NATIONAL PHYSICAL LABORATORY
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REPORT

25 METER MILLIMETER WAVE TELESCOPE
MEMO No. 142

The Power Transmission Spectra of Possible Millimetre Wavelength Radome Materials

Performed for: Science Research Council
Appleton Laboratory
Ditton Park
Slough, Bucks

Introduction

This work presents the results of an investigation into the effects of certain surface coatings on the millimetre and submillimetre wavelength (3 to 0.3mm) power transmission spectra of some materials that might be used in the construction of a radome for the proposed UK millimetre wavelength telescope. An earlier NPL investigation[1,2] identified a group of woven polymeric materials (sailcloths) that, while meeting the design specifications for dielectric loss, permittivity, thickness, mechanical strength and resistance to tearing, did not meet that for a rejection of the total near infrared and visible solar flux of at least 0.8. The solar rejection of these materials can be improved by loading the bulk of the material, or surface coating it, with another material that either absorbs or reflects the majority of the solar flux. (A reflecting material would be preferred to minimise the re-radiation of any absorbed solar energy). The purpose of this work was to investigate the extent to which various thicknesses and combinations of absorbing and reflecting coatings would degrade the power transmission spectra of the original materials.

Specimens

A total of 23 specimens were studied in transmission for the purpose of this investigation. The majority of these were nylon or terylene sailcloths, similar to those previously investigated,[1,2] that had been coated on one surface with various thickness and combinations of white or black polyurethane

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paints by the Paint Research Association. These specimens are described in table 1. As the specimens are uneven and somewhat porous the coating does not necessarily form a smooth even layer on the specimen surface. The column headed 'equivalent coating thickness' in table 1 refers to the layer thickness that would have been achieved had the same amount of paint been applied in the same manner to a smooth non-porous surface. The formulations of the two polyurethane

Sailcloth type and thickness (μm)	Identifier	Coating	Equivalent Coating thickness (μm)
Terylene, 175	A1	White polyurethane	5
	A2	"	10
	A3	"	15
	A4	"	20
	A9	Uncoated	-
Nylon, 85	B1	White polyurethane	5
	B3	"	15
	B4	"	20
	B8	White on black polyurethane	20 (each)
	B9	Uncoated	-
Nylon, 105	C1	White polyurethane	5
	C4	"	20
	C9	Uncoated	-

Table 1. Descriptions of the sailcloth specimens measured in transmission during this study. Cloths A and C were supplied by Windmaster Ltd. and cloth B by Carrington Performance Fabrics, Ltd.

paints used in coating the specimens are given in appendix 1. The white polyurethane paint, being based on titanium dioxide, was intended to provide a diffuse reflecting surface to reflect the incident solar flux, while the black polyurethane paint was intended to absorb the incident solar flux. Measurements were only made on one specimen having an absorbing layer (B8) as the rejection of the incident solar flux by reflection is the preferred solution.

In addition to coating these specimens the Paint Research Association also provided the various specimens of unsupported polyurethane paints described in table 2. These form two groups,

Paint	Identifier	Thickness
Clear polyurethane (formulation 510 excluding RCR titanium dioxide)	Y2 Y3 Y4	30 (μm) 15 50
White polyurethane (formulation 510)	Z1 Z2 Z3 Z4 Z5	17 22 32 66 59

Table 2. The specimens of unsupported polyurethane paints measured in transmission during this study. The thickness figures are only approximate.

clear and white polyurethane, that differ only in the presence of titanium dioxide in the latter paint. Thus, measurements on these would provide data on the absorption loss due to the presence of the titanium dioxide in the paint layer.

Power transmission measurements were also made on one specimen of expanded polyethylene approximately 12.5mm thick of unknown origin and on one specimen of 90μm thick glass fibre cloth coated with PTFE. This latter material is manufactured by a company known as Birdair and is referred to by this name in the results section of this report.

During the period of this investigation measurements were also made of the 45° incidence power reflectivity spectra of three dichroic reflectors. As this was quite separate from the main investigation on radome materials the results of this reflectivity study are described in appendix 2.

Experimental

It was originally intended to measure both the amplitude attenuation and the phase shift caused by each specimen using the techniques of dispersive Fourier transform spectrometry [3] in which the specimen is placed in one of the active arms of the interferometer. This would have allowed an 'effective' refractive index to be estimated for each of these composite specimens. It was found, however, that when measurements were made in this configuration significant systematic errors in both attenuation and phase occurred for some of the specimens. This was ascribed to a lack of homogeneity of these woven, coated specimens, and the effect that this has on the phase of the wavefront in the specimen arm of the interferometer. Conventional Fourier transform spectrometry is not susceptible to this type of error as the specimen is placed between the interferometer and the detector so that both beams from the interferometer go through it. Thus, both wavefronts are similarly changed by the optical properties of the specimen, avoiding such systematic effects. All of the specimens were therefore studied by conventional Fourier transform spectrometry to determine their power transmission spectra between 3 and 30 cm^{-1} using a two beam interferometer of modular construction [4] employing phase modulation of the radiation within itself and a liquid helium cooled indium antimonide hot electron bolometer as the radiation detector. The measurements were made at normal incidence on a 40mm diameter portion of each specimen with its coated surface irradiated by the incident radiation. The measurements were made at an apodised spectral resolution of about 0.5 cm^{-1} and a temperature of 290K.

Results and Discussion

The results of the determination of the power transmission of these specimens are presented in figures 1 to 28. Each curve is the average of four independent determinations of the power transmission. Above 7 to 8 cm^{-1} the signal-to-noise levels in the detected spectra are such that these individual determinations are reproducible to about 0.005. Below these wavenumbers the signal levels in the instrument fall rapidly with decreasing wavenumber and the measurement reproducibility worsens, and can approach $\sim$0.02, leading to measured values of the power transmission that can exceed unity. The results shown in these figures are also tabulated in tables 3 to 25.

(a) Terylene sailcloth, specimens A1 to A9

The power transmission of the uncoated specimen. A9 (Figure 5) is quite highly structured. It has what appear to be two narrow absorption lines at about 21.2 and 25.1 cm^{-1} superimposed on a slowly varying shallow channel spectrum with a period of between 20 and 25 cm^{-1}. If this channel spectrum were due to interference between the multiple internally reflected rays within the specimen one would expect this period to be about $(2nd)^{-1}$ where n is the refractive index of the material and d the specimen thickness. Assuming n to be 1.5 and taking d as 175 µm leads to a period of 19 cm^{-1}, in reasonable agreement with observation.

It is not easy to summarise the effects of the paint layer on the specimen transmission as the spectra of specimens A1 to A4 do not show any completely systematic trends with paint layer thickness. For example, below 15 cm^{-1} the effect of the paint is to reduce the transmission level below that of the uncoated specimen by up to 0.1, while, in the region of the two absorption lines, the behaviour is much more complex. The position and the intensity of the lines vary in an apparently erratic manner with the paint layer thickness. If these lines were truly absorptive in origin one would not expect a great deal of variation in either of these parameters to be caused by the application of a paint layer. Such effects might be seen, however, if the sailcloth were inhomogenous, so that a similar variation occured between the transmission spectra of several uncoated specimens, or if, during the application of the paint and its drying, a reaction occured between the cloth and some of the paint components that significantly changed the optical constants of the cloth.

(b) Nylon sailcloth, specimens B1 to B9

The transmission spectra of these specimens are shown individually in figures 6 to 10 and also plotted on the same set of axes in figure 11, for comparison. There is no evidence for any discrete absorption features in the spectral range measured, and the variation of the transmission spectra with paint layer thickness appears to be fairly well-behaved. If specimen B8 is neglected, as it has a black polyurethane layer in addition to the white one of the other specimens, then at all wavenumbers the power transmission falls smoothly with increasing paint layer thickness. This is illustrated in figure 12 which shows the power transmission as a function of the equivalent paint layer thickness for four wavenumbers between 12 and 25 cm^{-1}. The transmission spectra of specimens B3 and B4 appear to go to a minimum in the region of 25 cm^{-1}, which indicates that a portion of the transmission loss of all of these B-specimens is due to the effects of multiple beam interference and not absorptive loss. The spectrum of specimen B8, which has 20 μm thick layers of black and while polyurethane, exhibits a very well-defined channel spectrum with a much smaller period than those of specimens B1, B3, B4 and B9, in accordance with its larger optical thickness.

(c) Nylon sailcloth, specimens C1 to C9

The transmission spectra of these specimens, shown in figures 13 to 16, show similar qualitative behaviour to those of the B-specimens. Again, there is no evidence for any discrete absorption features, the transmission decreases smoothly with increasing paint layer thickness and the thickest layer specimen, C4, has an overall optical thickness that is sufficient for the first minimum of its channel spectrum to fall within the spectral range measured.

(d) Polyurethane paints, Y- and Z- specimens

Both clear (Y) and white (Z) polyurethane specimens show similar well-behaved spectra (figures 17 to 26). Each spectrum decreases with increasing wavenumber, and the transmission at any wavenumber decreases smoothly with increasing specimen thickness. The spectra of the thicker Z - specimens show that internal interference effects contribute significantly to the measured transmission loss. In principle, these results should allow one to quantify the absorptive loss due to the titanium dioxide additive. Practically, however, this loss appears to be sufficiently low that the results of such an analysis might well end up by being dominated by any systematic errors in the determination of the thickness of such thin films.

(e) Expanded polyethylene

This specimen was included in the measurement program for two reasons. First, polyethylene is a well-known low loss material and, secondly, in its expanded form it possesses a bright white colour that might be expected to provide good diffuse reflection of the solar flux. The results of these measurements are shown in figure 27. The power transmission is close to unity below 10 cm^{-1}, but falls rapidly towards 0.4 as the wavenumber scale approaches 30 cm^{-1}. This large transmission loss seems unlikely in view of the known optical constants of bulk polyethylene and could, perhaps, be due in part to scattering.

(f) Birdair specimen

The transmission spectrum of this specimen is shown in figure 28. The transmission falls from near-unity at low wavenumbers to a fairly constant value of about 0.68 to 0.70 above 25 cm^{-1}. There are two discrete absorption lines in the transmission spectrum, one at about 16 cm^{-1} and one at about 19 cm^{-1}, which, although at lower wavenumbers than those present in the spectra of the A-specimen, are similar to them in terms of their relative positions and intensities.

This investigation was performed by Mr J D Dromey and Dr J R Birch of the Division of Electrical Science, NPL. Dr E A Nicol, also of the Division of Electrical Science, was responsible for the reflectivity measurements of appendix 2.

Appendix 1. The formulations of the two polyurethane paints used in coating the sailcloth specimens.

(i) Formulation 509 Black

Part 1	Desmophen 670	10 pbw
	Desmophen 690	10
	Solvent mixture	31.5
	Zinc octoate (10% in solvent mixture)	0.6
	Regal 300 black	8
	Bentone 27 (10% in solvent mixture)	1.6
Part 2	Desmodur N 75	12
	Solvent mixture	9.1

(ii) Formulation 510 White

Part 1	Desmophen 670	10 pbw
	Desmophen 690	10
	Solvent mixture	31.5
	Zinc octoate (10% in solvent mixture)	0.6
	RCR titanium dioxide	19.8
	Bentone 27 (10% in solvent mixture	1.6
Part 2	Desmodur N 75	12
	Solvent mixture	9.1

(iii) Solvent mixture

Ethyl acetate	1 pbw
Methylene ketone	1
Cellosolve acetate	1

Appendix 2. The determination of the 45^{o} incidence power reflectivity spectra of three dichroic reflectors.

Three specimens were supplied for measurement. Each consisted of a thin gold film vacuum deposited onto a 150 x 150 x 4 mm^3 float glass plate . Two of the reflectors, identified as 6 and 15, had resistivities of 2.3 and 5.1 ohm per square, respectively. (Their identifiers refer to the percentage power transmission in the visible region of the spectrum). The remaining reflector had a protective surface coating and its resistivity could not be easily measured. It is referred to as the 'protected' specimen.

The power reflection spectrum of each of these specimens was measured at 45^{o} incidence with the specimen placed in the 50mm diameter collimated output beam from an interferometer similar to that used for the transmission measurements described in the main body of this report. The measurements were made in the spectral range between 6 and 30 cm^{-1} at a spectral resolution of 1 cm^{-1} below 10 cm^{-1} and 2 cm^{-1} above 10 cm^{-1}. The measurement temperature was 290K.

The results of these determinations of the three power reflection spectra are presented in figures A1 to A3. The spectra for specimens 6 and 15 are similar and approximately independent of wavenumber over this restricted spectral range. Specimen 6 is slightly more reflecting than specimen 15, as one would expect from its thicker gold film. The reflectivity of the protected specimen is also approximately independent of wavenumber and is typically about 0.02 below that of the other two specimens. Unless its gold film is significantly thinner than those of specimens 6 and 15 this difference would be due to the presence of the protective layer.

