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Effect of Translucence of Engineering Ceramics on Heat Transfer in Diesel Engines

Final Report

S. Wahiduzzaman
T. Morel

CERAMIC TECHNOLOGY FOR ADVANCED HEAT ENGINES

MANAGED BY
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EFFECT OF TRANSLUCENCE OF ENGINEERING CERAMICS ON HEAT TRANSFER IN DIESEL ENGINES

S. Wahiduzzaman and Thomas Morel

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FINAL REPORT

Prepared by
Integral Technologies Incorporated
645 Blackhawk Drive
Westmont, Illinois 60559
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ABSTRACT

This report describes the experimental portion of a broader study undertaken to assess the effects of translucence of ceramic materials used as thermal barrier coatings in diesel engines. In an earlier analytical work a parametric study was performed, varying several radiative properties over ranges typical of engineering ceramics, thereby identifying the most important radiative properties and their impact on in-cylinder heat transfer. In the current study these properties were experimentally determined for several specific zirconia coatings considered for thermal barrier applications in diesel engines.

The methodology of this study involved formulation of a model capable of describing radiative transfer through a semitransparent medium as a function of three independent model parameters, ie, absorption coefficient, scattering coefficient and refractive index. A set of radiative measurements was then fitted to this model by optimization of the above model parameters. The radiative measurements were comprised of hemispherical reflectance and transmittance spectra from samples of several different thicknesses of each ceramic under collimated (unidirectional) illumination. A four-flux model was required to extract accurate radiative properties from the measurements.

For the zirconia-based ceramics investigated in this study, it was concluded that for usual coating thicknesses (1.5-2.5 mm) these ceramics are optically thick and hence, are effective as radiative heat transfer barriers. These ceramics possess high scattering coefficients and low absorption coefficients causing them to be highly reflective (60-80%) in the spectral region where thermal radiation is important. As a consequence, only a small portion of the incident energy is captured by the coating system and transmitted to the metal substrate via conduction.

The convective heat flux, which is driven by the temperature differential between the gas and the ceramic-gas interface, was found to be highly dependent on the location where radiative energy is absorbed. If a significant amount of energy is absorbed near the surface, as is the case for ceramics investigated, surface temperature is raised causing convective heat flux to be decreased. On the other hand, for ceramics that are transparent the radiative energy is absorbed at the ceramic/metal interface

and consequently, the gas/ceramic interface remains relatively cool promoting convective heat transfer.

The performance of the investigated ceramics and the mechanism of heat transfer were found to depend on surface condition, specifically on soot deposition. If the surface fouling is small, the ceramics behaved as described above, i.e., as optically thick materials characterized by high scattering coefficient and low absorption coefficient. In this case, the energy transport is primarily due to convective heat transfer since only a small fraction of the incident radiant energy can be trapped by the coating. On the other hand, if the coating surface is totally covered by soot, its performance will be similar to that of a clean optically thick material characterized by small scattering coefficient and high absorption coefficient. In this case, there will be a significant increase in radiation heat transfer absorbed at the surface with an associated decrease in convective heat transfer.

Although the coatings investigated in this study were found to be optically thick at or near nominal thicknesses (2.5 mm), this is by no means representative of all engineering ceramics. For example, based on available literature data, monolithic ceramics have been found to be more transparent than the ceramics investigated in this study and, consequently, are less effective as radiation heat transfer barriers.

Based on the results, it is concluded that ceramics with high scattering and low absorption coefficients are the most suitable for engine applications where in-cylinder surfaces can be expected to remain clean. If surfaces are expected to be sooted an opaque ceramic characterized by either high scattering coefficient and/or high absorption coefficient should be chosen in order to bring about a substantial decrease in convective heat flux. Thus, to insure the optimum thermal barrier operation for either clean or heavily sooted surfaces, a ceramic material with high scattering coefficient provides the best choice.

INTRODUCTION

Ceramic materials are being developed for application as heat barrier materials in insulated diesel engines. Their purpose is to reduce the heat transfer rate from the gases to the walls, with the twin benefits of increased engine efficiency and of lower heat rejection to the coolant.

The idea of a heat barrier layer is to create a path of high resistance to heat transfer, and this is accomplished by using high temperature materials which have low thermal conductivity. Certain ceramics, e.g. zirconia, combine these properties with the potential for low material cost, which accounts for the interest in their development for this application. Computer simulations of in-cylinder heat transfer processes and of the heat conduction through the structural components of the engine indicate that ceramics can indeed provide very substantial reductions in engine heat transfer, translating into important thermal efficiency gains, reduced heat rejection to coolant and increased exhaust energy availability.[1]

However, it is increasingly being realized that some of the ceramics proposed for diesel engine thermal barriers are partially transparent in the spectral region where most of the thermal energy associated with the combustion process is concentrated (Liebert[2,3] and Makino et al[4]). This causes concern about the effectiveness of such ceramic layers in reducing heat transfer in insulated diesel engines, where it is known that radiation can account for a significant portion of the total heat transfer.[6]

The gas-to-wall heat transfer in diesel engines is produced by convection from cylinder gases and by radiation from the soot-laden burning zone. In the high output turbocharged engines typically used in highway truck applications, the heat radiation accounts for some 20 percent of the total heat transfer from gases to walls at the rated engine conditions. When the combustion chamber is insulated, the convective component of the heat transfer is selectively reduced. The proportion of heat transfer that is due to radiation then rises to over 50 percent, thereby becoming a much more significant fraction of the overall heat rejection and a more important design consideration.[5]

In all simulations of diesel engine heat transfer processes reported to date, the assumption has been made that the absorption coefficient of the ceramic is very large so that all of the incident radiation is deposited at the gas/ceramic interface -- i.e., the radiation has not been allowed to penetrate into the interior. This is a carryover from studies of metallic engines where this treatment provides a fairly accurate description of the actual process. However, since some ceramics of engineering interest are known to be translucent, especially at infrared radiation wavelengths, this approximation may be quite incorrect.

The work carried out on this contract is divided into two parts. A previous report7 described the results of the first part, which concerned an analytical study of the radiation process within engineering ceramics, and showed how heat transfer is affected by the radiation properties of ceramics (absorption coefficient, scattering coefficient, index of refraction and surface reflectivities). This report presents the results of the second part of the work concentrating on an experimental determination of the radiative properties of some specific ceramics, and then predicting their effectiveness as heat barrier materials when used in a diesel engine environment.

There were three principal aspects to work described in this report. The first was the selection and implementation of an appropriate methodology to determine the radiative properties of the ceramic materials. The second was the use of the method to determine the radiative properties of several existing coatings that have been developed for diesel engine application. The last was an analysis of the heat transfer through a ceramic-coated wall of a diesel engine, including all three heat transfer mechanisms -- convection, radiation and conduction -- and through it an assessment of the effectiveness of these specific ceramics as heat barrier materials.

METHODOLOGY

The principal parameters required to describe radiative transport in a semitransparent medium are the absorption coefficient (k), scattering coefficient (s), refractive index (n) and scattering phase function (p). For many ceramic materials in which scattering can be assumed to be isotropic, the first three parameters are adequate to describe radiative transport, and in this work we concentrate on these three. An additional assumption, implicit in this description, is that the interfacial reflectivities are known or can be determined using Fresnel's equation. The latter approach is chosen for this study which requires that the interfaces are optically smooth.

The approach adopted here to determine these parameters for a given material is to take radiative measurements of several samples of that material fashioned into thin coupons of different thicknesses. A model describing the radiative transfer in semi-transparent media can be then fitted to the acquired data to determine the above radiative properties. The parameter inversion process involves matching the measured reflectance and transmittance data of a set of coupons of different thicknesses with the model computed values. An objective function based on a sum of squares of normalized differences between measured and computed reflectance and transmittance values can be minimized to obtain the values of n, k and s which give the best correspondence between measurement and model predictions.

The approach discussed above was implemented using measurements obtained at two different locations (wavelengths of 0. to 2.5 μm at NBS* and 2.0 to 20.0 at Willey Corporation**). In both laboratories hemispherical reflectance and transmittance spectra were measured under collimated illumination and consequently include contributions of the collimated flux in addition to the diffuse flux which can be created from the collimated flux undergoing multiple scattering. This necessitates the use of a radiation model capable of describing decay of the collimated flux into a diffuse flux due to multiple scattering unless the incident radiation is diffuse to begin with. A four flux model as opposed to a two flux model is better equipped to handle the problem at hand. Initially a two flux model was used for parameter inversion and was soon discovered to be inadequate at low scattering levels and was discarded in favor of a four flux model. However, for the sake of completeness both models will be discussed below and a comparison of the model performances will be presented in a later section.

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*Center for Radiation Research, National Measurement Laboratory, National Bureau of Standards, Gaithersburg, Maryland 20899.

**Willey Corporation, P.O. Box 670, Melbourne, Florida 32901.

FOUR FLUX MODEL

The model chosen in this study is the four-flux model, which predicts specular and diffuse reflectivity and transmissivity for a planar medium illuminated by diffuse and/or collimated flux. The parameters k, s, n and the material thickness are the only inputs to the model. The model (Ishimaru[5] and Makino and Kunitomo[4]) assumes that the radiation transport in a cold (non-emitting) medium can be described by four fluxes. Two of these are a diffuse forward flux and a diffuse backward flux, both of which remain diffuse upon interfacial reflection and scattering. The other two fluxes are a collimated forward and a collimated backward flux which undergo isotropic scattering, thereby contributing equally to the forward and backward diffuse fluxes. The collimated fluxes are assumed to remain collimated after specular (mirror-like) interfacial reflections. Under these assumptions the governing equations and associated boundary conditions are (Figure 1):

governing equations:

$$\frac{dD^+}{dx} = -(2k+s)\,D^+ + sD^- + \frac{s}{2}\,C^+ + \frac{s}{2}\,C^- \tag{1}$$

$$-\frac{dD^-}{dx} = -(2k+s)\,D^- + sD^+ + \frac{s}{2}\,C^- + \frac{s}{2}\,C^+ \tag{2}$$

$$\frac{dC^+}{dx} = -(k+s)\,C^+ \tag{3}$$

$$-\frac{dC^-}{dx} = -(k+s)\,C^- \tag{4}$$

boundary conditions:

$$D^+(0) = (1-R_{do})\,F_d + R_{di}\,D^-(0) \tag{5}$$

$$D^-(d) = R_{di}\,D^+(d) \tag{6}$$

$$C^+(0) = (1-R_{co})\,F_c + R_{ci}\,C^-(0) \tag{7}$$

$$C^-(d) = R_{ci}\,C^+(d) \tag{8}$$

where 0 and d denotes front and back surface, respectively.

A general solution to the above set of equations is:

$$D^+(x) = \alpha_1 A e^{-\tau} + \alpha_2 B e^{\tau} + \alpha_3\,(1+\beta)\,e^{-2\beta\tau} + \alpha_4\,(1-\beta)\,e^{2\beta\tau} \tag{9}$$

$$D^{-}(x) = \alpha_1 B e^{-\tau} + \alpha_2 A e^{\tau} + \alpha_3 (1-\beta) e^{-2\beta\tau} + \alpha_4 (1+\beta) e^{2\beta\tau} \quad (10)$$

$$C^{+}(x) = \alpha_1 e^{-\tau} \quad (11)$$

$$C^{-}(x) = \alpha_2 e^{\tau} \quad (12)$$

where

A	=	$3\omega/(8\beta^2-2)$
B	=	$A/3$
C^+	=	collimated forward flux
C^-	=	collimated backward flux
d	=	depth of the layer
D^+	=	diffuse forward flux
D^-	=	diffuse backward flux
F_d	=	diffuse incident flux
F_c	=	collimated incident flux
k	=	absorption coefficient
R_{di}	=	diffuse interfacial internal reflection
R_{do}	=	diffuse interfacial external reflection
R_{ci}	=	collimated interfacial internal reflection
R_{co}	=	collimated interfacial external reflection
s	=	scattering coefficient
β	=	$\sqrt{1-\omega}$
λ	=	wavelength
ω	=	$s/(s+k)$ = albedo
E	=	$s+k$ = extinction coefficient
τ	=	$(k+s)x$ = optical depth at x
τ_d	=	$(k+s)d$ = optical thickness of the translucent layer

The coefficients α_1, α_2, α_3 and α_4 are determined by solving the following simultaneous equations obtained using the boundary conditions:

$$
\begin{bmatrix}
1 & -R_{ci} & 0 & 0 \\
-R_{ci}e^{-\tau d} & e^{\tau d} & 0 & 0 \\
(A-R_{di}B)e & (B-R_{di}A)e & \begin{matrix}(1+\beta)\\ -(1-\beta)R_{di}\end{matrix} & \begin{matrix}(1-\beta)\\ -(1+\beta)R_{di}\end{matrix} \\
(B-R_{di}A)e^{-\tau d} & (A-R_{di}B)e^{\tau d} & \begin{matrix}[(1-\beta)\\ -(1+\beta)R_{di}]e^{-2\tau d}\end{matrix} & \begin{matrix}[(1+\beta)\\ -(1-\beta)R_{di}]e^{2\tau d}\end{matrix}
\end{bmatrix}
\begin{bmatrix}
\alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4
\end{bmatrix}
=
\begin{bmatrix}
(1-R_{co})F_c \\ 0 \\ (1-R_{do})F_d \\ 0
\end{bmatrix}
\qquad (13)
$$

Then collimated and diffused reflected fluxes at the inside front surface can be calculated after substitution of Eqs. (10) and (12) in the following equations:

$$S_c = R_{co} F_c + (1-R_{ci})C^-(0) \qquad (14)$$

$$S_d = R_{do} F_d + (1-R_{di})D^-(0) \qquad (15)$$

respectively.

Similarly, the collimated and diffused transmitted fluxes at the back surface of the ceramic are obtained after substituting Eqs. (9) and (11) in the following equations:

$$H_c = (1-R_{ci})\, C^+(d) \qquad (16)$$

$$H_d = (1-R_{di})\, D^+(d) \qquad (17)$$

From these fluxes reflectance and transmittance can be appropriately defined as follows:

$$R_h = (S_c + H_c)/(F_d + F_c) \tag{18}$$

$$T_h = (S_d + H_d)/(F_d + F_c) \tag{19}$$

TWO FLUX MODEL

Under purely diffuse illumination, only two diffuse fluxes are necessary to describe radiative transport in a planar medium provided assumptions previously made are still valid. It was assumed that a collimated flux transforms into diffuse forward and backward fluxes by undergoing isotropic scattering. If the scattering level is high this conversion will happen early and a simpler two (diffuse) flux model can then be used as a further approximation of the radiative transport in such media. The flux equations and the boundary conditions for the model can be written as:

$$\frac{dD^+}{dx} = -(2k+s)D^+ + sD^- \tag{20}$$

$$-\frac{dD^-}{dx} = -(2k+s)D^- + sD^+ \tag{21}$$

The accompanying boundary conditions are:

$$D^+(0) = (1-R_{do})F_d + R_{di}D^-(0) \tag{22}$$

$$D^-(d) = R_{di}D^+(d) \tag{23}$$

It should be noted here that the above equations are identical to those obtained from the four flux model under purely diffuse illumination.

The general solution to the above equations is:

$$D^+ = \alpha_3(1+\beta)e^{-2\beta\tau} + \alpha_4(1-\beta)e^{2\beta\tau}$$

$$D^- = \alpha_3(1-\beta)e^{-2\beta\tau} + \alpha_4(1+\beta)e^{2\beta\tau}$$

The coefficients α_3 and α_4 are then determined from the boundary conditions as follows:

$$\begin{bmatrix} (1+\beta) - (1-\beta)R_{di} & (1-\beta)-(1+\beta)R_{di} \\ [(1-\beta)-(1+\beta R_{di}]e^{-2\beta\tau_d} & [(1+\beta)-(1-\beta)R_{di}]e^{2\beta\tau_d} \end{bmatrix} \begin{bmatrix} \alpha_3 \\ \alpha_4 \end{bmatrix} = \begin{bmatrix} (1-R_{do})F_d \\ 0 \end{bmatrix} \quad (24)$$

After solution one obtains

$$\alpha_3 = \frac{F_d(1-R_{do})Ue^{2\beta\tau_d}}{U^2e^{2\beta\tau_d} - V^2e^{-2\beta\tau_d}} \quad (25)$$

$$\alpha_4 = \frac{-F_d(1-R_{do})Ve^{-2\beta\tau_d}}{U^2e^{2\beta\tau_d} - V^2e^{-2\beta\tau_d}} \quad (26)$$

where

$$U = (1+\beta) - R_{di}(1-\beta)$$

$$V = (1-\beta) - R_{di}(1+\beta)$$

The reflected and transmitted fluxes are:

$$S_d = R_{do}F_d + (1-R_{di})D^-(0) \quad (27)$$

$$H_d = (1-R_{di})D^+(d) \quad (28)$$

Then the reflectance is given by:

$$R_d = S_d/F_d$$

$$= R_{do} + (1-R_{do})(1-R_{di}) \frac{(1-\beta)Ue^{2\beta\tau_d} - (1+\beta)Ve^{-2\beta\tau_d}}{U^2e^{2\beta\tau_d} - V^2e^{-2\beta\tau_d}} \quad (29)$$

and the transmittance is given by:

$$T_d = H_d/F_d$$

$$= (1-R_{do})(1-R_{di}) \frac{(1+\beta)U-(1-\beta)V}{U^2 e^{2\beta\tau_d} - V^2 e^{-2\beta\tau_d}} \qquad (30)$$

It should be noted here that the reflectance and transmittance in equations 18, 19, 29 and 30 are spectral quantities (i.e., have unique values for each wavelength).

The essence of the method involves minimizing the differences between the computed reflectance and transmittance spectra using these equations with the measured spectra by suitable choice of model parameter in order to obtain spectral distributions for these parameters.

EXPERIMENTAL DATA AND THEIR ANALYSIS

RADIATIVE MEASUREMENTS

Four different ceramics were available for radiative parameter inversion. These included plasma sprayed zirconia (PSZ) (13% Yttria stabilized) from Plasma Technics*, PSZ and TZP (Tridiagonal Zirconia Polycrystals) from Oak Ridge National Laboratory** and PSZ (24% Ceria stabilized) from Caterpillar***. The success of the above procedure, i.e. obtaining the radiative properties of a given ceramic, depends on acquiring a set of experimental data which are independent of each other. This requires measurement of reflectances and transmittances at sufficiently distinct optical depths. Hence, it is desirable to select thicknesses of samples such that an optically thin, an optically thick and an intermediate optical thickness are included in the set of samples. However, without a priori information, which was the case in the present study, one can only guess at the best thicknesses for this purpose. Based on feasibility of fabrication of the thinnest samples, mechanical strength, and literature values of properties of similar materials, three to four thicknesses were specified and fabricated for each of the four ceramics investigated in this study. All of these samples are labeled and described in the Table I.

---

*Plasma Technics Inc., 1143 West Newport Center Drive, Deerfield Beach, Florida 33442.

**Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, Tennessee 37831.

***Caterpillar Inc., Technical Center, P.O. Box 1875, Peoria, Illinois 61656-1875.

The original plans were to obtain normal incidence diffuse reflectance for all thirteen samples. The transmittance measurements were planned only for nine samples, excluding the thickest sample of each set which were expected to be too thick to allow any transmission. The first set of measurements was made over a wavelength band spanning 2 μm to 20 μm at Willey Corporation, a private firm specializing in radiometry. In this wavelength range meaningful transmittance measurement could be obtained only for seven samples, because only the thinnest sample of the PSZ samples from Caterpillar (set D) transmitted enough energy to obtain reliable transmittance data.

The measurements at lower wavelength, extending from 0.25 to 2.5 μm, were conducted at the National Bureau of Standards. Again for some of the samples (A2, D11, D12) poor transmittance results were obtained owing to low signal-to-noise ratio. In addition, sample A1 was found to be broken during transit and no transmittance measurement could be obtained from this sample. The matrix of radiative measurements carried out by Willey Corporation and NBS are summarized in Table II.

ANALYSIS OF CONSISTENCY OF THE EXPERIMENTAL DATA

In this study, the emphasis of the analysis was placed on the wavelength range from the visible (0.4 μm) to 5 μm where thermal radiative energy is important in diesel engine applications. (Note that the peak radiant intensity of a blackbody occurs at 2.9 μm at 1000K and at 1.45 μm at 2000K.) This wavelength band contains the overlap region (2.0 μm to 2.5 μm) where data was obtained at both laboratories. The agreement between the data in the overlap range was examined from the two sources and it was found satisfactory. (It should be noted that the data from Willey Corporation exhibited noise inherent to the measuring instrument[8] and had to be smoothed.) The composite plots of data belonging to both sources are shown in Figures 2 to 5. (The unsmoothed data from Willey Corporation is presented in the Appendix.)

The available data were carefully scrutinized to determine their suitability for radiative parameter inversion. The following observations of unusual trends were made:

(1) Sample sets B and C from Oak Ridge exhibited very similar reflectance and transmittance spectra despite different composition (Figures 3 and 4). This similarity was evident in the data obtained at both Willey and NBS. It was concluded that the two sets are radiatively identical.

(2) The qualitative trend of the reflectance data of sample C9 was markedly different than those of thinner samples of the same material (C7 and C8). The differences include a) lower reflectance values below 0.5 μm, b) relatively constant reflectance values between 0.5 μm and 2.5 μm and c) most importantly, a dip in the reflectance values around 2.75 μm (Figure 4b). These characteristic differences suggest that the

sample C9 may have been contaminated during its fabrication. Hence it was necessary to exclude the data from this sample from parameter inversion analysis for set C. A similar conclusion can be made for sample B4 as evidenced in Figure 3a.

(3) Reflectance spectra for samples belonging to set D exhibited an inconsistent trend with thickness. The spectra of samples D10 and D13 possessed characteristics which are absent in the spectra for samples D11 and D12 (Figure 5b). These characteristics include a dip at 2 μm and high reflectance values beyond 3 μm. Since transmittance data were available for sample D10, it was decided that only data from samples D10 and D13 would be used for parameter inversion for set D. The choice D11 and D13 would only provide two sets of measurements as opposed to three sets of measurements for the choice made.

After careful consideration of the above factors, consistent sets of data from the two laboratories were merged. Since data obtained at Willey Corporation are less reliable in the overlap region (2 μm to 2.5 μm), the data from NBS were given higher weight in this band during merger. Figures 6 to 8 show merged data for sample sets B, C and D. It can again be noted here, allowing for the measurement uncertainties, sets B and C possess identical spectra.

Unfortunately, the data for sample A is too sparse for parameter inversion. It can be seen in Figure 2(b) that reflectance is nearly identical for all three samples (A1, A2, A3). (The spectrum A1 presented here was measured from a damaged sample and as such NBS has not certified this data.) This signifies that even at the smallest thickness (0.51 mm) the ceramic is optically thick and therefore the samples do not produce sufficiently independent information required for parameter inversion. It should be noted that transmittance spectrum of A1 is unreliable since it was measured from a damaged sample. Despite the deficiencies in the measurements, some conclusions can still be drawn for this material and will be discussed in a later section.

PARAMETER INVERSION

As discussed in the previous section, for sets B and/or C we have two reflectance and two transmittance spectra that are consistent within each set. For the set D, there are only two reflectance and one transmittance spectra that have consistency. Thus, for both sets, the number of spectra available for parameter inversion is rather small. It was found that it is a difficult, if not impossible, task to extract three independent radiative parameters from such a sparse input data set. Initial analysis showed that of the three chosen parameters (n, k, s), the refractive index n is the least sensitive. Upon analysis, one observes that the refractive index affects radiative transport in two ways; through interfacial reflectivities (Fresnel's reflectivity) and through the self-emission term. Since the ceramics studied here possess high scattering coefficients, interfacial reflectivities have little contribution to layer reflectances. In addition, reflectance and transmittance of the samples were measured at room temperature, consequently, the self-emission term is negligible in comparison to other fluxes and may be dropped from the transport equation. Under these circumstances, it was decided to keep the refractive index fixed at 1.58 and to determine only the remaining two parameters (s and k) through the parameter inversion procedure. This value of refractive index is based on previous observations and trends observed during current data analysis. It was reported in previous investigations (e.g. Makino and Kunitomo[4]), that refractive index remains nearly constant from 0.5 μm to 5 μm. Its value is expected to be between 1.2 to 2.5. In yet another study (Matthews[9]) involving a similar nonlinear parameter inversion technique, the refractive index of zirconia was estimated to be 1.6. Thus the value of 1.58 chosen for this study is expected to be close to the actual value of the parameter. The total uncertainty on the remaining parameters introduced by this range in refractive index is of the order of 25% and 35% for scattering and absorption coefficient, respectively.

With the above restrictions, the parameter inversion model was applied to data obtained for sample sets B and C. The results are shown in Figures 9 and 10. As expected, two samples exhibited nearly identical radiative properties. The scattering coefficient is found to be high in the visible band, and it steadily decreases as wavelength is increased. On the other hand, absorption coefficient is relatively small and remains constant except in the visible band (0.4-0.7 μm), and beyond 4 μm where it starts to increase very sharply. Figures 11a and 11b show model-predicted reflectance and transmittance for sample set C using the k and s values deduced from the data. It can be observed that the predicted reflectances and transmittance are in good agreement with the experiment except for the 10 mm sample (Figure 4b). It may be recalled that the measured reflectance spectrum for this sample was excluded from the data analysis owing to its inconsistent characteristics.

