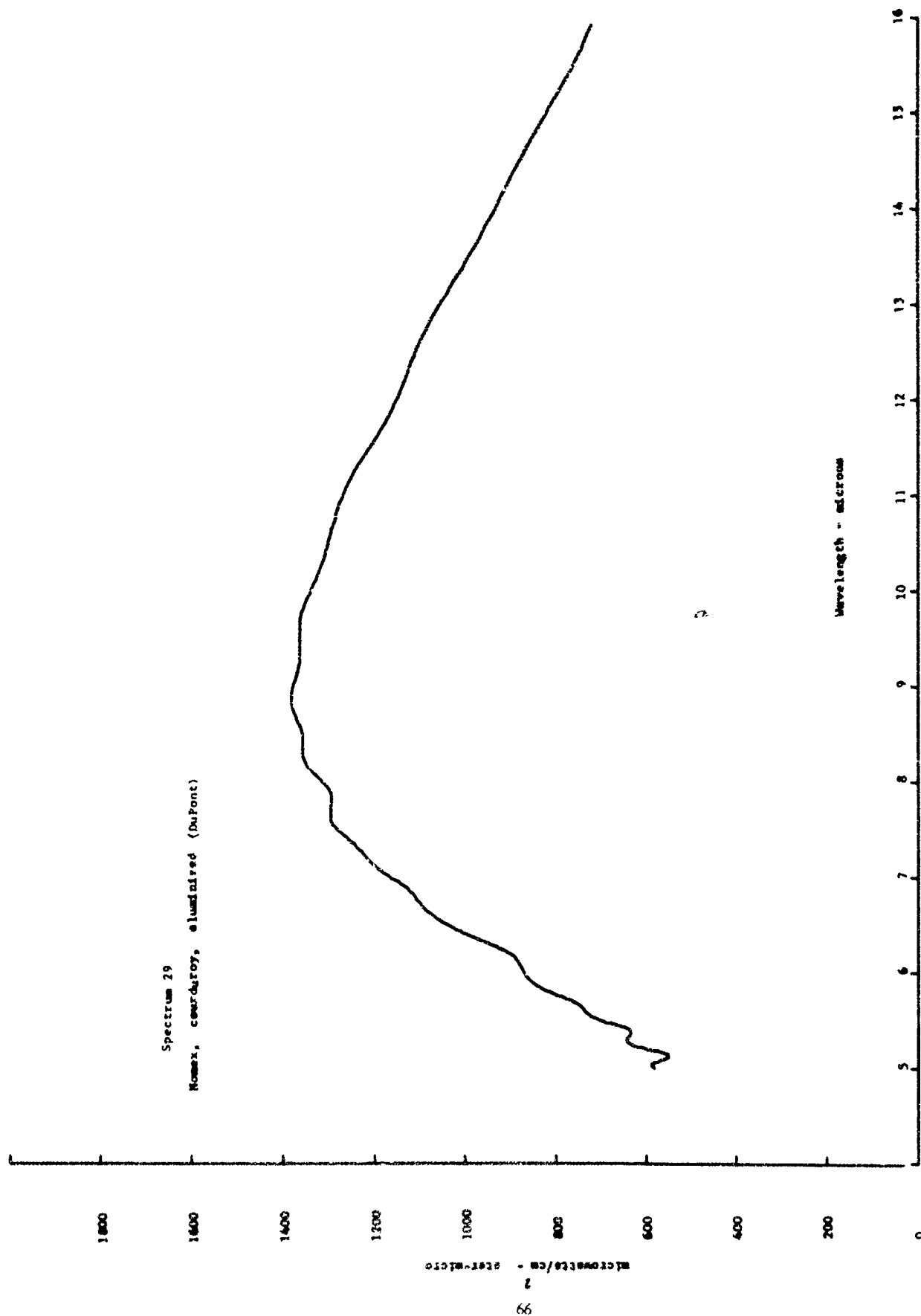






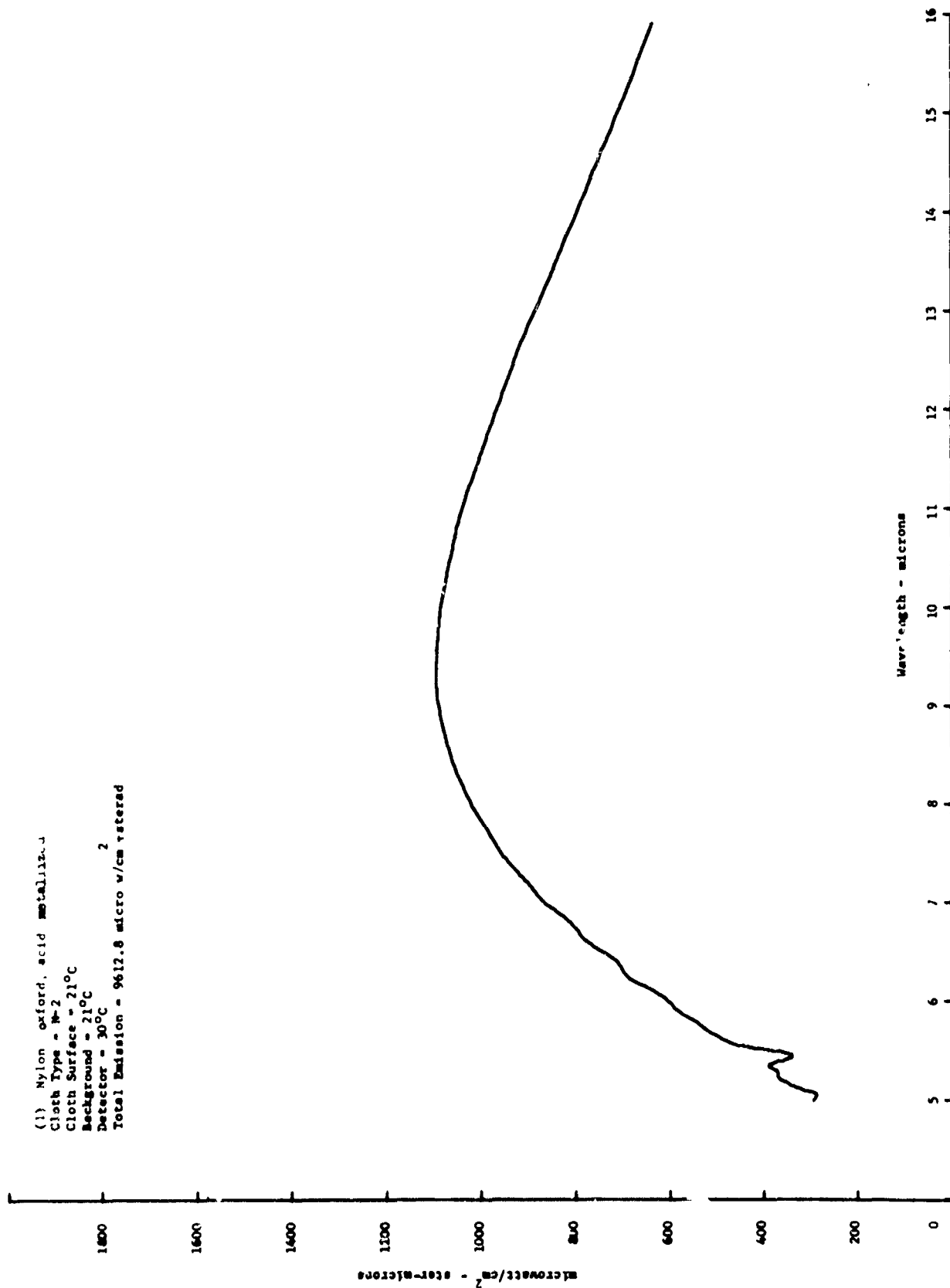


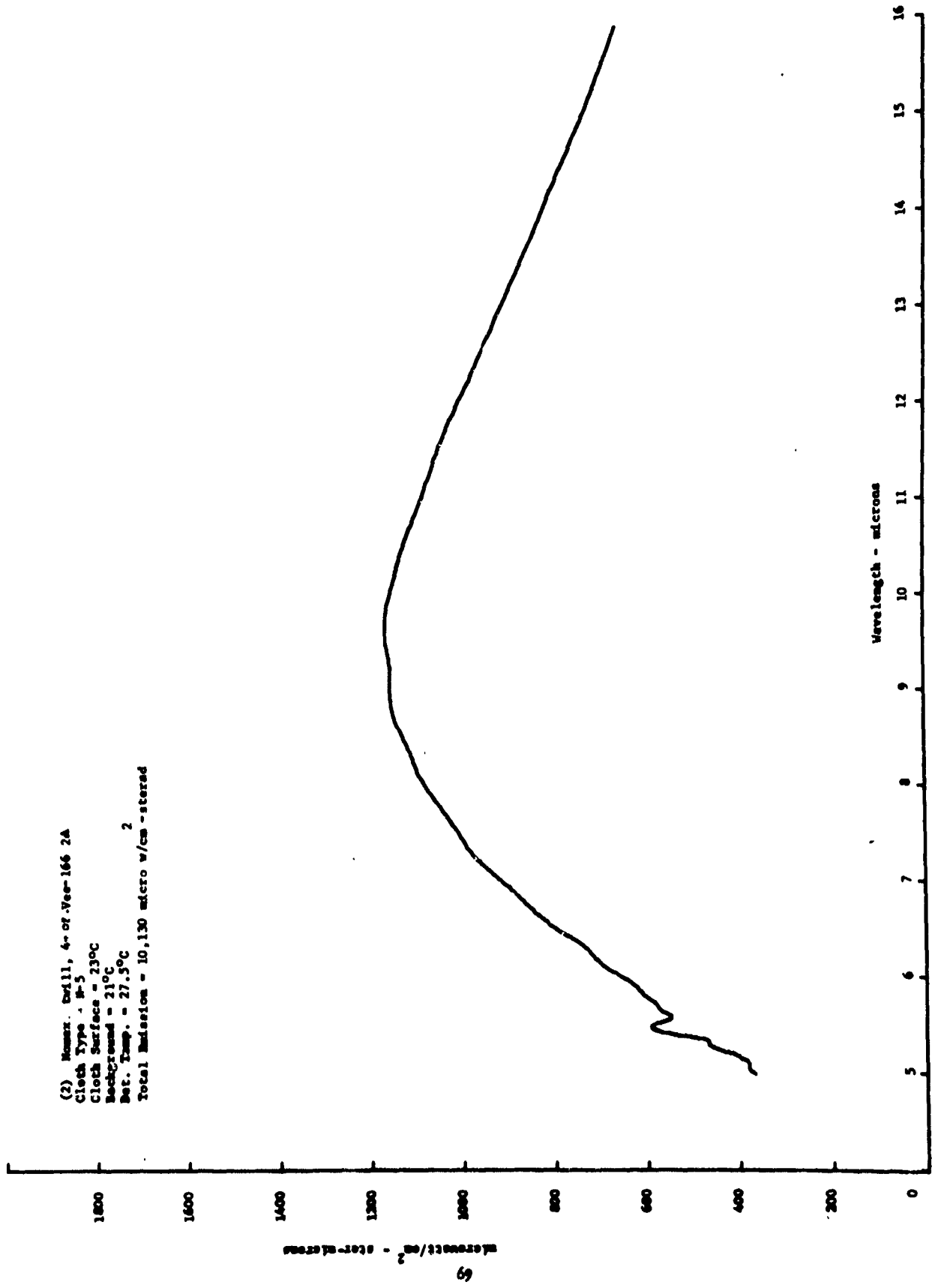


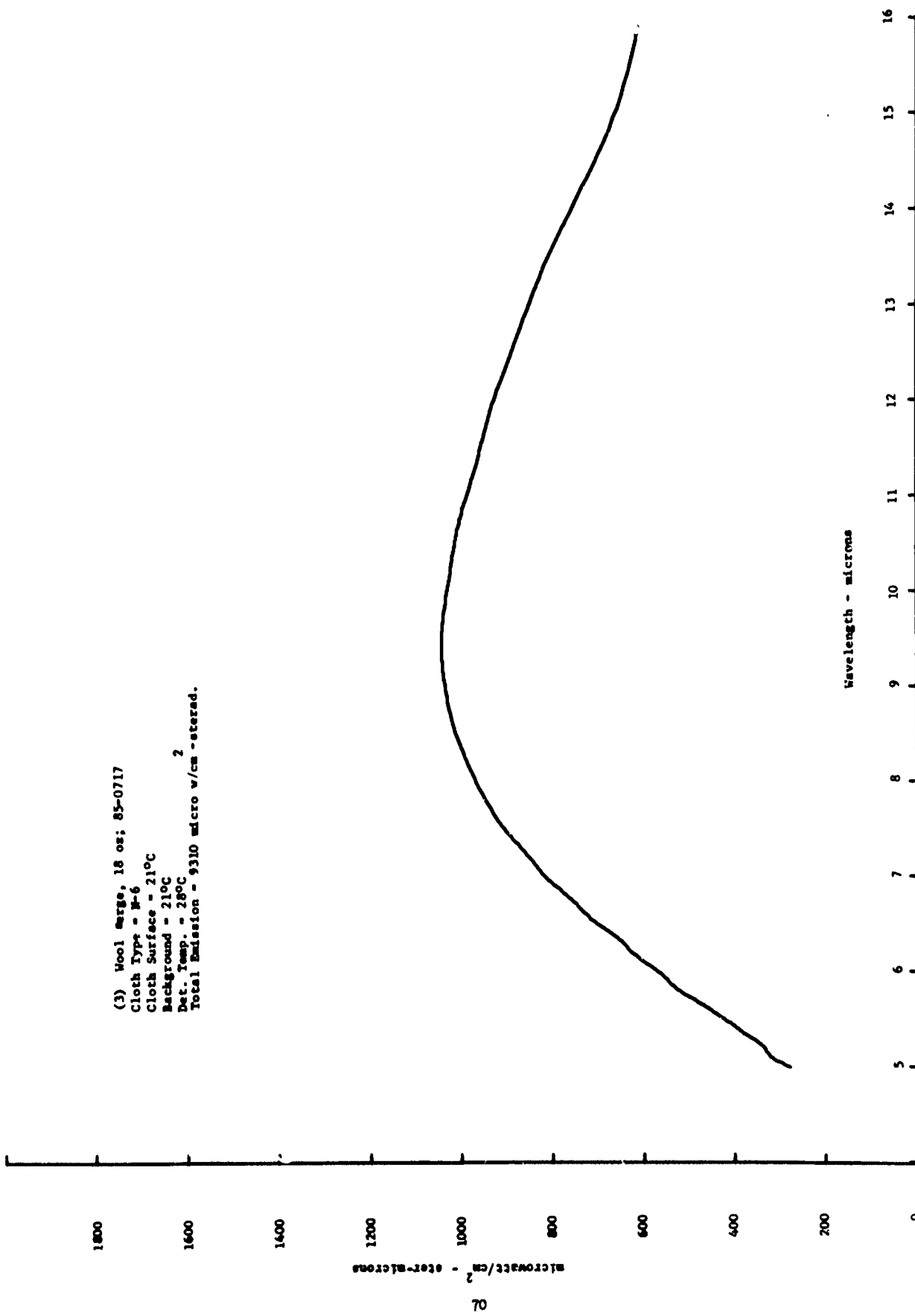


GROUP II SPECTRA

(1) Nylon oxford, acid metallized
 Cloth Type - W-2
 Cloth Surface - 21°C
 Background - 21°C
 Detector - 30°C
 Total Emission - 9612.8 micro w/cm² sterad

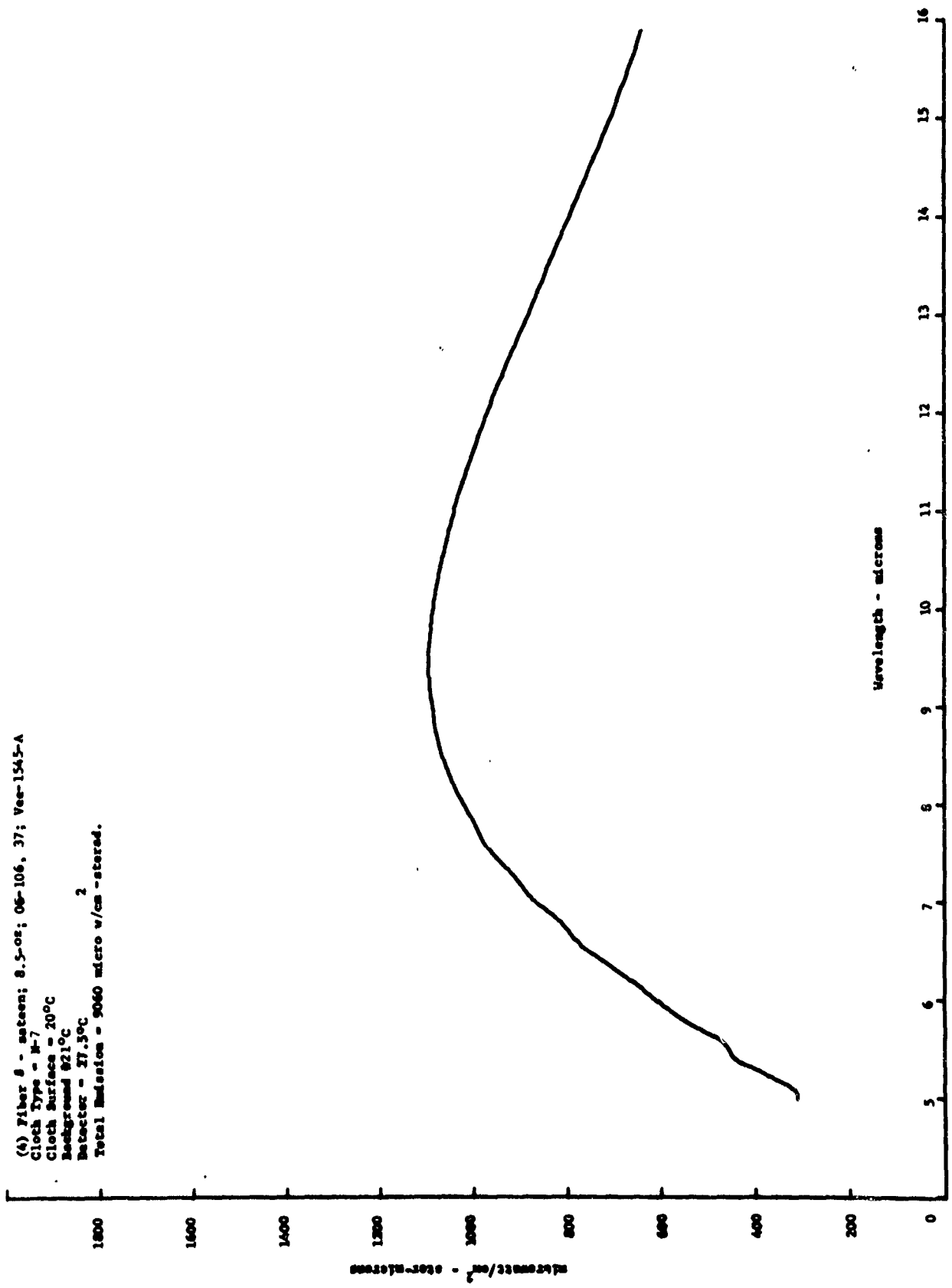