References

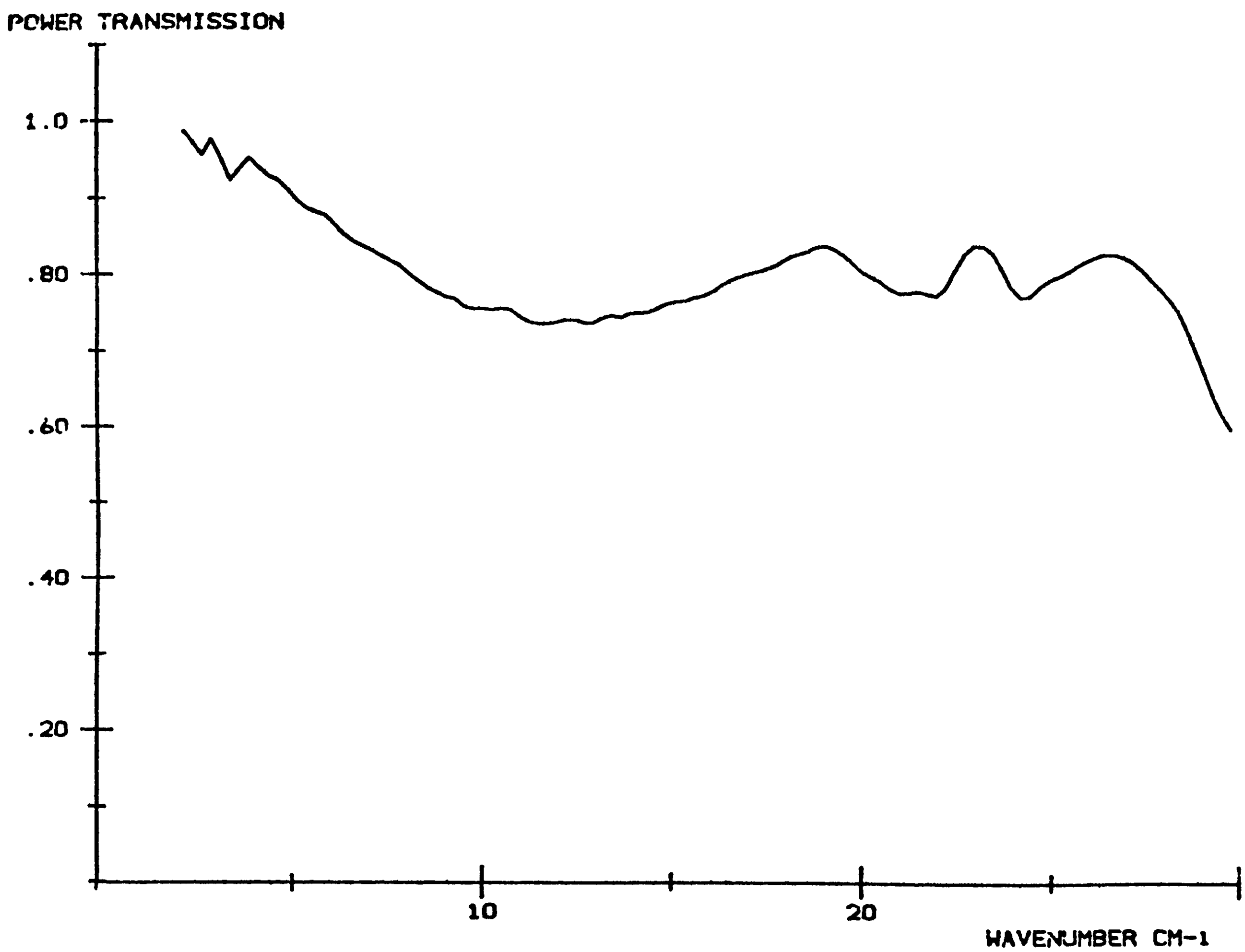
1. 'An Investigation of Possible Millimetre Wavelength Radome Materials', NPL Elec Sci 89/0376.

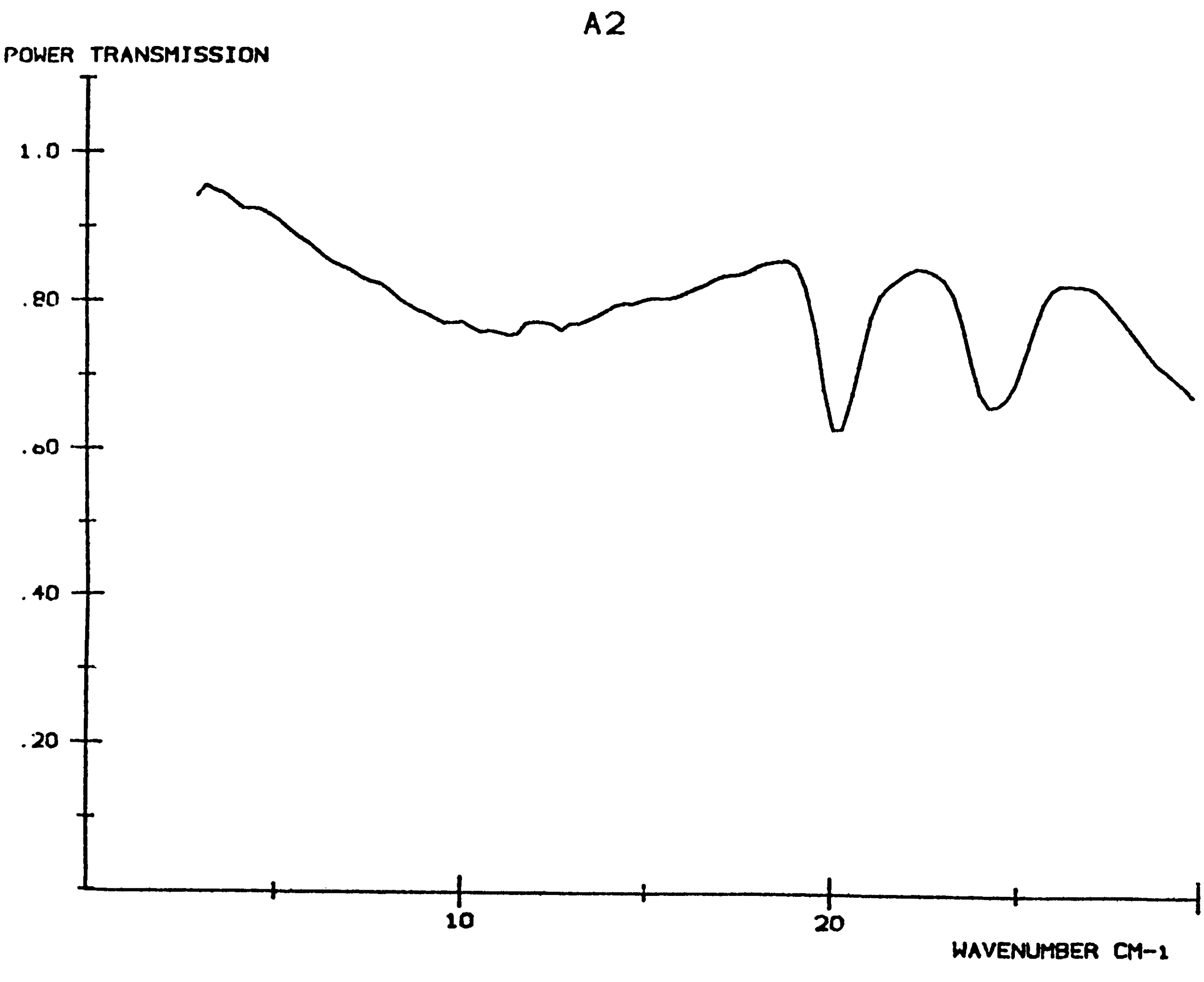
2. 'Sailcloth, A Low Loss Material for Millimetre and Submillimetre Wavelengths', J R Birch, G W Chantry, D B Shenton, R E Hills, M E A Cudby and H A Willis, Infrared Physics 17, 425, 1977.

3. 'Dispersive Fourier Transform Spectrometry', J R Birch and T J Parker in 'Infrared And Millimetre Waves, Vol.2' Ed. K J Button, Academic Press, New York 1979.

4. 'Absorption And Dispersion Studies In The Range 10-1000 cm^{-1} Using A Modular Michelson Interferometer'. G W Chantry, H M Evans, J Chamberlain and H A Gebbie, Infrared Physics 9, 85, 1969.

A1

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.60
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.20
10
20
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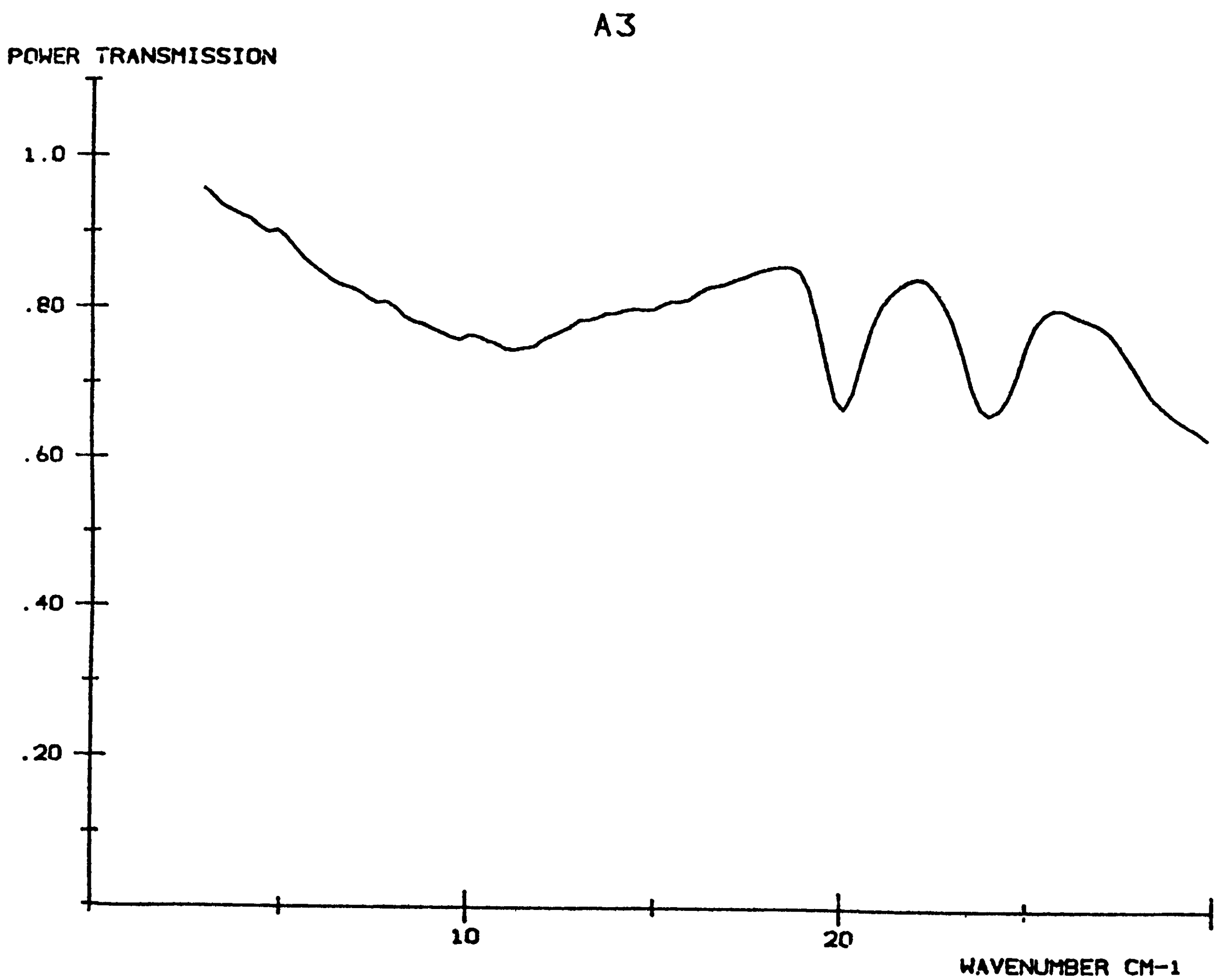
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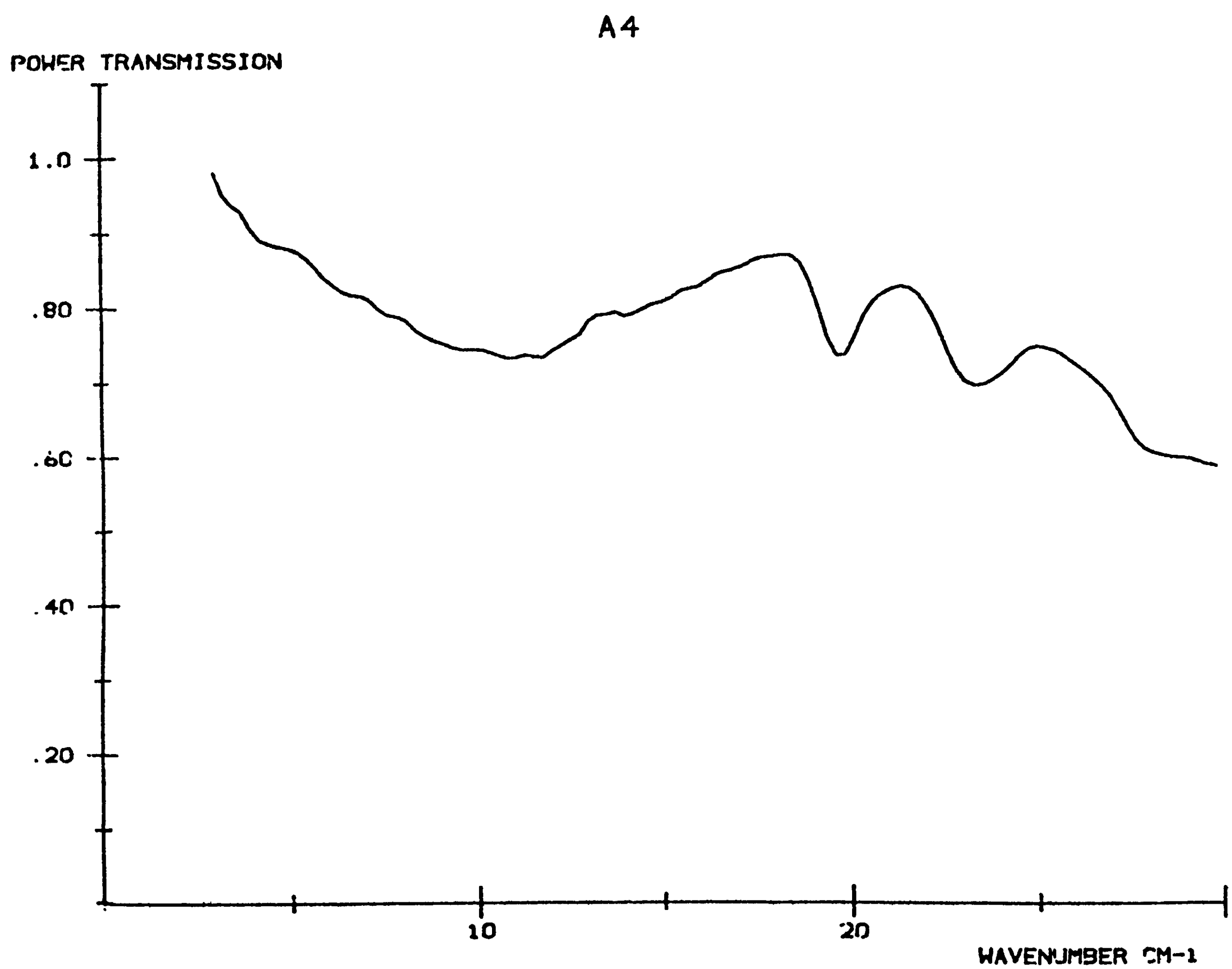
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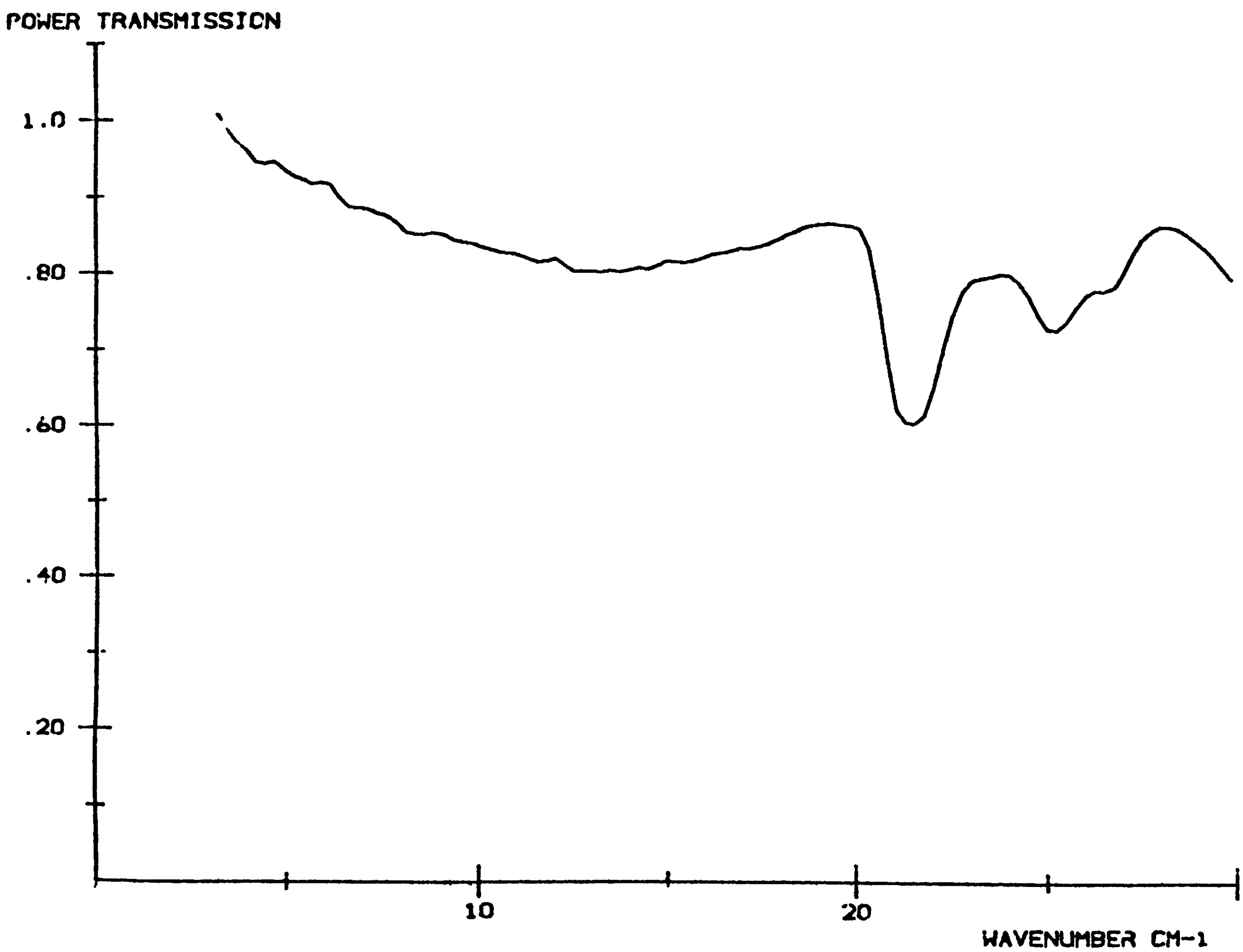
20
WAVENUMBER CM-1