Analysis was also performed on the data belonging to set D. The inverted parameters are shown in Figures 12a and 12b. The predicted reflectance and transmittance are shown in Figure 13a. There is good agreement between measured (Figure 13b) and predicted (Figure 13a) transmittance values, however, the predicted reflectances for the two different thicknesses are nearly identical to the measured reflectance of the thinnest sample (D10). If an absorptance spectrum is computed for this sample from the measured reflectance and transmittance (Absorptance = 1 - Transmittance - Reflectance) spectra, it can be readily observed that for much of the spectrum the optical depth of the sample is high. Hence, there is no reason to believe that for higher thickness reflectance will be markedly different, contrary to the trends suggested by the data. Rather, it is likely that the apparent differences in the measured reflectance spectra are due to variations in surface preparations.

The scattering coefficients for set D possess the same qualitative trend as those of set B and C except their values are about twice as high. On the other hand, the absorption spectrum shows a distinctive peak at 3 μm corresponding to the valleys in the reflectance and transmittance spectra. In general, set D is more opaque than B and C due to its higher scattering and absorption coefficients.

It is worth noting here that the radiative parameters obtained in this study are derived from room temperature measurements. However, in a previous study Makino and Kunitomo[4] did not observe any major dependence of radiative properties on temperature for zirconia and alumina. Hence, it is believed that the parameter values reported here will be valid for diesel engine applications where temperatures (1000 K) are not too dissimilar to the range investigated in the referenced study (~300 K to 700 K).

FOUR FLUX MODEL VS. TWO FLUX MODEL

The parameter inversion procedure discussed in the previous section utilizes a four flux radiation model. However, initially a two flux radiation model was used before it was discarded in favor of the four flux model. The experimental measurements described earlier were made under collimated (near normal beam) illumination. The two flux model is inadequate for describing propagation of collimated flux through a semi-transparent medium. However, if the fraction of incident energy that penetrated the medium in properly calculated (using directional reflectivities), the two flux model may still be valid for a medium where collimated flux undergoes quick transformation into diffuse flux due to high scattering level. On the other hand, for samples having small optical depths where the extinction coefficient is of the order of unity the contribution of the internal collimated flux on total transmittance and reflectance will be comparable to the contribution from the internal diffuse flux. Hence, in this case it is necessary to solve for both collimated and diffuse fluxes simultaneously, which the two flux model cannot accomplish.

In order to remove this weakness in the originally planned radiative parameter inversion model, replacement of the the two flux model by a four flux model was essential as it was confirmed by comparisons of parameters evaluated by both models. (Both of these models have been described in previous sections.) Initial results obtained using the original two-flux inversion model revealed that for ceramics under study the scattering level tapers off at higher wavelength. It seemed likely that the validity of two-flux model will break down at these high wavelengths. The revised model utilizing a four-flux model was applied to the available experimental data. The radiative parameters thus deduced were compared against the parameters from the two-flux model. Figures 14a and 14b show a comparison of radiative parameters obtained using both models for ceramic D. It was observed that the two-flux model underpredicted the scattering coefficient by as much as 50% at higher wavelengths, whereas the absorption coefficient remained almost unchanged.

RECOMMENDATION FOR FUTURE MEASUREMENTS

It is evident that the proper choice of the sample thicknesses is an essential prerequisite for successful parameter inversion. However, prior knowledge regarding optical thickness is required to make such choices. Hence the recommended procedure would be to make preliminary transmittance measurements to obtain some knowledge about the opacity of the sample, or making a larger number of samples (at least 5) of various thicknesses to increase the likelihood of capturing the right sample thickness range. The recommended set of optical thicknesses is kL = 0.5, 1.0, 1.5, 2.0 and 2.5 which assures that meaningful values of transmittance and reflectance can be attained. For example if a material has an extinction coefficient of 10,000 m^{-1} in the wavelength region of interest, the required samples will have thicknesses of 0.05 mm to 0.25 mm. If samples that thin cannot be fabricated, a thicker set of samples may be substituted, but a lower accuracy will result.

As discussed earlier, the refractive index is the least sensitive of the chosen parameters. In order to extract this parameter, one needs measurement techniques which possess stronger dependence. One approach could be a separate measurement of the diffuse and directional reflectance and transmittance (in the present case the sum of the diffuse and directional values was measured). However, this would require greater attention to surface preparation; the sample surfaces should be smooth, parallel and consistent from sample to sample. Another approach would measure polarized components of this reflectance.

Further, the number of samples should be as large as possible. A large number of samples is often necessary (eight for Makino[10]) to obtain reliably at least three linearly independent measurements. As for the data reduction method, it is recommended that it be based on the four-flux radiation model (or a higher order model) which has been shown here to be better capable of dealing with radiative properties of typical engineering ceramics than the two-flux model.

ANALYSIS OF TRANSLUCENCE EFFECTS ON HEAT TRANSFER

APPROACH

The general scheme of evaluating the heat transfer in diesel engines involves the solution of the energy equation (heat transfer) within the wall under appropriate gas side and coolant side boundary conditions. In the present study the cylinder walls were assumed to be composed of two layers: an insulating ceramic wall facing the combustion gas and a metallic substrate. The energy equation is a one-dimensional conduction equation with an additional source term representing radiation energy absorbed/emitted within the medium. This energy equation was solved for two distinct regions: a semitransparent region within the ceramic, and a fully opaque region within the substrate. A two-flux radiative transport equation was solved to compute the radiative heat flux vector. Since the radiation process in a diesel engine has no collimated component, both the two-flux model and four-flux yield the same result. However, equations 1, 2, 20 and 21 do not contain a self emission term. This term was included since the wall temperature of ceramics in diesel engine applications is expected to be in a region where self emission begins to be important. The resulting equation is given in a previous report (Wahiduzzaman and Morel[7]).

The gas side boundary conditions were established by computer simulation of in-cylinder processes taking place in a heavy duty truck diesel engine operating at rated conditions using IRIS engine design analysis code[11]. This provides cyclic histories of radiation/convection temperatures, heat transfer coefficients and the products of soot volume fractions and radiation path length. These histories are shown in Figures 15a, 15b and 15c. The coolant side boundary condition consisted of a fixed coolant temperature (640K) and a very high heat transfer coefficient to impose a temperature of about 650K at the ceramic/metal interface. Details of the implementation of the energy equation and the boundary conditions were given in an earlier report describing the analytical phase of the study (Wahiduzzaman and Morel[7]). It is worth noting here that during the part of the cycle when no radiating combustion gas is present, it was assumed that the volumetric and surface emission outward from the ceramic is exactly balanced by the energy received from the other walls. This is equivalent to the assumption of equal radiosity for all walls.

For typical radiation temperatures encountered during combustion (T_{gas} = 1800-2500K), the fraction of total radiation energy existing beyond 5 μm is small (5-11%). At the same time, it was also evident from the experimental results that the ceramics under study become highly opaque beyond this wavelength. Hence, the ceramic layer can be assumed to have an opaque band from 5 μm to ∞, where the absorption and emission of radiation energy beyond 5 μm is accounted for as a surface phenomenon. For the rest of the wavelength domain, the absorption and scattering coefficient spectra were discretized into a number of bands having constant radiative properties within each band. The number of bands was carefully chosen so as to preserve a satisfactory match with the original spectra, without imposing an excessive computational burden in the subsequent analysis. The band model representation of absorption and scattering coefficient spectra is summarized in the following tables.

Ceramic B and C

λ (μm)	0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.5	2.5-4.0	4.0-5.0
k (1/m)	150.0	35.0	20.0	20.0	20.0	112.0
s (1/m)	35000.	27400.	10700.	7200.	6200.	4600.

Ceramic D

λ (μm)	0-1.5	1.0-1.5	1.5-2.75	2.75-3.5	3.5-5.0
k (1/m)	710.0	300.0	10.0	1570.0	14.0
s (1/m)	45200.	45200.	30600.	14300.	20400.

The thermophysical properties (conductivity and heat capacity) of the ceramic samples were not available and their determination was beyond the scope of the present study. It was shown earlier (Wahiduzzaman and Morel[6]) that thermal conductivity is an important parameter influencing the relative sensitivity to translucence. Presently, in the absence of such data, nominal values of 0.8 W/mK and 2.91×10^6 J/Km^3, pertaining to Plasma Technics plasma sprayed PSZ, were used for thermal conductivity and volumetric heat capacity, respectively, of all the materials considered in this study.

Heat transfer analysis was carried out for several thicknesses of ceramic coatings ranging from 0.04 mm to 5.0 mm, where 2.5 mm (~0.100 inches) is chosen as the nominal thickness for most of the calculation to be discussed later on. The grid points in the ceramic and the substrate were generated in such a manner that the grid spacing was compact near the gas-ceramic and ceramic-substrate interfaces. The smallest elements were located at either side of the ceramic-substrate interface and at the gas-ceramic interface, and they were 0.015 mm (0.0006 inch) thick. There were twenty-one grid points in the insulating ceramic layer.

EFFECTIVENESS OF INVESTIGATED CERAMICS AS HEAT BARRIER MATERIALS

The effectiveness of the ceramics under study to act as a barrier to thermal radiation was investigated by subjecting these and three idealized (limiting-case) ceramics to identical boundary conditions. The results of these simulations are summarized in Table III. The idealized ceramics were either completely transparent or completely opaque. The opaque limiting cases were of two types, ie, ceramics characterized either by high scattering coefficient ($>10^7$ m^{-1}) and negligible absorption coefficient (denoted as opaque (s) in Table III) or by high absorption coefficient ($>10^7$ m^{-1}) and negligible scattering coefficient (denoted as opaque (a) in

Table III). All five ceramics had a thickness of 2.5 mm, and the nominal thermophysical properties discussed above. The resulting temporal history of various components of the total heat flux for ceramics C and D is shown in Figures 16a and 16b. The solid curve represents the net radiation flux just inside the ceramic at node #1. The dashed line represents the amount of this flux transmitted to the ceramic/metal interface. The dotted line represents the radiation flux comprising the reflected and emitted radiation from the ceramic coating to the gas. The remaining line represents the convective heat flux to the ceramic coating.

It may be noted that the total flux for the clean C case is only one quarter of the metal case. This is due to the much higher surface temperature which reduces the convective heat transfer. On the other hand the swing is about three times as high, and that is due to the lower value of the product ρck.

It can be seen from Table III that the effectiveness of the two actual ceramic coatings (each 2.5 mm thick) as a barrier to total heat transfer is about the same. However, the ratio of the radiative heat flux to convective heat flux is different. For the more opaque ceramic (D), much of the radiation is absorbed near the surface, raising the mean surface temperature. This lowers the effective temperature difference between the combustion gas and the surface, and the convective heat flux is reduced. It is interesting to note that the radiative heat flux through ceramic C is less than that with ceramic D, despite the fact that C is more transparent than D. This is a consequence of differences in reflectance between the two materials. Since both materials have a high scattering coefficient, the one which has a lower absorption coefficient scatters more energy out of the coating before it can be absorbed. Hence ceramic C has a higher total reflectance than ceramic D. Consequently, less net radiation energy is absorbed in ceramic C than D.

If the thicknesses of the samples are sufficiently reduced this trend can be reversed, since for the ceramic C more of the radiation energy will reach the ceramic-substrate interface and be absorbed there before being scattered back out. Figures 17a and 17b show distributions of radiative and total heat fluxes as a function of layer thickness, and show that this reversal happens at around a thickness of 1.25 mm. In either case, however, the heat flux decreases with increasing layer thickness. It may be noted that the total heat fluxes for the two ceramics appear to not converge as the coating thickness is reduced towards zero. That is not really so, because in the limit the two curves must coincide. However, at even very small thicknesses, e.g., 0.05 mm for these specific ceramics, the product of the scattering coefficient and the layer thickness is large enough to produce significant scattering which augments the reflected component of radiation heat flux. Since the scattering coefficient of ceramic D is greater than that of ceramic C its net radiative flux is smaller and this persists to even quite small thicknesses.

In terms of the total heat flux, it appears from Table III that the ceramics under study are much closer to both opaque limiting cases than to the transparent limiting case. However, the mechanism of the heat transfer process is closer to the opaque(s) limit; in this opaque limit most of the heat transfer is due to the convective flux, since very little radiative flux can penetrate the coating due to high reflectance caused by its high scattering and low absorption coefficients. In ceramics C and D a large fraction of incident radiant energy will be reflected away for the same reason. Consequently, a smaller fraction of the radiation energy can be trapped by the coating system and the surface temperature only increases moderately due to absorption of this radiation energy. This in turn will cause a small reduction of the convective heat flux from the maximum value obtainable in the fully transparent case. For the opaque (a) limiting case much of the incident radiation will be absorbed at the surface raising its temperature which will cause a larger reduction in the convective heat flux at the cost of an increased radiative heat transfer.

In the case of the ideal transparent case, both radiative and convective heat fluxes are high. Since there is no scattering, a very small portion of the incoming radiative energy is reflected (due to interfacial Fresnel's reflectivity) and most of the energy is absorbed at the ceramic-substrate interface. This leaves the gas-ceramic interface at a relatively lower temperature, which increases the convective heat transfer.

EFFECT OF SURFACE CONDITIONS

In the preceding analysis it is implicitly assumed that the surface of the ceramic thermal barrier is the same as that of the samples obtained for our analysis. Further it is assumed that it remains free of soot and other deposits and that its surface layer does not become impregnated with foreign materials and/or discolored.

These are very significant assumptions and one needs to understand how do the results obtained here translate to situations where the surface condition is different from that found on the supplied test samples. In an operating diesel engine it is expected that surface fouling will occur and degree of which will depend on the particular engine and the operating condition. This surface fouling could be due to absorption of moisture/fuel by the coating and/or deposition of solid particulates in the ceramic surface. The absorption of solid and liquid particulates can be expected to affect the thermophysical and radiative properties of the coating. The effect of this change is difficult to anticipate or model. In terms of radiative properties, the absorption of combustion products by the coating will tend to make the coating more radiatively opaque and the opaque (a) limit of the coating will provide an indication of its effect on heat transfer.

If the ceramic surface departs from being optically smooth ($\ell/\lambda<1$, where ℓ is rms value of surface roughness) more and more incident radiation will be trapped thereby reducing effective reflectance and increasing hemispherical emissivity. In general, this will tend to promote radiation heat transfer. It is difficult, if not impossible, to predict the effect of impregnated surface impurities. It will, most likely, be dependent on the nature of impurities. It can however be speculated that impurities will also alter the surface finish and make it optically rough and thereby will have a similar impact on radiant heat transfer as surface roughness. However, definitive conclusions can only be made if reflectance measurements are made for the ceramic coatings before and after being exposed to the engine environment.

MODELING OF SOOT EFFECT

The effect of soot deposit is one that can be modeled. Let us consider a thin layer of soot deposited on the coating. Since this deposit layer will be composed mostly of carbonaceous material it will readily absorb radiative heat flux incident on it. This layer can be modeled as a thin coating of negligible thermal capacity (uniform temperature) and having a negligible thermal resistance between the layer and the ceramic coating. Under these assumptions, in order to compute radiative and convective heat flux, it is sufficient to modify the boundary condition imposed on the first ceramic node point. A modification of the boundary condition has to be constructed, which is capable of modeling any state of fouling between clean to completely soot-covered ceramic coating. In the first limiting case the ceramic is clean and the incident radiation penetrates directly into the ceramic without first being absorbed by intervening deposit layer. In the second limiting case the incident radiation is totally absorbed by the deposit and the deposit reradiates into the ceramic coating. Intermediate levels of fouling are represented by a fouling factor (G) which can take any value between 0 and 1. A value of one for the fouling factor represents fully sooted surface and a value of zero represent clean surface. The intermediate values can be thought of as a representation of soot layer with varying degrees of surface coverage. The detail of the requisite boundary conditions representing this physical situation is described below.

Radiation energy passing through at the gas-soot layer interface (node #1)

$$Q(0) = q_1 - q_2 - q_3 + q_4 \tag{31}$$

where

$$q_1 = \int_o^{\lambda_c} \{1-R_{do}(1-G)\}\, q_i d\lambda \tag{31a}$$

$$q_2 = \int_0^{\lambda_c} GE_{b\lambda}\, d\lambda \tag{31b}$$

$$q_3 = \int_0^{\lambda_c} (1-R_{di})(1-G)F^-(0)d\lambda \tag{31c}$$

$$q_4 = \int_{\lambda_c}^{\infty} \{\alpha + G(1-\alpha)\}\{q_i - E_{b\lambda}\} d\lambda \tag{31d}$$

$E_{b\lambda}$ = blackbody emissive power

G = fouling factor

q_i = incident radiation

λ = wavelength

λ_c = 5 μm - cutoff wavelength for transparent/opaque bands

α = surface absorptance in the opaque band

The first term of equation (31) represents the fraction of the incident energy within the transparent band of the ceramic (0 to λ_c) that will be either absorbed or pass through the gas/ceramic interface. The second term represents emission of the soot deposit back to the radiating gas. The contribution of this term will be present only if there is a soot layer on the surface. The third term represents emitted and scattered radiation from within the coating escaping to the gas. Here again if the surface is fully sooted no radiation will escape and consequently this term will vanish. The final term of the equation (31) is the fraction of the incident energy within the opaque band (λ_c to ∞) that is absorbed at the surface. This term is composed of the difference between the net incident energy (incident energy - reflected energy) and the emitted energy from the surface.

This deposited energy at the first node will be transported to the interior node by either conduction or radiation. The radiation flux at node #1 is given by

$$q_r(0) = F^+(0) - F^-(0) \tag{32}$$

where

$$F^+(0) = q_5 + q_6 + q_7 \tag{33}$$

$$q_5 = \int_0^{\lambda_c} (1-R_{do})(1-G) q_i d\lambda \tag{33a}$$

$$q_6 = \int_o^{\lambda_c} G n_i^2 E_{b\lambda} d\lambda \tag{33b}$$

$$q_7 = \int_0^{\lambda_c} R_{di} F^-(0)(1-G)d\lambda \quad (33c)$$

$F^+(0)$ = toward diffuse flux at node 1 (pointing to the interior)

$F^-(0)$ = backward diffuse flux at node 1 (pointing to the exterior)

The first term in equation (33) is the fraction of the incident radiation within the transparent band that passes through the gas ceramic interface. (Note that this term is different from q_1 inasmuch as it does not include the radiation absorbed at the surface.) The second term is the radiation energy within the transparent band ($0-\lambda_c$) that is emitted by the surface into the coating. The final term is the portion of the backward flux that reflected back into the coating by the front interface. (This is the complementary term of q_3.)

The conduction flux at node #1 is the difference between the total flux passing through the surface and the radiation flux at that node

$$q_c(0) = Q(0) - q_r(0) + h_g (T_g - T_w) \quad (36)$$

The other boundary conditions (e.g. at ceramic/metal interface and coolant/metal interface were given in a previous report (Wahiduzzaman and Morel[6]) and are only summarized here. The continuity condition for temperature at the ceramic/metal substrate is given by

$$T_c(d) = T_m(d) \quad (37)$$

where T_c and T_m are ceramic side and metal side temperatures respectively. The radiative flux boundary condition at ceramic/metal interface is

$$\int_0^{\lambda_c} F^-(d)d\lambda = \int_0^{\lambda_c} (\rho_s F^+(d) + \epsilon_s E_{b\lambda})d\lambda \quad (38)$$

and at the gas/ceramic interface it is

$$\int_0^{\lambda_c} F^+(0)d\lambda = \int_0^{\lambda_c} (R_{di}(1-G)F^-(0) + (1-R_{do})(1-G)q_i)d\lambda \quad (39)$$

This model was checked by setting it to zero to obtain clean ceramic results. It should be noted here that the above integrations are performed over several discrete bands, as discussed in a previous section.

The results obtained with this model are presented in Table III. With G set to unity (fully sooted case) the results labeled "sooted" were generated. It can be seen that the presence of the soot layer produced a variety of changes. The surface temperature was increased, one big reason being the elimination of surface reflectivity by the presence of black soot and the resultant higher radiative flux. A larger change is seen in the surface swing, this being caused by the absorption right at the surface rather than sub-surface. The convective flux was reduced due to the higher surface temperature. Finally, the total heat flux was generally slightly increased, except for the fully transparent case where a 10% reduction was seen due to the reduction in convective flux. It is very interesting to see that even though the soot reduced the differences in total heat flux between the fully transparent and the fully opaque cases from 70 to 49 kW/m^2, there remained a substantial difference between them. This indicates that if the ceramic surface temperature is high, exceeding 1000K, the time-averaged radiation produced by the soot layer with its high emissivity, approaches and can exceed that produced by the much hotter diesel flame, which however persists for only a short fraction of time. It is also interesting to note that for the two opaque limits soot deposit produces identical results. This is because in the opaque(s) case soot emitted radiation is reabsorbed by the soot layer after being scattered back to the soot/ceramic interface. This is very similar to the situation existing in opaque (a) case where soot radiation is quickly absorbed by the coating close to the soot/ceramic interface.

The distributions of the radiative, convective and total heat fluxes computed for different levels of fouling on a 2.5 mm ceramic (type C) coating are given in Figure 18. As the fouling level is increased, the radiative transport increases sharply, accompanied by a decrease in the convective heat flux. This decrease in convective heat flux is due to increase in surface temperature caused by the absorption of radiative energy at the surface. As expected, at the highest fouling level ceramic C behaves more like the sooted opaque limiting case rather than the transparent one (Table III). This is again due to absorption of radiative energy at or very near the surface as in opaque limiting case. There is a small increase in total heat flux with increasing surface fouling, indicating that although the mechanism of the heat transfer changes with surface fouling, its impact on total heat transfer is moderate at least for the boundary conditions used in this study.

DISCUSSION

The radiative properties of several existing ceramic coating materials were determined experimentally. This involved measuring reflectance and transmittance spectra of the ceramic samples of different thicknesses. A model describing the radiative transport process in semitransparent media was then fitted to the measured data sets. An optimization technique was used to adjust the radiative parameters until the best fit to the measured data was obtained.

The model describes the radiative transport within a medium using three parameters, namely scattering coefficient, absorption coefficient and refractive index. This involves some implicit assumptions about interfacial reflectivities and phase function for the material. It was assumed that the interfacial reflectivities can be approximated by Fresnel's equations which is strictly valid for optically smooth surfaces ($\ell/\lambda<1$, where ℓ is the rms value of the surface roughness). It was determined a posteriori that accurate determination of the surface reflectivities was not critical in view of the high scattering coefficients of the studied ceramics. Another assumption regards the phase function. Since the grains of the ceramic are densely packed and randomly oriented, there will not be any preferred direction of scattering. Consequently, a uniform scattering phase function was used. In addition, a fixed value of refractive index, as discussed earlier, was used for all parameter inversion. This constraint had to be imposed due to the small number of independent data points available, keeping in mind that the results are relatively insensitive to this parameter (Wahiduzzaman and Morel[7]).

In order to perform a systematic error analysis on the inverted parameter, the variability of the measured quantities (reflectance and transmittance spectra) are needed. This in turn depends on the repeatability of the sample preparation and uncertainty associated with the measuring instrument. Unfortunately, such study was beyond the scope of this program, since the number of samples of each material used in this study was limited and no repeat measurements with identical samples were made. Nevertheless, based on the assumptions involved in the technique and an expected variability in measured data, an assessment can be made of the uncertainty in the values of the inverted parameters. For errors of ±5% in transmittance, ±5% in reflectance and ±25% in refractive index, maximum error over the entire spectral range was found to be of the order of 53% for scattering coefficients and 40% for absorption coefficient. Although this uncertainty appears to be large, the calculated heat transfer is affected only moderately over this range. Thus despite the uncertainty in the properties, the basic results of this work, as discussed below, should be unchanged.

The ceramic samples used in this study were found to be highly reflective (reflectance on the order of 0.6-0.8) and optically thick even at thicknesses of the order of 2 mm. In particular, the reflectance spectrum of the 0.51 mm sample (A1) of PSZ obtained from Plasma Technics was nearly identical to the corresponding spectra belonging to 1.092 and 5.74 mm samples (A2 and A3) indicating that even the thinnest sample is optically thick. It should be noted here that the level of reflectances of the material A are of same order as for materials B and C, and thus the scattering coefficients are probably of similar magnitude. However, the ceramics B and C are less optically dense than the ceramic A, based on the fact that their reflectances display dependence on thickness between 0.5 and 1 mm not seen in ceramic A. Thus one may make the indirect inference that the ceramic A has much higher absorption coefficients than ceramics B and C.

Ceramics B and C (PSZ and TZP from Oak Ridge Laboratory) were found to be radiatively identical. The reflectance and transmittance spectra of both materials were nearly identical and consequently, inverted properties were also the same for both materials. The absorption coefficients of ceramics B, C and D were found to be much smaller than the scattering coefficients (high scattering albedo). Material B and C possessed lower scattering and absorption coefficients in comparison to material D and hence, were optically less dense than D. In any event, a nominal thickness of 2 mm of any of the studied ceramics would be sufficient to prevent any appreciable radiation energy from reaching the metal substrate.