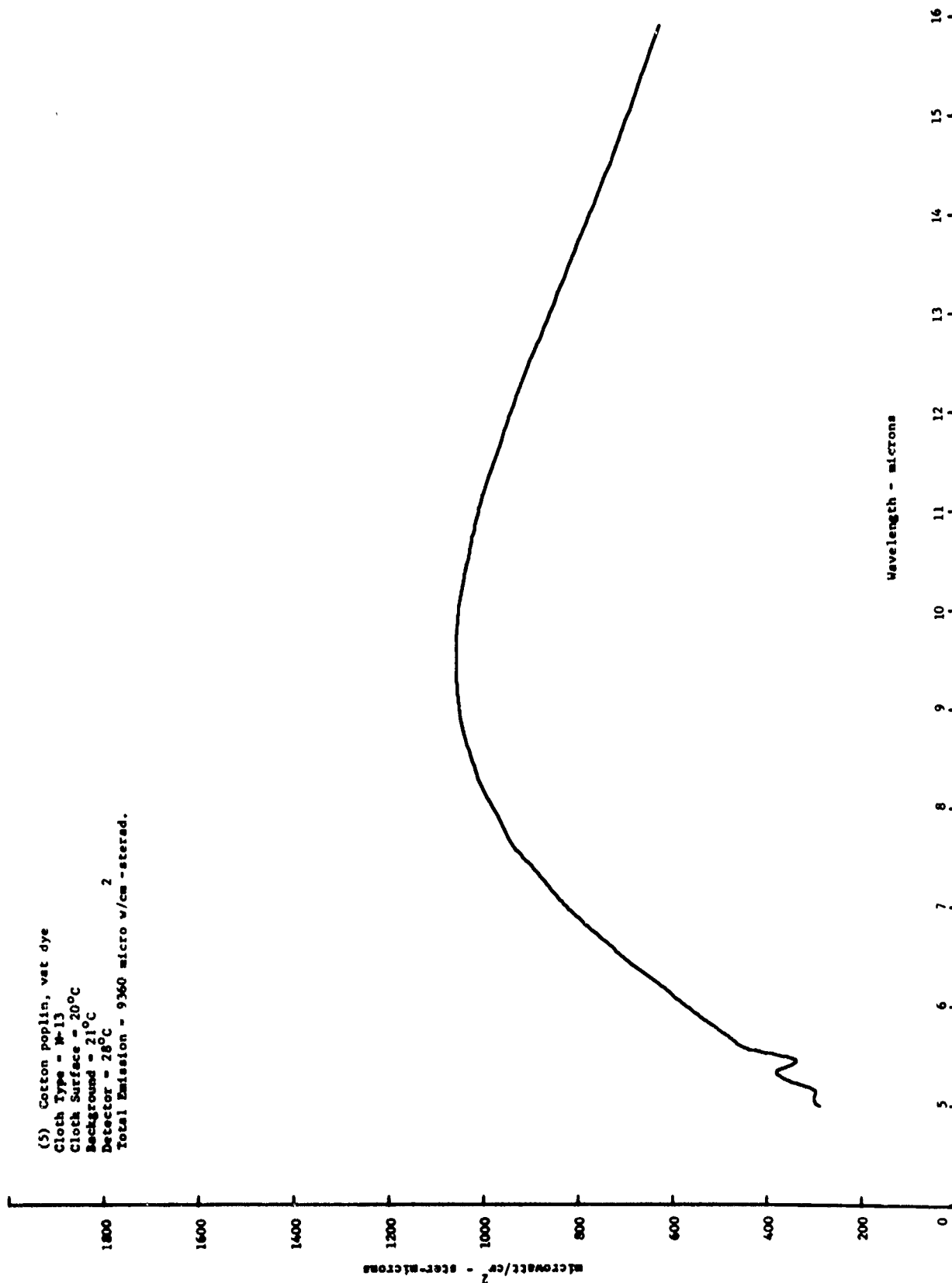


(3) Wool serge, 18 oz; 85-0717
Cloth Type - B-6
Cloth Surface - 21°C
Background - 21°C
Det. Temp. - 28°C
Total Emission - 9310 micro w/cm²-sterad.

(4) Fiber 8 - matten; 8.5-oz; 06-106, 37; Vee-1545-A
 Cloth Type - M-7
 Cloth Surface - 20°C
 Background 821°C
 Detector - 27.3°C
 Total Emission = 9060 micro w/cm²-sterad.