A9



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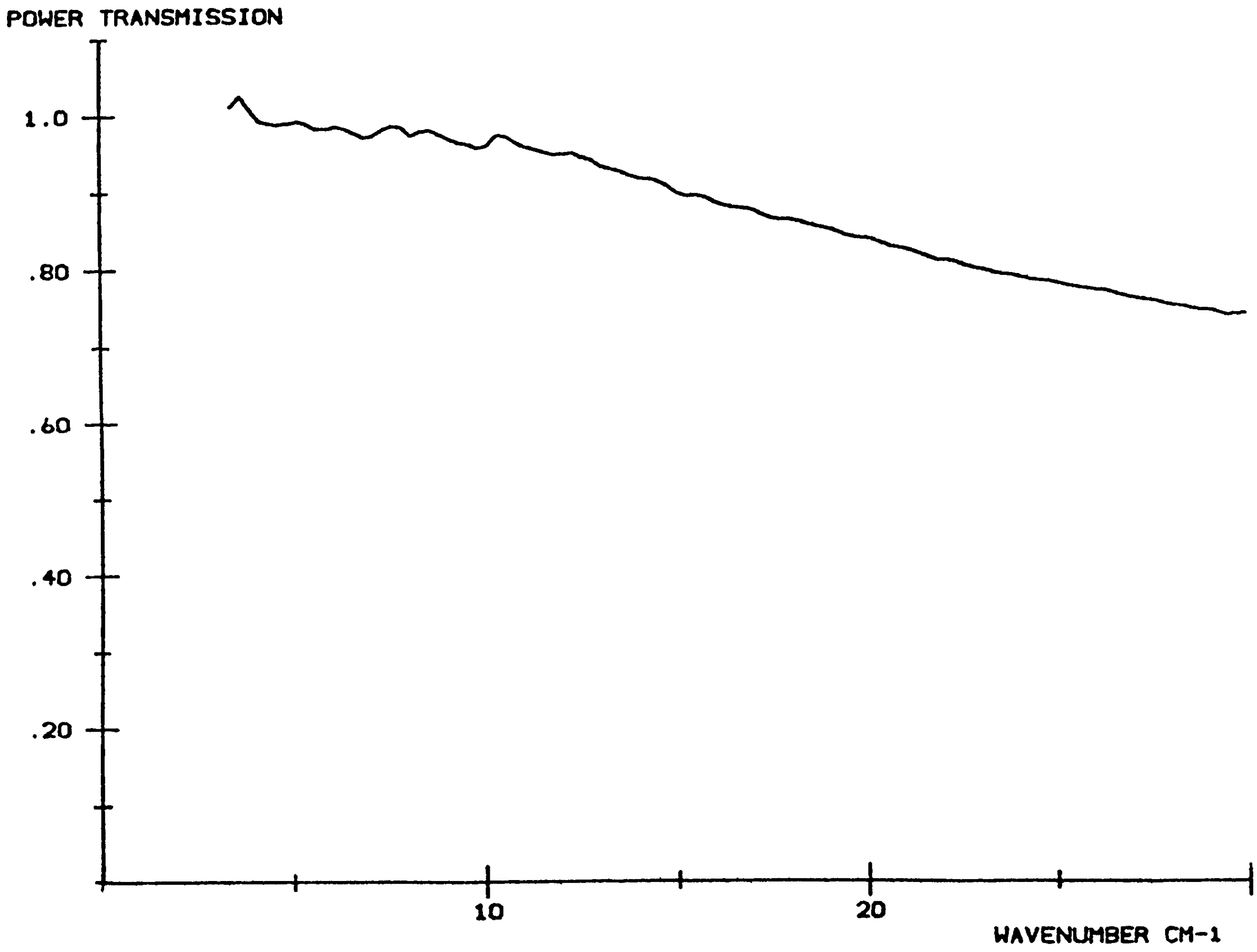