The radiative parameters of the materials studied here exhibited both qualitative and quantitative agreement with previous measurements (Makino et al[4]) made on a number of monolithic ceramics including zirconia (85% Zr02 by weight, with Y_2O_3, S_iO_3 and Al_2O_3). The scattering coefficients obtained in that study displayed similar decreasing trends at higher wavelengths, although the values of the coefficients were lower (12000 m^{-1} at shorter wavelengths). The absorption coefficients were of similar order of magnitude as those found here and the spectrum contained sharp rise around 4 μm, similar to that evidenced in the spectrum of ceramic C. The lower scattering coefficient found for the monolithic ceramics by Makino et al can be attributed primarily to the difference in microstructure of the two ceramics. To quantify the differences between the present coatings and Makino's monolithics, an analysis was carried out of the heat barrier effectiveness of a monolithic ceramic 2.5 mm thick subject to the same boundary conditions as done for the coatings in Table III. The results showed that for Makino's monolithic ceramics the radiation heat transfer was larger by 30% and the total heat transfer was 8% higher. This shows that these ceramics were less optically opaque and thus less effective as barriers to heat radiation than the present coatings (at the same thickness and assuming the same thermal conductivity and heat capacity).

A heat transfer analysis based on these radiative parameters showed that at the larger thicknesses (above 1.25 mm) materials C and B are more effective against radiative heat transfer than material D of same thickness. At lower thicknesses the situation is reversed. This trend is a consequence of reflectivity of the coatings which can be substantially influenced by the ceramic/metal interface depending on the coating thickness.

In general, the studied ceramics exhibited similar characteristics in terms of preventing radiative heat transfer. The scattering albedo of these ceramics were found to be large, causing them to be fairly reflective (60-80%) and optically thick at conventional coating thicknesses (1 to 2 mm). As a result, most of the radiation that penetrates the coating is absorbed within the coating as opposed to at ceramic/metal interface. Since a significant portion of this absorption occurs at or near the surface, the surface temperature is increased. This has a beneficial effect of reducing the convective component of the total heat transfer.

In an operating engine, the coating surface will lose a lot of its reflectivity due to carbonaceous deposits. In such a case the incident radiant energy will be readily absorbed by the deposit layer causing the surface temperature to go up even higher. This will further reduce the convective heat flux and partially compensate for the increased radiant heat transfer at the surface (less reflected radiation). On the other hand, the radiation of the surface deposit layer towards the interior of the ceramic increases rapidly with the increasing surface temperature and at high enough temperature could exceed the radiation from the flame (because it has high emissivity and acts all the time, whereas the gas radiates only some 5-7 percent of the time). It should be mentioned that when the surface temperature becomes sufficiently high the soot particles in the deposit layer will tend to burn off. Thus the ceramic will tend to return to its original clean state, probably before the point of excessive surface radiation is reached.

Based on the present results and the above observations, one can speculate on the ideal thermal barrier for engine applications. To prevent radiant heat transfer, the coating should be highly reflective, for example through a combination of high scattering coefficient (>20000 m^{-1}) and low absorption coefficient. If a homogeneous ceramic satisfying these conditions could not be found, one could contemplate a composite ceramic, or one having a thin reflective and opaque metallic coating on the surface. However, if significant soot deposition occurs at the coating surface a large portion of the incident radiation energy will be trapped by the deposit layer causing a substantial increase in radiation heat transfer. As mentioned previously, this will be associated with an increase in surface temperature. The level of this increase will depend on the location where the energy reradiated by the deposit layer is absorbed. If the coating is opaque it will be absorbed at or near the interface and the increase in surface temperature will be large which will in turn cause a large reduction in convective heat flux. This opacity could be achieved, as evidenced in Table III, either through high scattering coefficient or high absorption coefficient or a combination of both. In the case of transparent ceramic the reradiated energy will be absorbed at the coating/metal interface, leaving the surface at a lower temperature (Table III) and consequently the reduction in the convective heat flux will be small. Hence, to insure the best thermal barrier for either clean or heavily sooted surfaces, a ceramic material with high scattering and low absorption coefficient provides the best choice. To reduce the convective heat transfer relatively independently of the radiant heat transfer, one can follow the conventional approach of choosing a material having low thermal conductivity and as large as practicable coating thickness.

CONCLUSIONS

1) An experimental study was carried out to determine the radiative properties of four ceramics; A (PSZ, 13% yttria stabilized), B (PSZ), C (TZP) and D (PSZ, 24% ceria stabilized). Ceramics B and C were found to possess high scattering coefficient (in excess of 30000 m^{-1} in short wavelengths) and low absorption coefficients. Ceramic D had even higher scattering coefficients (in excess of 40000 m^{-1} at short wavelengths) and moderate absorption coefficients (2000 m^{-1} at 3 μm). Although parameter inversion was not possible for material A, a comparison of its reflection spectra with corresponding spectra of other ceramics tested indicates it to be the most optically dense material in the group.

2. In terms of overall radiation effect, these coatings were found to be highly reflective (reflectance around 0.6-0.8) due to their high scattering coefficients. They also were found optically thick even at thicknesses of 2 mm, i.e., permitting only a small fraction of radiation to pass through to the substrate. Comparison to literature data on monolithic zirconia ceramics showed those to be more transparent and thus less effective as barriers to heat radiation.

3. When compared to the limiting cases of completely transparent and completely opaque, the total heat transfer through the studied ceramics for 2.5 mm thickness was substantially closer to either of the opaque limits than to the transparent limit. However, when the surface is clean, the mechanism of the heat transfer more closely approached the opaque(s) limit rather than the opaque(a) limit. On the other hand, for a sooted surface, both opaque limits converged into a single limit.

4) With regard to the most desirable ceramic properties for diesel engine applications, it was concluded that a highly scattering ceramic with low absorption coefficient would be the best heat barrier material for blocking thermal radiation. An alternative would be a composite ceramic coated with an opaque high reflectance surface layer. From the point of view of convective heat transfer, any scheme aimed at raising surface temperature will be effective in reducing convective heat transfer, and low thermal conductivity is an essential element in this respect. However, other factors such as volumetric efficiency, thermal stress, etc. have to be considered in selection of an appropriate insulation package.

5) In experimental determination of radiative properties of ceramics it is highly desirable to perform preliminary transmittance measurements to obtain some knowledge on the opacity of the material. This knowledge can then be used for proper selection of material thicknesses to obtain samples ranging from optically thin to optically thick. In order to extract the refractive index, alternate type of measurements are recommended. These may include separate measurements of diffuse and directional reflectance and transmittance, and/or measurement of polarized components of the reflectance.

6) Both four-flux and two-flux methods were used and it was concluded that the four-flux method is more appropriate for parameter inversion models than the simpler two-flux method. This method is better equipped to handle collimated illumination and has the ability to predict both diffuse and directional quantities. It was found that the two-flux model underpredicts scattering coefficient substantially when the scattering level is low.

NOMENCLATURE*

A - $3\omega/(8\beta^2-2)$

B - $A/3$

C^+ - collimated forward flux

C^- - collimated backward flux

d - depth of the layer

D^+ - diffuse forward flux

D^- - diffuse backward flux

E - $s+k$ = extinction coefficient

$E_{b\lambda}$ - blackbody emissive power

F_d - diffuse incident flux

F_c - collimated incident flux

G - fouling factor

h_g - heat transfer coefficient

k - absorption coefficient

n - refractive index

p - phase function

q_i - incident radiation

R_{di} - diffuse interfacial internal reflection

R_{do} - diffuse interfacial external reflection

R_{ci} - collimated interfacial internal reflection

R_{co} - collimated interfacial external reflection

R_d - diffuse reflectance

R_h - hemispherical reflectance

S_c - reflected collimated flux

S_d - reflected diffuse flux

s - scattering coefficient

T_c - ceramic side temperature at the interface

T_d - diffuse transmittance

T_g - gas temperature

T_h - hemispherical transmittance

T_m - metal side temperature at the interface

*All variables are in S.I. units except where noted.

T_w - surface temperature of the wall

α - surface absorptance in the opaque band

α_1 - linear constant for flux equation

α_2 - linear constant for flux equation

α_3 - linear constant for flux equation

α_4 - linear constant for flux equation

β - $\sqrt{1-\omega}$

λ - wavelength

ω - s/(s+k) - albedo

τ - (k+s)x - optical depth at x

τ_d - (k+s)d - optical thickness of the entire translucent layer

λ - wavelength

λ_c - 5 μm - cutoff wavelength for transparent/opaque bands

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Table I. List of Ceramic Samples

Set	Sample #	Material	Supplier	Thickness (mm)
A	1	PSZ	Plasma Tech	0.51
A	2	PSZ	Plasma Tech	1.02
A	3	PSZ	Plasma Tech	5.74
B	4	TZP	Oak Ridge Lab	0.50
B	5	TZP	Oak Ridge Lab	1.00
B	6	TZP	Oak Ridge Lab	10.00
C	7	PSZ	Oak Ridge Lab	0.50
C	8	PSZ	Oak Ridge Lab	1.00
C	9	PSZ	Oak Ridge Lab	10.00
D	10	PSZ	Caterpillar	0.41
D	11	PSZ	Caterpillar	0.58
D	12	PSZ	Caterpillar	1.04
D	13	PSZ	Caterpillar	2.49

Table II. Matrix of Radiative Measurements

Sample ID	Reflectance <2.5 μm	Reflectance 2-20 μm	Transmittance <2.5 μm	Transmittance 2-20 μm
A1	√	√	s/u	√
A2	√	√	l/s	√
A3	√	√	n/r	n/r
B4	√	√	√	√
B5	√	√	√	√
B6	√	√	n/r	n/r
C7	√	√	√	√
C8	√	√	√	√
C9	√	√	n/r	n/r
D10	√	√	√	√
D11	√	√	l/s	l/s
D12	√	√	l/s	l/s
D13	√	√	n/r	n/r

Key: √ - measurement made; s/u - sample unavailable; n/r - measurement not requested; l/s - measurement attempted but failed due to low signal-to-noise ratio.

Table III. Effect of Ceramic Properties and Surface Fouling on Time-Averaged Heat Flux and Temperatures

Ceramic	Surface Temp.	Indepth* Temp.	Surface Swing	Radiative Flux	Convective Flux	Total Flux
	K		K	kW/m^2	kW/m2	kW/m^2
Metal baseline	701.9		25.2	86.5	316.2	402.8
Clean C	943.5	650.0	90.7	22.0	84.0	106.0
Clean D	953.7	649.5	90.4	25.8	75.2	101.0
Transparent	937.5	657.0	91.7	91.3	89.2	180.5
Opaque (a) #	995.2	650.0	116.6	82.2	28.1	110.3
Opaque (s) #	935.3	648.6	92.1	0.7	91.1	91.8
Sooted C	1001.4	651.0	122.3	97.4	20.6	118.0
Sooted D	1001.3	650.7	121.4	96.8	18.1	114.9
Sooted trans.	948.8	655.2	131.9	97.6	65.2	162.8
Sooted opaque (a)	1005.8	650.6	121.2	96.4	17.1	113.5
Sooted opaque (s)	1005.6	650.6	121.2	96.5	17.1	113.6

*Temperature at the ceramic/metal interface, i.e. at a depth of 2.5 mm from the surface.

#Opaque (a) is the opaque limit attained by high absorption and negligible scattering.

#Opaque (s) is the opaque limit attained by high scattering and negligible absorption.

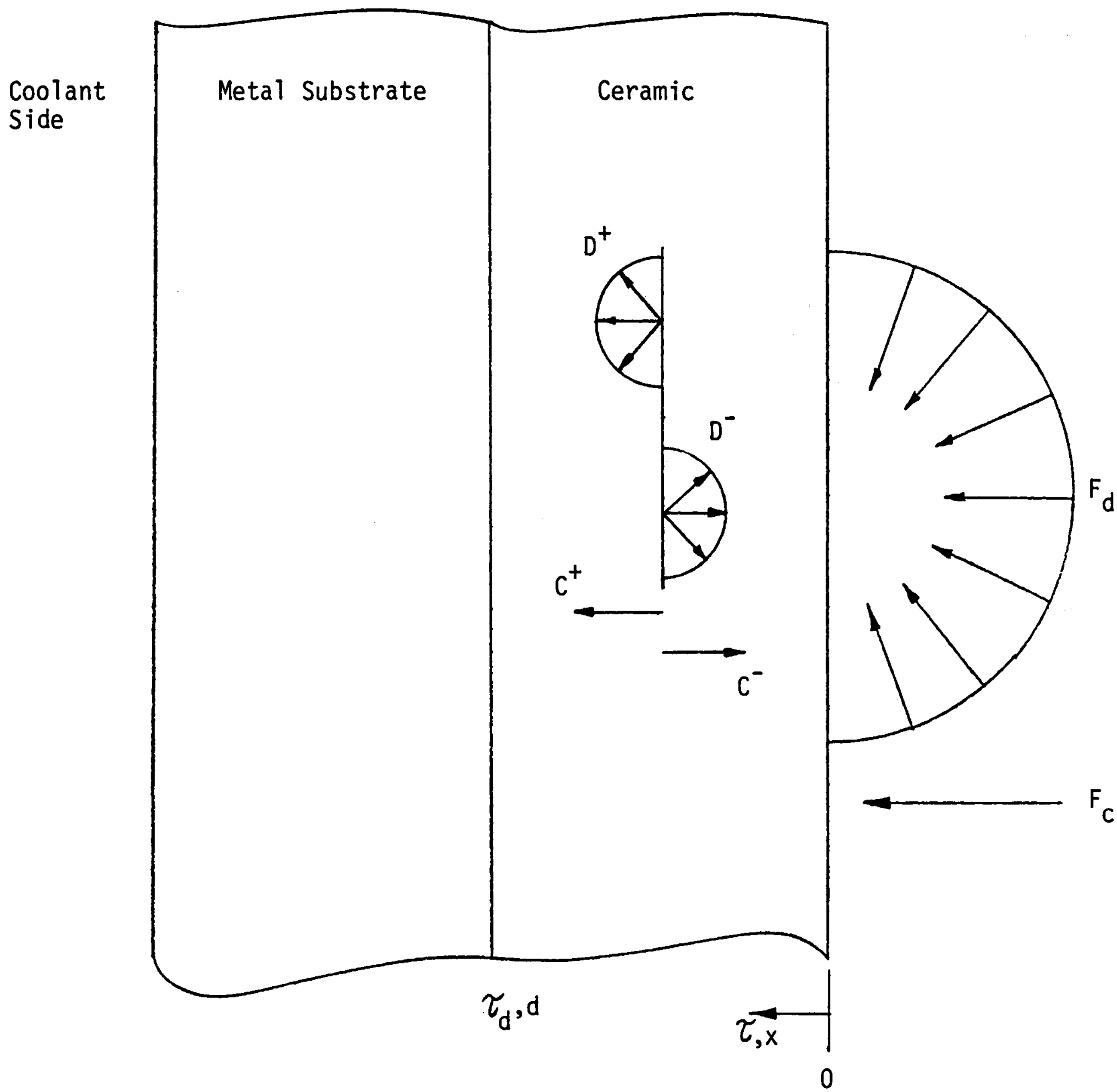

Figure 1. Physical model of the insulating coating.

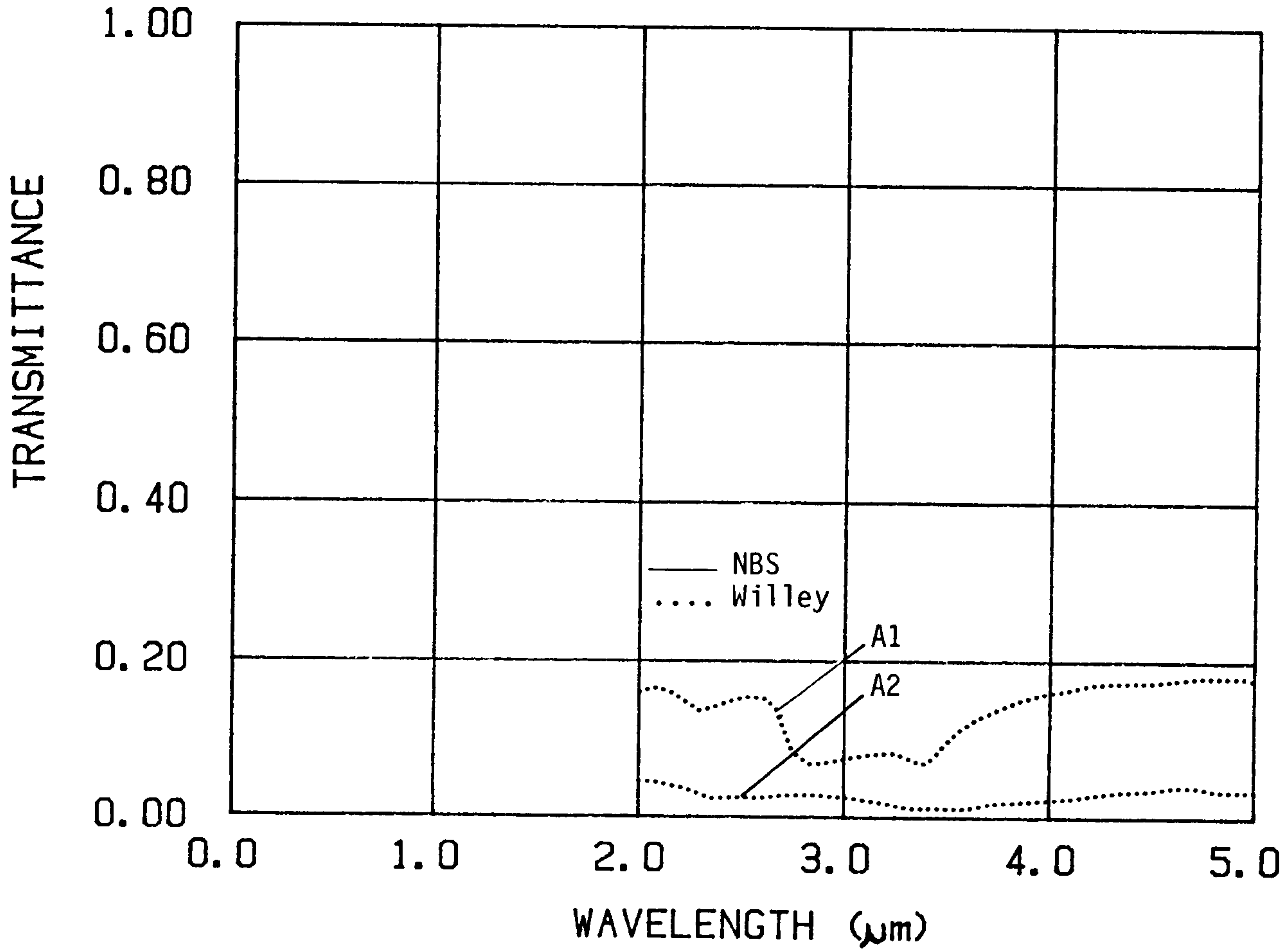

Figure 2(a). Transmittance spectra of material A (PSZ, 13 ytttria stabilized) from Plasma Techniques.

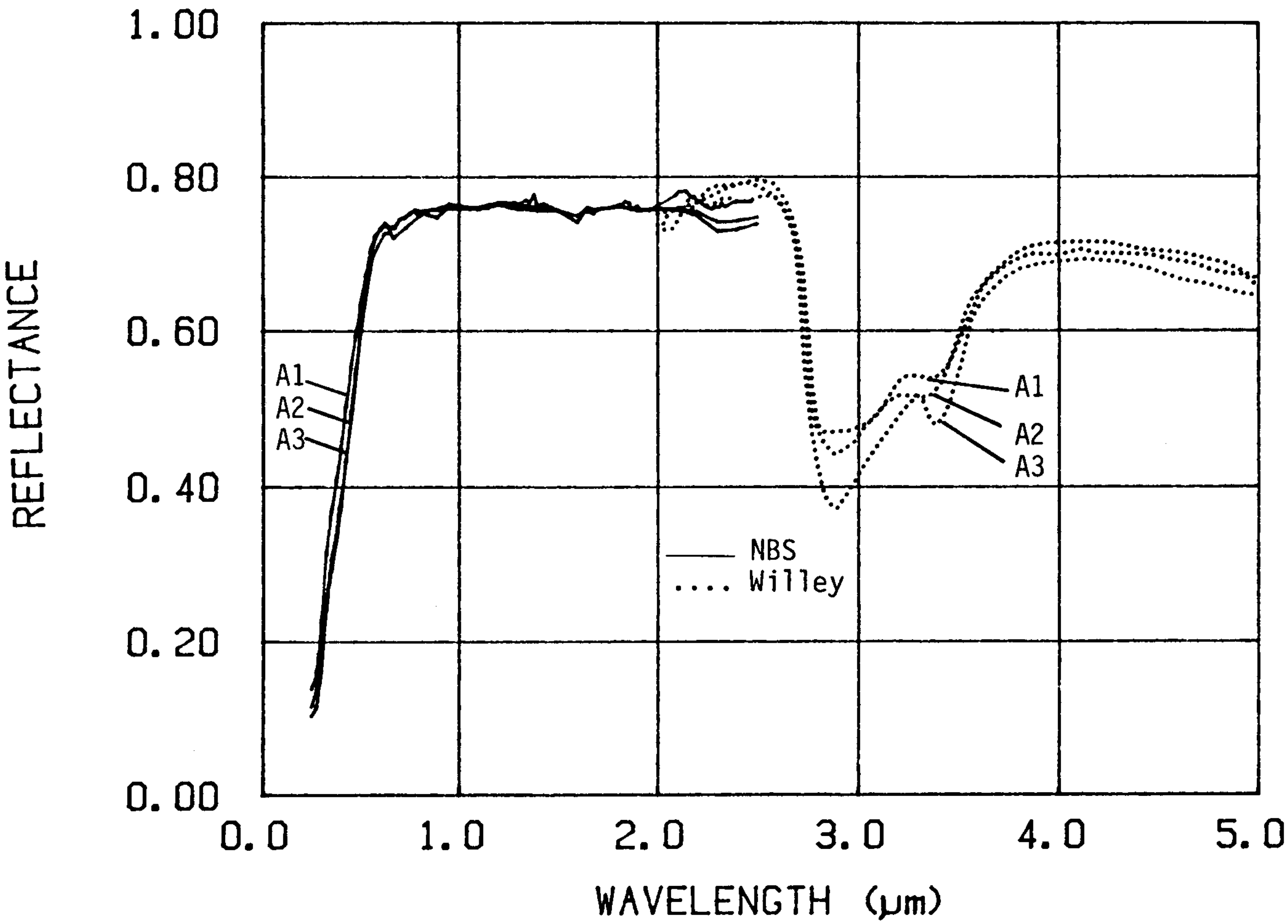

Figure 2(b). Reflectance spectra of material A.

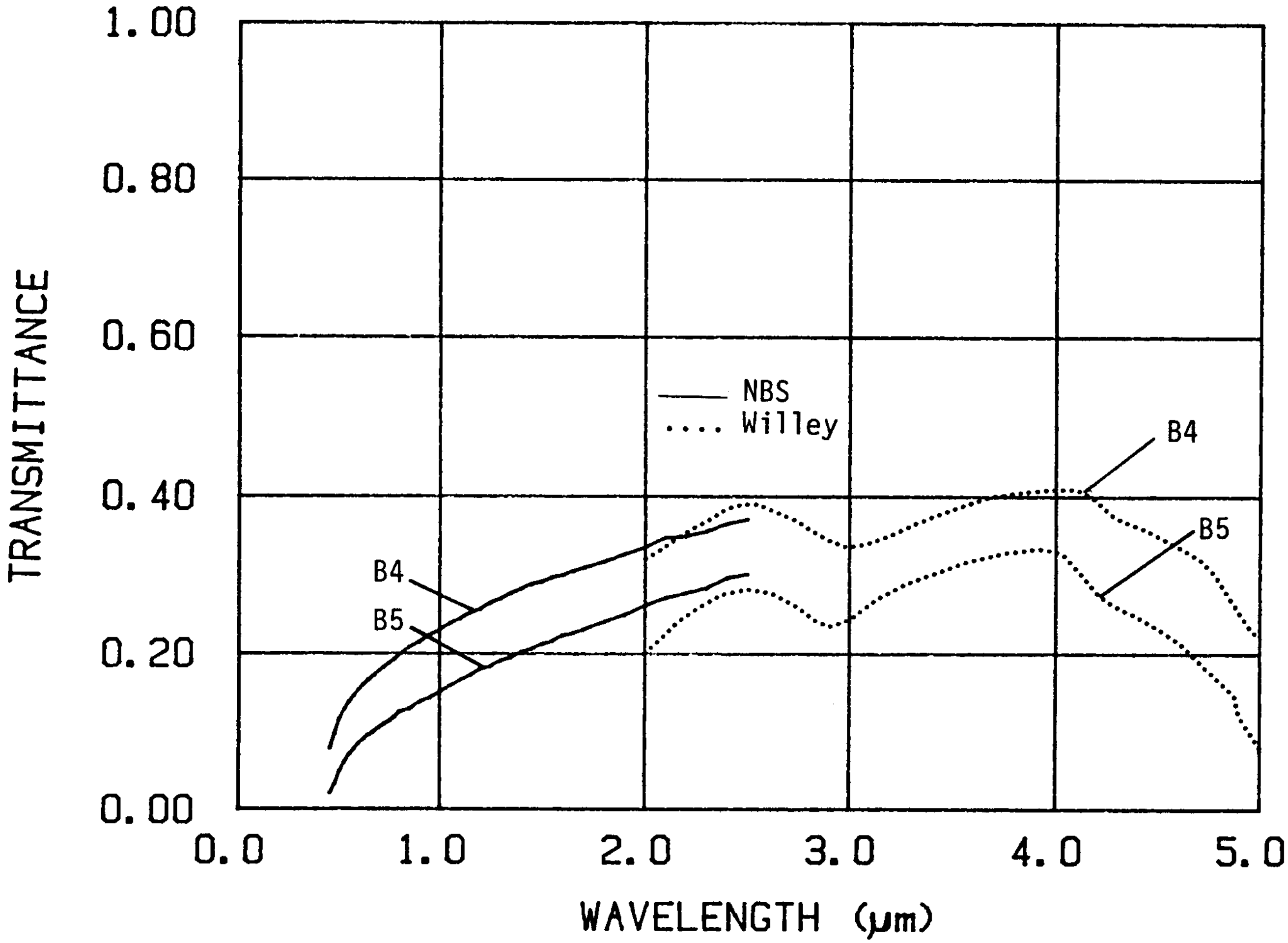

Figure 3(a). Transmittance spectra of material C (PSZ) from Oak Ridge National Laboratory.