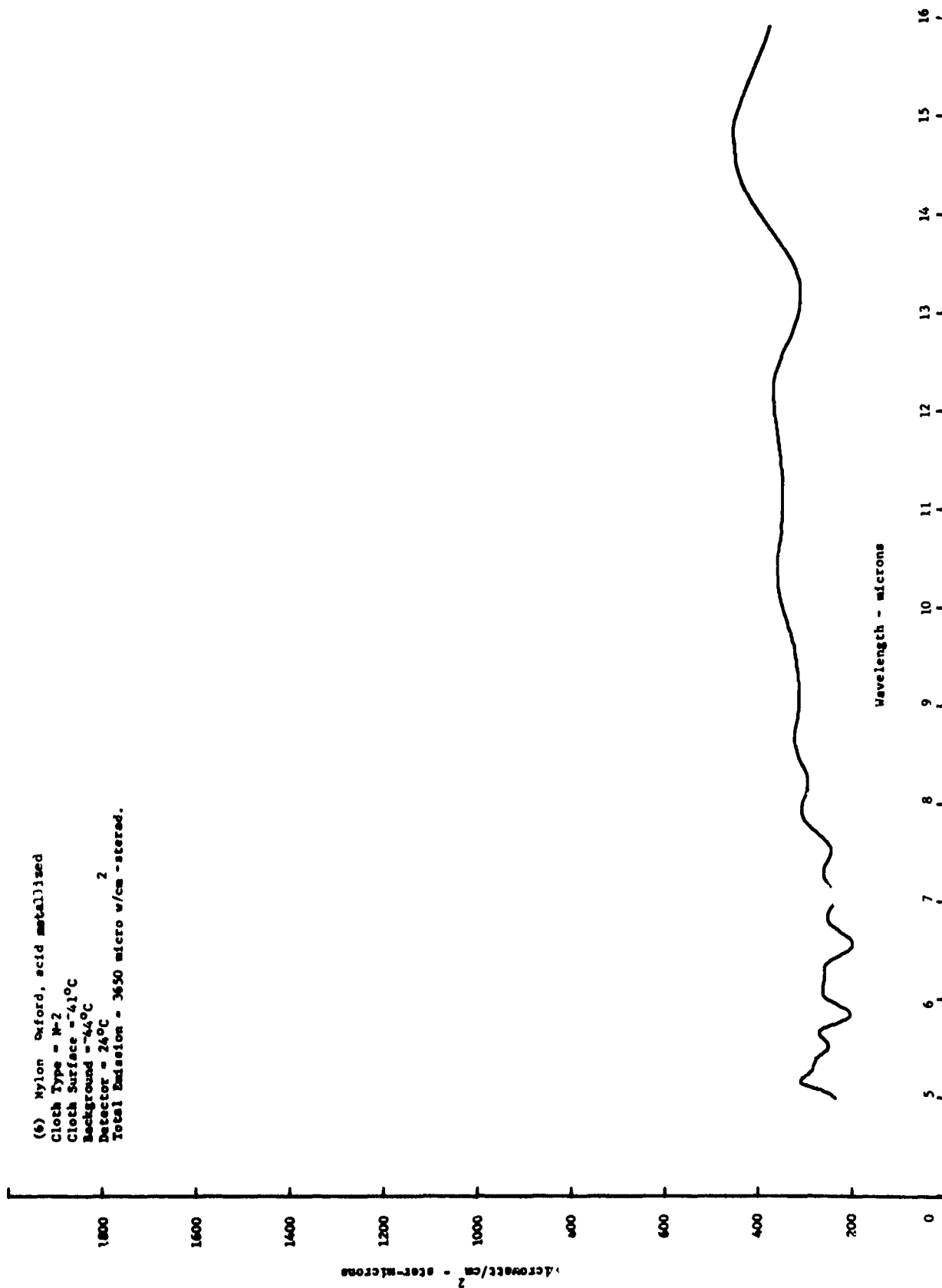


(5) Cotton poplin, vat dye
 Cloth Type - M-13
 Cloth Surface - 20°C
 Background - 21°C
 Detector - 28°C
 Total Emission - 9360 micro w/cm²-sterad.

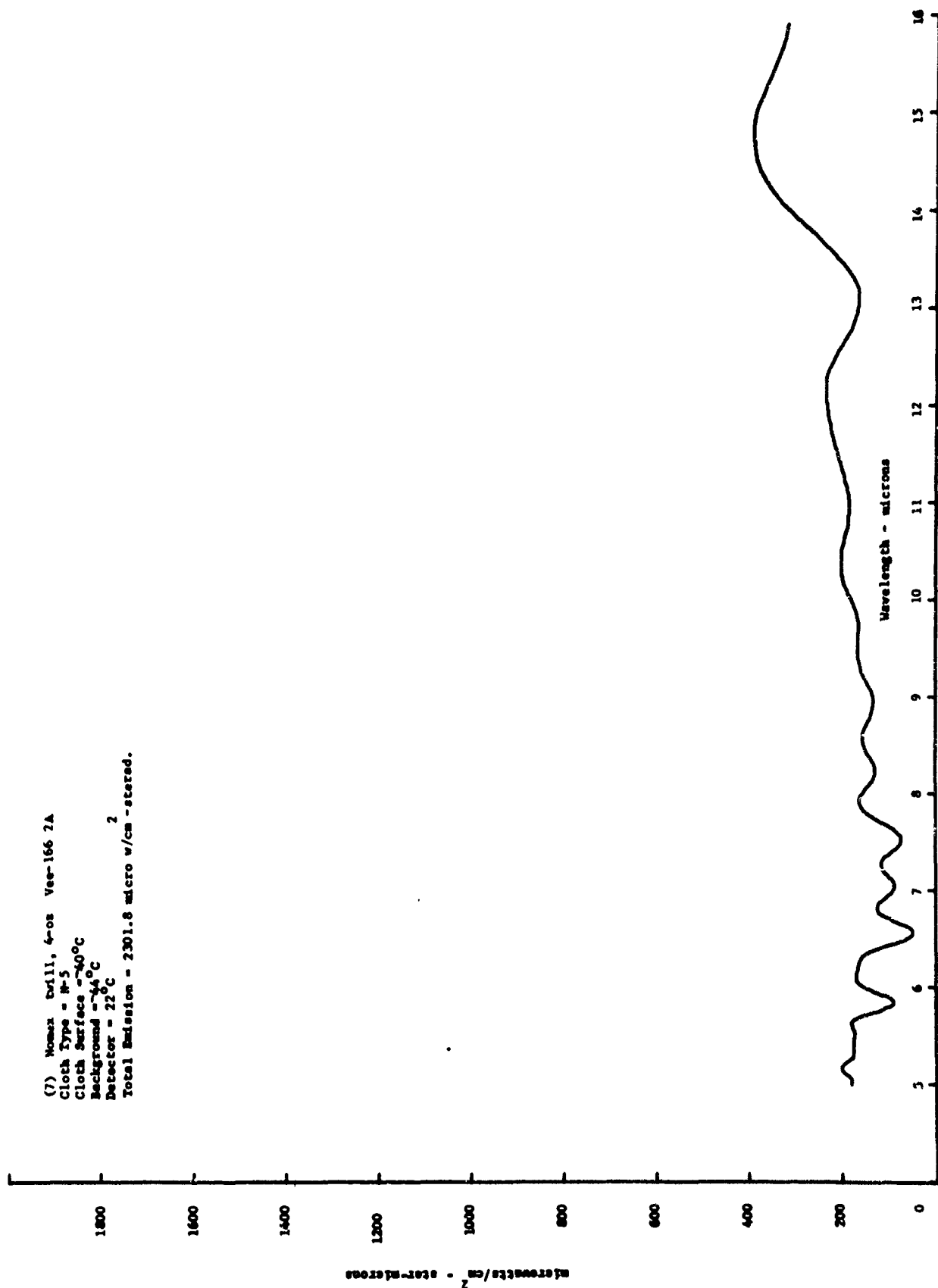


GROUP III SPECTRA

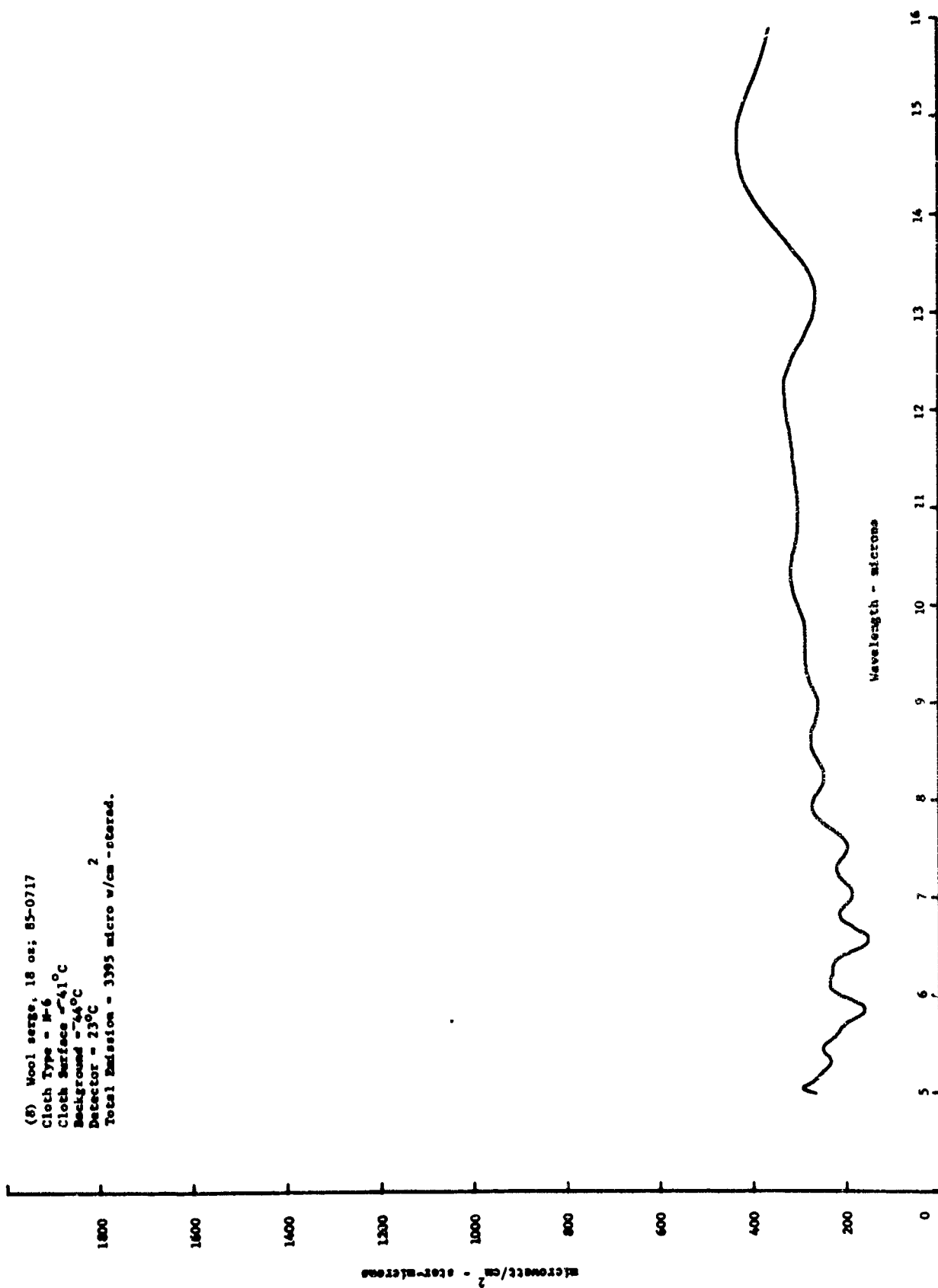
(6) Nylon Oxford, acid metallized
 Cloth Type - M-2
 Cloth Surface - 41°C
 Background - 44°C
 Detector - 24°C
 Total Emission - 3650 micro w/cm²-sterad.