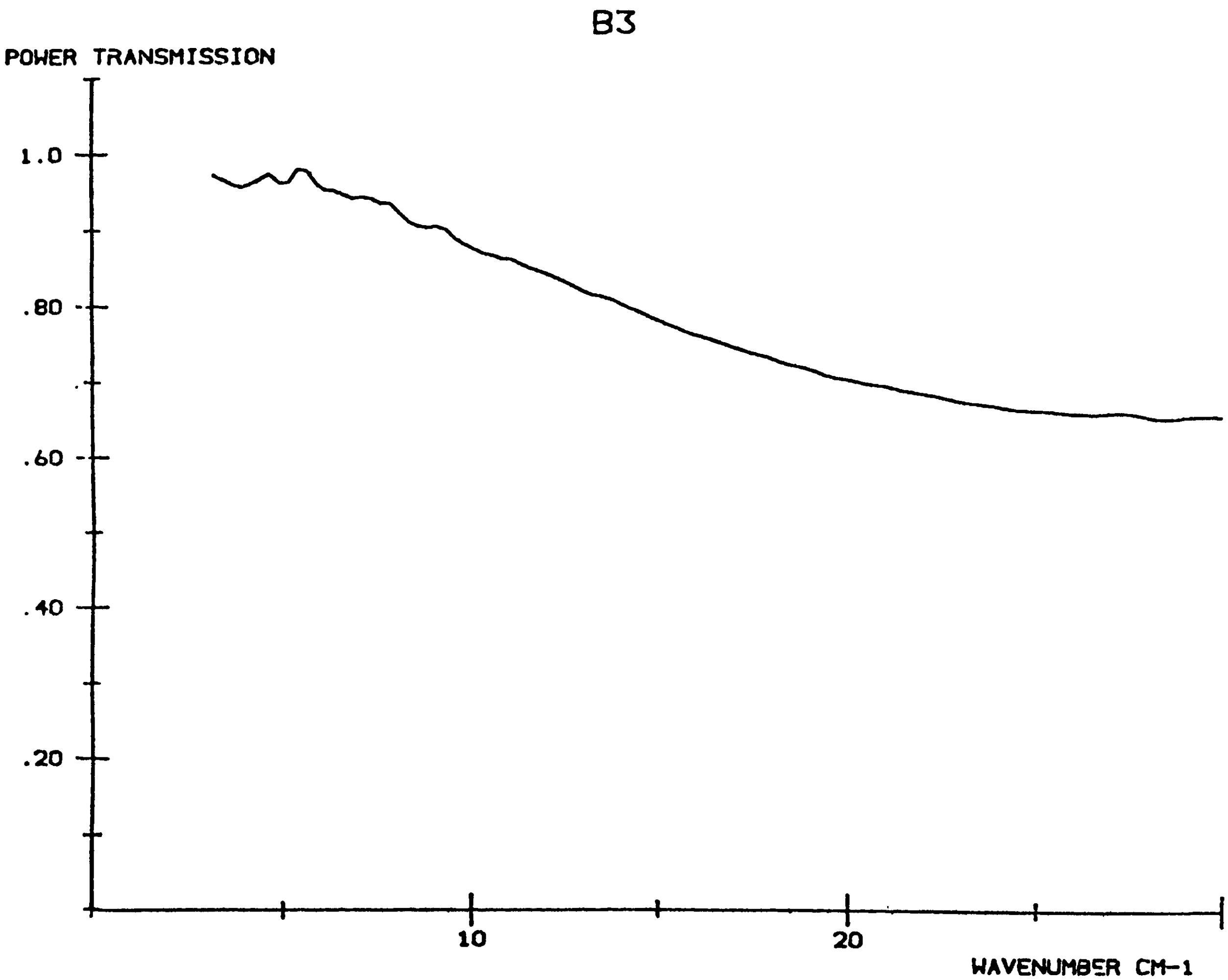
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POWER TRANSMISSION
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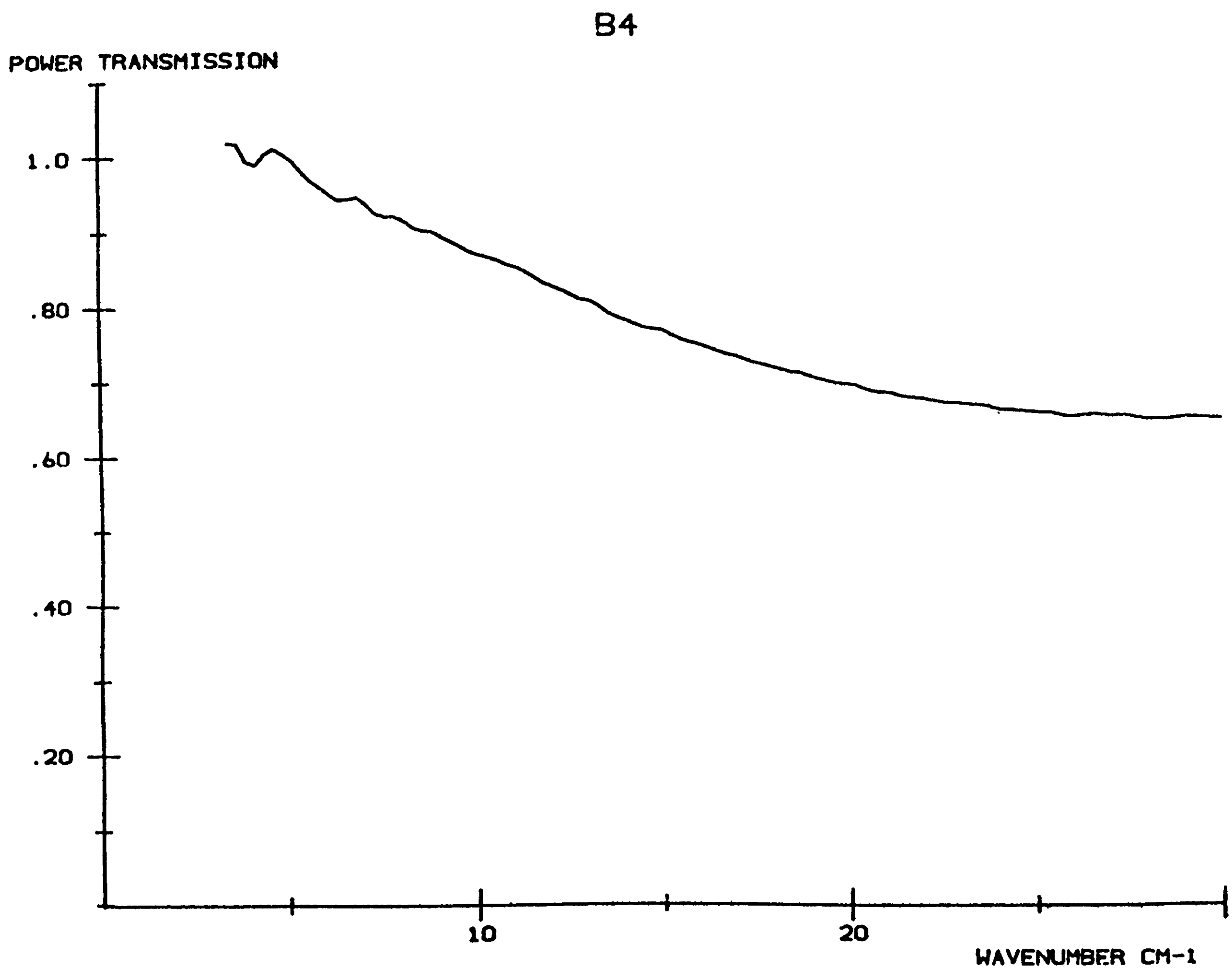
.80
.60
.40
.20
10
20
WAVENUMBER CM-1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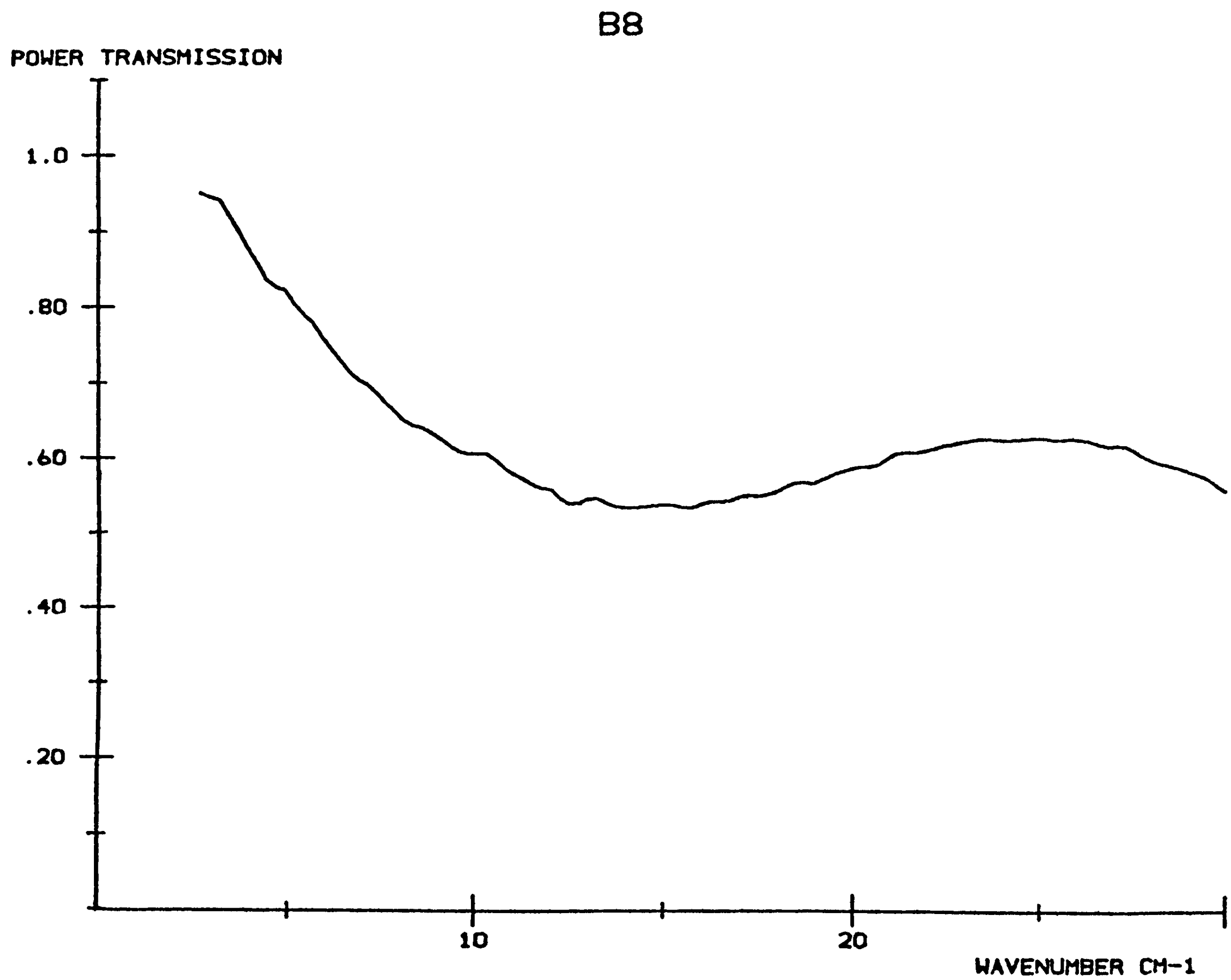
.60
.40
.20
10
20
WAVENUMBER CM-1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.40
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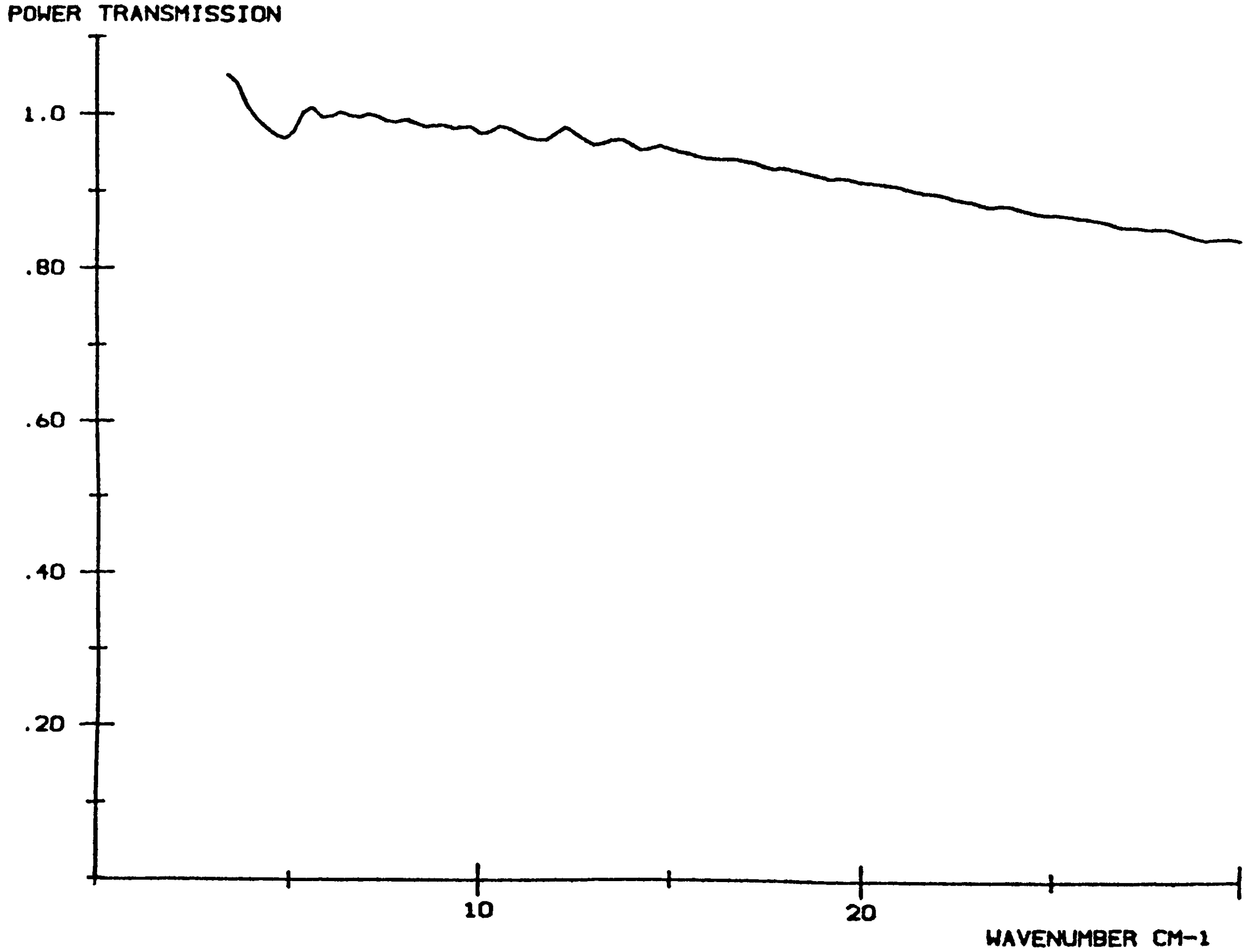
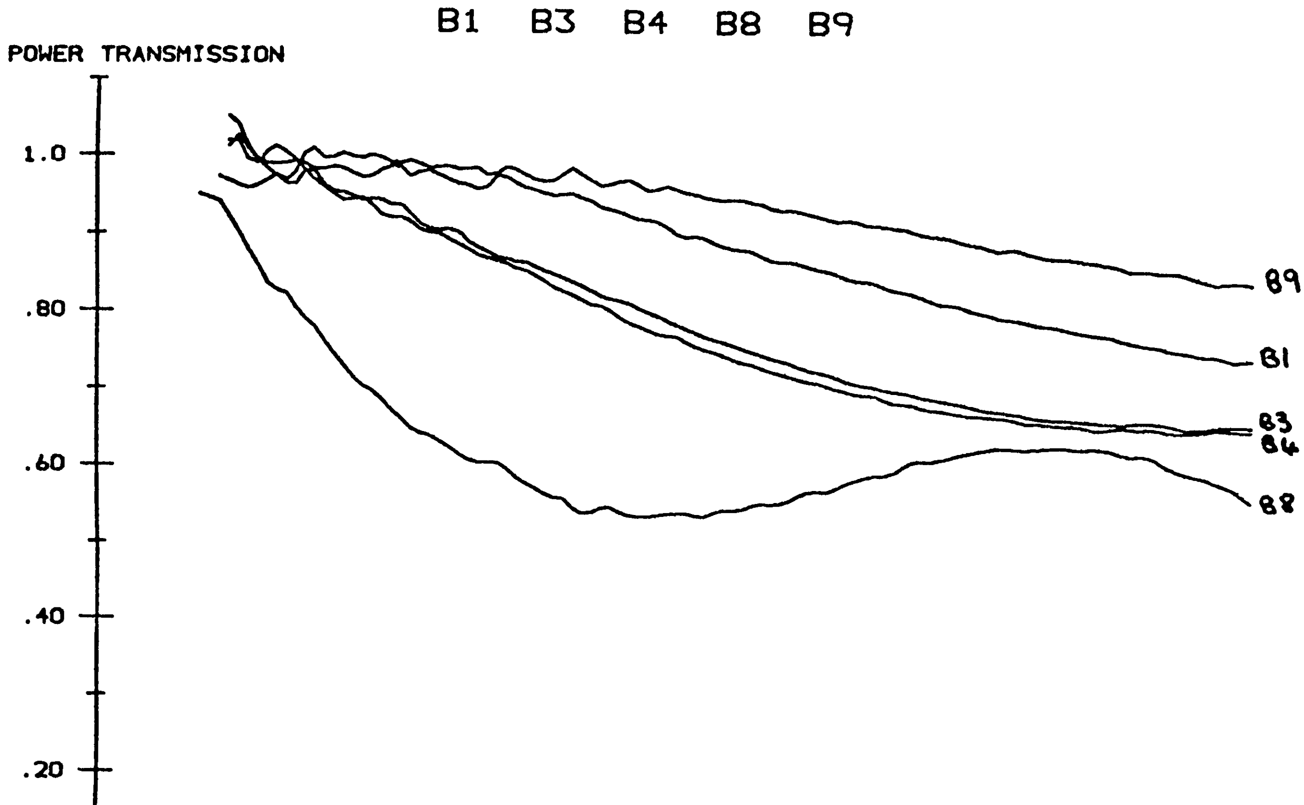
10
20
WAVENUMBER CM-1