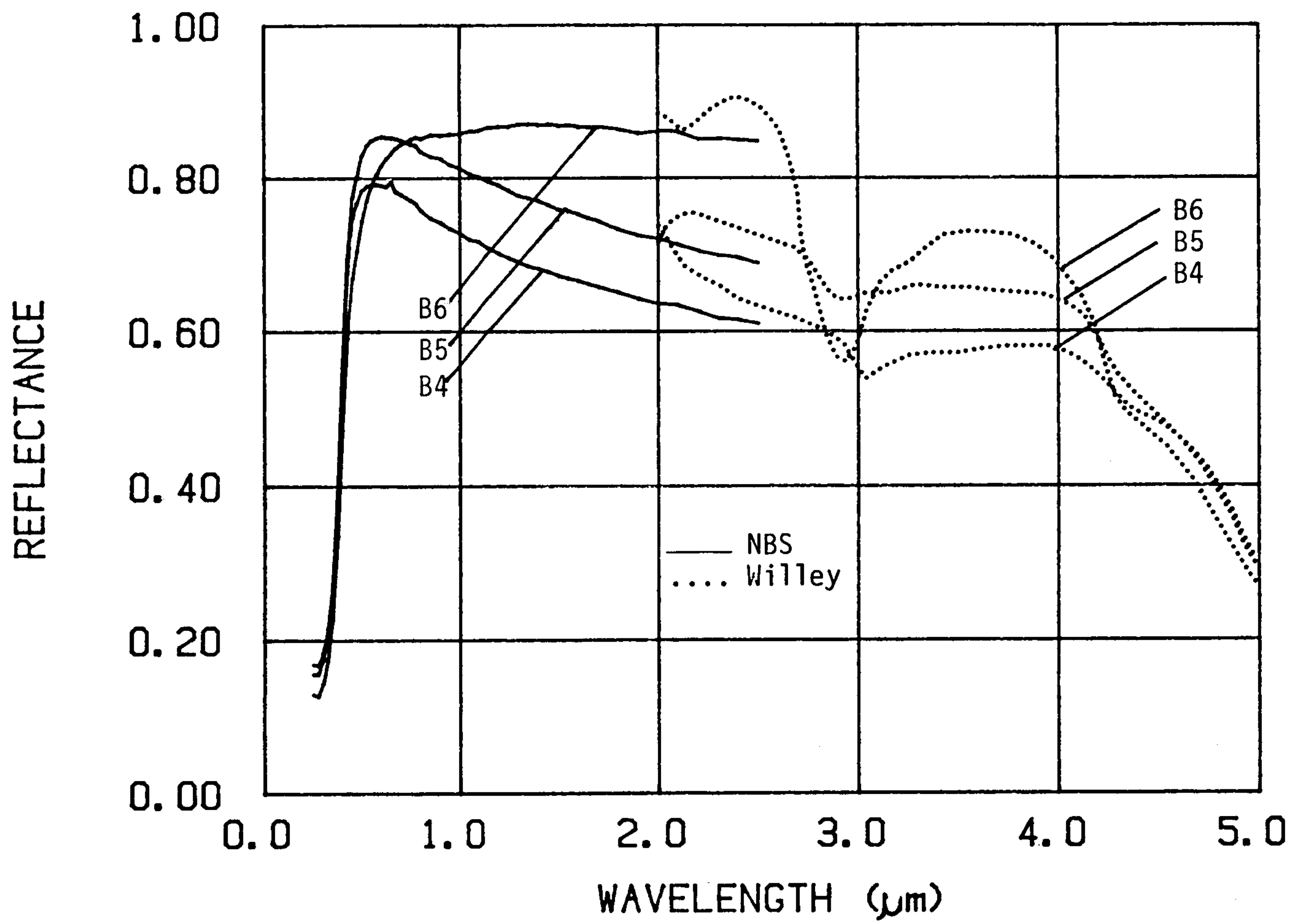

Figure 3(b). Reflectance spectra of material C.

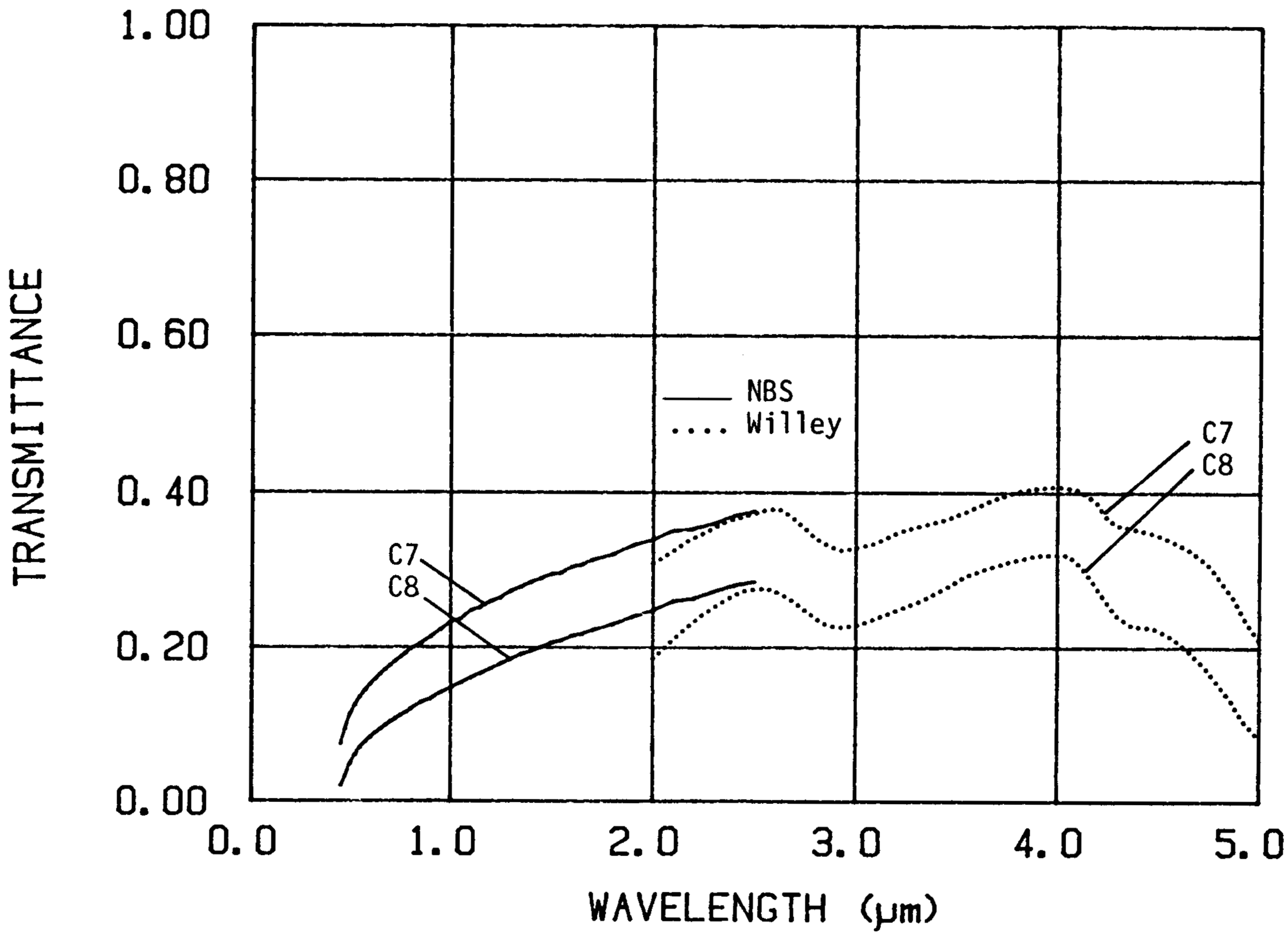

Figure 4(a). Transmittance spectra of material C (PSZ) from Oak Ridge National Laboratory.

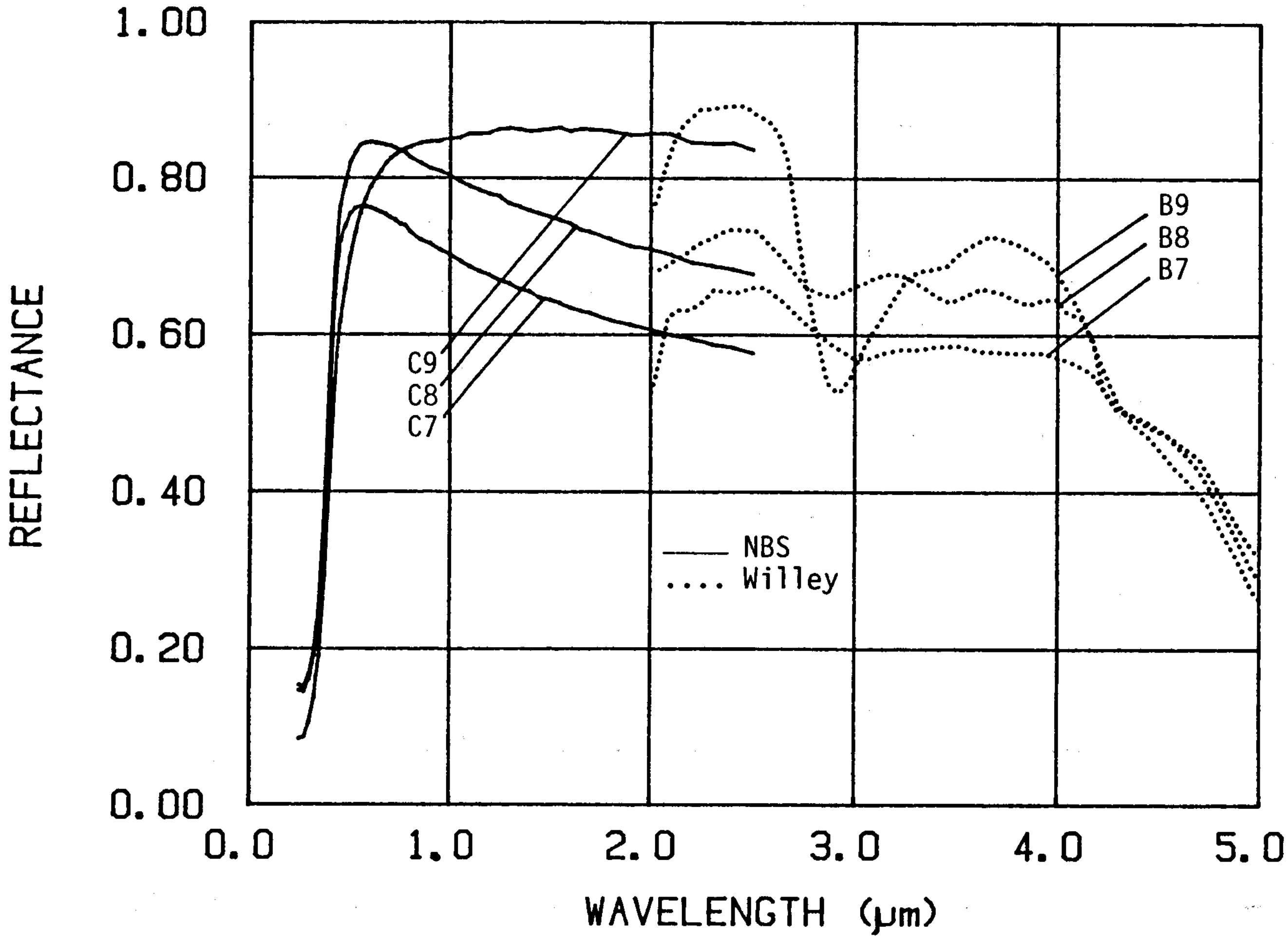

Figure 4(b). Reflectance spectra of material C.

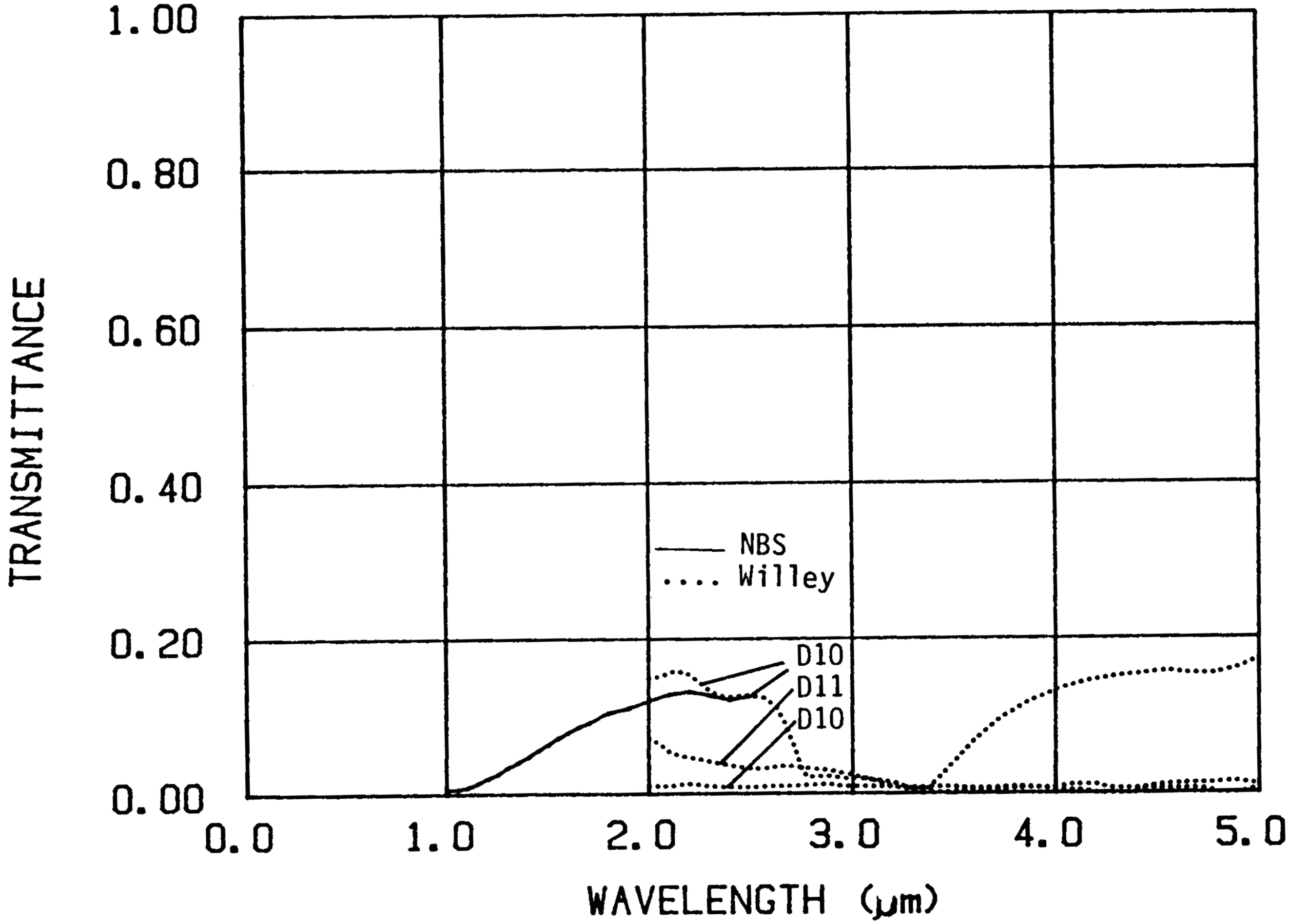

Figure 5(a). Transmittance spectra of material D (PSZ, 24% ceria stabilized) from Caterpillar.

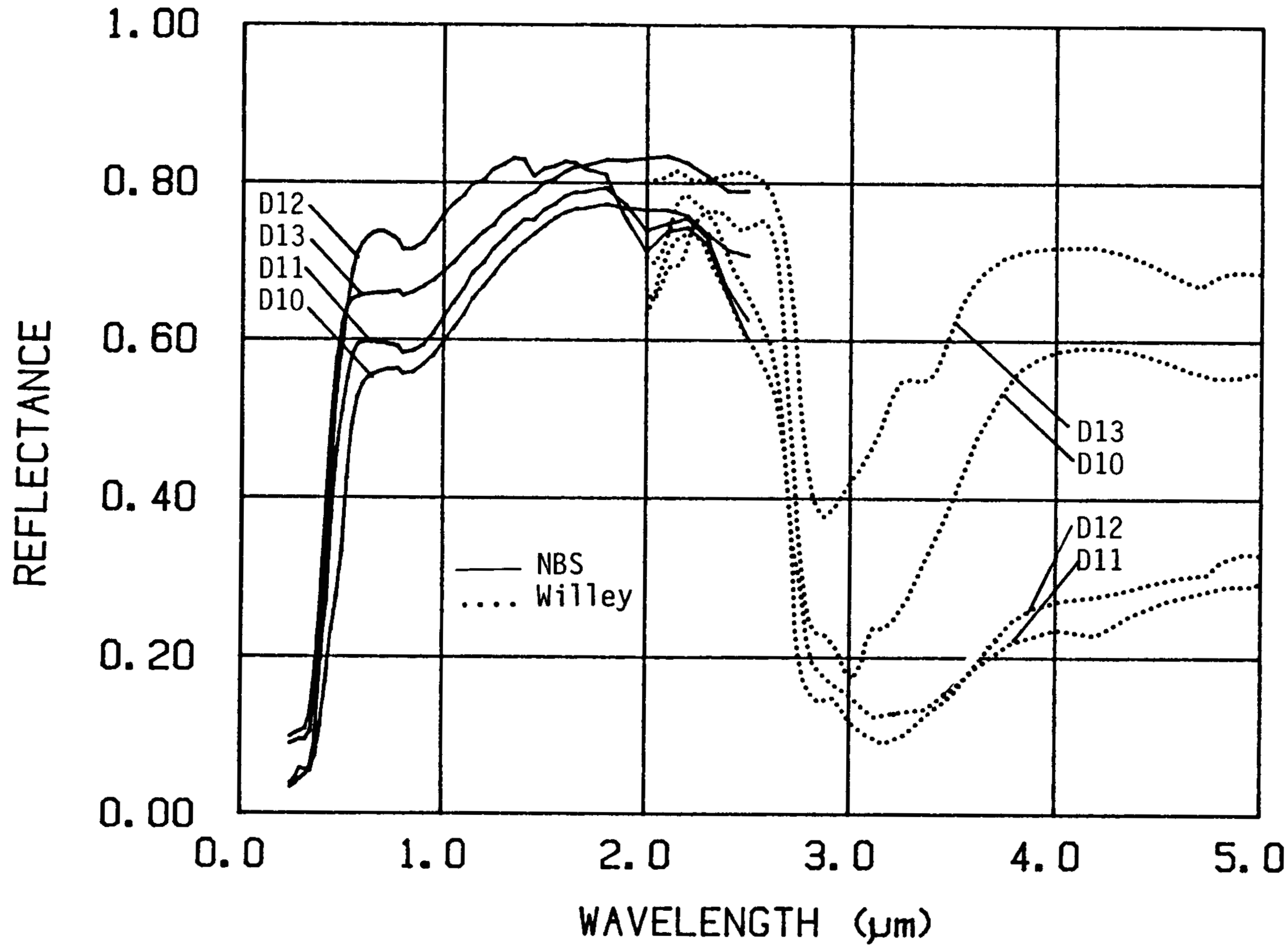

Figure 5(b). Reflectance spectra of material D.

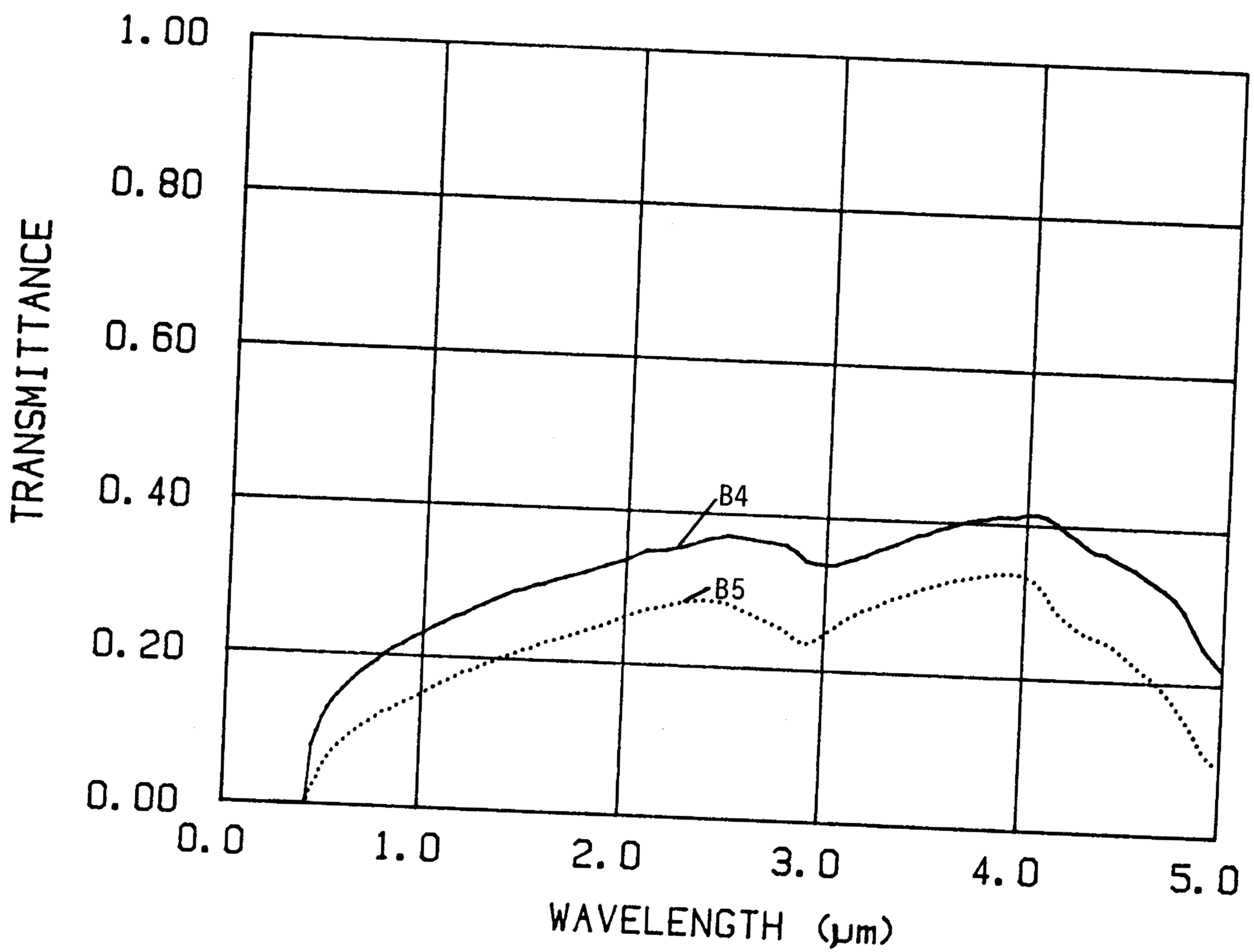

Figure 6(a). Merged transmittance spectra of material B used for parameter inversion.