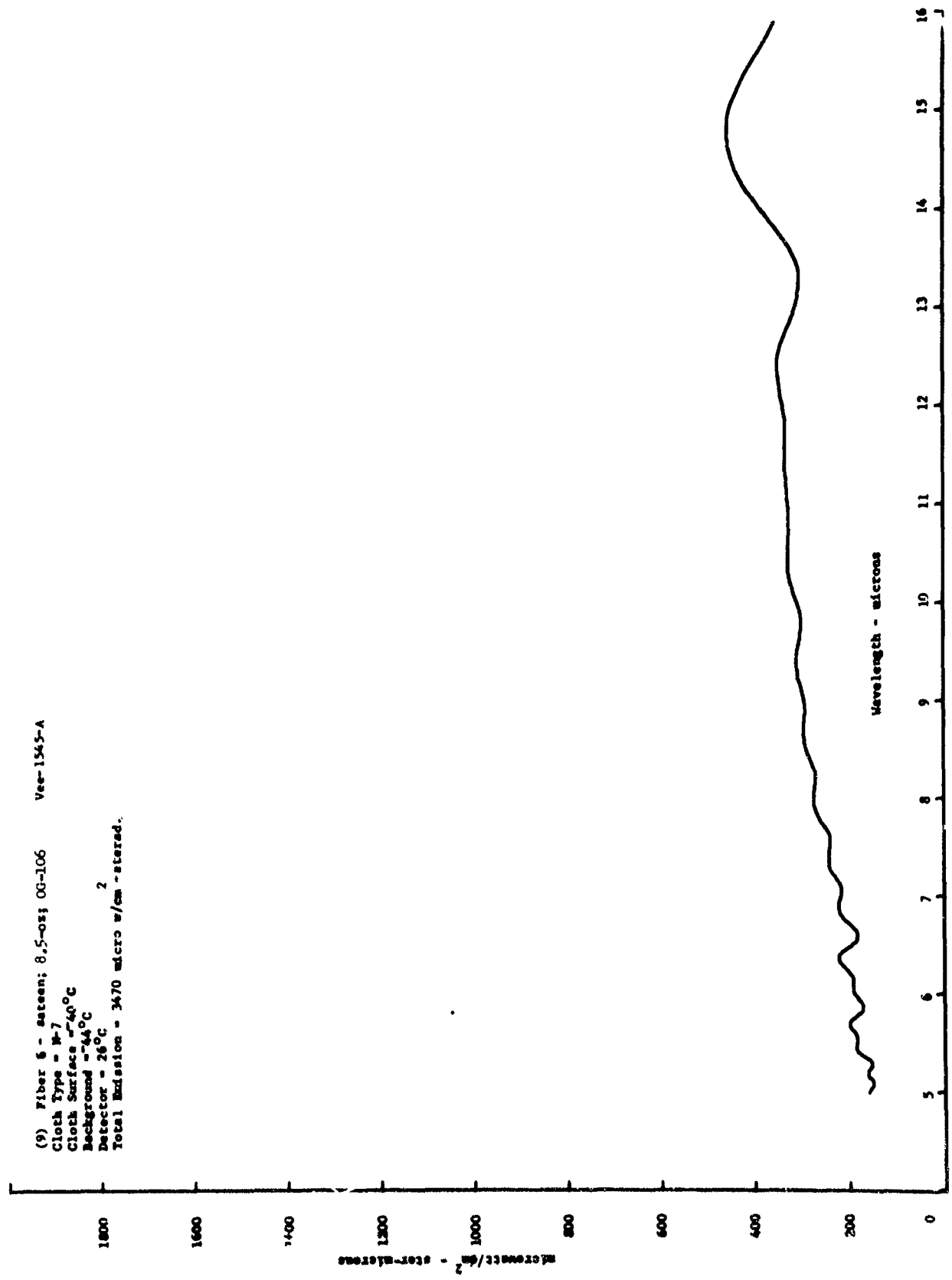
(7) Nomex Drill, 4-oz Veer-166 2A
 Cloth Type - N-5
 Cloth Surface - -40°C
 Background - -44°C
 Detector - 22°C
 Total Emission - 2301.8 micro w/cm²-sterad.

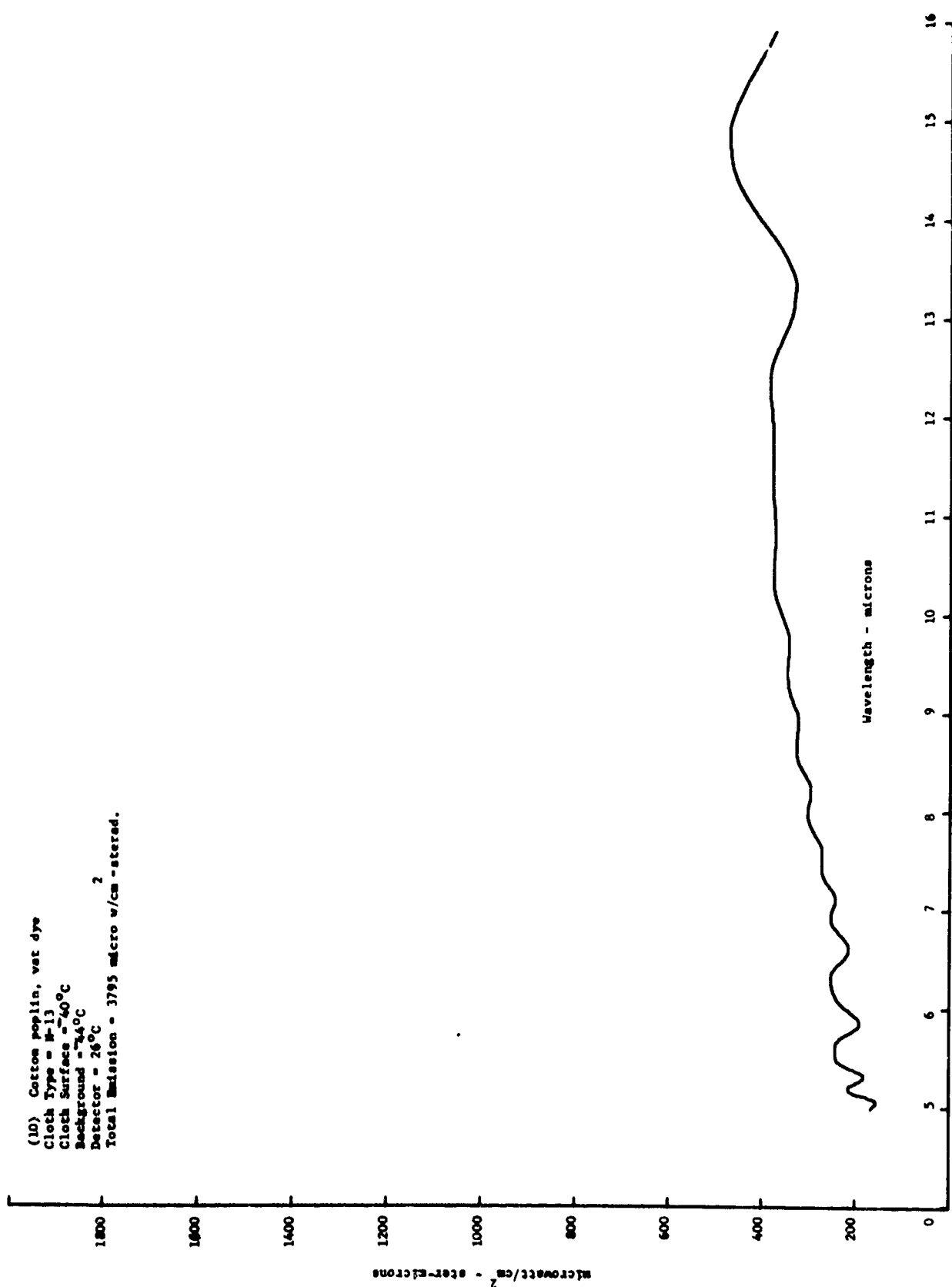


(8) Wool serge, 18 oz; 85-0717
 Cloth Type - B-6
 Cloth Surface - 41°C
 Background - 44°C
 Detector - 23°C
 Total Emission - 3395 micro w/cm² - stored.



(9) Fiber 5 - asten; 8,5-oz; 00-106 Vee-1545-A
Cloth Type - M-7
Cloth Surface - 40°C
Background - 44°C
Detector - 26°C
Total Emission - 3470 micro w/cm - sterad.