B9




B1 B3 B4 B8 B9
POWER TRANSMISSION
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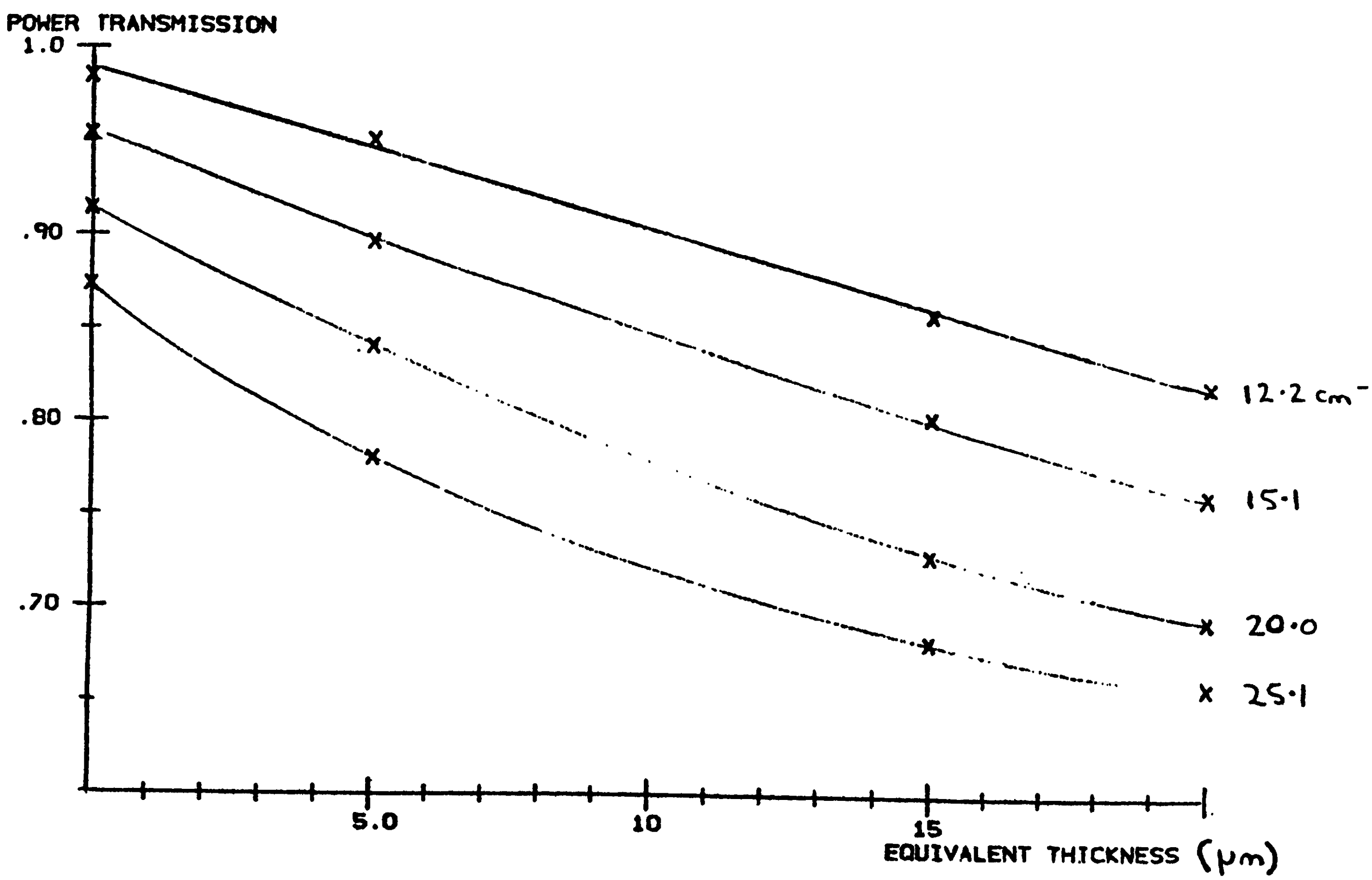
.60
.40
.20
10
20
WAVENUMBER CM-1
B9
B1
B3
B4
B8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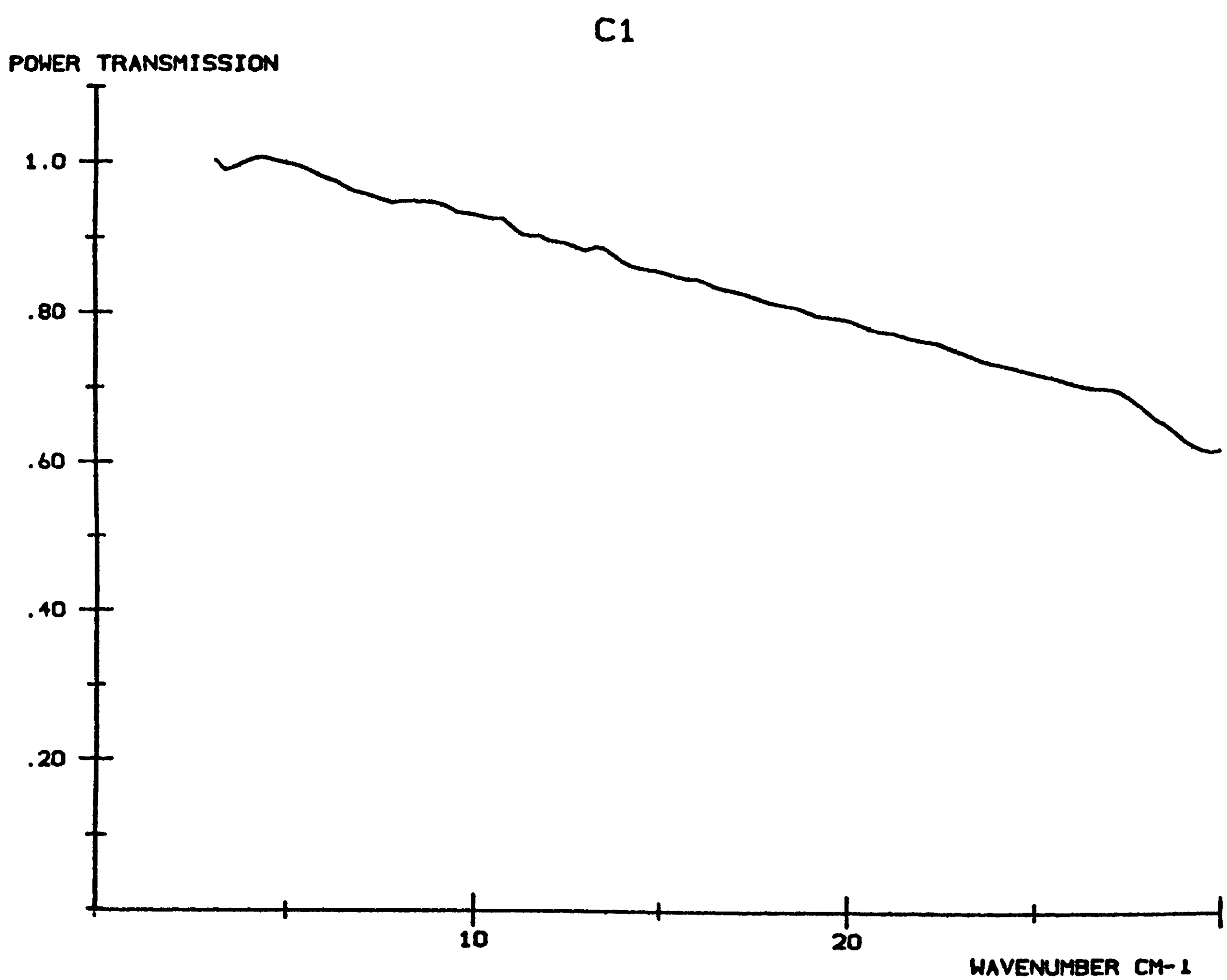
.70
5.0
10
15
EQUIVALENT THICKNESS (μm)
12·2 cm⁻¹
15·1
20·0
25·1



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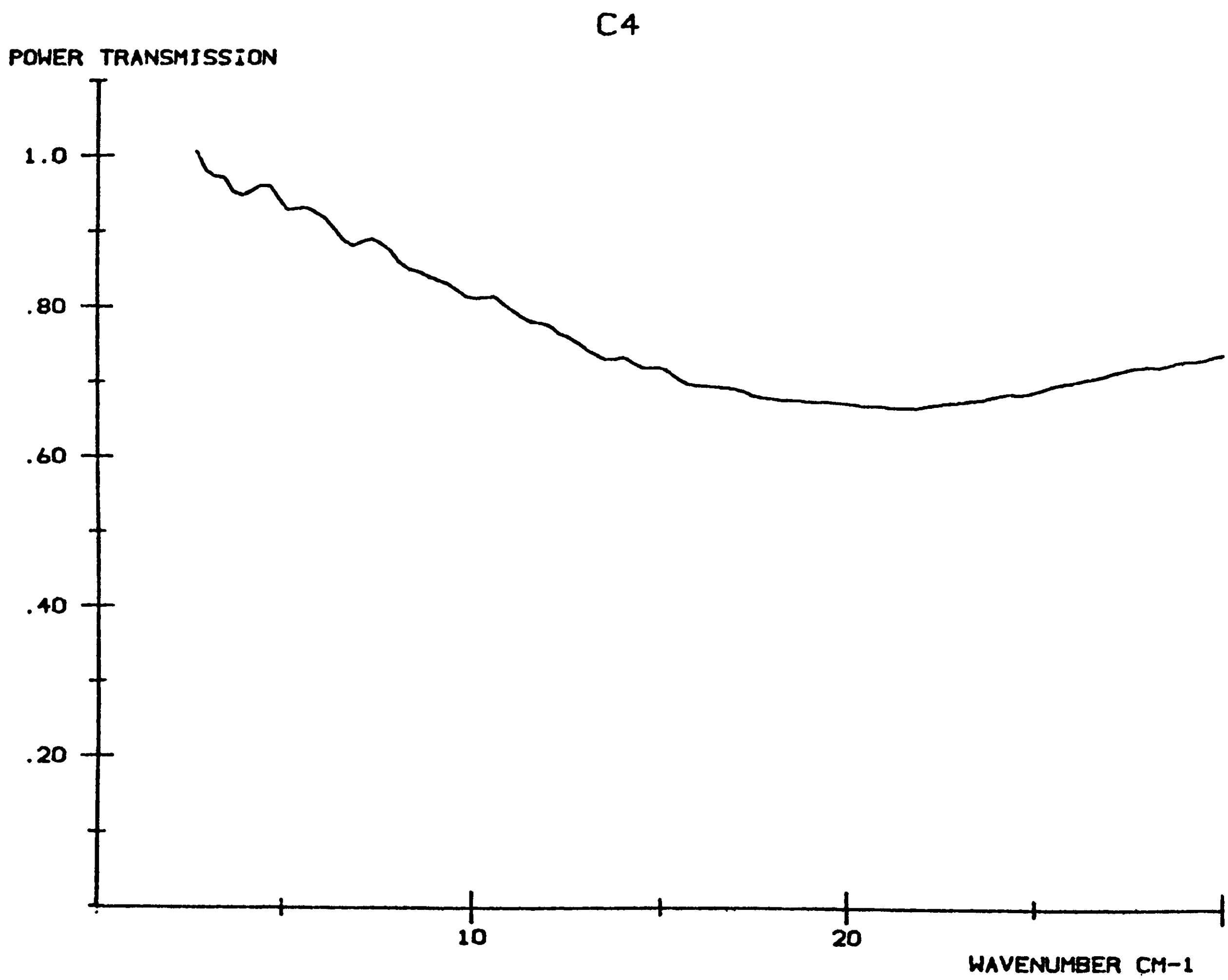