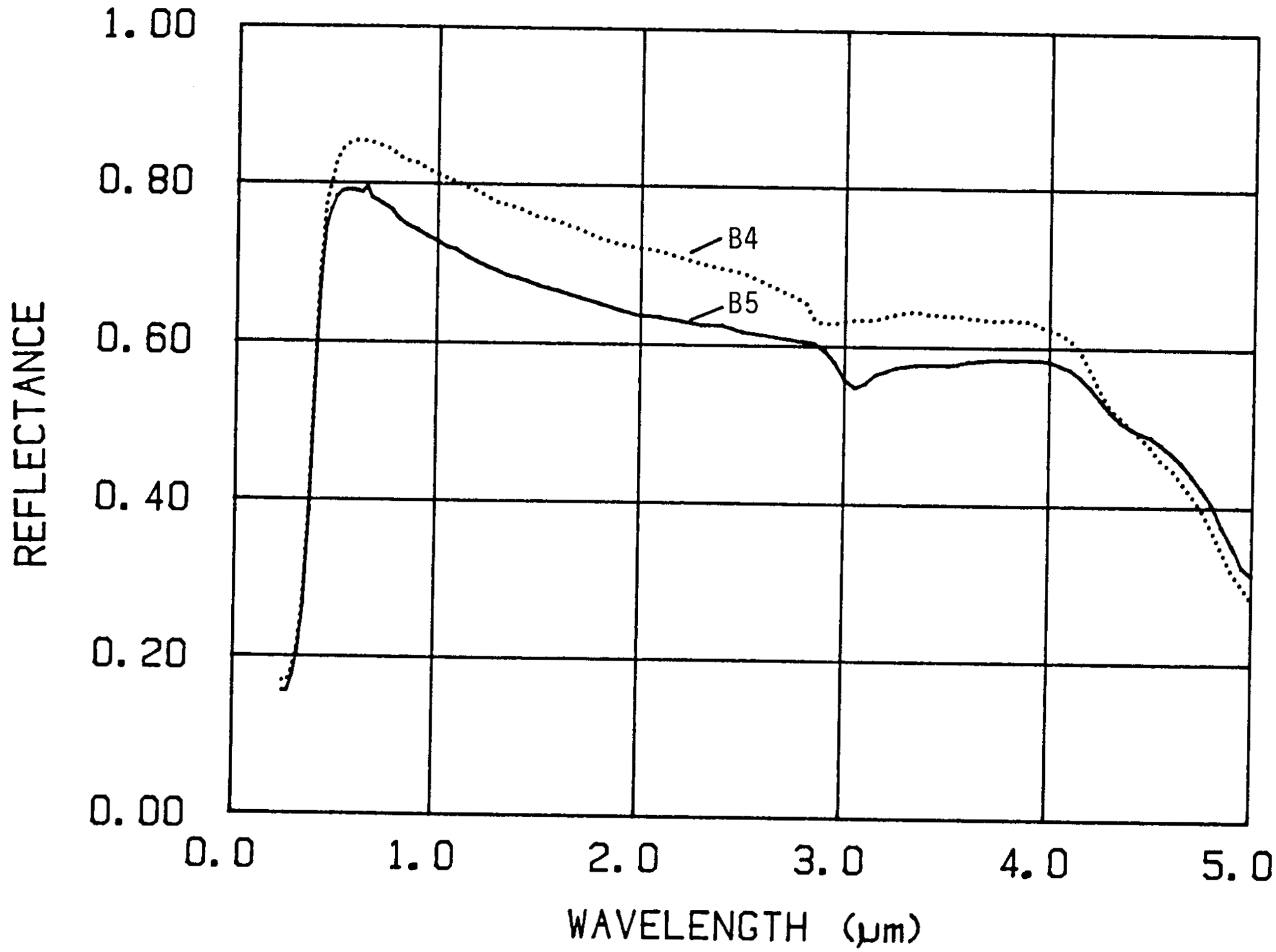

Figure 6(b). Merged reflectance spectra of material B used for parameter inversion.

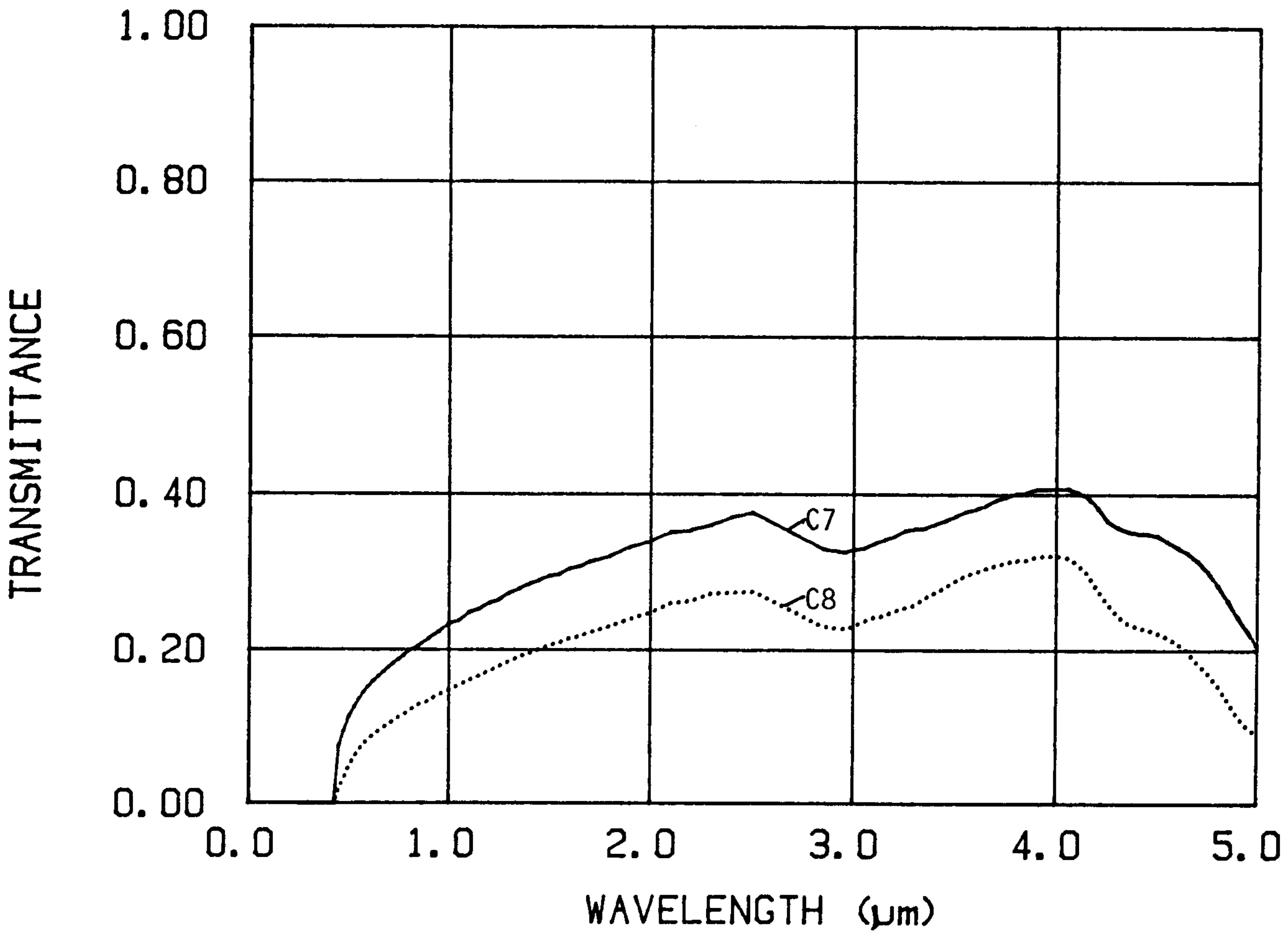

Figure 7(a). Merged transmittance spectra of material C used for parameter inversion.

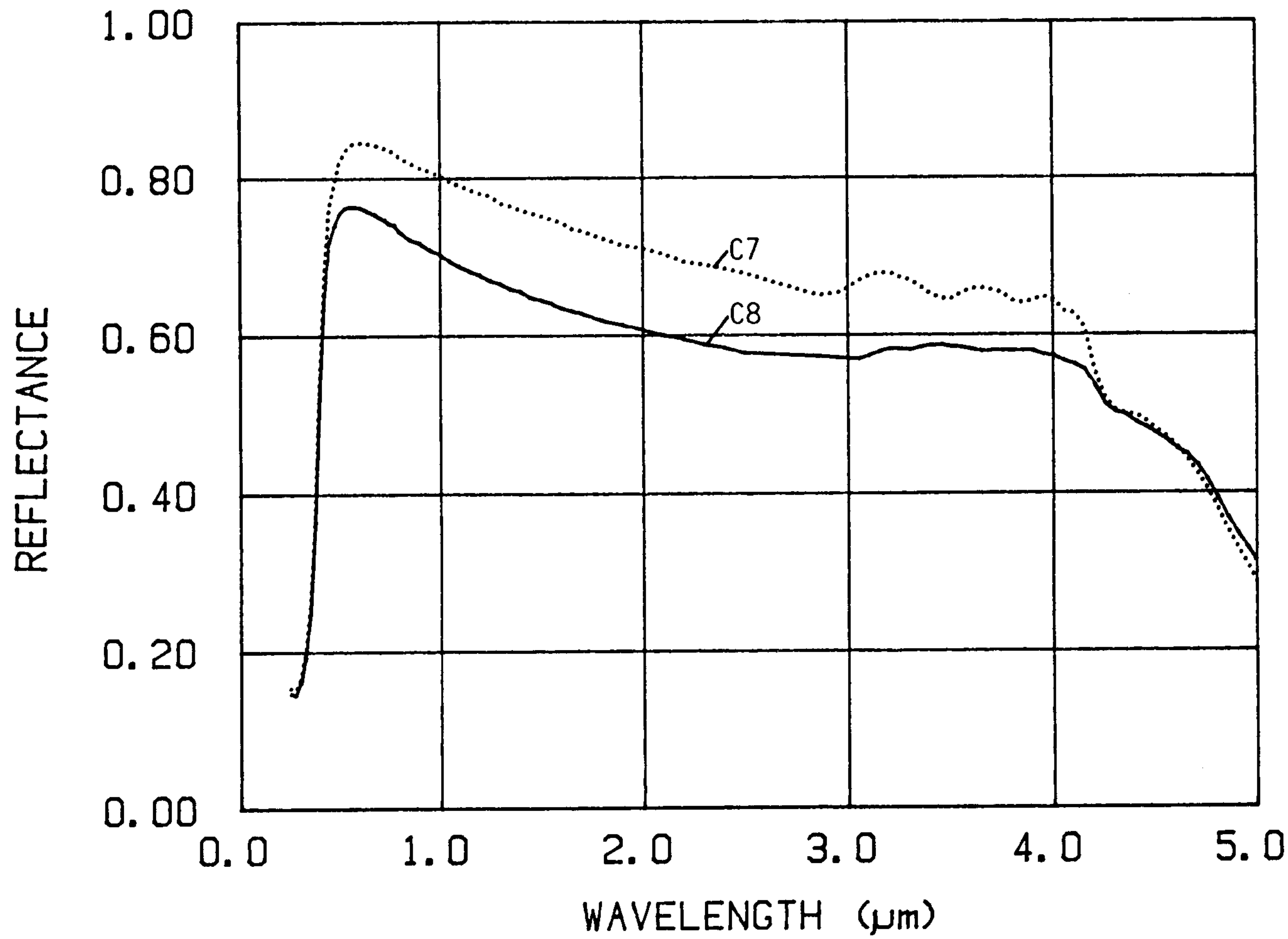

Figure 7(b). Merged reflectance spectra of material C used for parameter inversion.

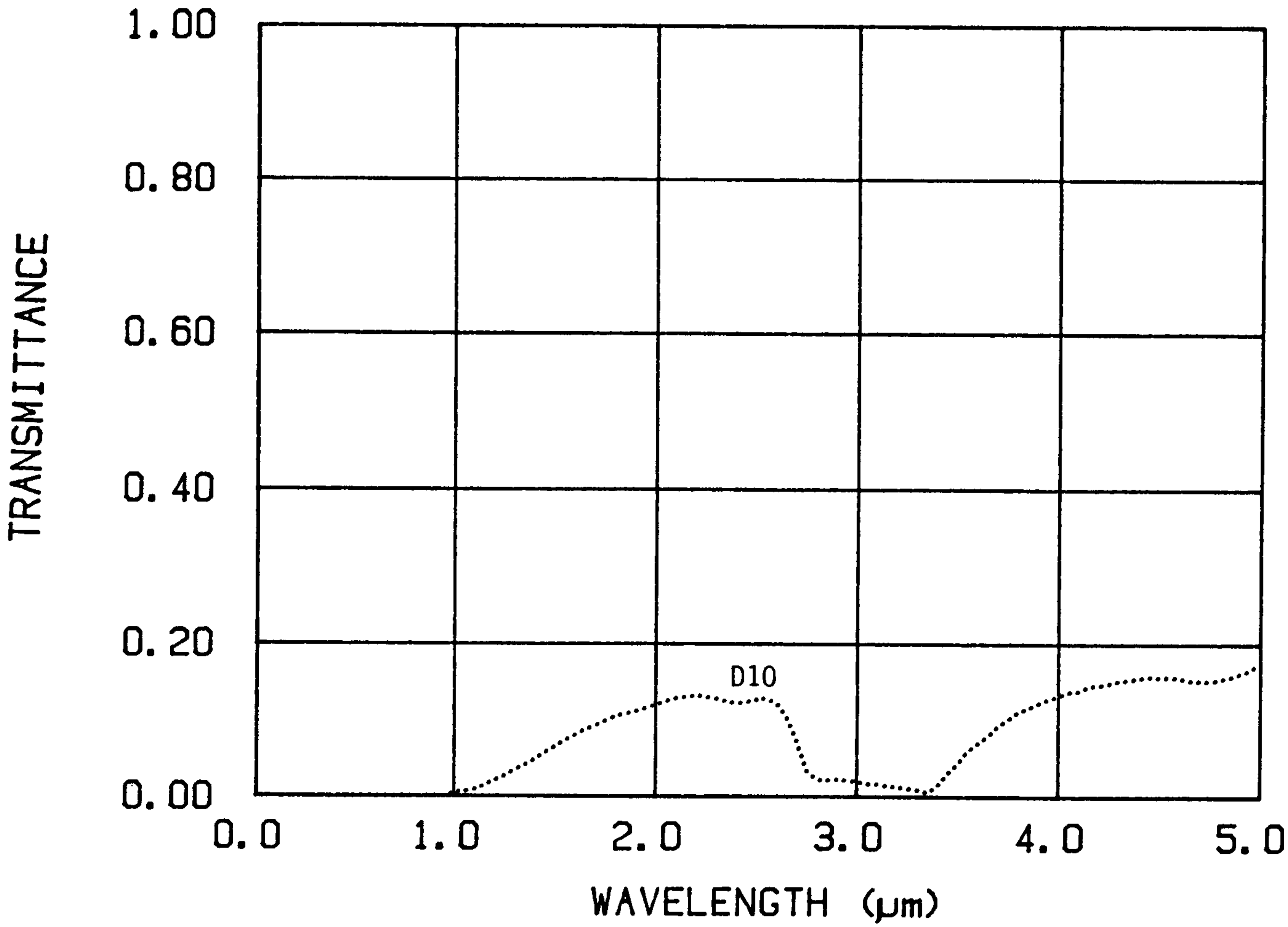

Figure 8(a). Inverted scattering coefficient spectrum of material B.

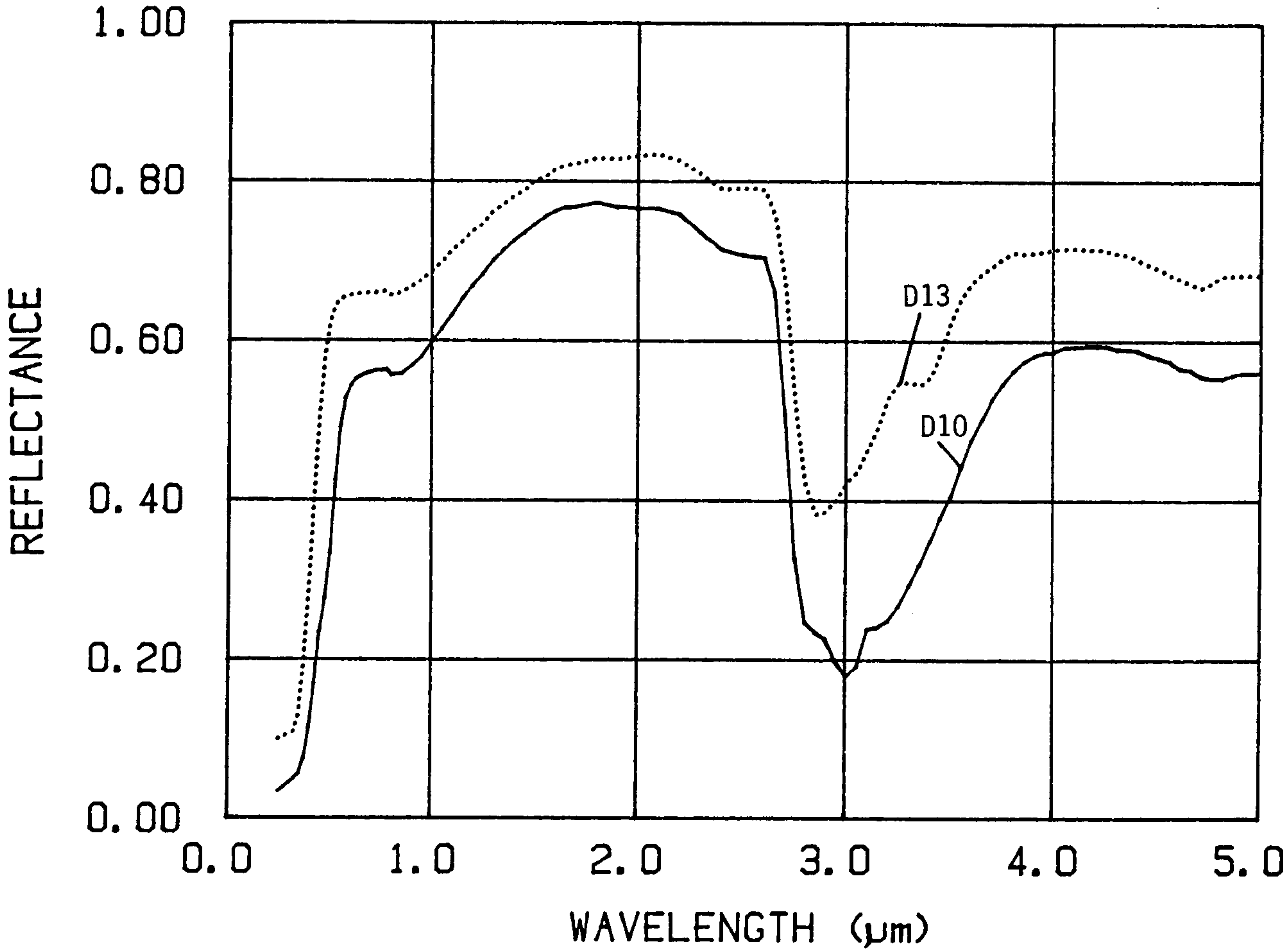

Figure 8(b). Inverted absorption coefficient spectrum of material B.

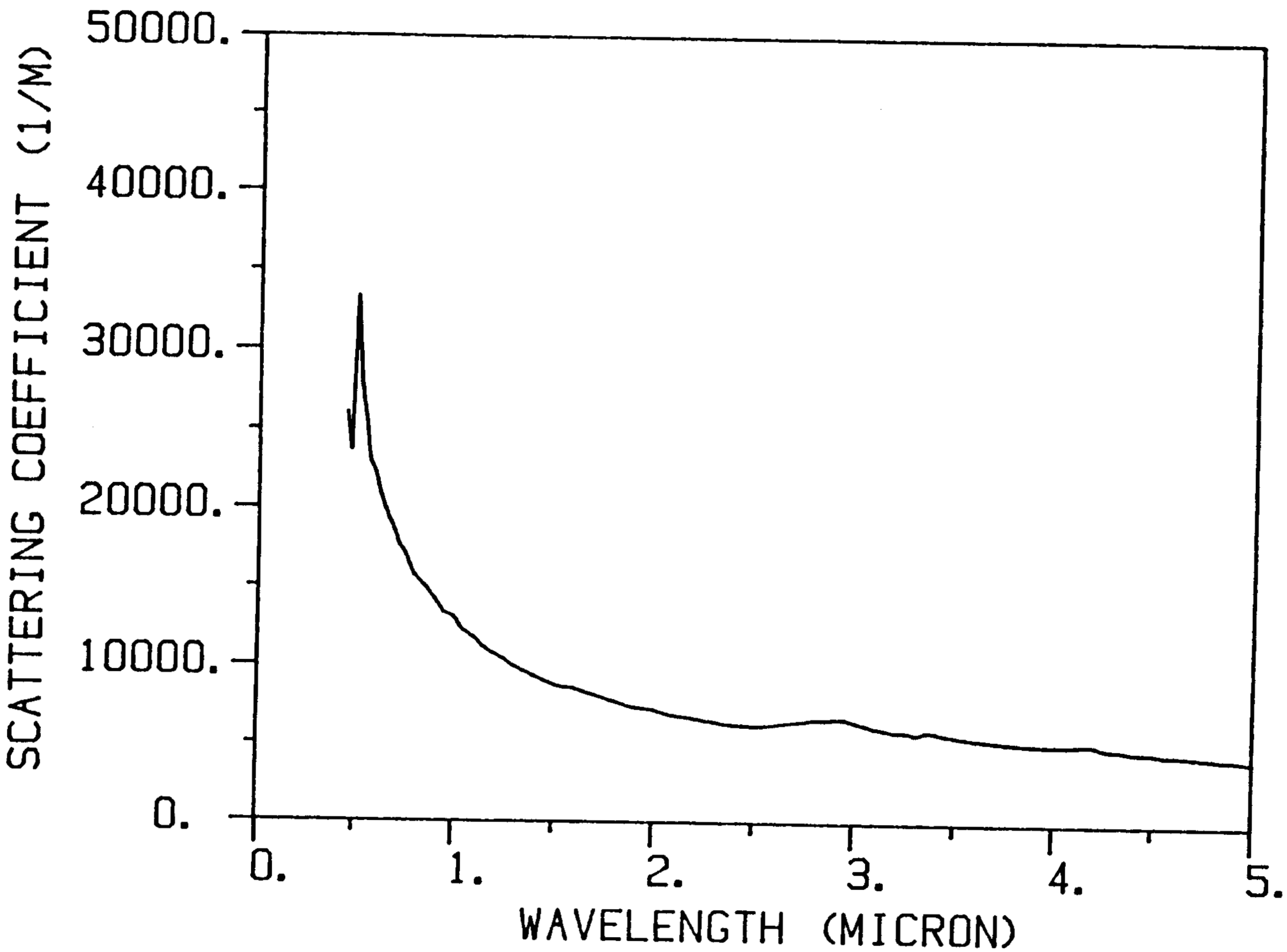

Figure 9(a). Inverted scattering coefficient spectrum of material B.

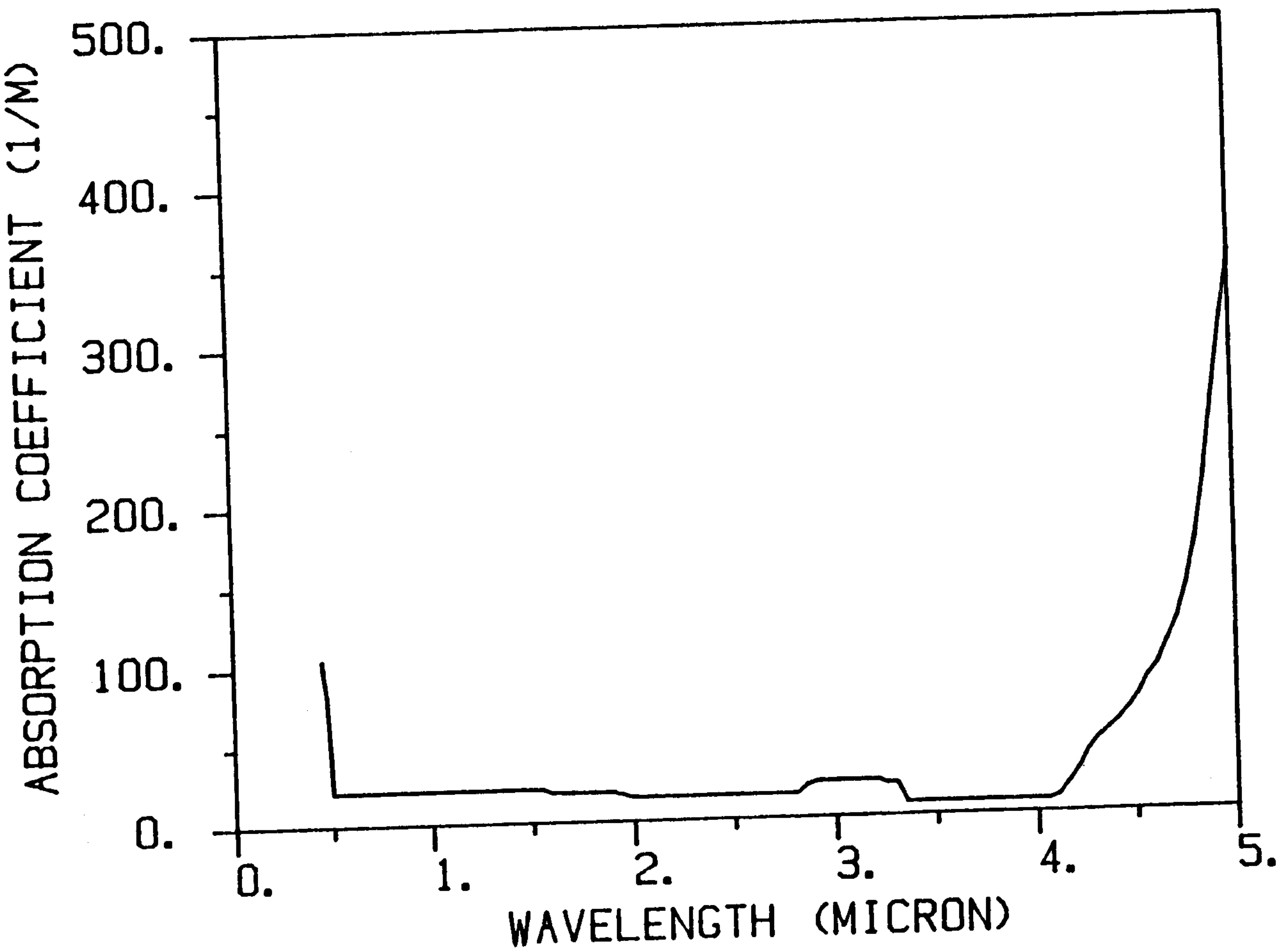

Figure 9(b). Inverted absorption coefficient spectrum of material B.