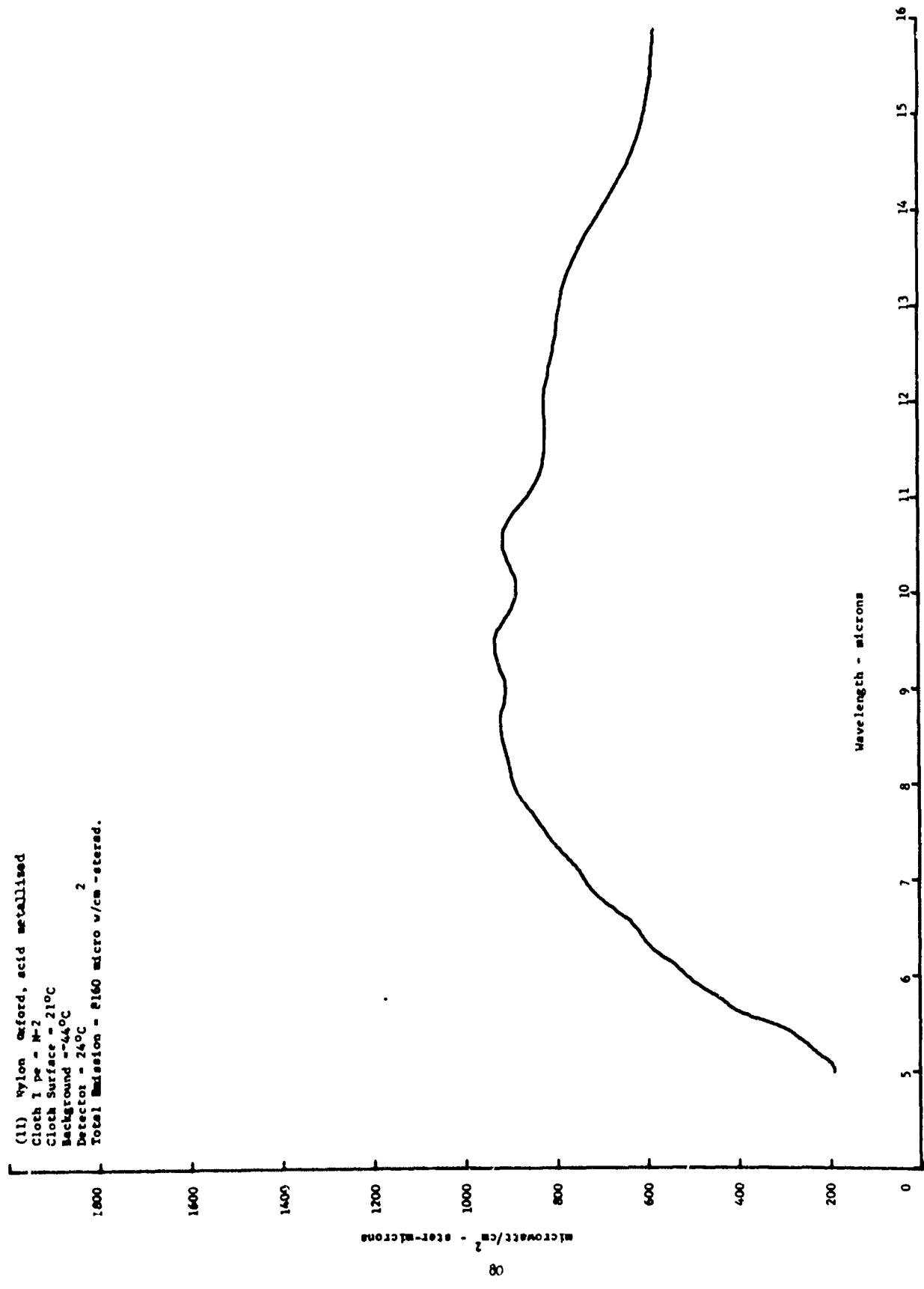




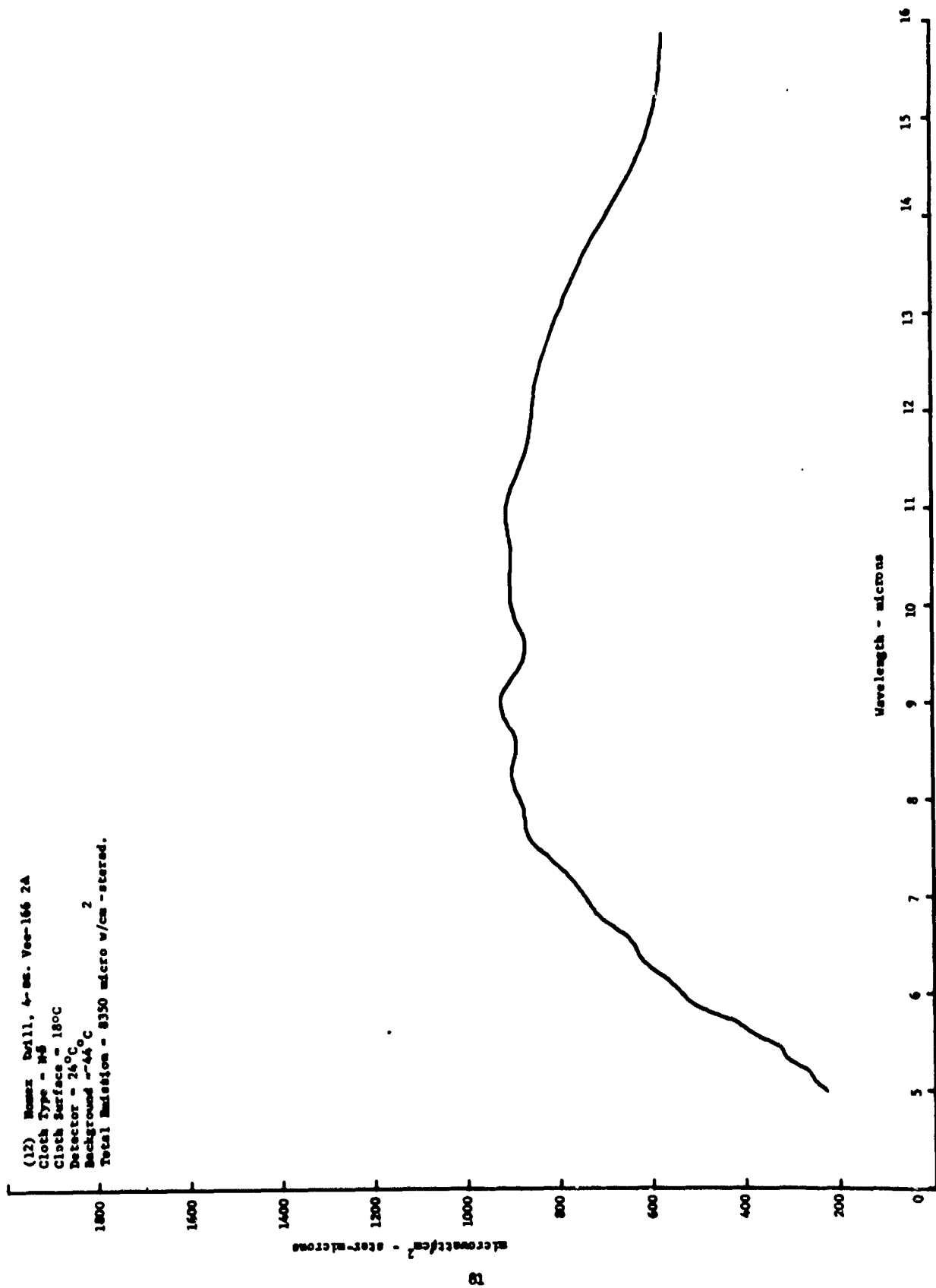
(10) Cotton poplin, vat dye
Cloth Type - M-13
Cloth Surface - 40°C
Background - 40°C
Detector - 26°C
Total Emission - 3795 micro w/cm² - sterad.

GROUP IV SPECTRA

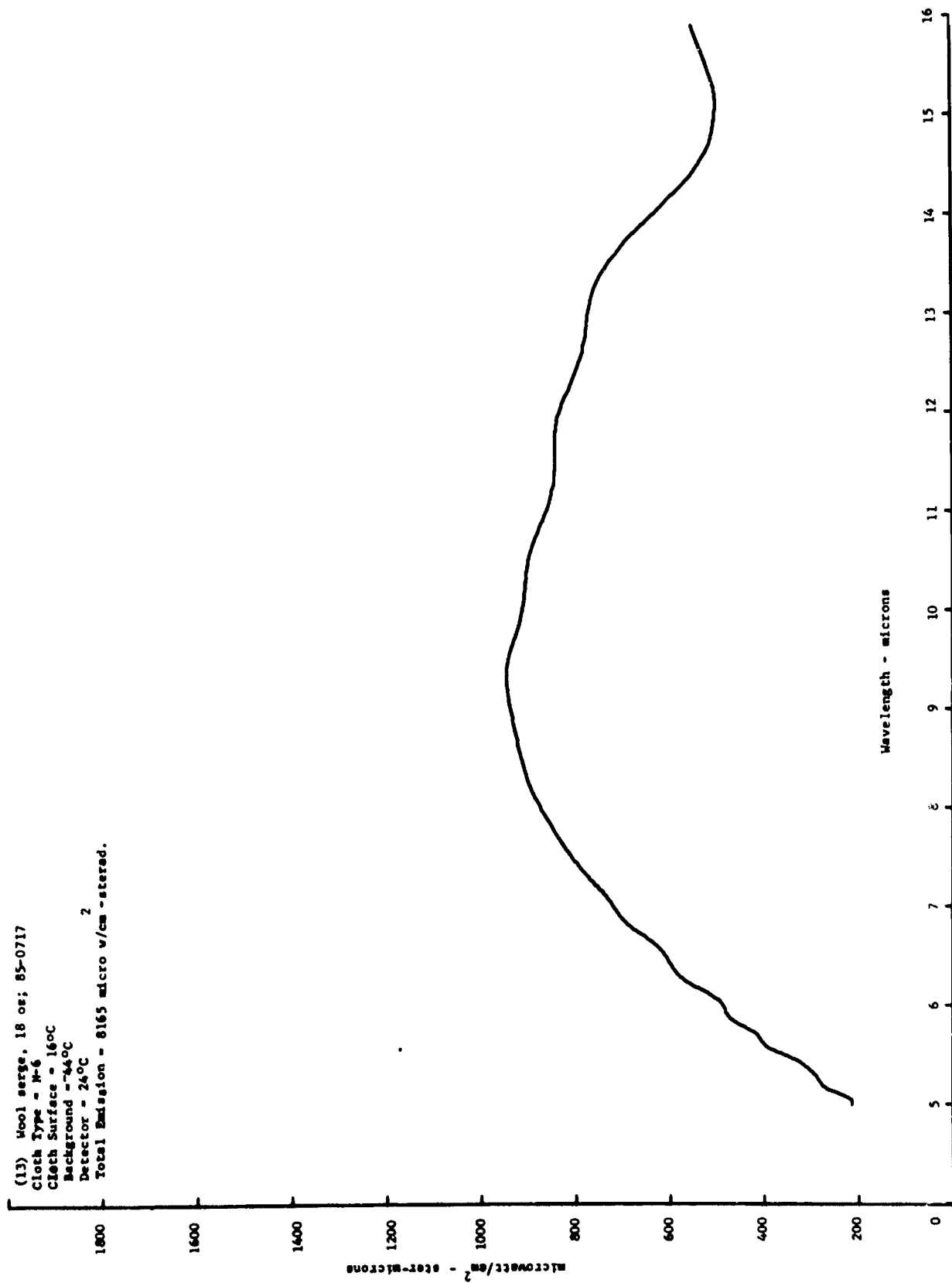
(11) Nylon Oxford, acid metallized
Cloth type - M-2
Cloth Surface - 21°C
Background - -44°C
Detector - 24°C
Total Emission - 8160 micro w/cm²-sterad.



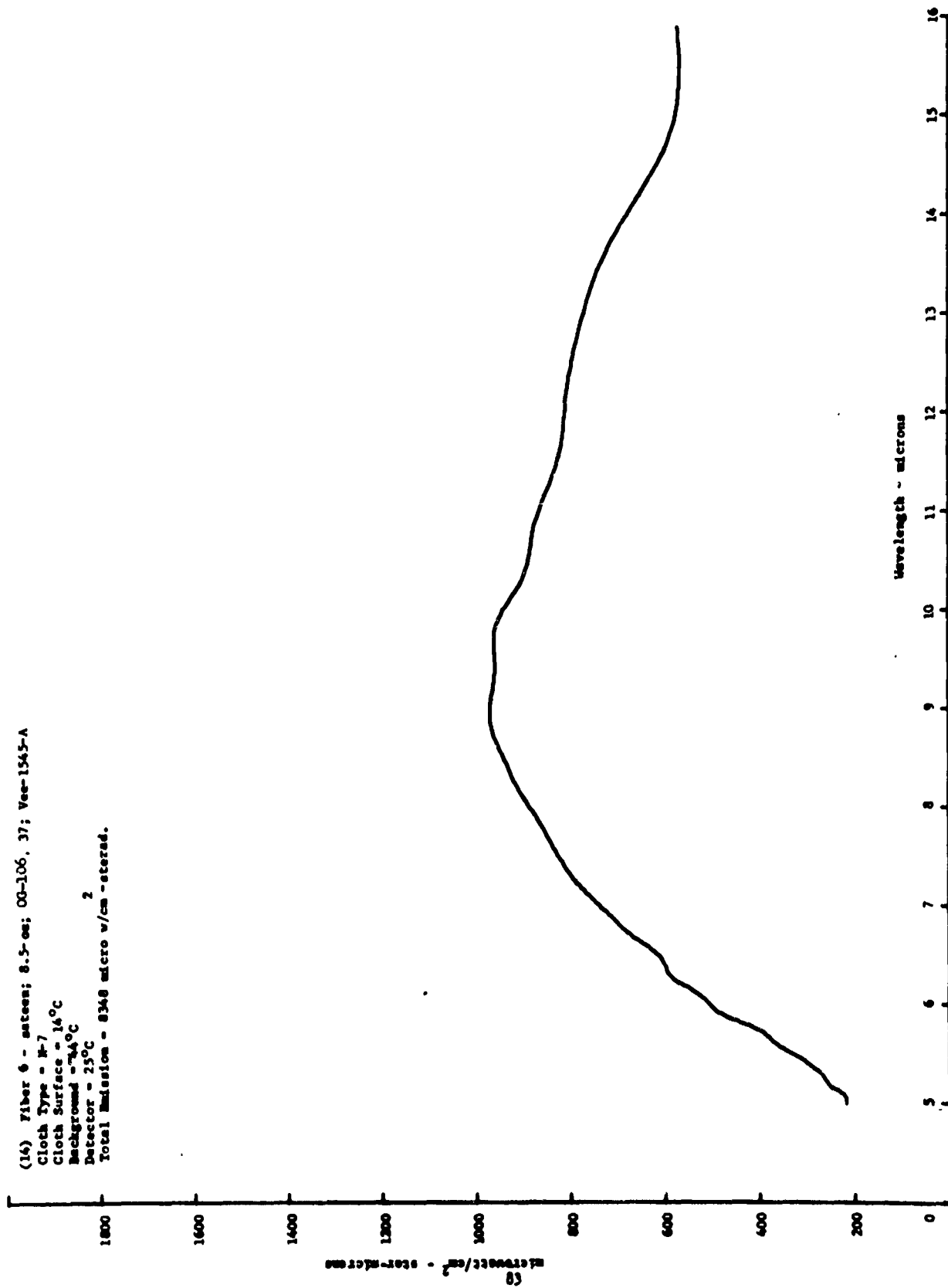
(12) Roman Drill, 4-ss. Veer-166 2A
 Cloth Type - M-8
 Cloth Surface - 180C
 Detector - 24°C
 Background - 44°C
 Total Emission - 8350 micro w/cm² -stered.