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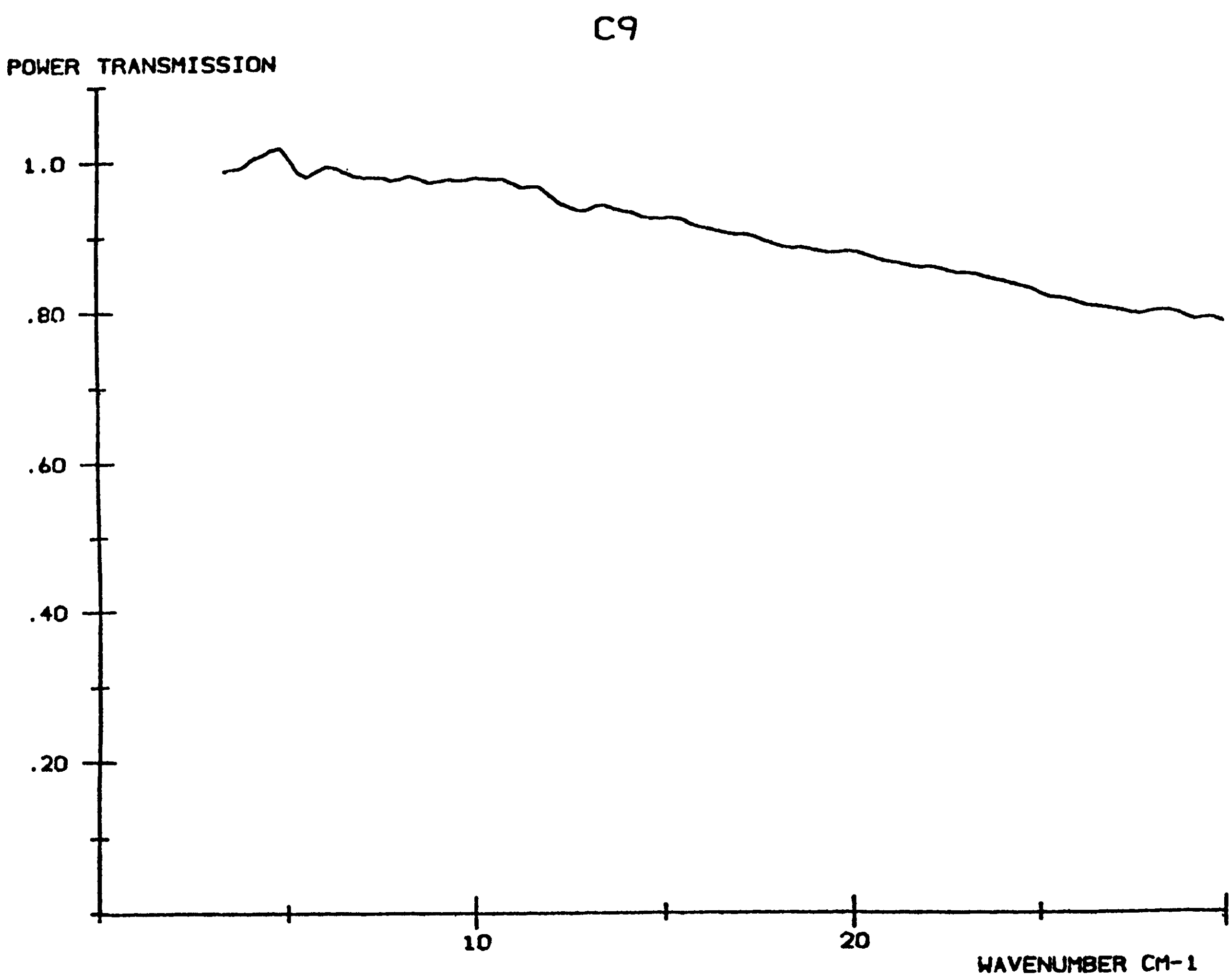
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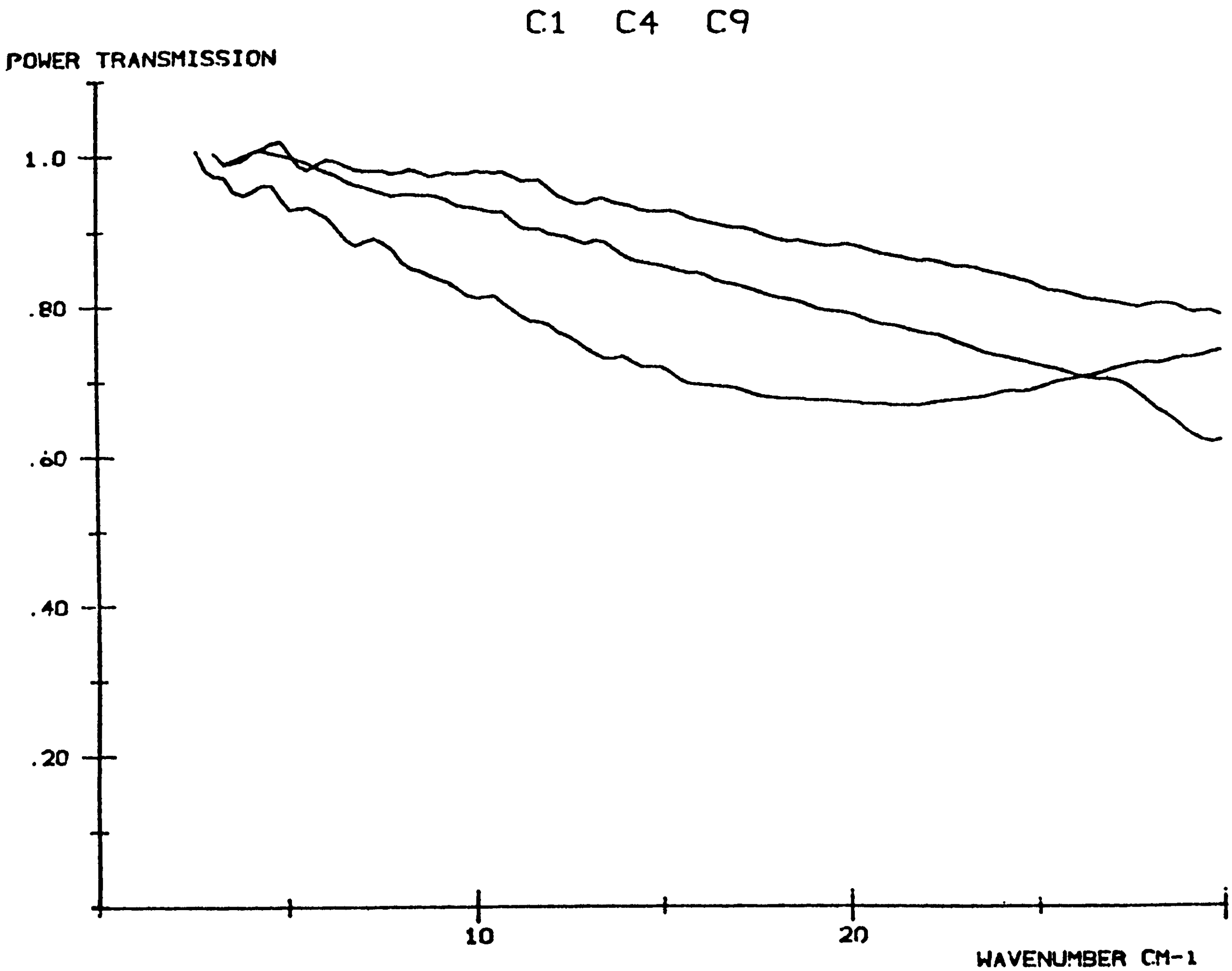
C1 C4 C9
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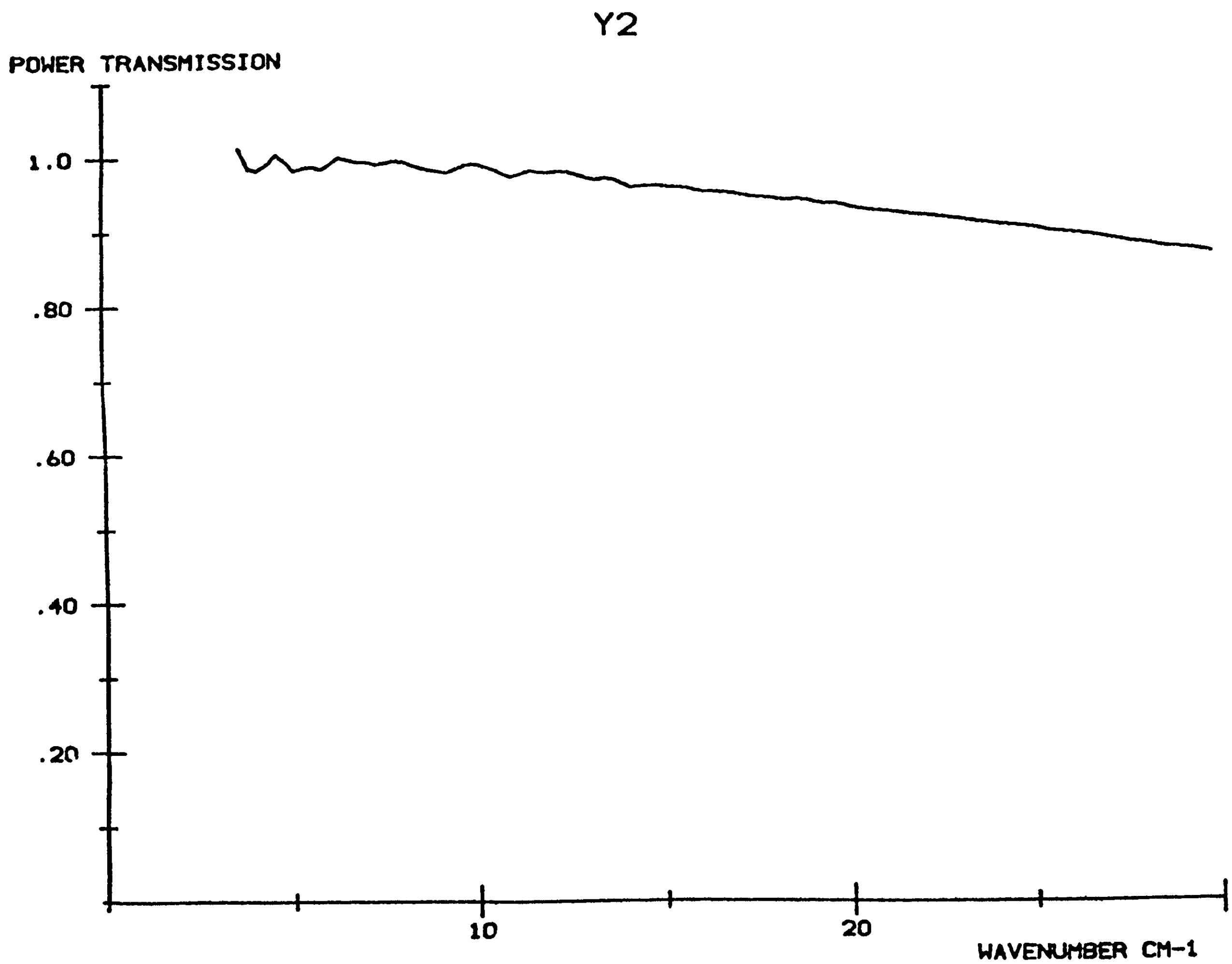
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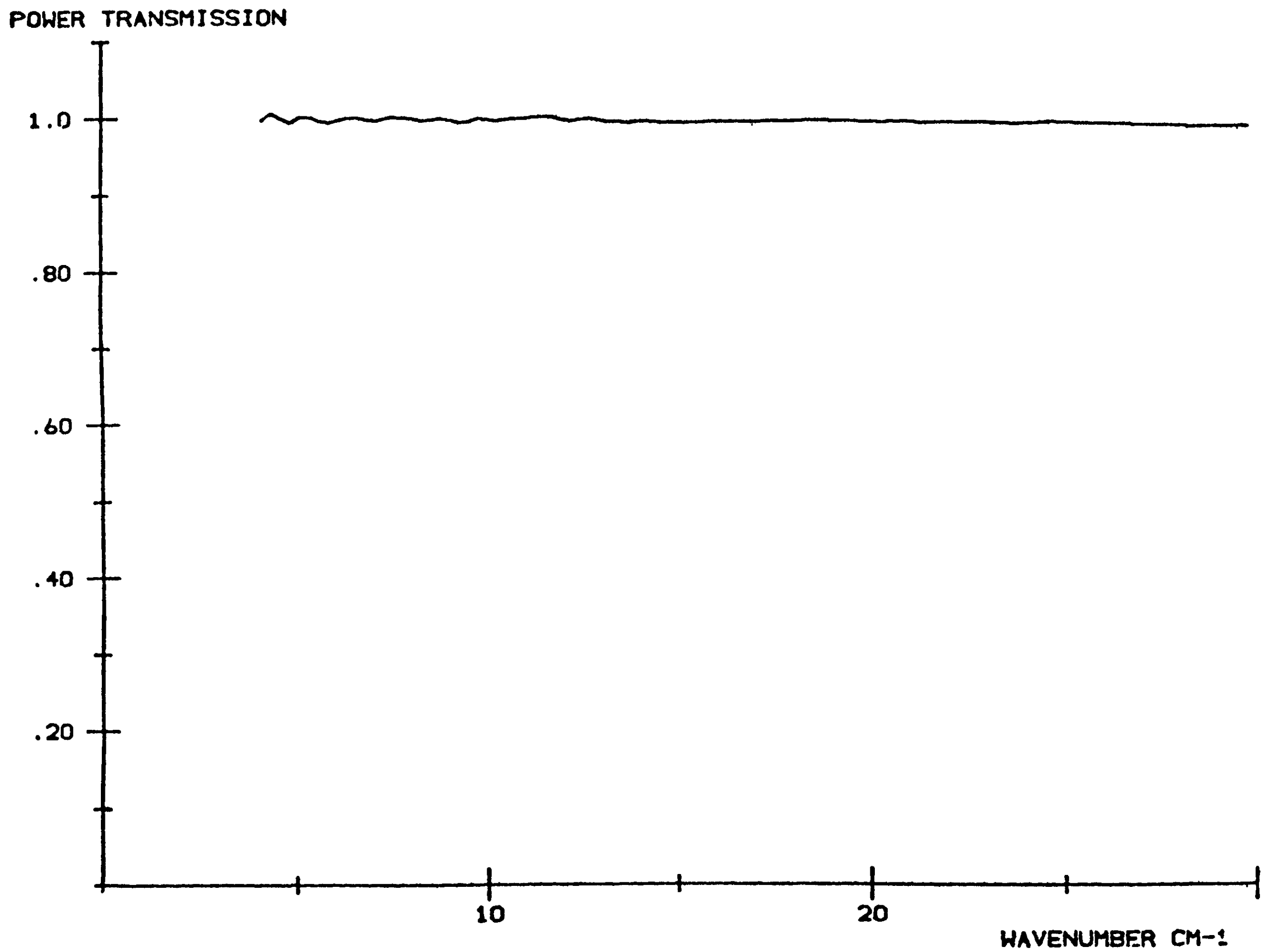
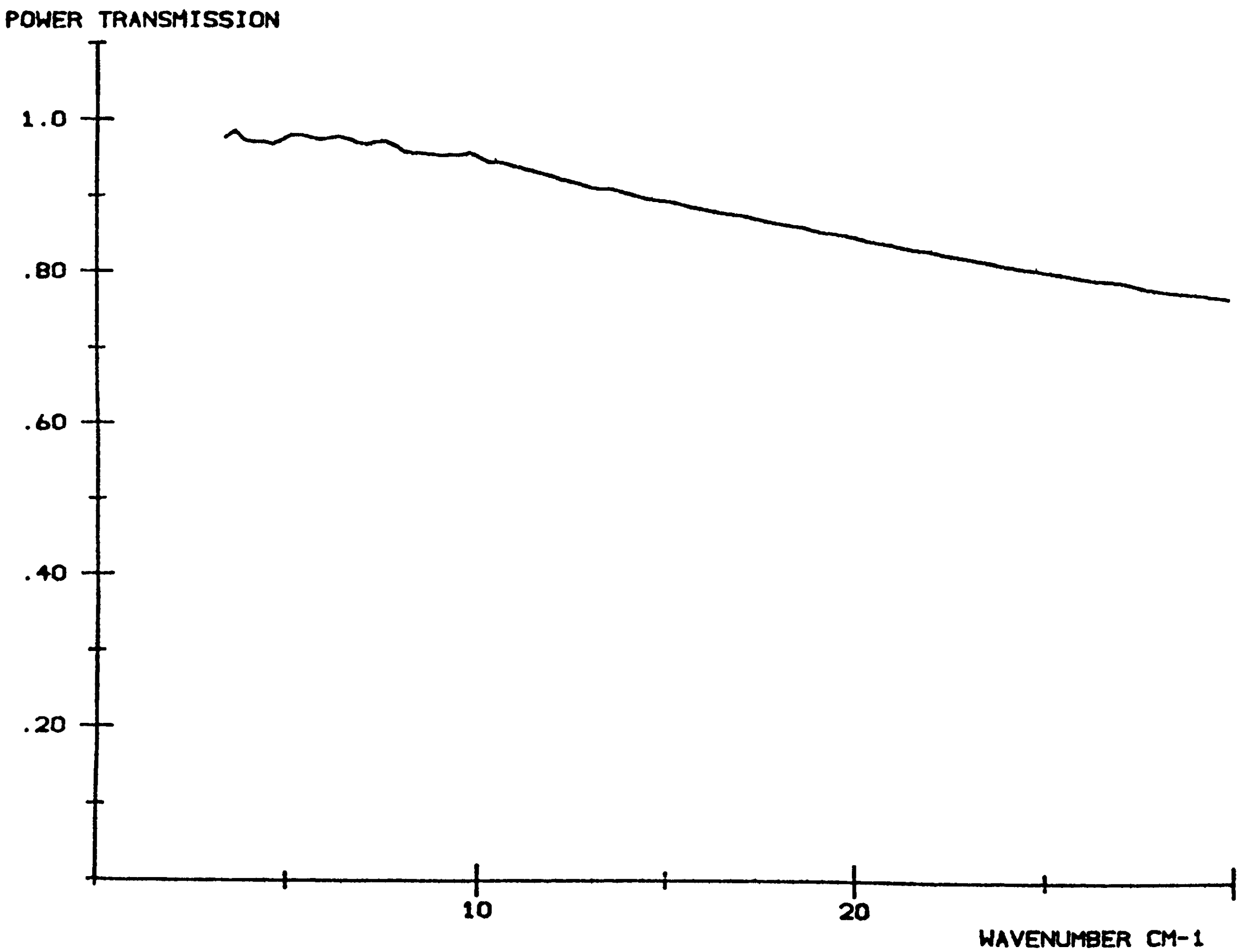
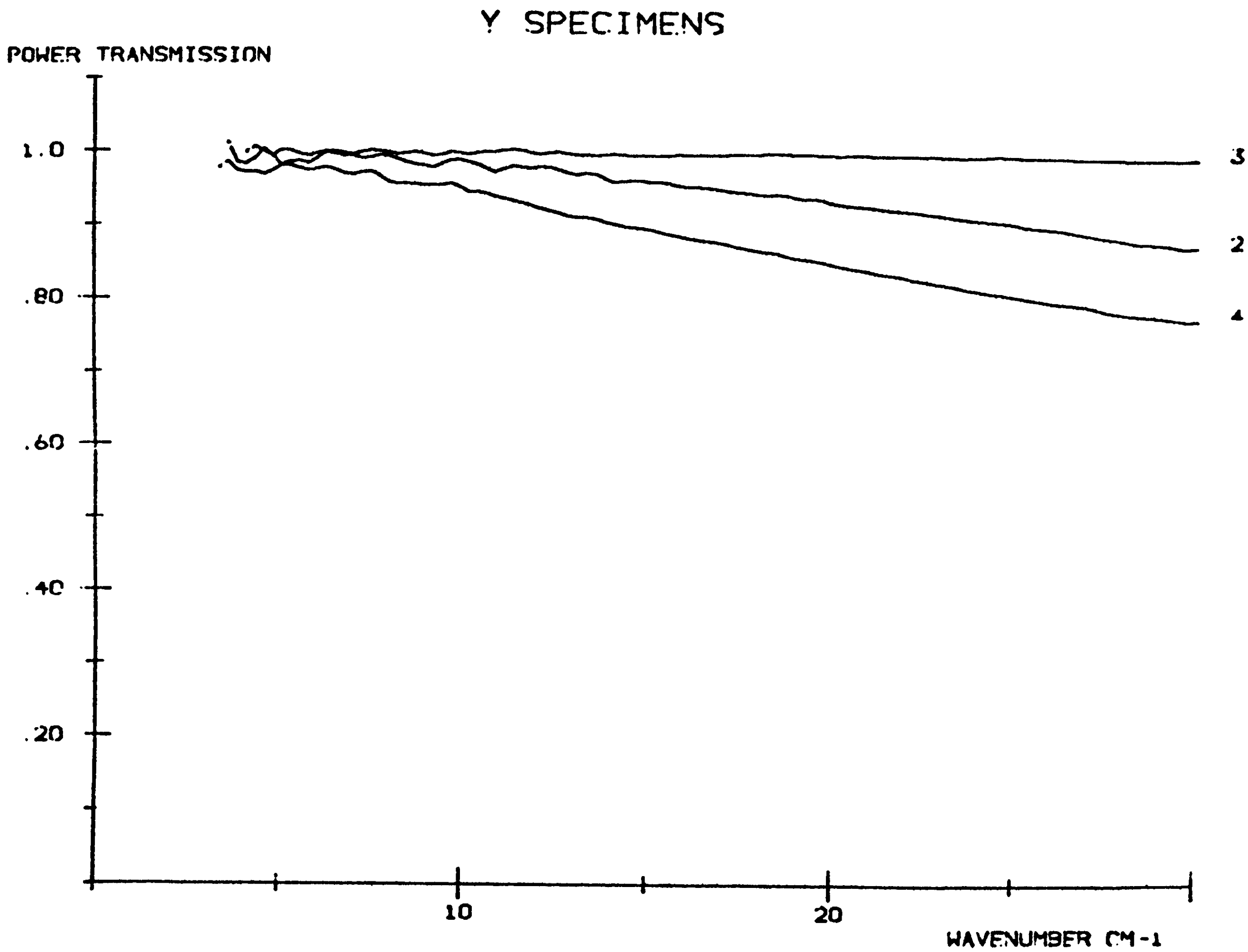
Y3