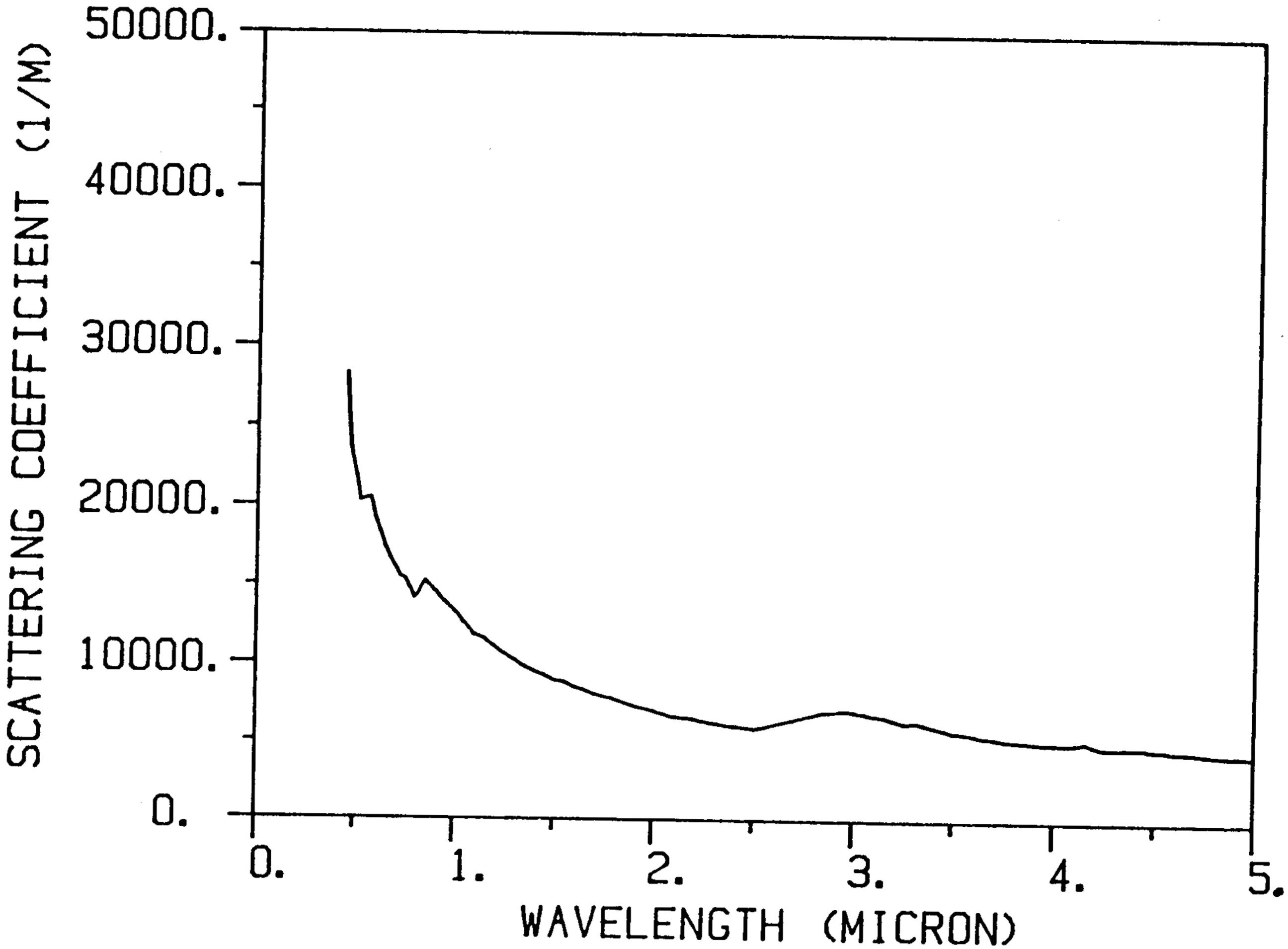

Figure 10 (a). Inverted scattering coefficient spectrum of material C.

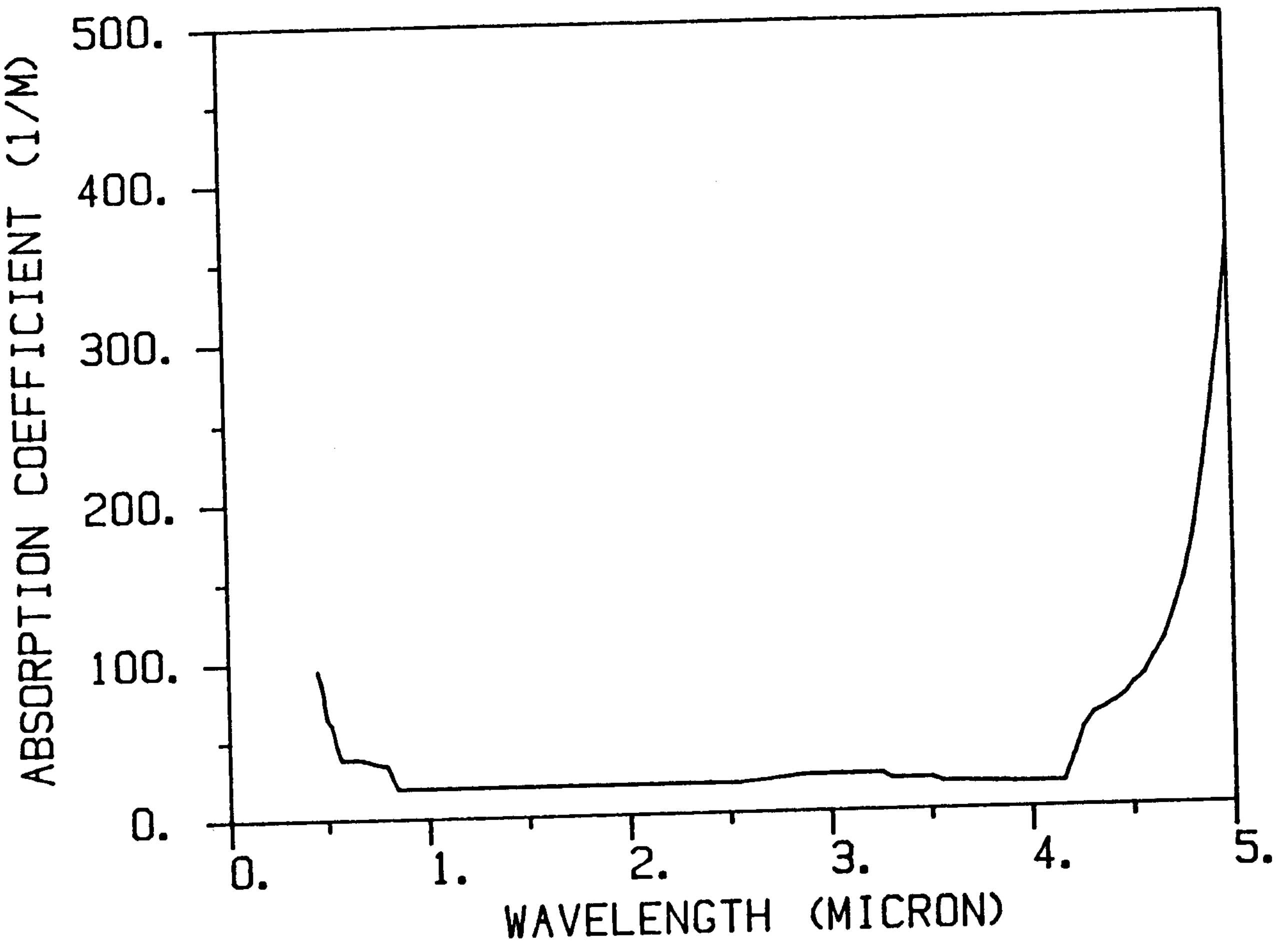

Figure 10 (b). Inverted absorption coefficient spectrum of material C.

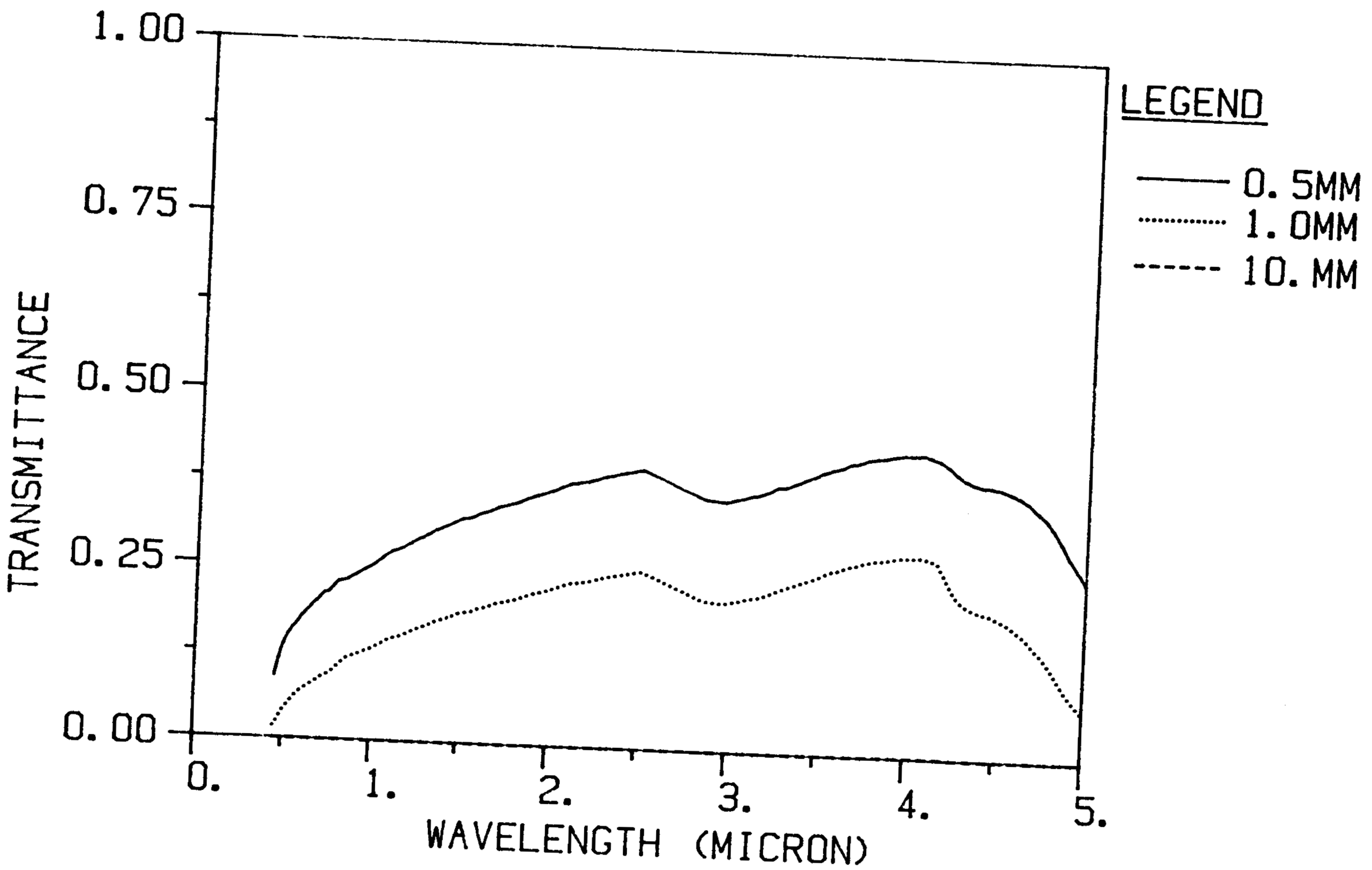

Figure 11(a). Calculated transmittance spectra of material C.

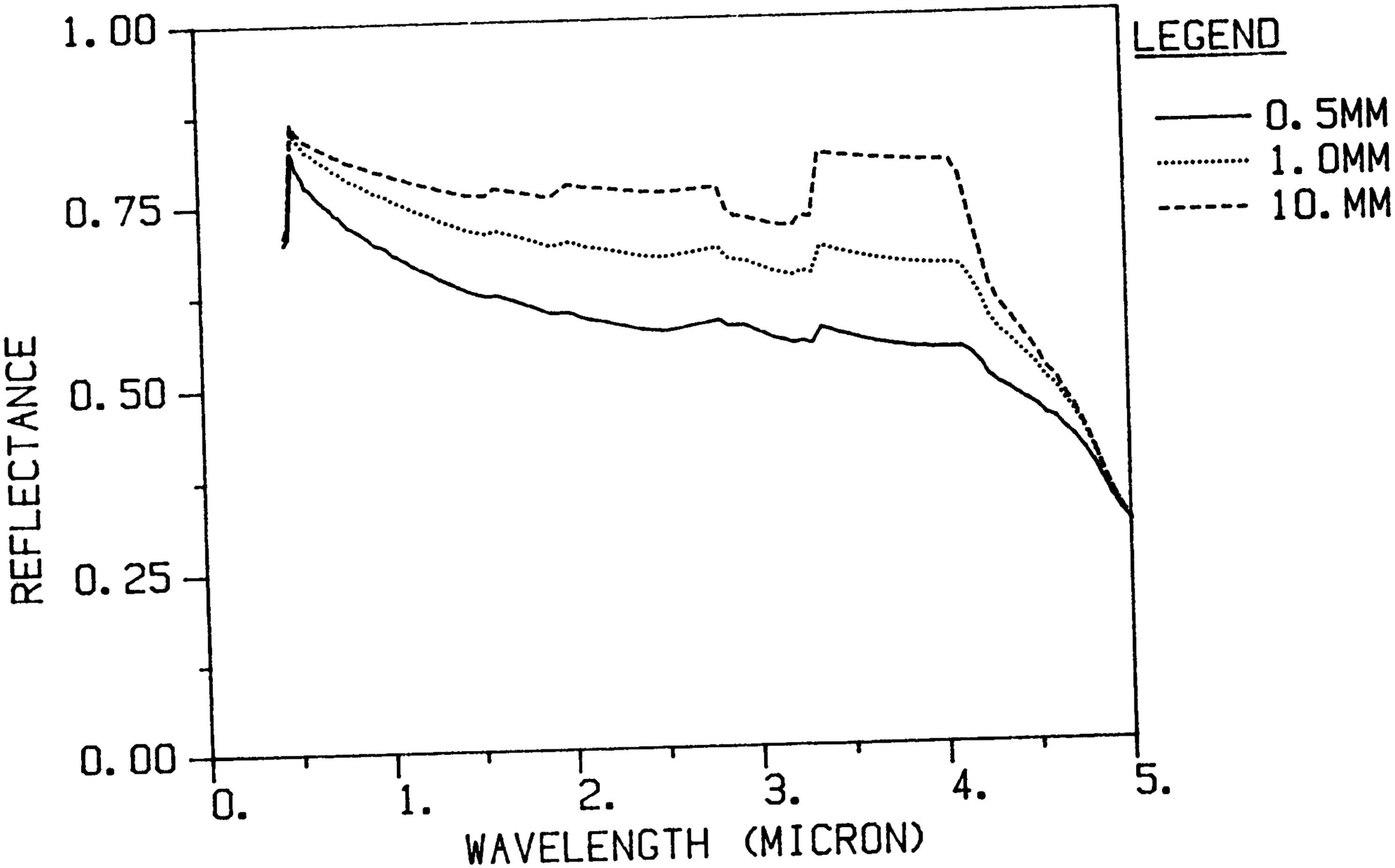

Figure 11(b). Calculated reflectance spectra of material C.

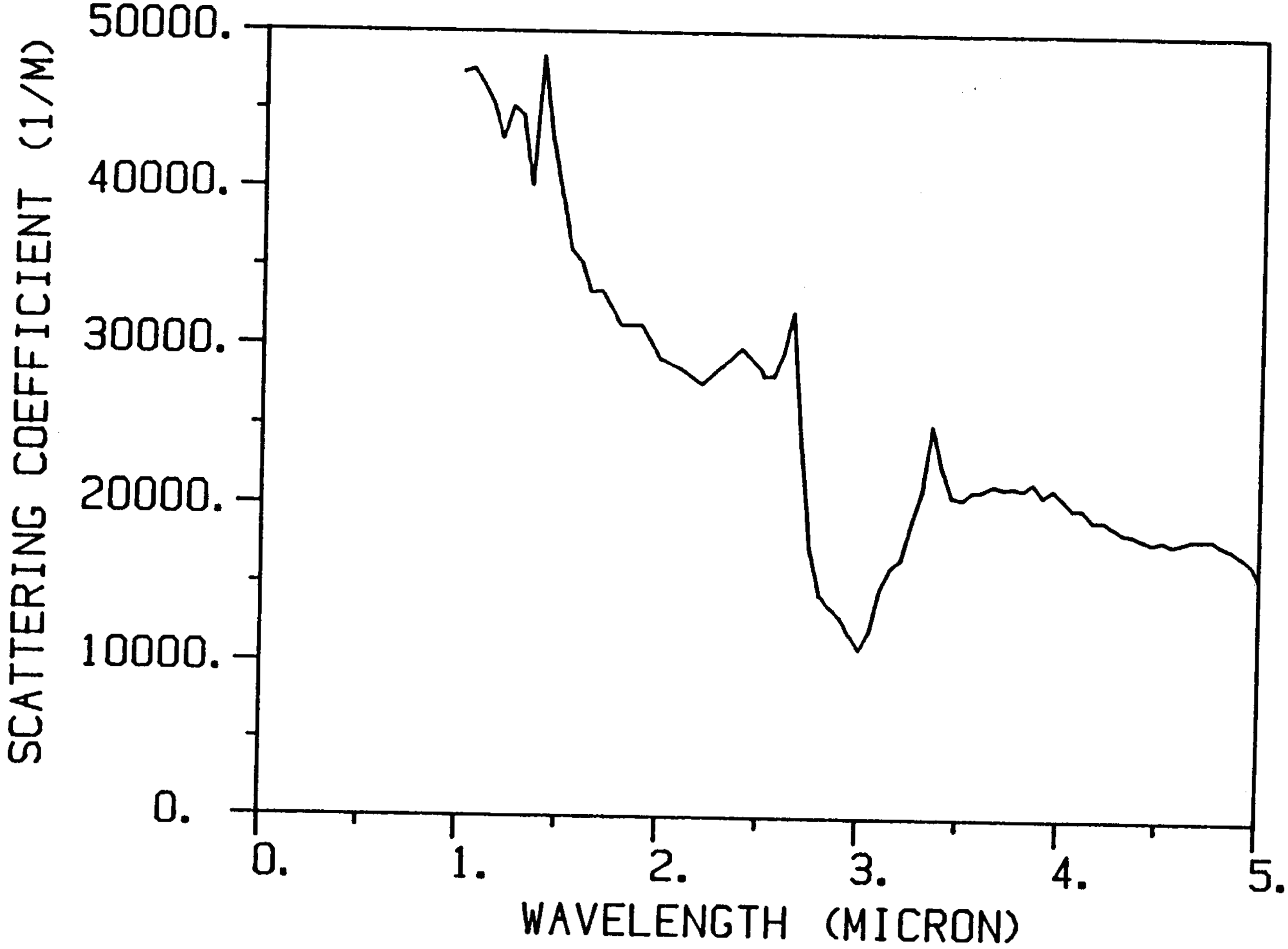

Figure 12(a). Inverted scattering coefficient spectrum of material D.

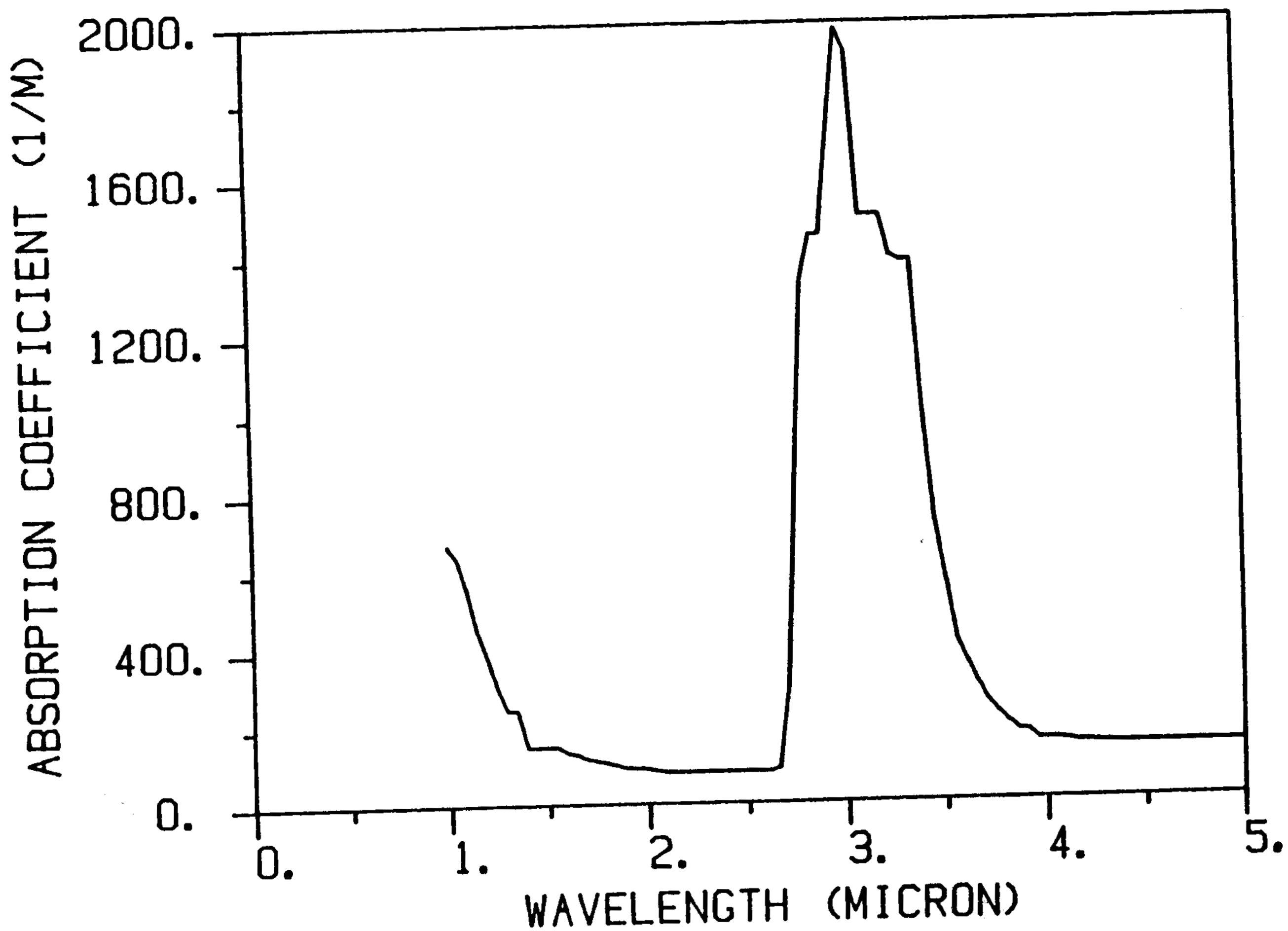

Figure 12(b). Inverted absorption coefficient spectrum of material D.