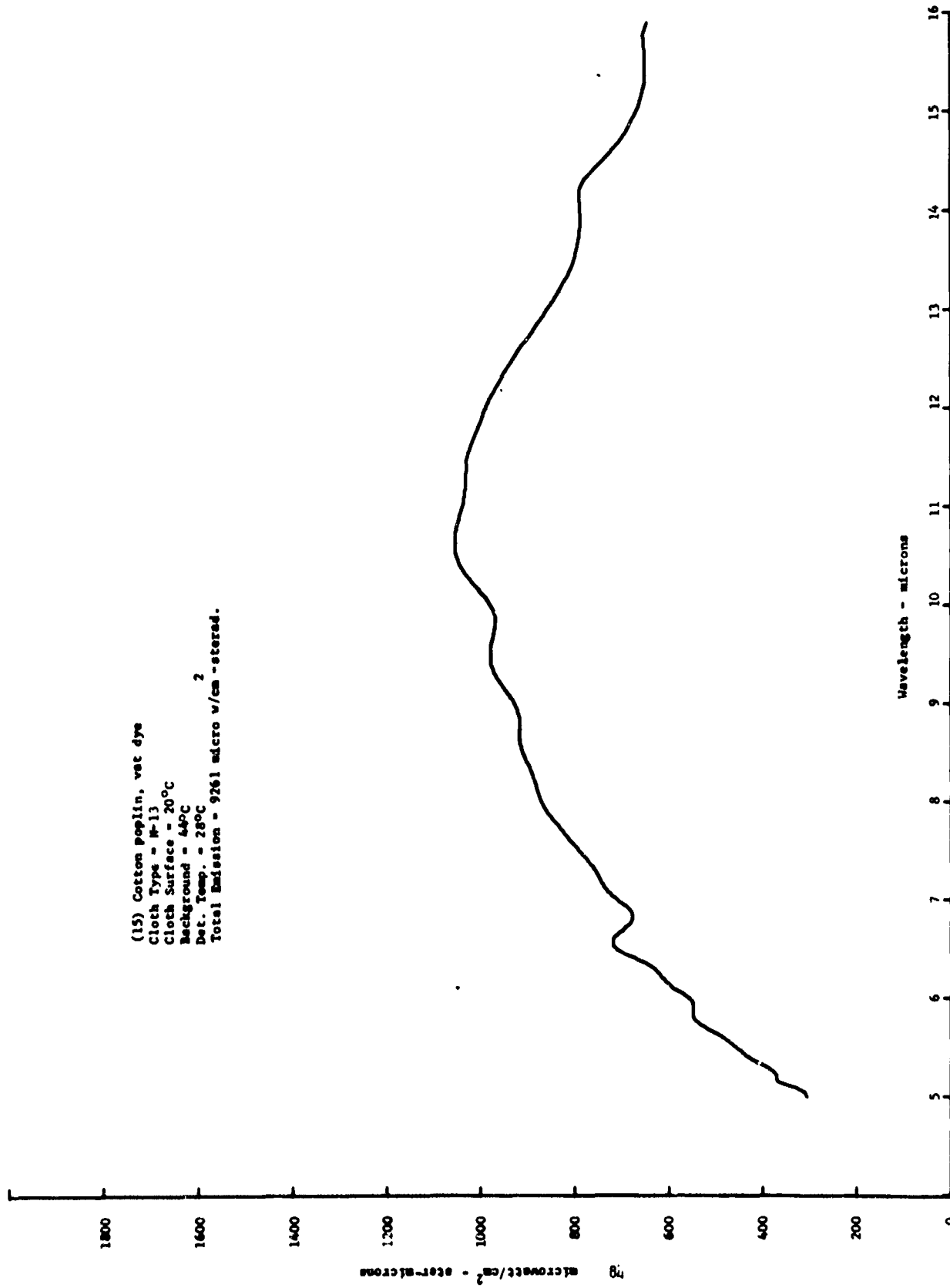
(13) Wool serge, 18 oz; 85-0717
 Cloth Type - M-6
 Cloth Surface - 160C
 Background - 440C
 Detector - 240C
 Total Emission - 8165 micro w/cm²-sterad.²



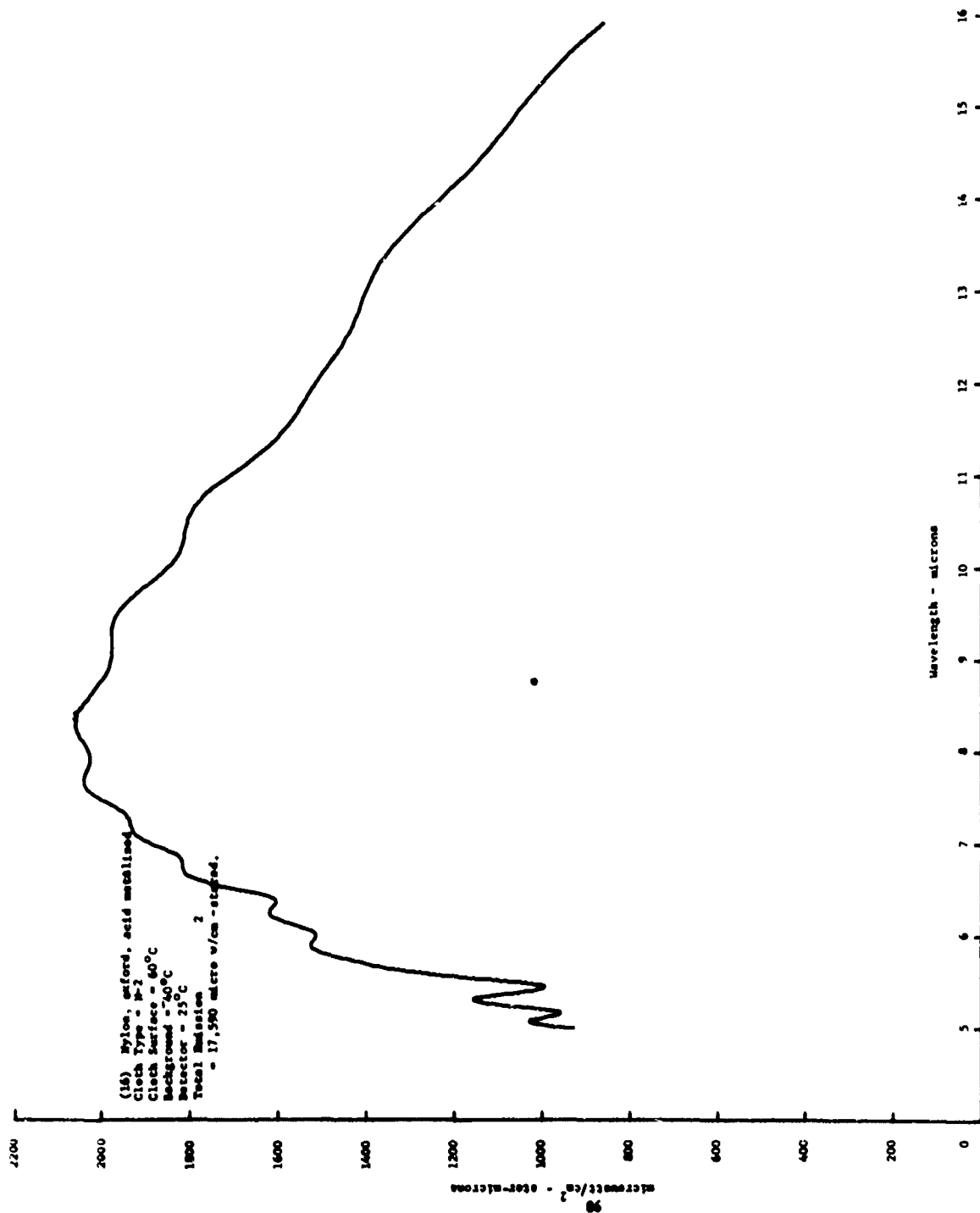
(14) Fiber 6 - anteen; 8.5-oz; 00-106, 37; Vee-1545-A
 Cloth Type - M-7
 Cloth Surface - 14°C
 Background - 24°C
 Detector - 25°C
 Total Emission - 8348 micro w/cm² - sterad.



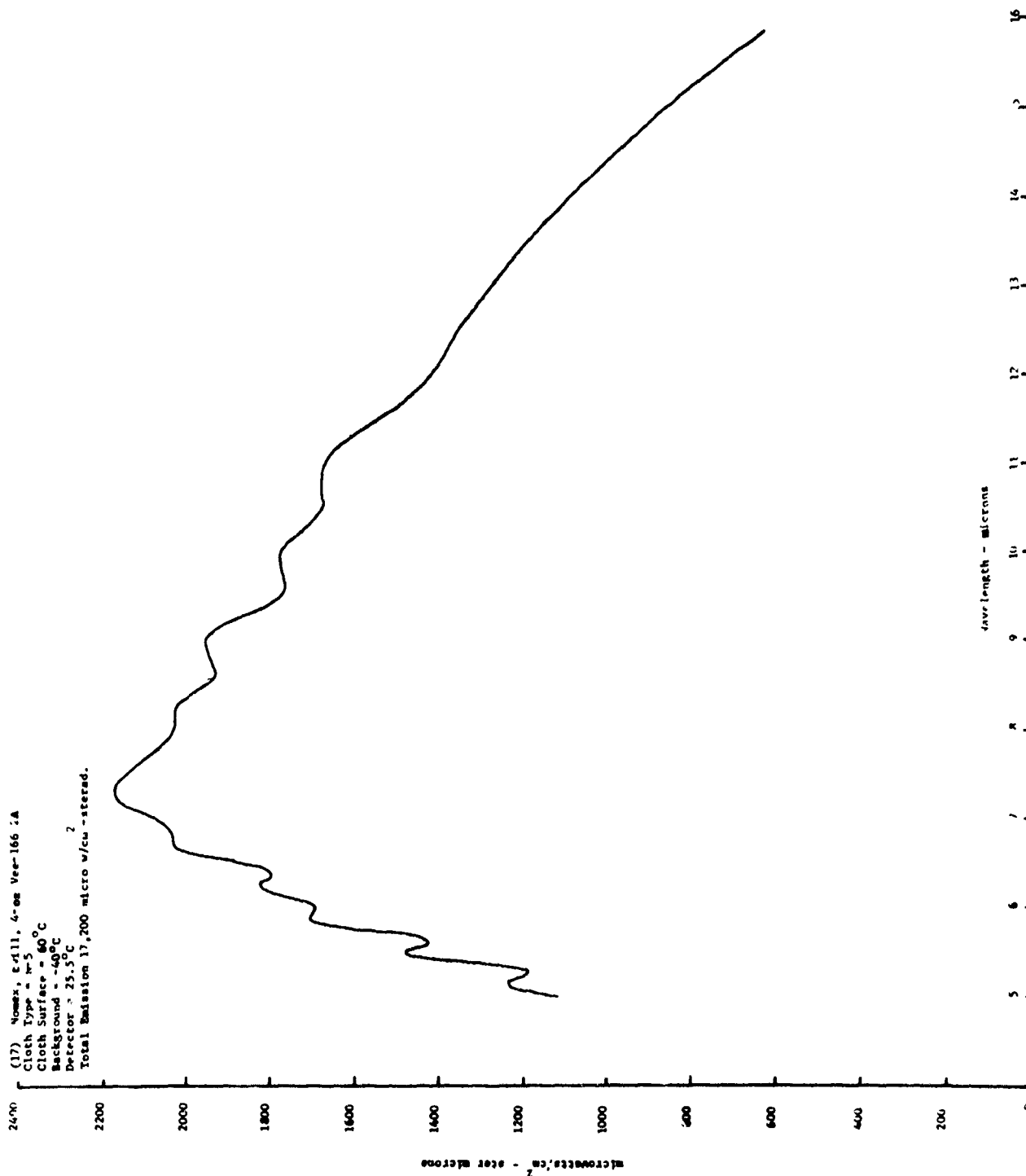
(15) Cotton poplin, vat dye
Cloth Type - M-13
Cloth Surface - 20°C
Background - 44°C
Det. Temp. - 28°C
Total Emission - 9261 micro v/cm -sterad.²