Y4

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WAVENUMBER CM-1
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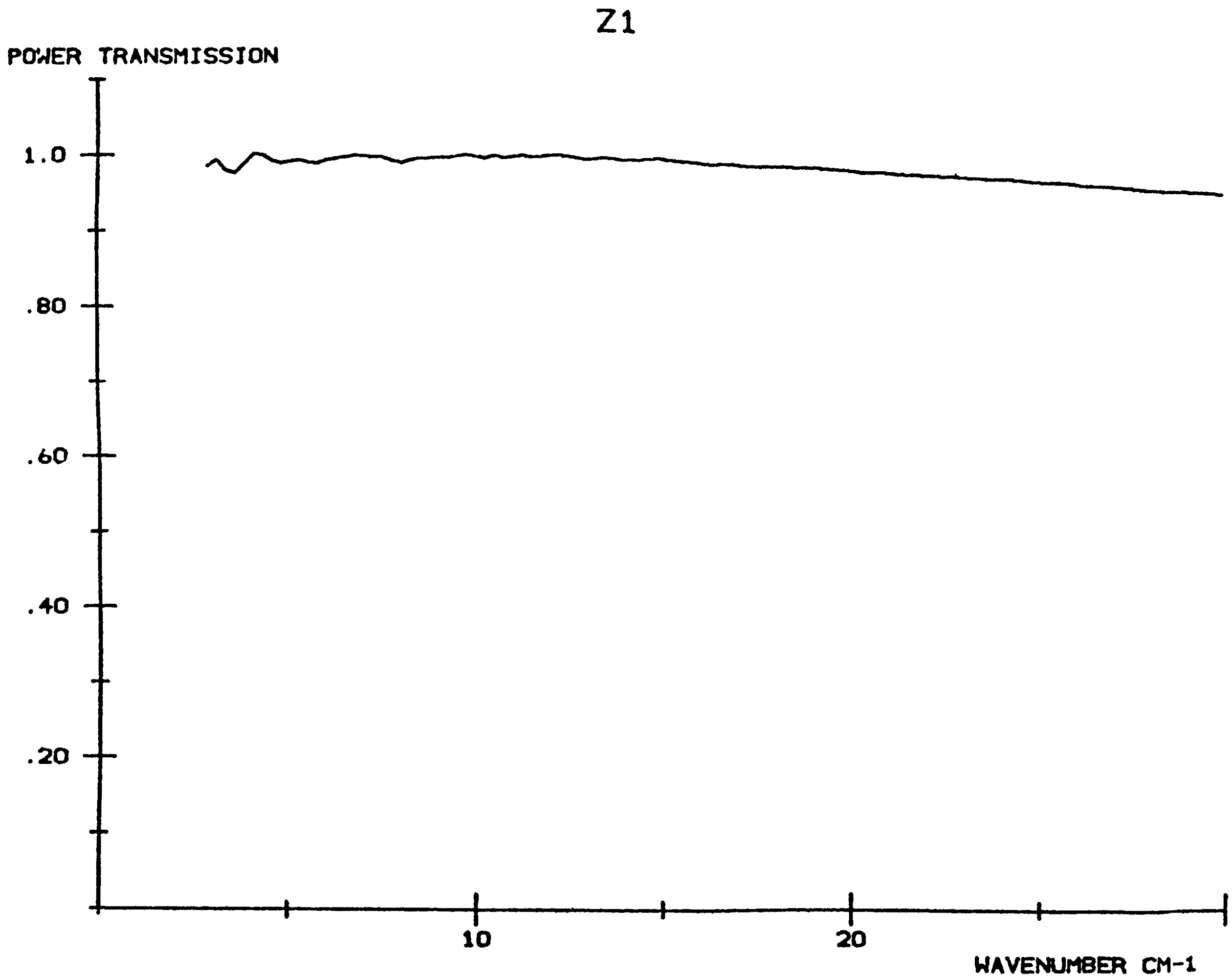
2
4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WAVENUMBER CM-1


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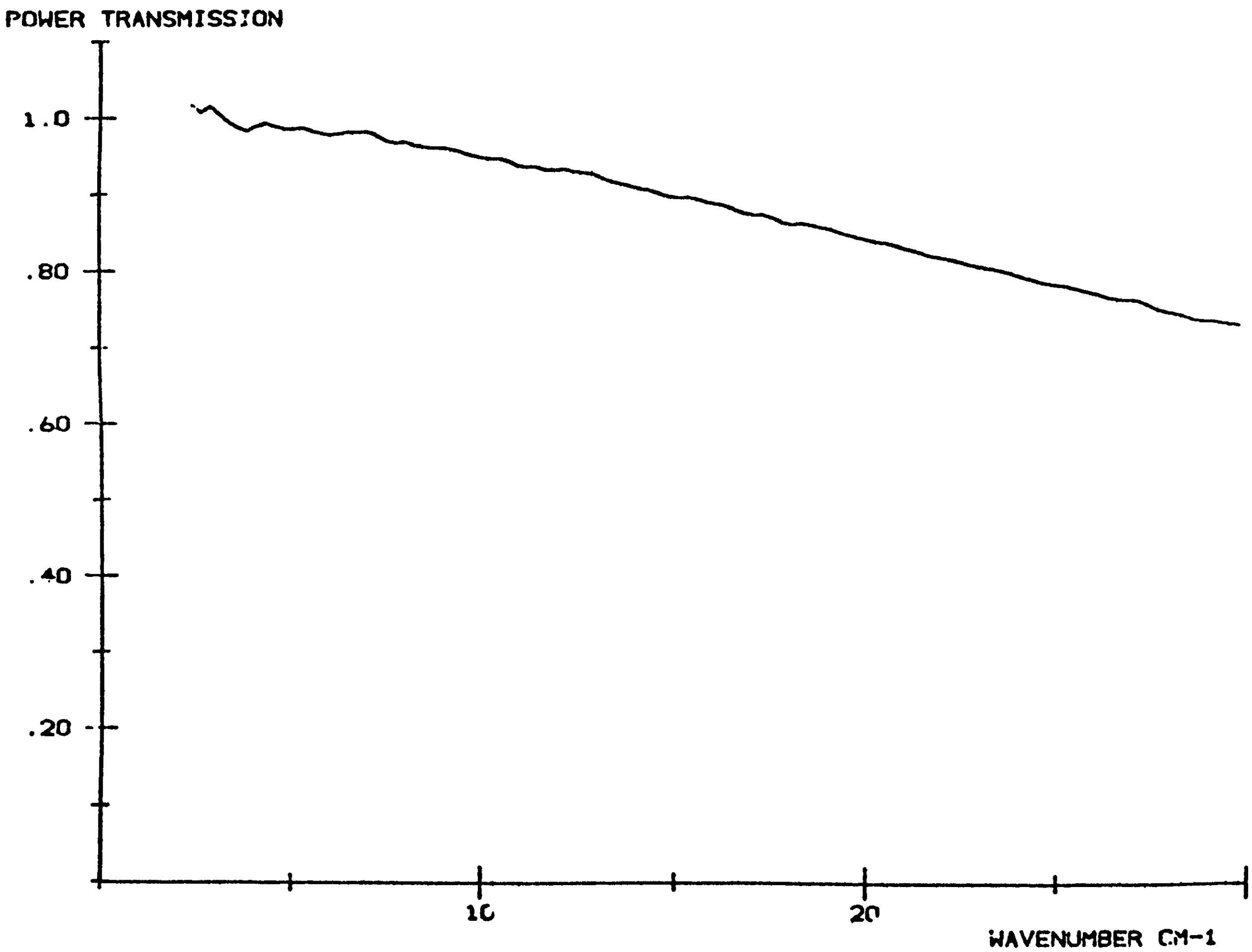
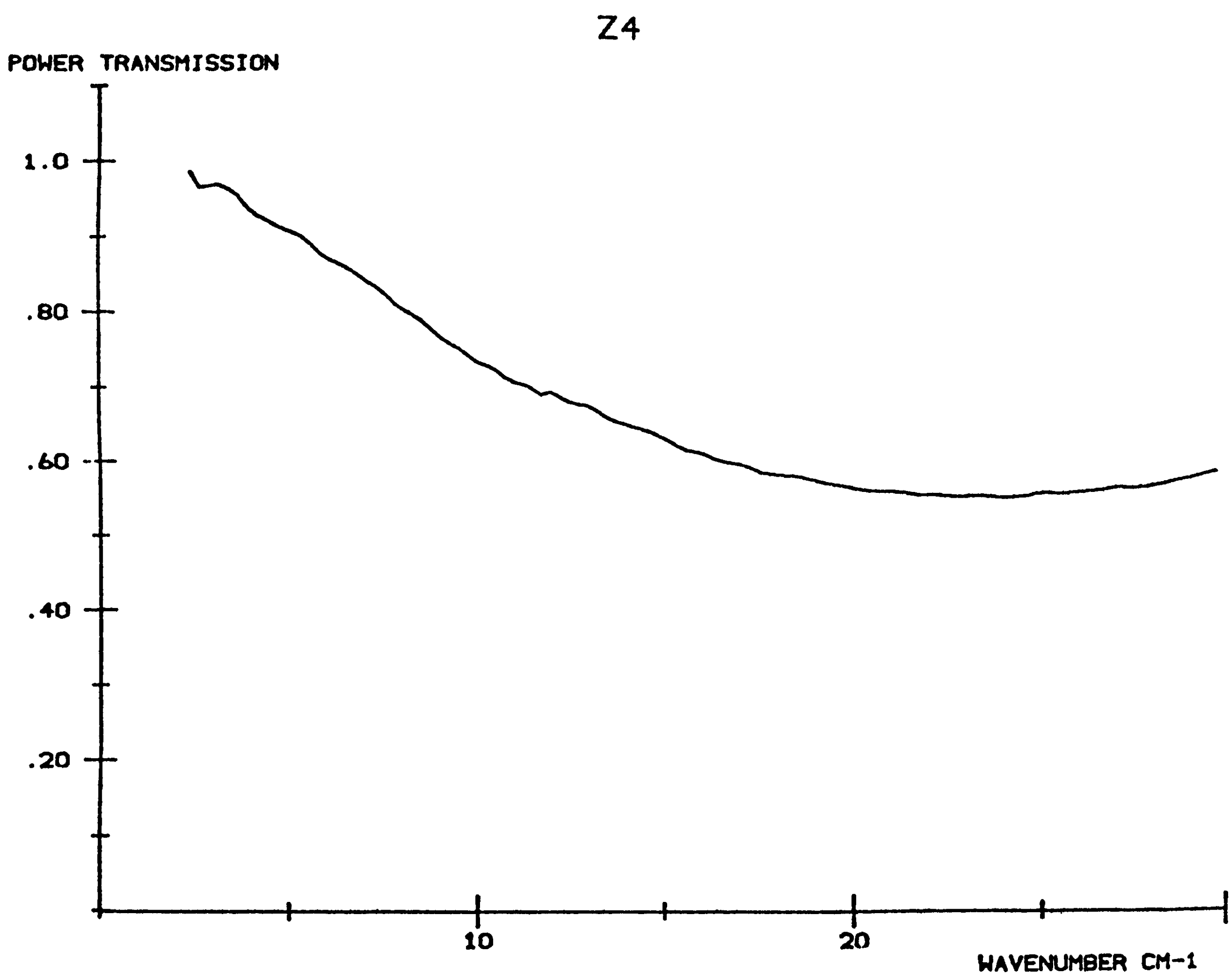
10
20
WAVENUMBER CM-1