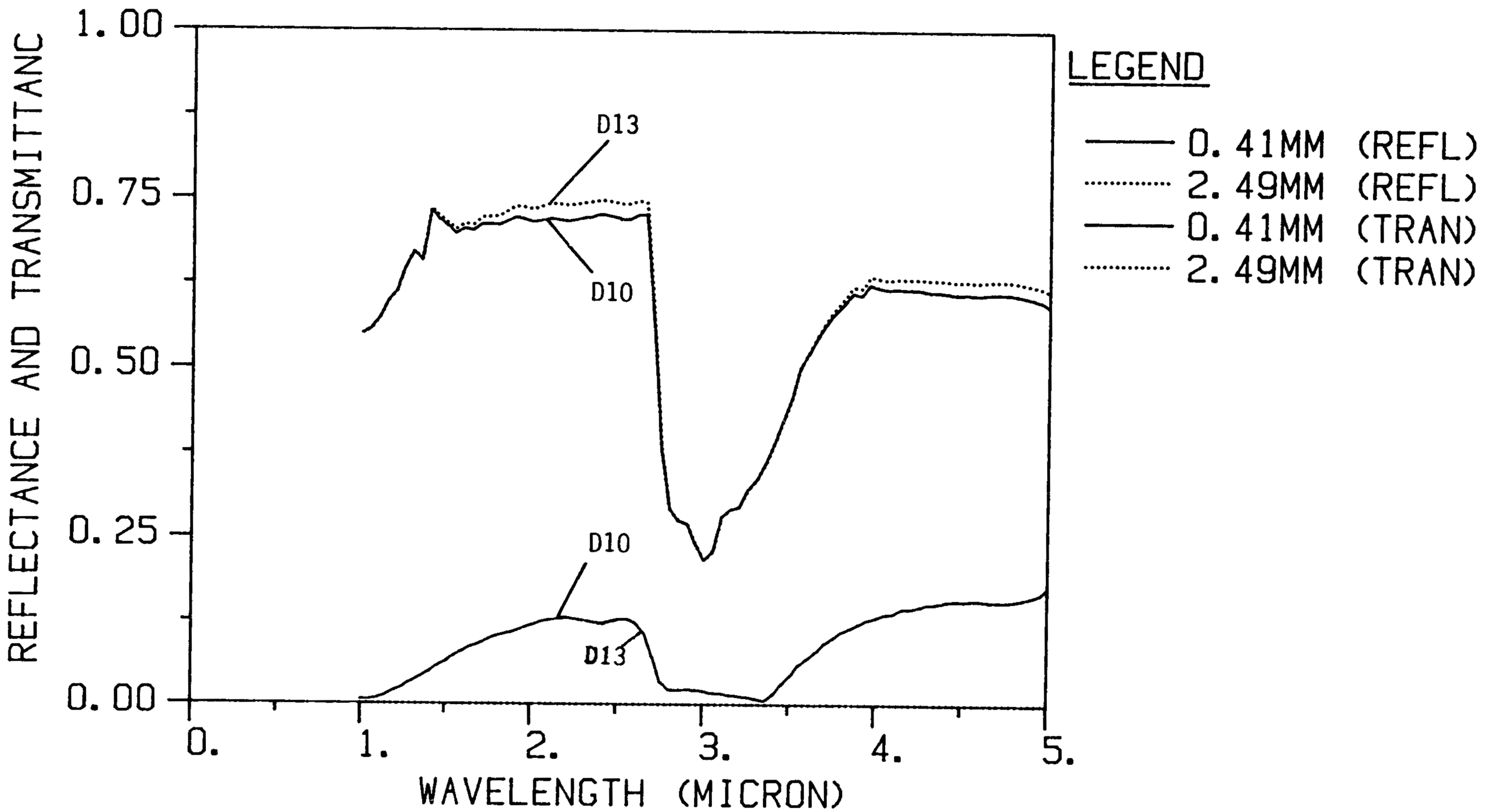

Figure 13(a). Calculated transmittance and reflectance spectra of material D.

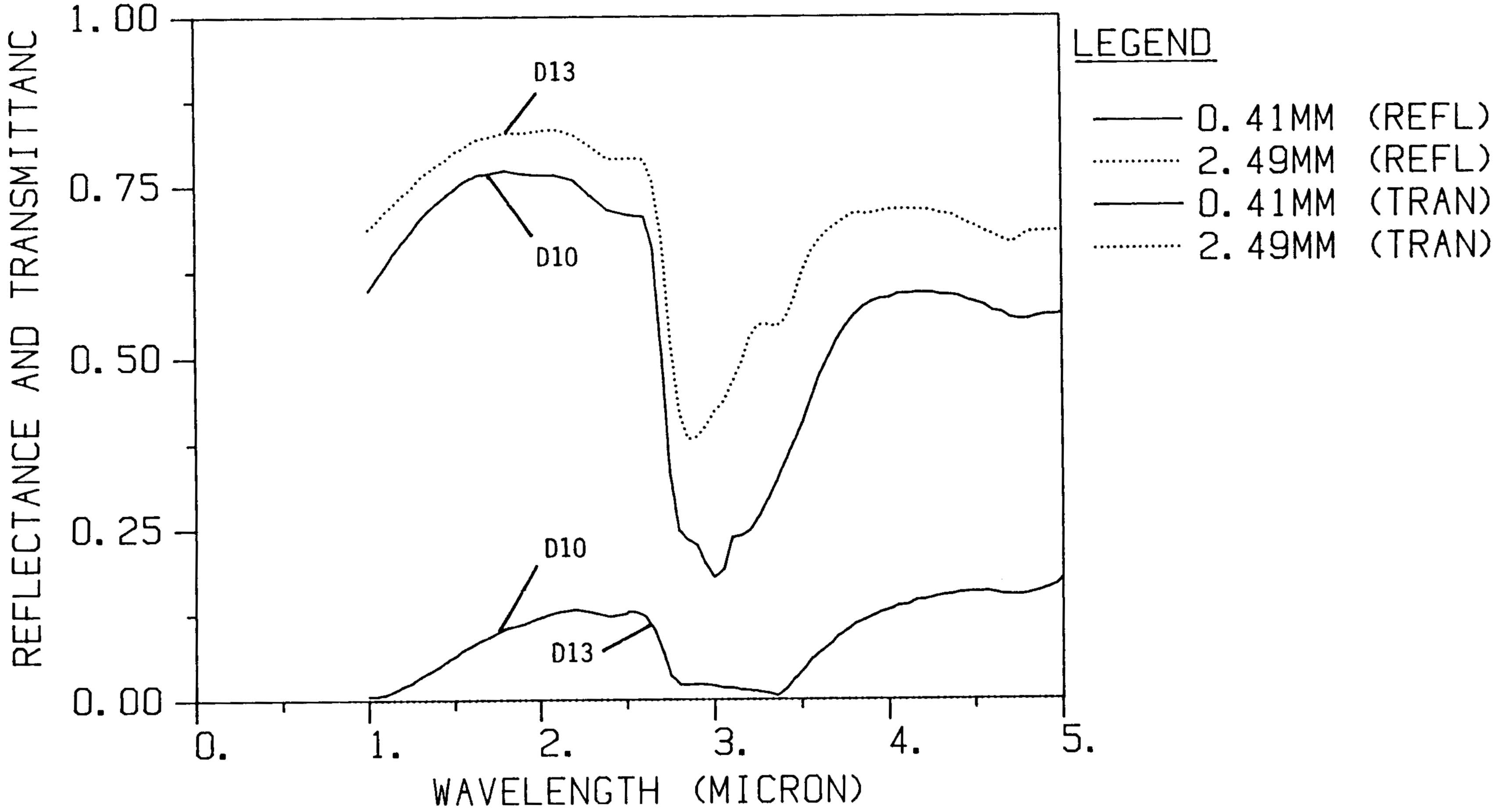

Figure 13(b). Measured transmittance and reflectance spectra of material D.

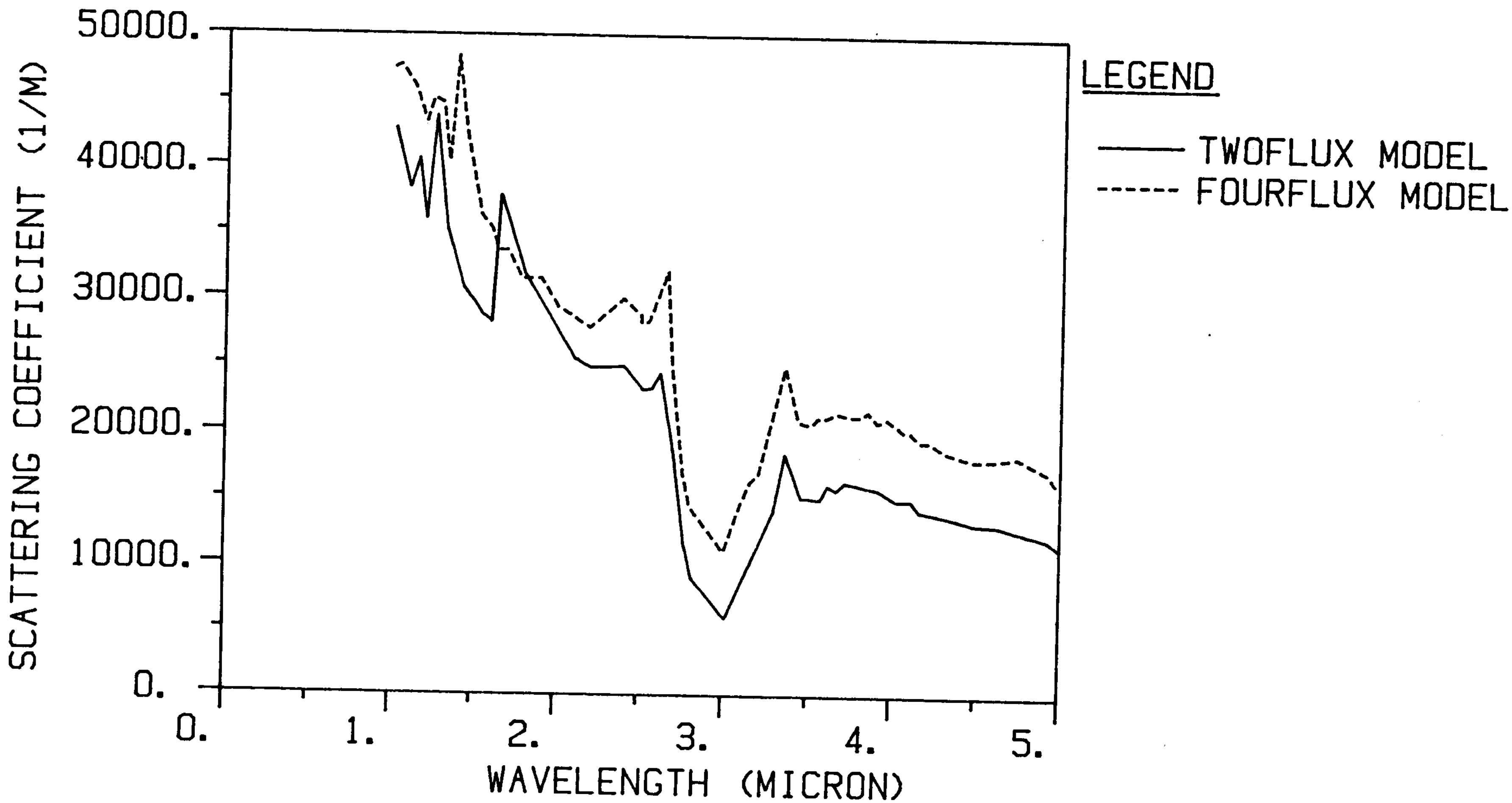

Figure 14(a). Comparison of inverted scattering coefficient spectrum of material D for four flux and two flux models.

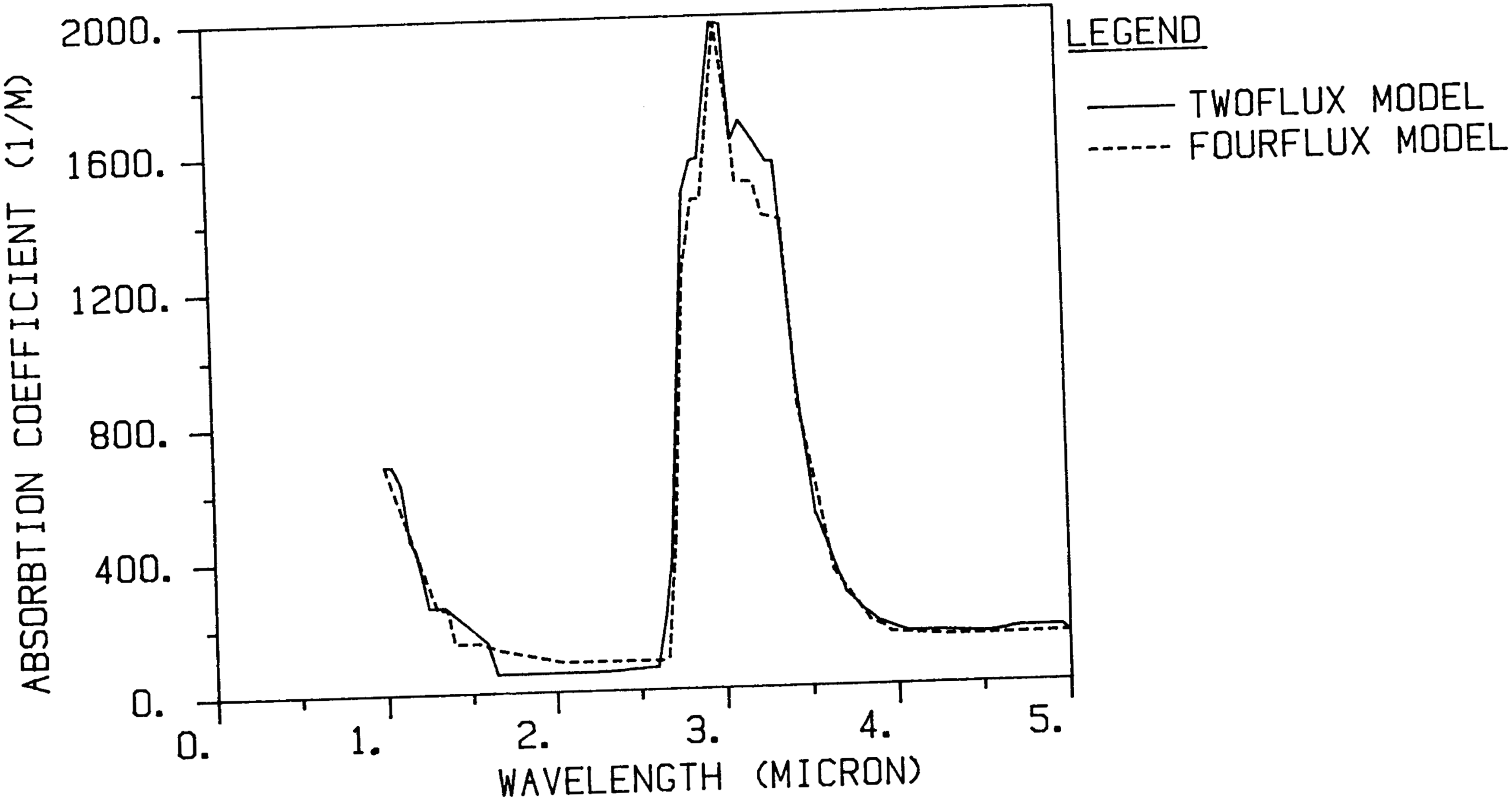

Figure 14(b). Comparison of inverted absorption coefficient spectrum of material D for four flux and two flux models.

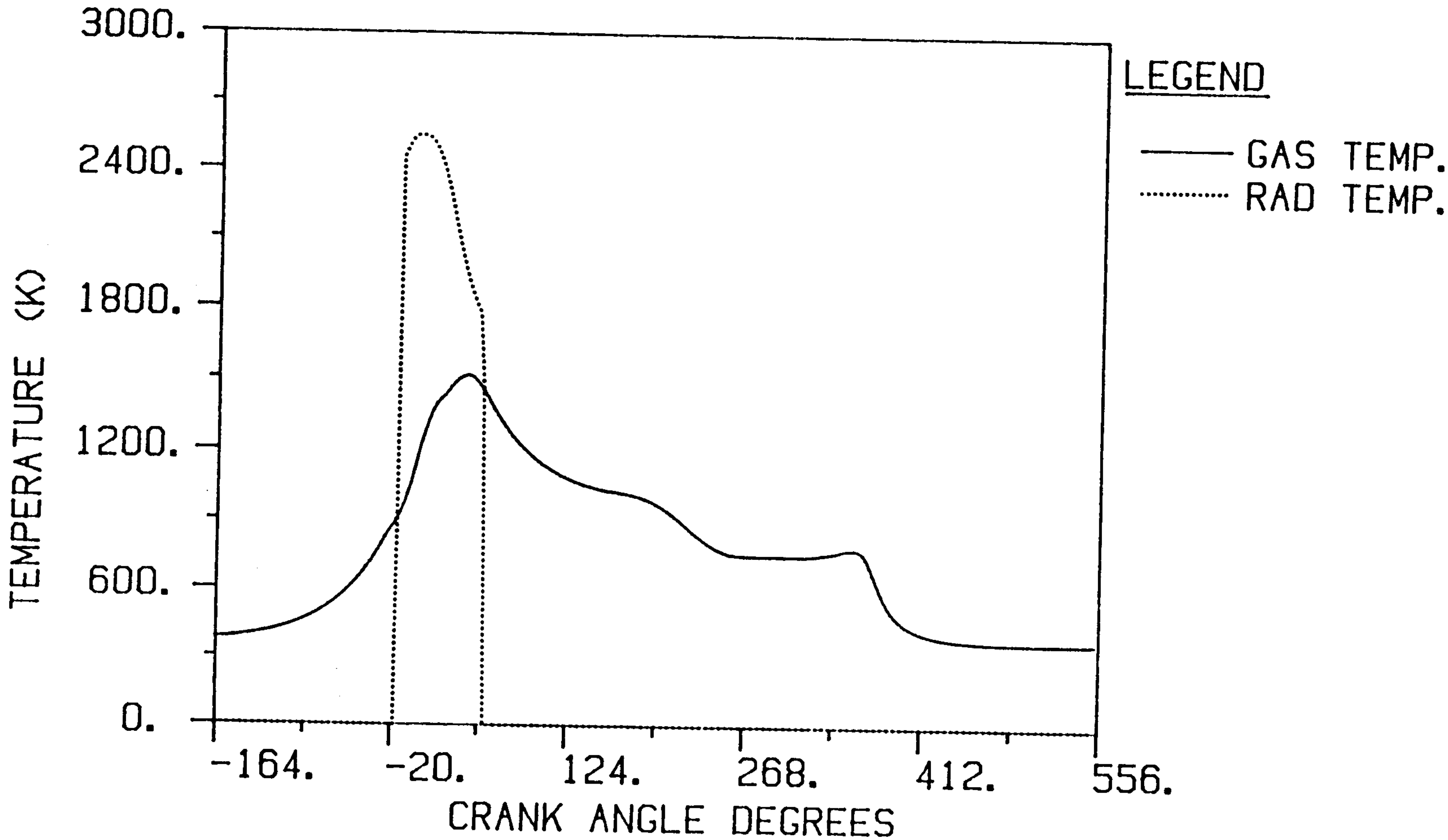

Figure 15(a). Gas and radiation temperature history used as gas side boundary condition on the heat barrier coating.

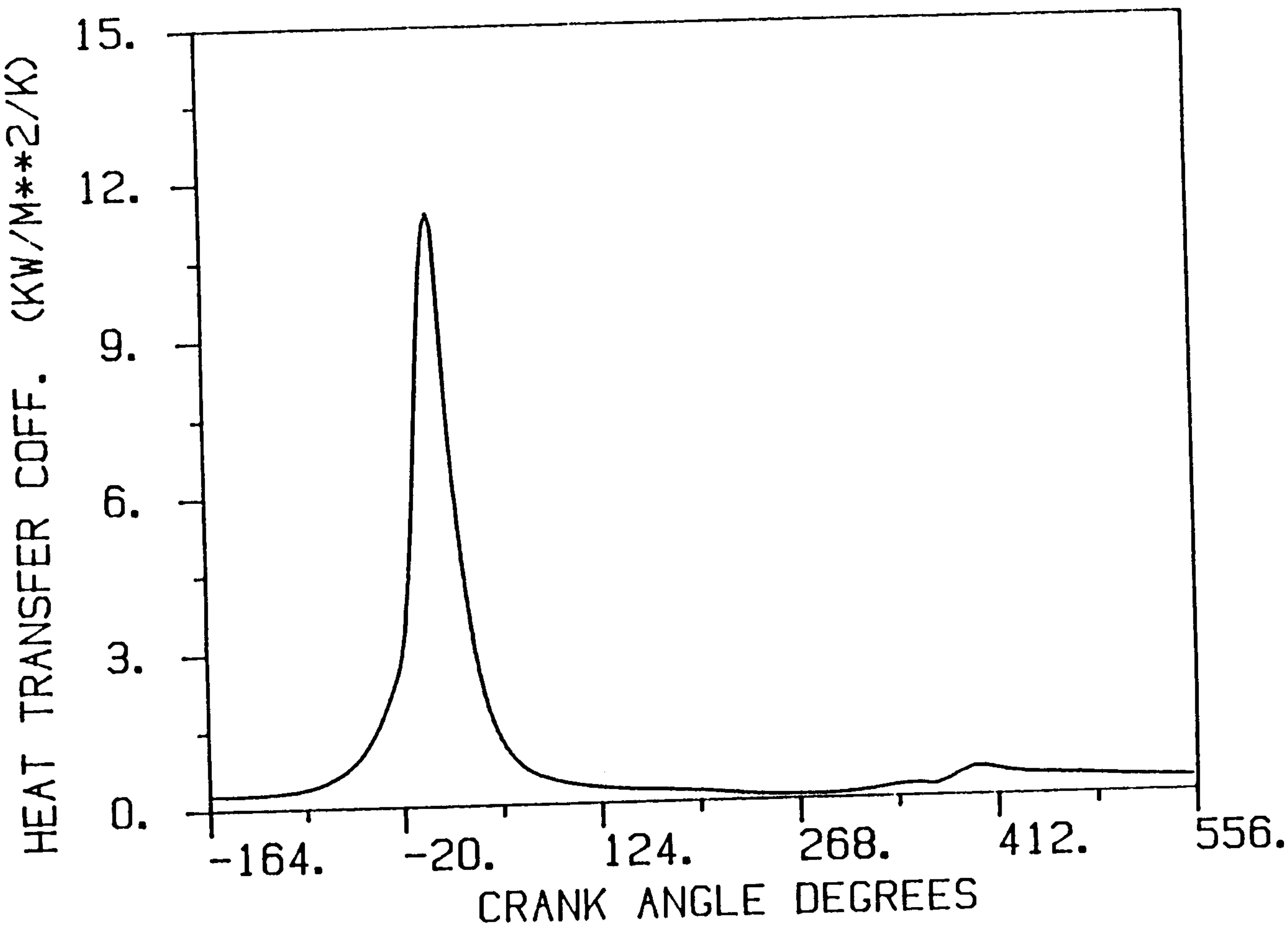

Figure 15(b). Heat transfer coefficient history used as gas side boundary condition on the heat barrier coating.

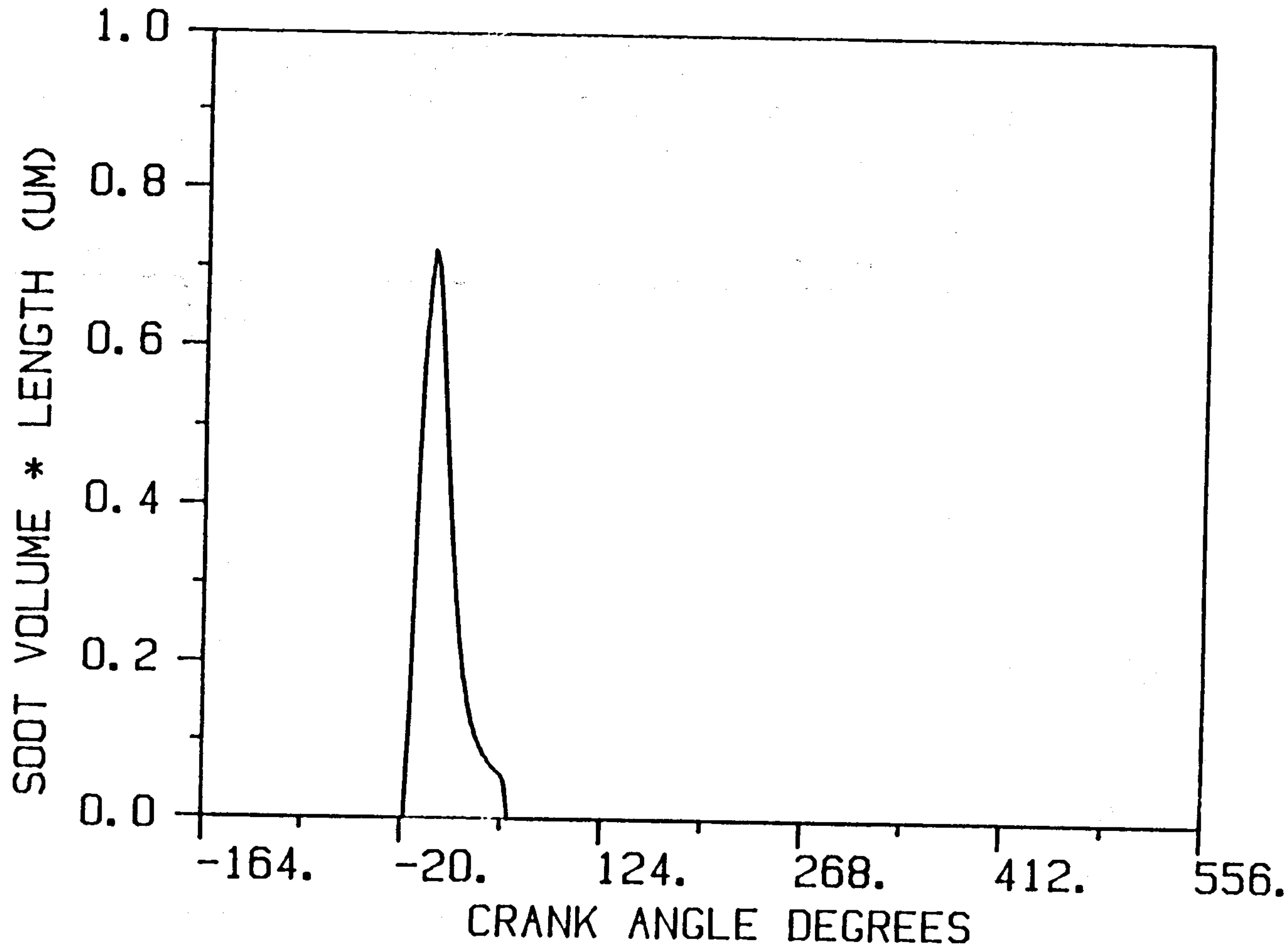

Figure 15(c). History of soot volume fraction times radiation path length used as gas side boundary condition on the heat barrier coating.