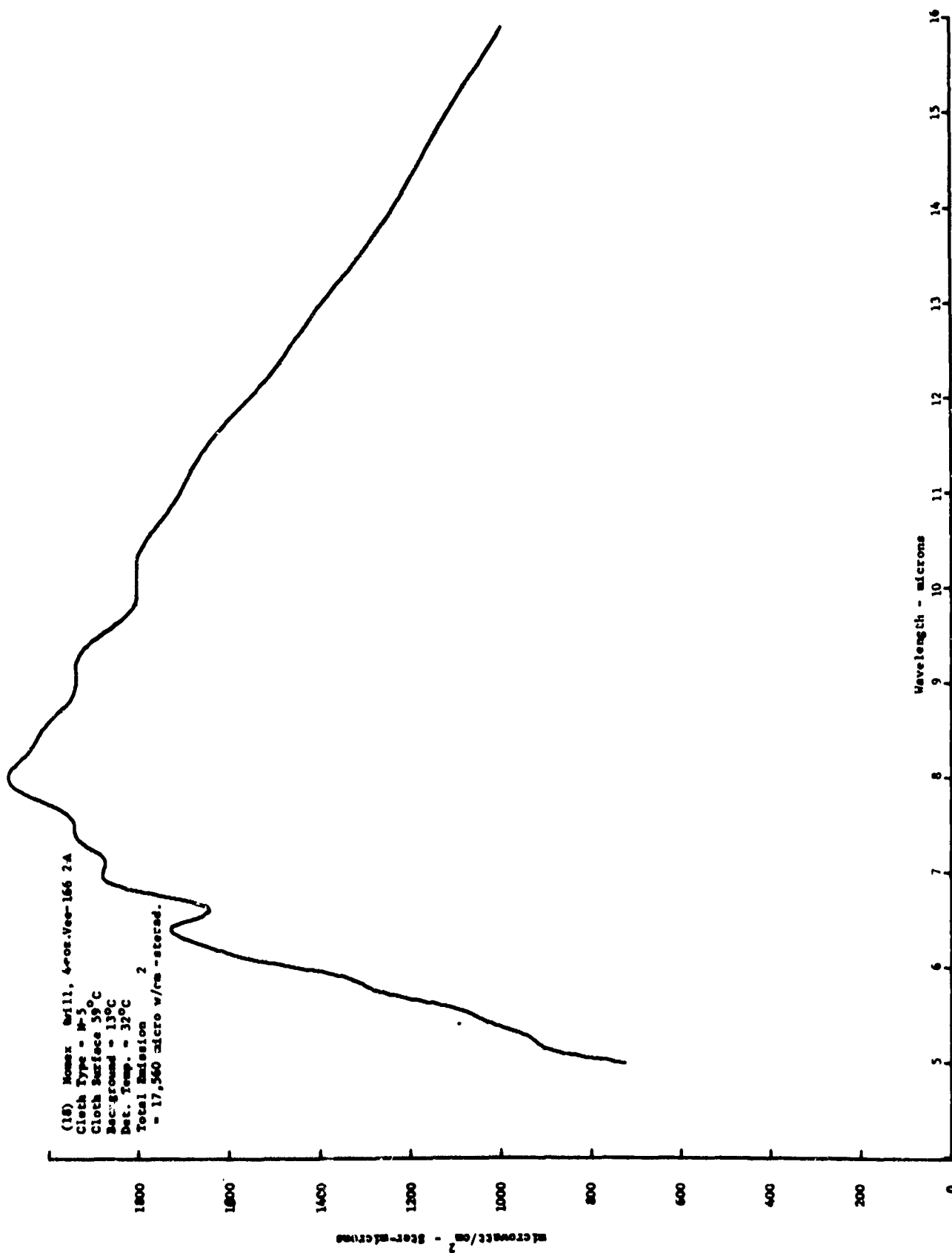
GROUP V SPECTRA



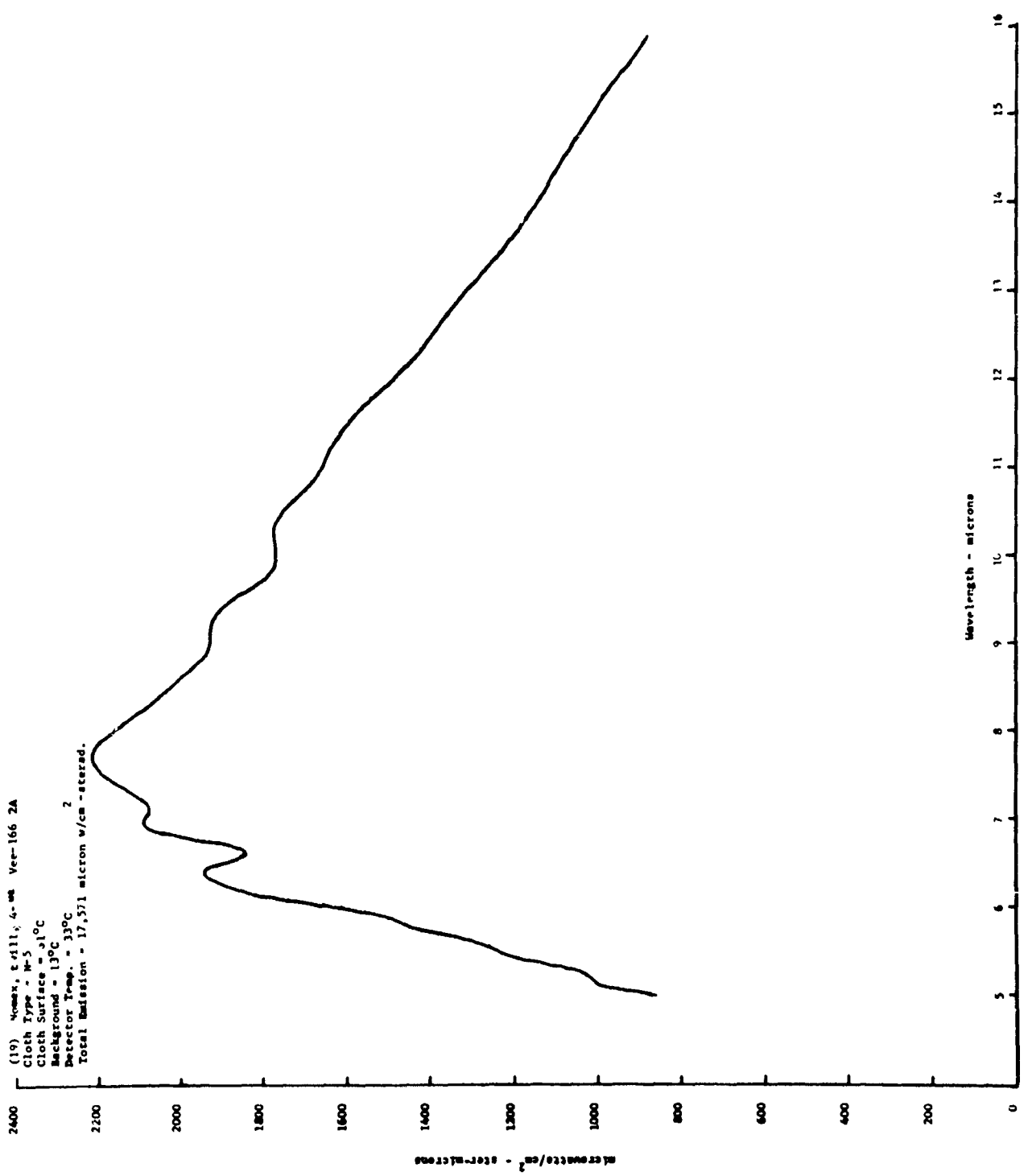
(17) Nomex, E411, 4-oz Vee-166 1A
 Cloth Type - W-5
 Cloth Surface - 60°C
 Background - -40°C
 Detector - 25.5°C
 Total Emission 17,200 micro w/cw -sterad.

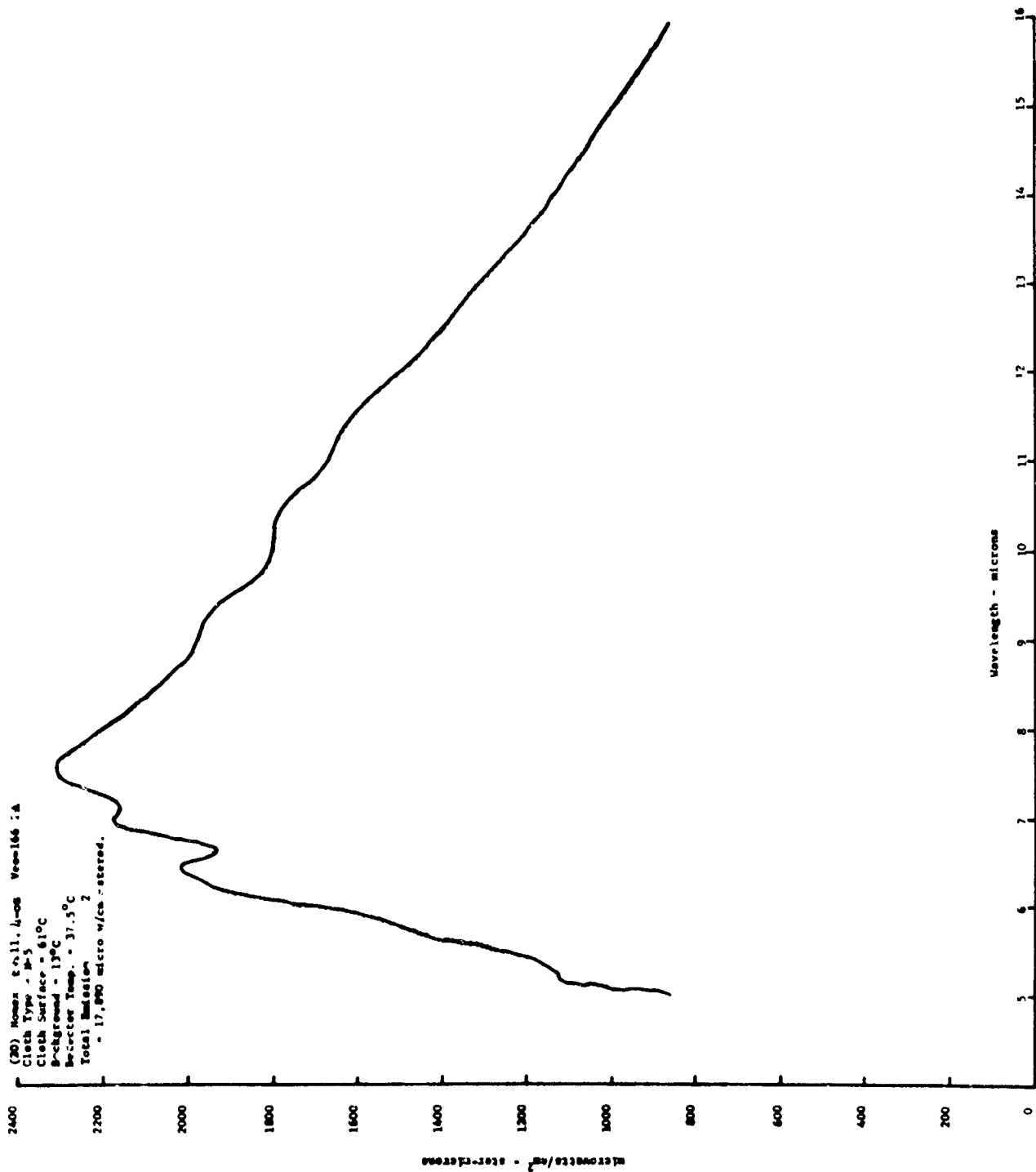


GROUP VI SPECTRA



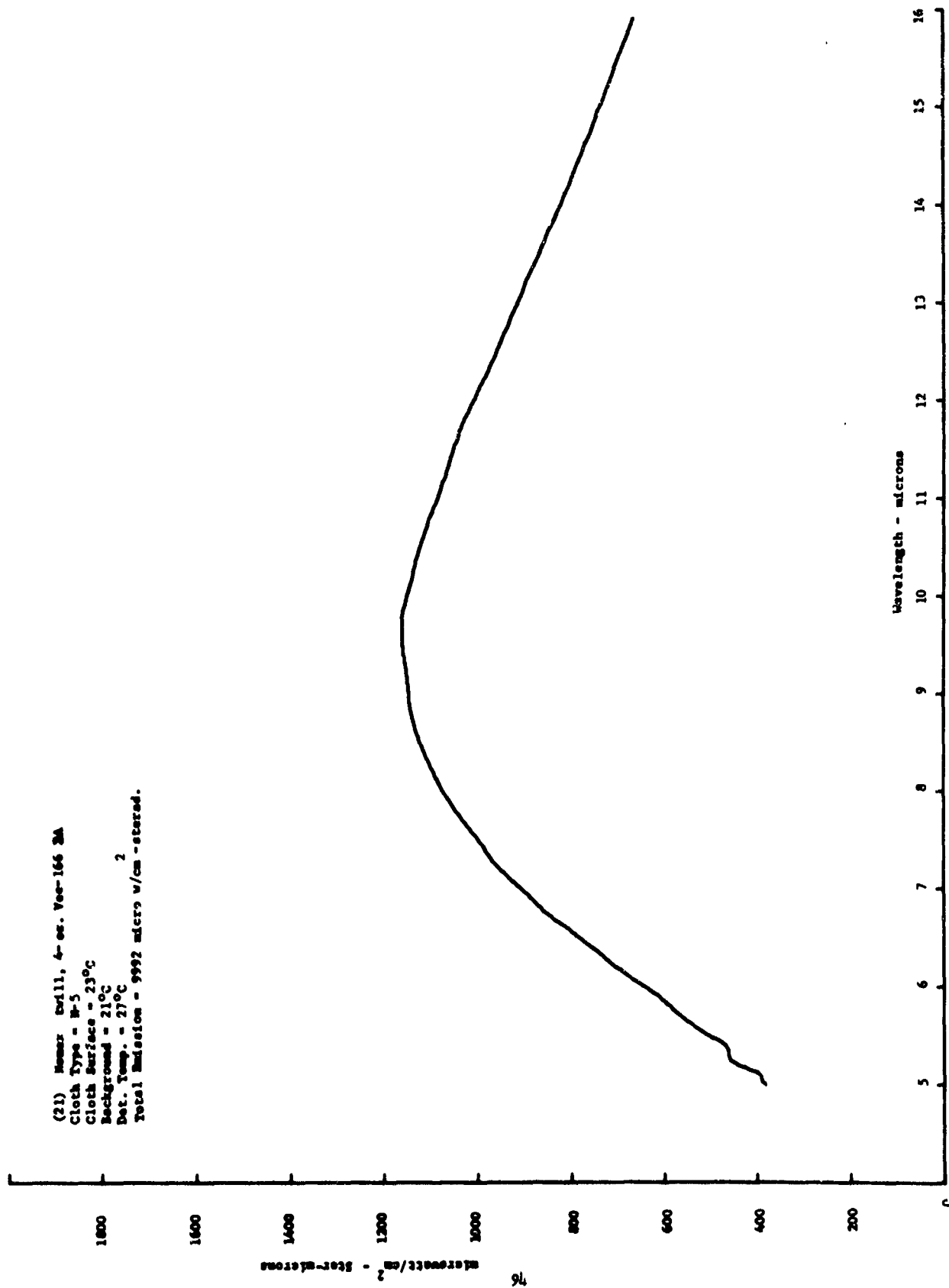
(19) Nomax, 4-um Vee-166 2A
 Cloth Type - M-5
 Cloth Surface - 31°C
 Background - 13°C
 Detector Temp. - 33°C
 Total Emission - 17,571 micron w/cm-sterad. 2