Z3

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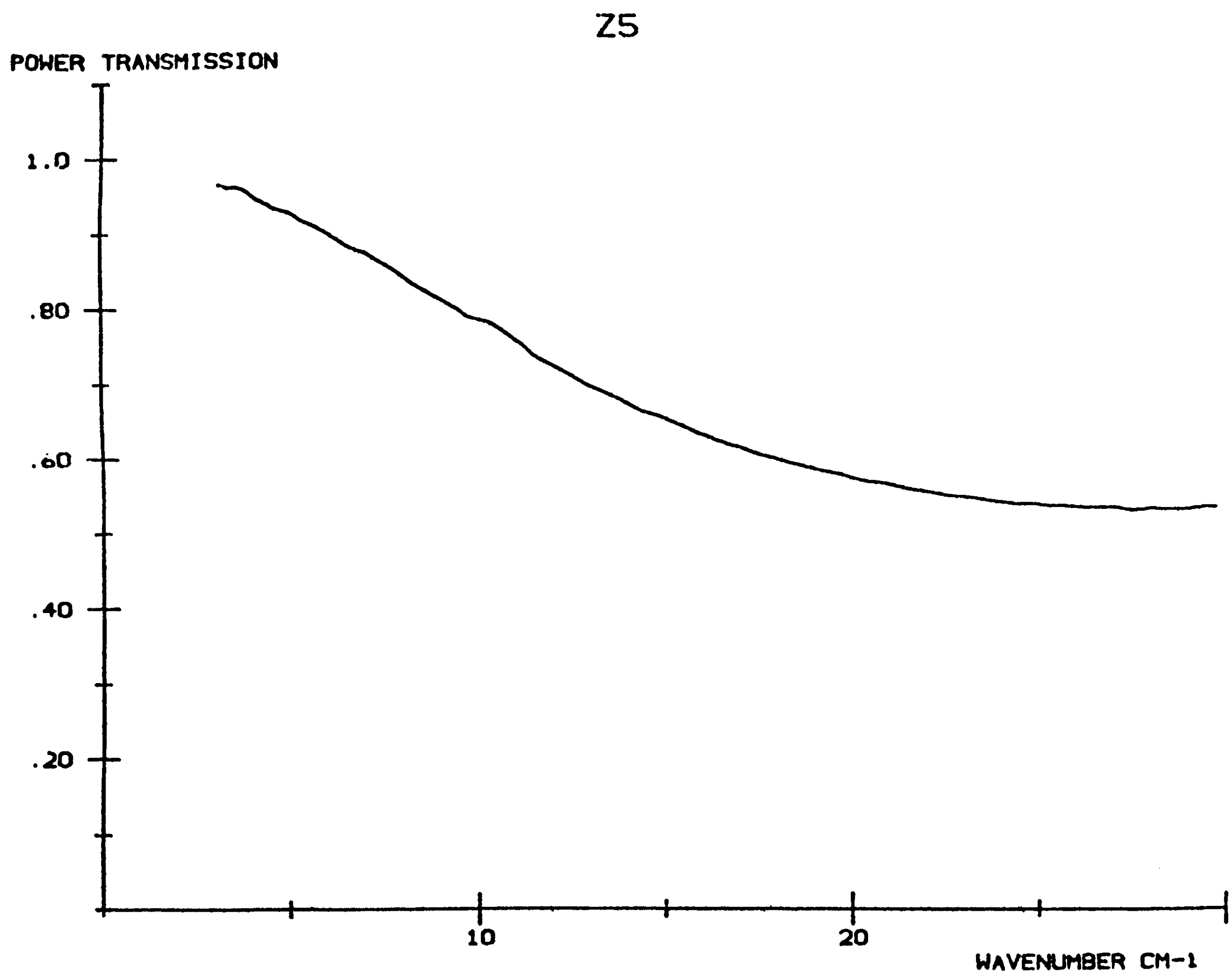

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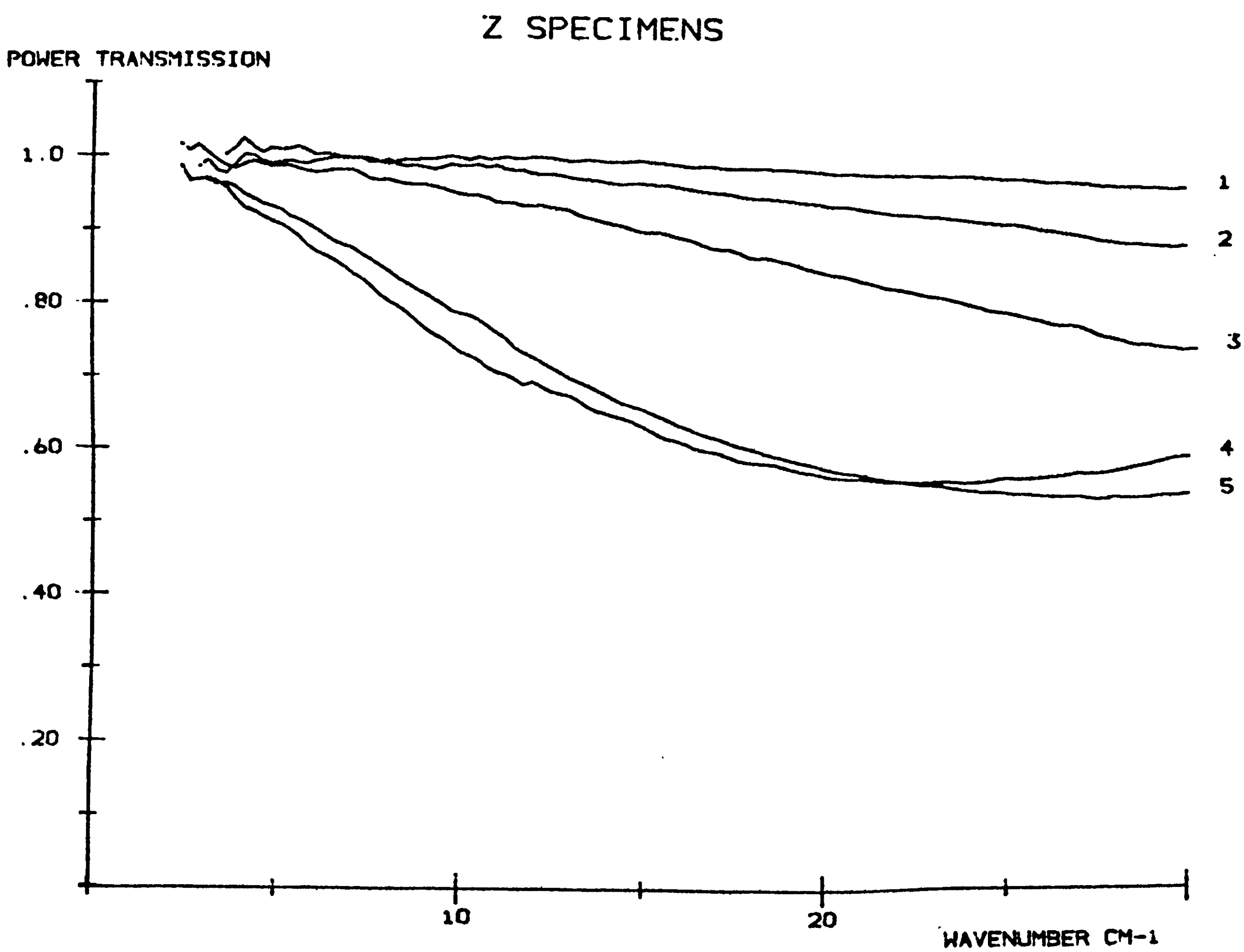
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WAVENUMBER CM-1
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3
4
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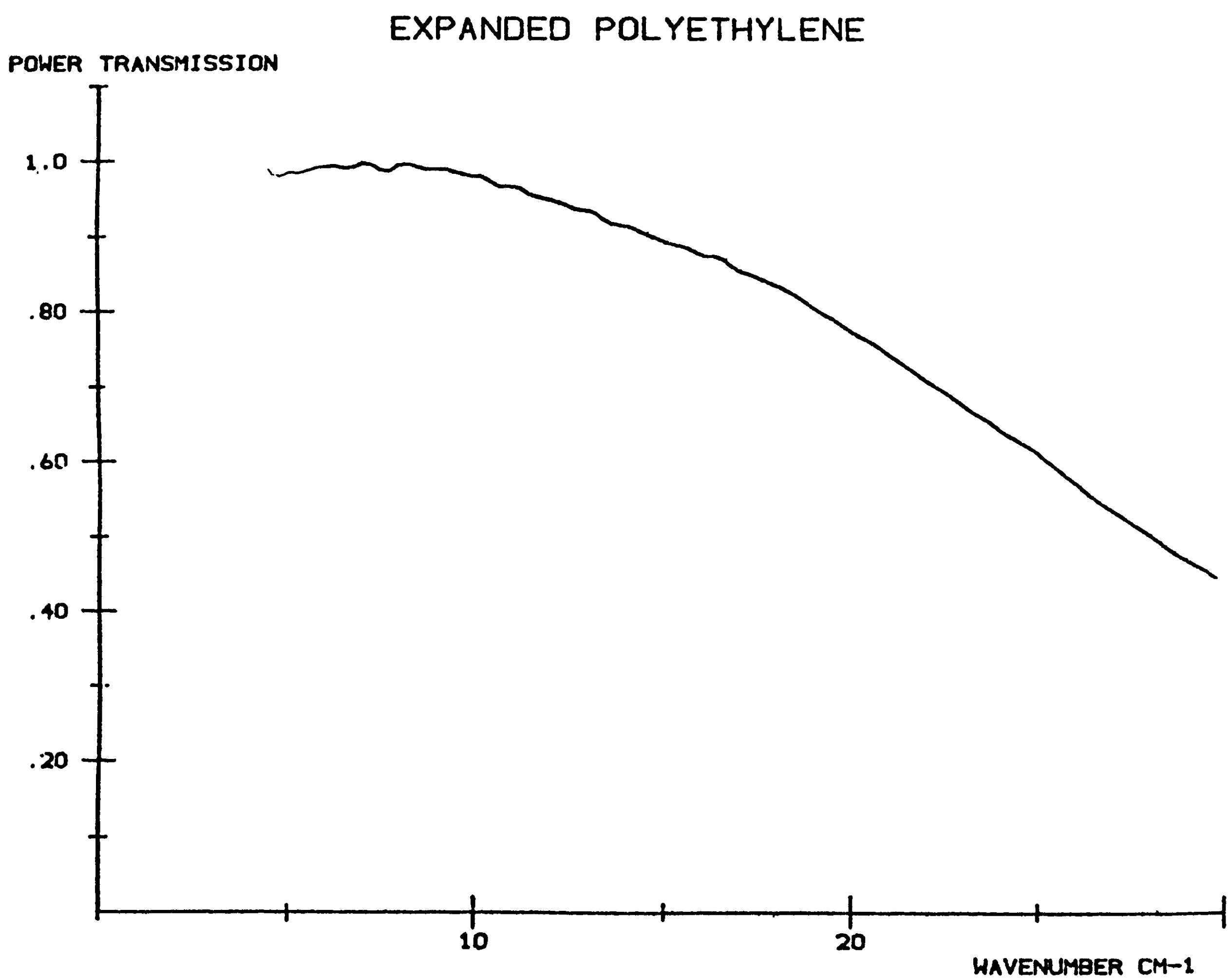

EXPANDED POLYETHYLENE
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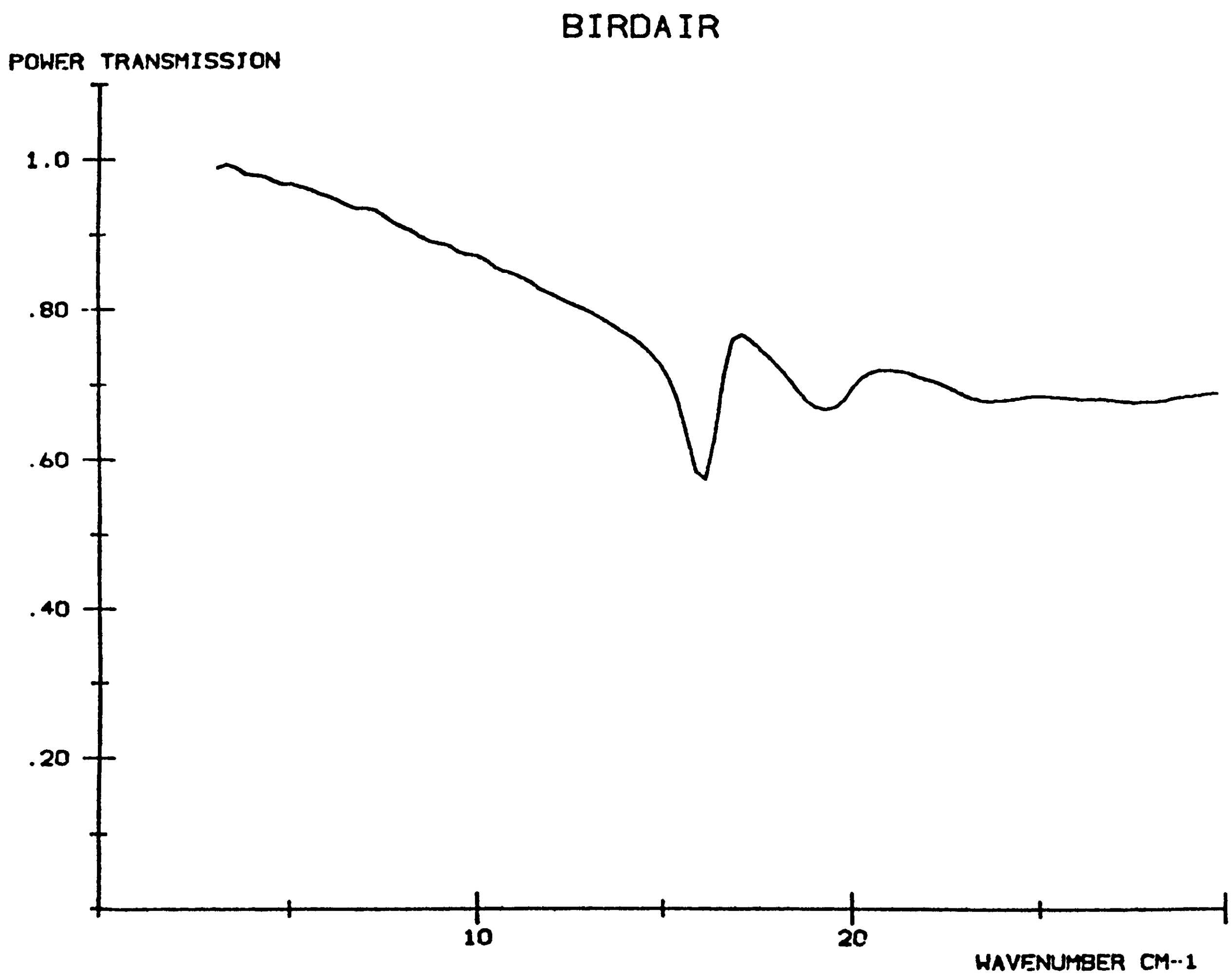
.80
.60
.40
.20
10
20
WAVENUMBER CM-1


BIRDAIR
POWER TRANSMISSION
1.0
.80
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.20
10
20
WAVENUMBER CM-1