GROUP VII SPECTRA

(21) Hower Drill, 4-oz. Vee-166 2A
 Cloth Type - M-5
 Cloth Surface - 23°C
 Background - 21°C
 Det. Temp. - 27°C
 Total Emission - 9992 micra w/cm - started.



APPENDIX B

COMPUTER PROCESSED SPECTRA DATA

RADIANCE

	NATICK	ABSOLUTE
2400	FCA	2454.0
	FST	2456.0
2401	CLA	2404.0
	STA	2422.1
2402	CLA	2405.0
	STA	2424.0
2403	STA	2433.1
	TRA	2410.0
2404	CLA	0000.0
	-00	4200.0
2405	CLA	0400.0
	CLA	5400.0
2406	FDV	2476.0
	FAD	2670.0
2407	FST	2714.0
	TRA	2413.1
2410	CLA	2450.0
	TYA	7760.0
2411	CLA	2451.0
	TYA	7760.0
2412	TRA	2500.0
	TRA	2410.0
2413	TRA	2406.0
	CLA	2452.0
2414	TYA	7760.0
	TRA	2500.0
2415	TRA	2413.1
	FST	2460.0
2416	CLA	2453.0
	TYA	7760.0
2417	TRA	2500.0
	TRA	2416.0
2420	FDV	2460.0
	FST	2462.0
2421	CLA	5000.0
	ARS	0001.0
2422	XAR	0000.0
	CLA	4630.0
2423	FNM	0000.0
	FMP	2462.0
2424	FDV	1450.0
	FST	2464.0
2425	FCA	2456.0
	FMP	2466.0

2426	FST	2470.0
2427	FCA	2472.0
	FDV	2470.0
2430	TRA	2700.0
	FMP	2472.0
2431	FDV	2470.0
	FDV	2470.0
2432	TSB	2433.0
	FAD	2464.0
2433	TRA	2433.1
	FSB	2464.0
2434	FST	6456.0
	CLA	2422.0
2435	ADD	2444.0
	STO	2422.0
2436	SUB	2445.0
	TZE	0330.0
2437	CLA	2424.0
	ADD	2446.0
2440	STO	2424.0
	CLA	2433.0
2441	ADD	2447.0
	STO	2433.0
2442	FCA	2456.0
	FAD	2474.0
2443	FST	2456.0
	DIS	2433.0
2444	TRA	2421.0
	CLA	0000.0
2445	-00	0001.0
	XAR	0000.0
2446	CLA	4630.0
	CLA	0002.0
2447	-00	0000.0
	CLA	0000.0
	-00	0002.0

NATICK ABSOLUTE RADIANCE CONT.

2700	FST	2712.0
	FCA	2722.0
2701	FDV	2712.0
	FDV	2714.0
2702	ARS	0000.0
	TRA	0170.0
2703	CLA	7774.0
	HTR	2702.1
2704	FSB	2716.0
	FMP	2712.0
2705	FMP	2712.0
	FMP	2712.0
2706	FMP	2712.0
	FMP	2712.0
2707	FST	2712.0
	FCA	2720.0
2710	FDV	2712.0
	TRA	2430.0

NATICK ABSOLUTE RADIANCE CONT.		NATICK ABSOLUTE RADIANCE CONT.	
0330	FCA 2750.0	2730	+00 2752.0
0331	FST 2456.0	2731	+00 2770.0
0332	CTV 2770.0	2732	+00 2754.0
0333	TRA 0110.0	2733	+12 2451.0
0334	CLA 2730.0	2734	+12 2451.0
0335	TRA 0010.0	2735	+06 1430.1
0336	CLA 0335.0	2736	+06 1430.1
0337	STA 0364.1	2737	+35 2470.0
0338	TRA 0336.0	2740	+07 5376.0
0339	-00 0000.0	2741	+00 2764.0
0340	HTR 0000.0		+00 2770.0
0341	HTR 6454.0		+43 0614.0
0342	FCA 2770.0		+43 0614.0
0343	FST 2754.0		+22 4512.0
0344	FAD 2756.0		+22 4512.0
0345	FST 2754.0		+00 2462.0
0346	FSB 2760.0		+00 2460.0
0347	TPL 0346.0		
0348	TRA 0340.0		
0349	CLA 2735.0		
0350	TRA 0010.0		
0351	CLA 2736.0		
0352	TRA 0011.0		
0353	CLA 2737.0		
0354	PNA 7760.0		
0355	CLA 2740.0		
0356	PNA 7760.0		
0357	FCA 2754.0		
0358	FAD 2756.0		
0359	FST 2754.0		
0360	FSB 2760.0		
0361	TPL 0346.0		
0362	TRA 0340.0		
0363	CLA 2735.0		
0364	TRA 0010.0		
0365	CLA 2736.0		
0366	TRA 0011.0		
0367	CLA 2737.0		
0368	PNA 7760.0		
0369	CLA 2740.0		
0370	PNA 7760.0		
0371	FCA 2754.0		
0372	FAD 2756.0		
0373	FST 2754.0		
0374	FSB 2760.0		
0375	TPL 0346.0		
0376	TRA 0340.0		
0377	CLA 2735.0		
0378	TRA 0010.0		
0379	CLA 2736.0		
0380	TRA 0011.0		
0381	CLA 2737.0		
0382	PNA 7760.0		
0383	CLA 2740.0		
0384	PNA 7760.0		
0385	FCA 2754.0		
0386	FAD 2756.0		
0387	FST 2754.0		
0388	FSB 2760.0		
0389	TPL 0346.0		
0390	TRA 0340.0		
0391	CLA 2735.0		
0392	TRA 0010.0		
0393	CLA 2736.0		
0394	TRA 0011.0		
0395	CLA 2737.0		
0396	PNA 7760.0		
0397	CLA 2740.0		
0398	PNA 7760.0		
0399	FCA 2754.0		
0400	FAD 2756.0		
0401	FST 2754.0		
0402	FSB 2760.0		
0403	TPL 0346.0		
0404	TRA 0340.0		
0405	CLA 2735.0		
0406	TRA 0010.0		
0407	CLA 2736.0		
0408	TRA 0011.0		
0409	CLA 2737.0		
0410	PNA 7760.0		
0411	CLA 2740.0		
0412	PNA 7760.0		
0413	FCA 2754.0		
0414	FAD 2756.0		
0415	FST 2754.0		
0416	FSB 2760.0		
0417	TPL 0346.0		
0418	TRA 0340.0		
0419	CLA 2735.0		
0420	TRA 0010.0		
0421	CLA 2736.0		
0422	TRA 0011.0		
0423	CLA 2737.0		
0424	PNA 7760.0		
0425	CLA 2740.0		
0426	PNA 7760.0		
0427	FCA 2754.0		
0428	FAD 2756.0		
0429	FST 2754.0		
0430	FSB 2760.0		
0431	TPL 0346.0		
0432	TRA 0340.0		
0433	CLA 2735.0		
0434	TRA 0010.0		
0435	CLA 2736.0		
0436	TRA 0011.0		
0437	CLA 2737.0		
0438	PNA 7760.0		
0439	CLA 2740.0		
0440	PNA 7760.0		
0441	FCA 2754.0		
0442	FAD 2756.0		
0443	FST 2754.0		
0444	FSB 2760.0		
0445	TPL 0346.0		
0446	TRA 0340.0		
0447	CLA 2735.0		
0448	TRA 0010.0		
0449	CLA 2736.0		
0450	TRA 0011.0		
0451	CLA 2737.0		
0452	PNA 7760.0		
0453	CLA 2740.0		
0454	PNA 7760.0		
0455	FCA 2754.0		
0456	FAD 2756.0		
0457	FST 2754.0		
0458	FSB 2760.0		
0459	TPL 0346.0		
0460	TRA 0340.0		
0461	CLA 2735.0		
0462	TRA 0010.0		
0463	CLA 2736.0		
0464	TRA 0011.0		
0465	CLA 2737.0		
0466	PNA 7760.0		
0467	CLA 2740.0		
0468	PNA 7760.0		
0469	FCA 2754.0		
0470	FAD 2756.0		
0471	FST 2754.0		
0472	FSB 2760.0		
0473	TPL 0346.0		
0474	TRA 0340.0		
0475	CLA 2735.0		
0476	TRA 0010.0		
0477	CLA 2736.0		
0478	TRA 0011.0		
0479	CLA 2737.0		
0480	PNA 7760.0		
0481	CLA 2740.0		
0482	PNA 7760.0		
0483	FCA 2754.0		
0484	FAD 2756.0		
0485	FST 2754.0		
0486	FSB 2760.0		
0487	TPL 0346.0		
0488	TRA 0340.0		
0489	CLA 2735.0		
0490	TRA 0010.0		
0491	CLA 2736.0		
0492	TRA 0011.0		
0493	CLA 2737.0		
0494	PNA 7760.0		
0495	CLA 2740.0		
0496	PNA 7760.0		
0497	FCA 2754.0		
0498	FAD 2756.0		
0499	FST 2754.0		
0500	FSB 2760.0		

13. Abstract (continued)

field, there is inter-reflection between the terrain features and the sample, sky radiance, atmospheric absorption, and reflection from background objects of the fabric, giving a spectrum that is not representative of the sample.

Unclassified

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Security Classification

DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
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		2b. GROUP
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4. DESCRIPTIVE NOTES (Type of report and inclusive dates) 26 March 1965 to 26 March 1966		
5. AUTHOR(S) (Last name, first name, initial) Mason, Mark T. and Coleman, Isaiah		
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10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited. Release to CFSTI is authorized.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Natick Laboratories Natick, Massachusetts 01760	
13. ABSTRACT Laboratory measurements of the total and spectral infrared radiation emitted by textile materials, as applicable to the outer layer of a uniform, were made with an interferometer spectrometer. The effects of changes in the environmental parameters of the fabric, such as background temperature, fabric temperature, and humidity, were studied. For this report twelve different fabrics with a diversity of weaves and surface roughnesses were studied. The fifty-five spectra of these fabrics, which are published in this report, cover a wide range of fabric temperature, background temperature, and humidity. It was found that the weave of the fabric acts as many small blackbody radiators and tends to mask any spectral detail that may be present. Further masking of detail is done by reflected background radiation. It was found that a fluctuation in background temperature, fabric temperature, or humidity caused a change in the spectral characteristics of the fabric. Spectra of terrain features are presented and are compared to the spectra of the fabrics. It is shown that there is a spectral similarity between the fabric and terrain features because both are subject to spectral masking by background and sample characteristics. In the		

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Measurement	8					
Infrared Radiation	9		7			
Fabrics	9		6,7			
Temperature			6			
Humidity			6			
Terrain			6			
Interferometers	10					
Spectrum analyzers	10					

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