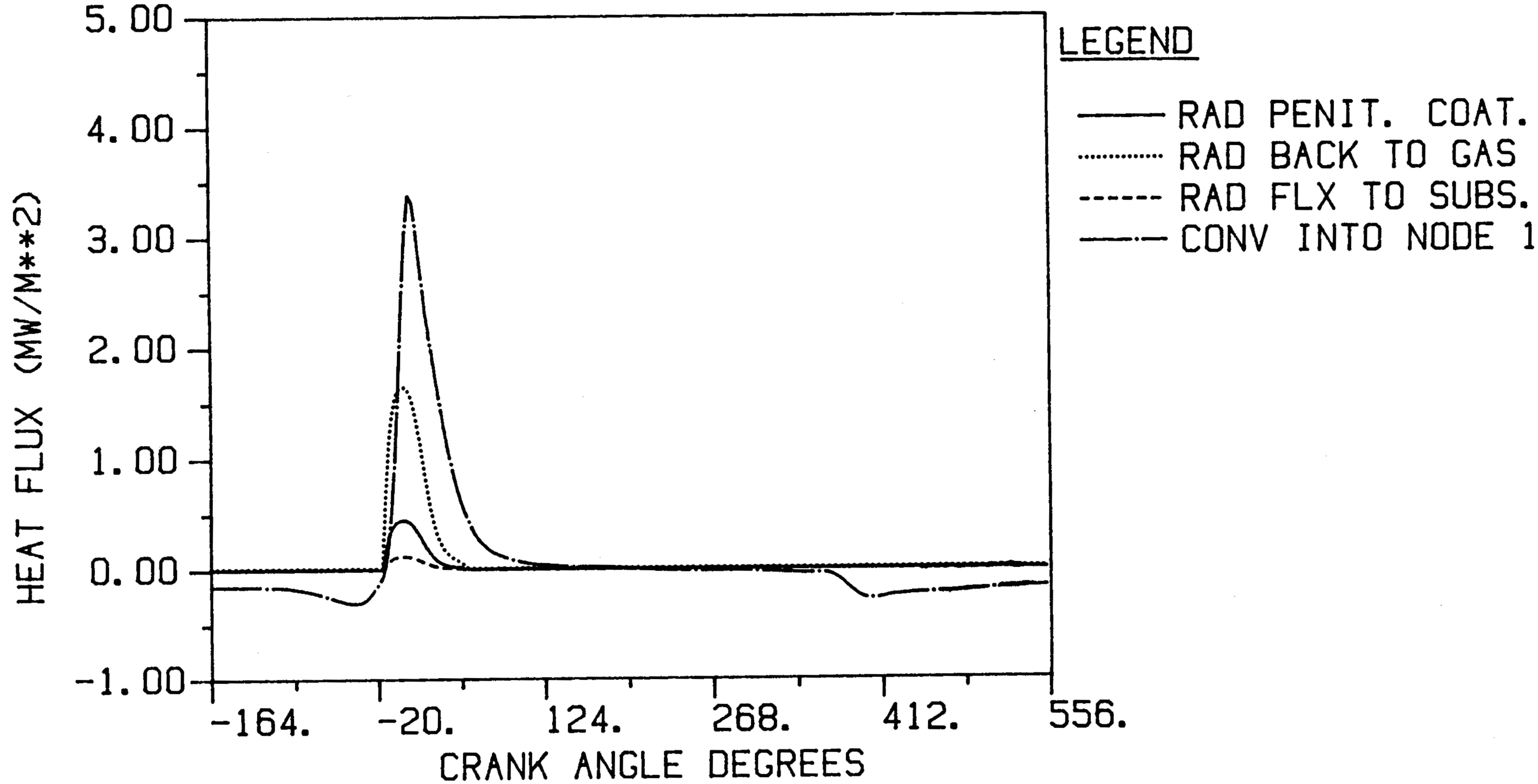

Figure 16(a). Time dependent fluxes computed for 2.5 mm heat barrier coating using radiative properties of material C.

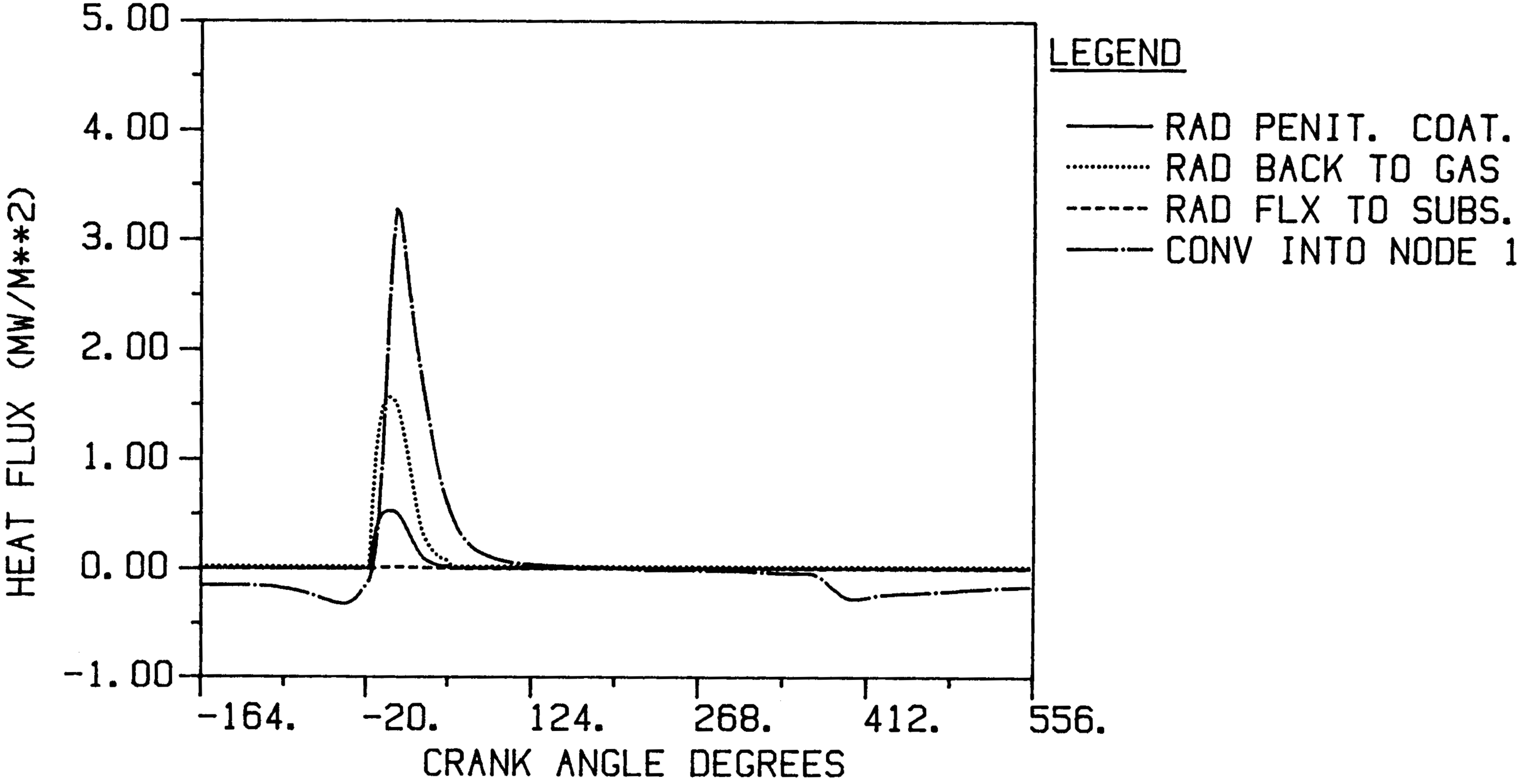

Figure 16(b). Time dependent fluxes computed for 2.5 mm heat barrier coating using radiative properties of material D.

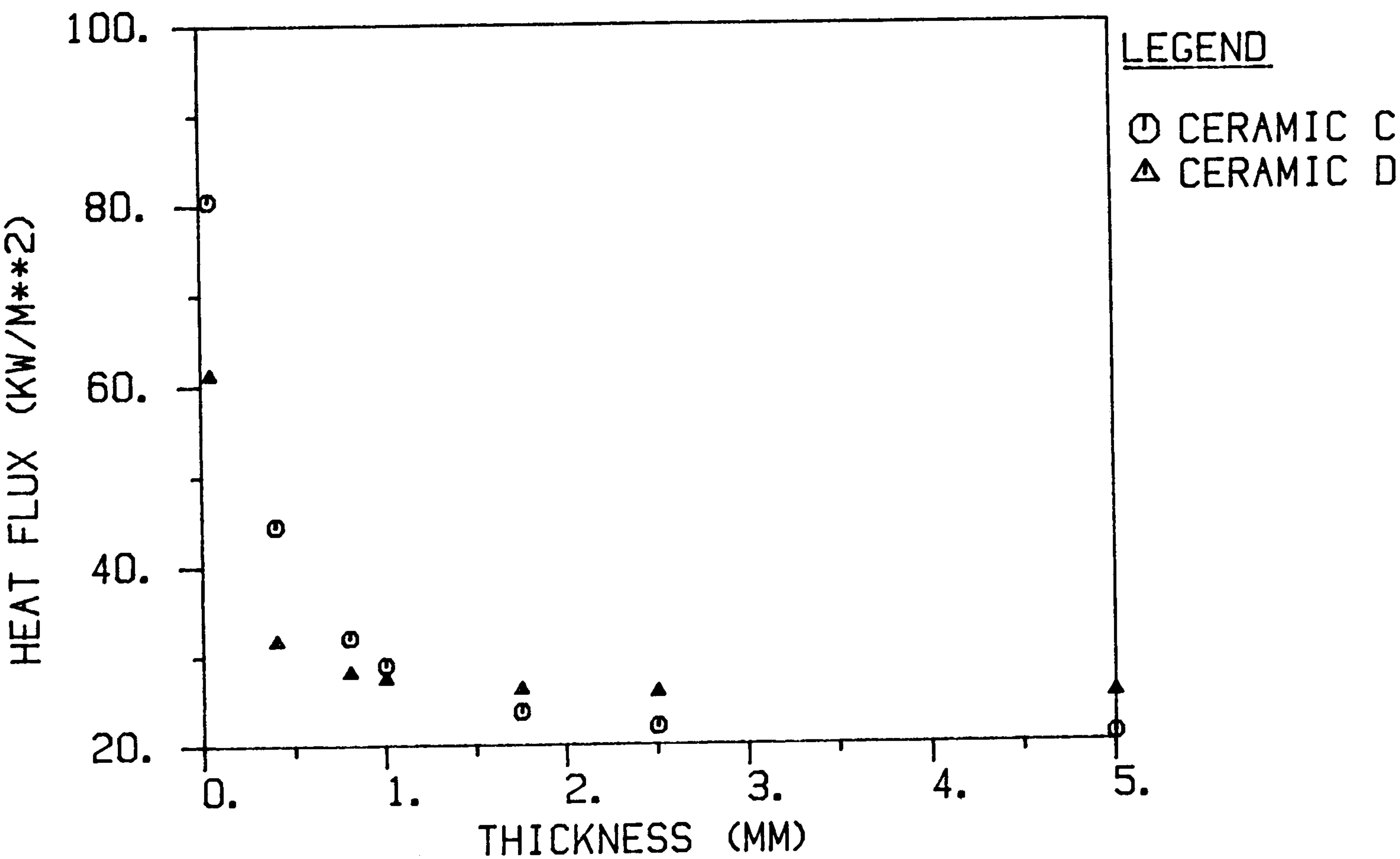

Figure 17(a). Time averaged radiative heat flux for ceramics C and D as a function of thickness.

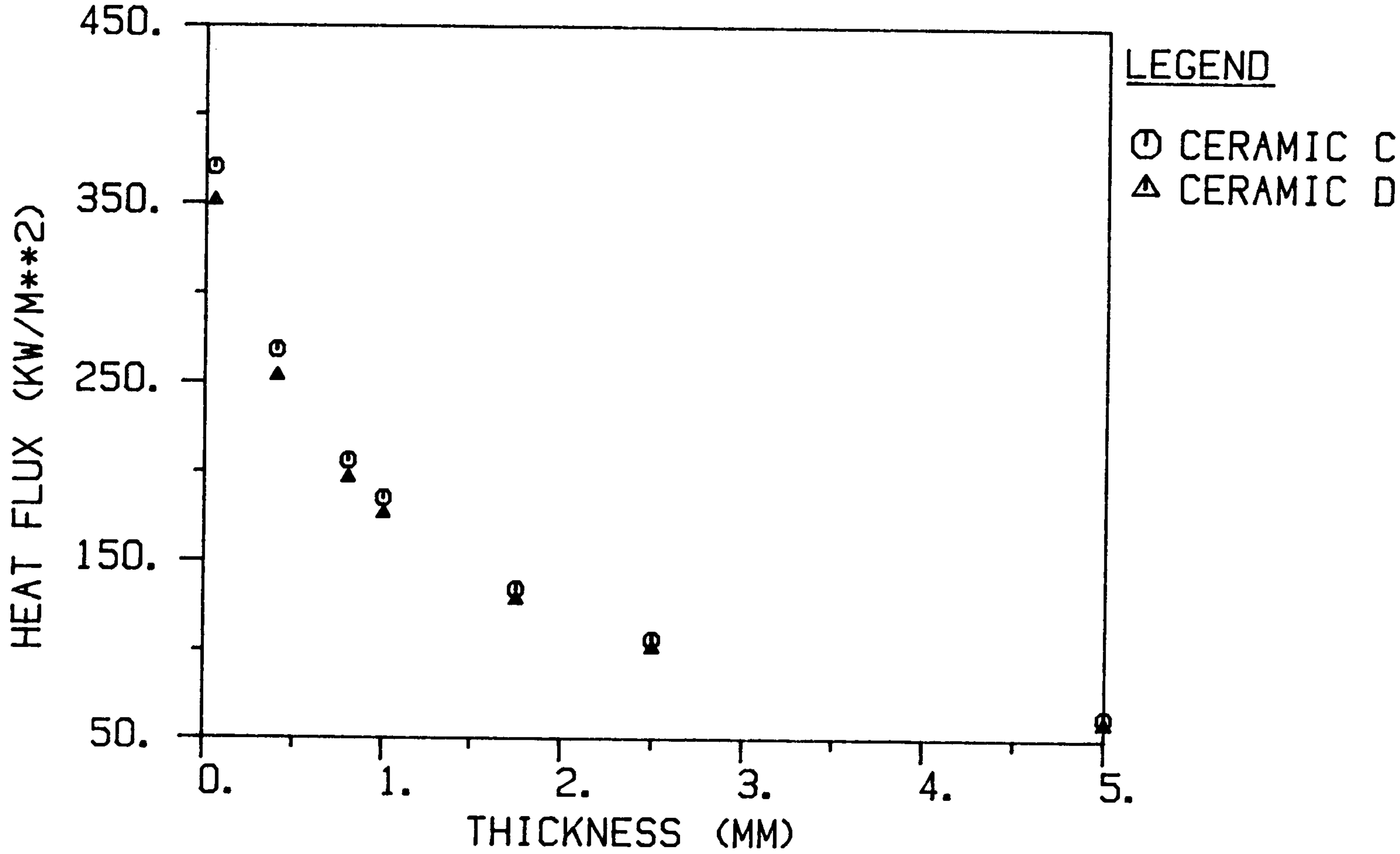

Figure 17(b). Time averaged total heat flux for ceramics C and D as a function of thickness.

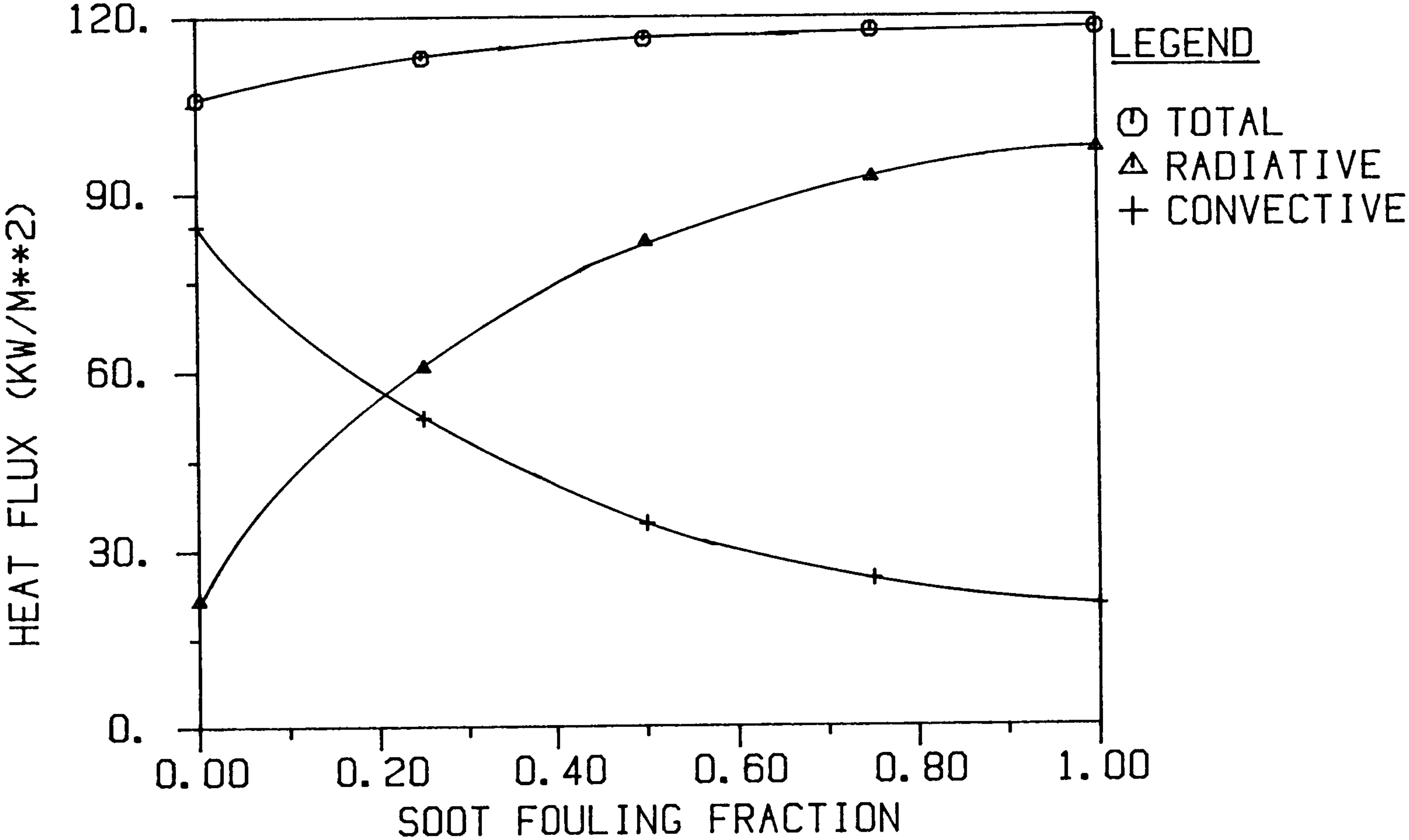

Figure 18. Effect of soot fouling for 2.5 mm Ceramic C coating used as heat barrier on time averaged fluxes.

APPENDIX

The reflectance and transmittance measurements at short to long infrared regions (2 μm to 20 μm were measured at the Willey Corporation. The data obtained were quite noisy at shorter wavelengths and necessitated smoothing. The smoothed profiles shown in the text have been used in the analysis. However, for reference purposes, the unsmoothed data is also presented in the following figures. (Note: Per instruction from the Willey Corporation the values in the reflectance spectra need to be divided by 0.95). The corresponding NBS mesurements carried out in the range 0.25 μm to 2.5 μm were furnished in tabular form and plots obtained from these tables are presented without modification in the general text of this report and will not be repeated here.

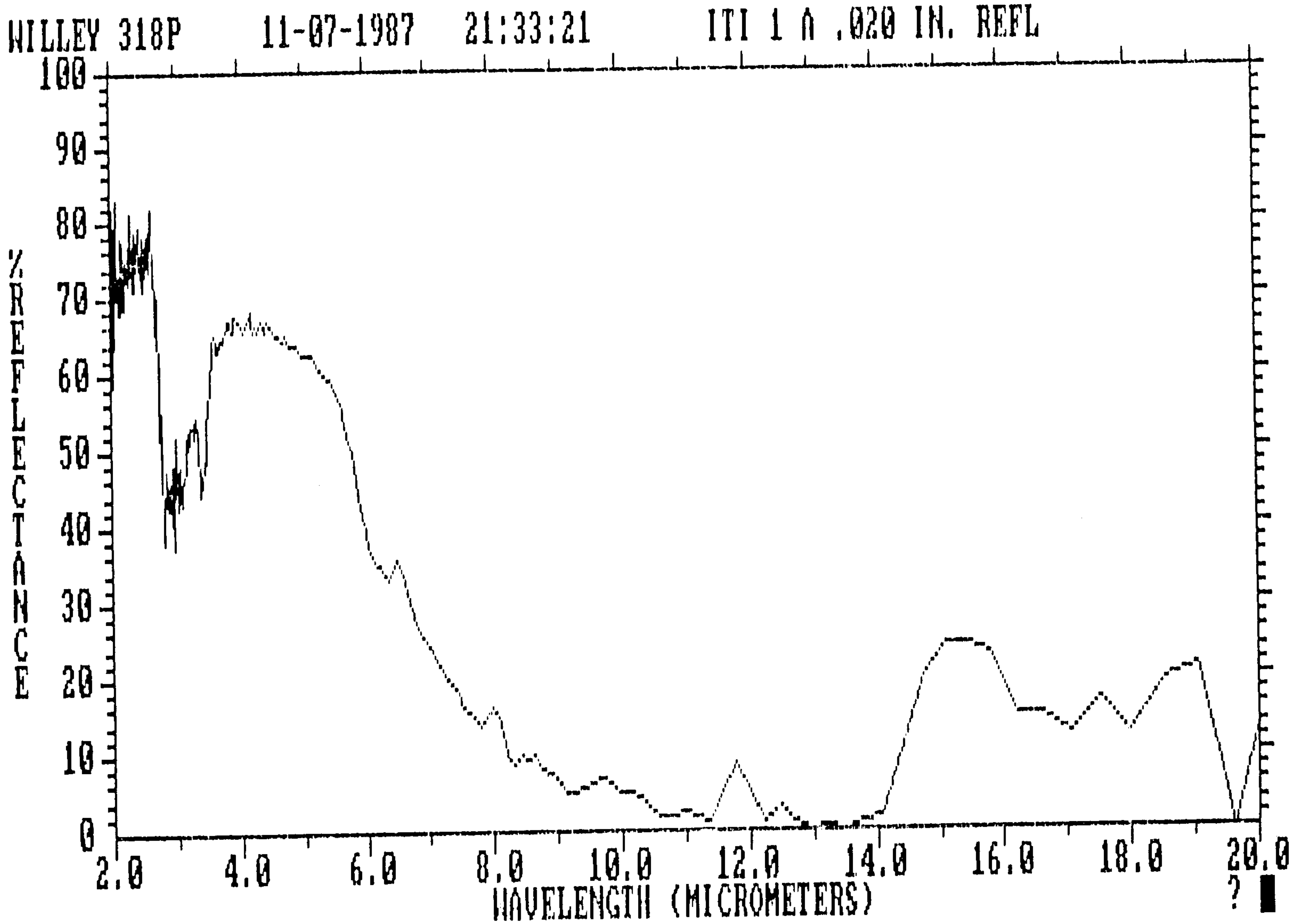

Figure A-1 Unsmoothed Reflectance Spectra of Sample A1

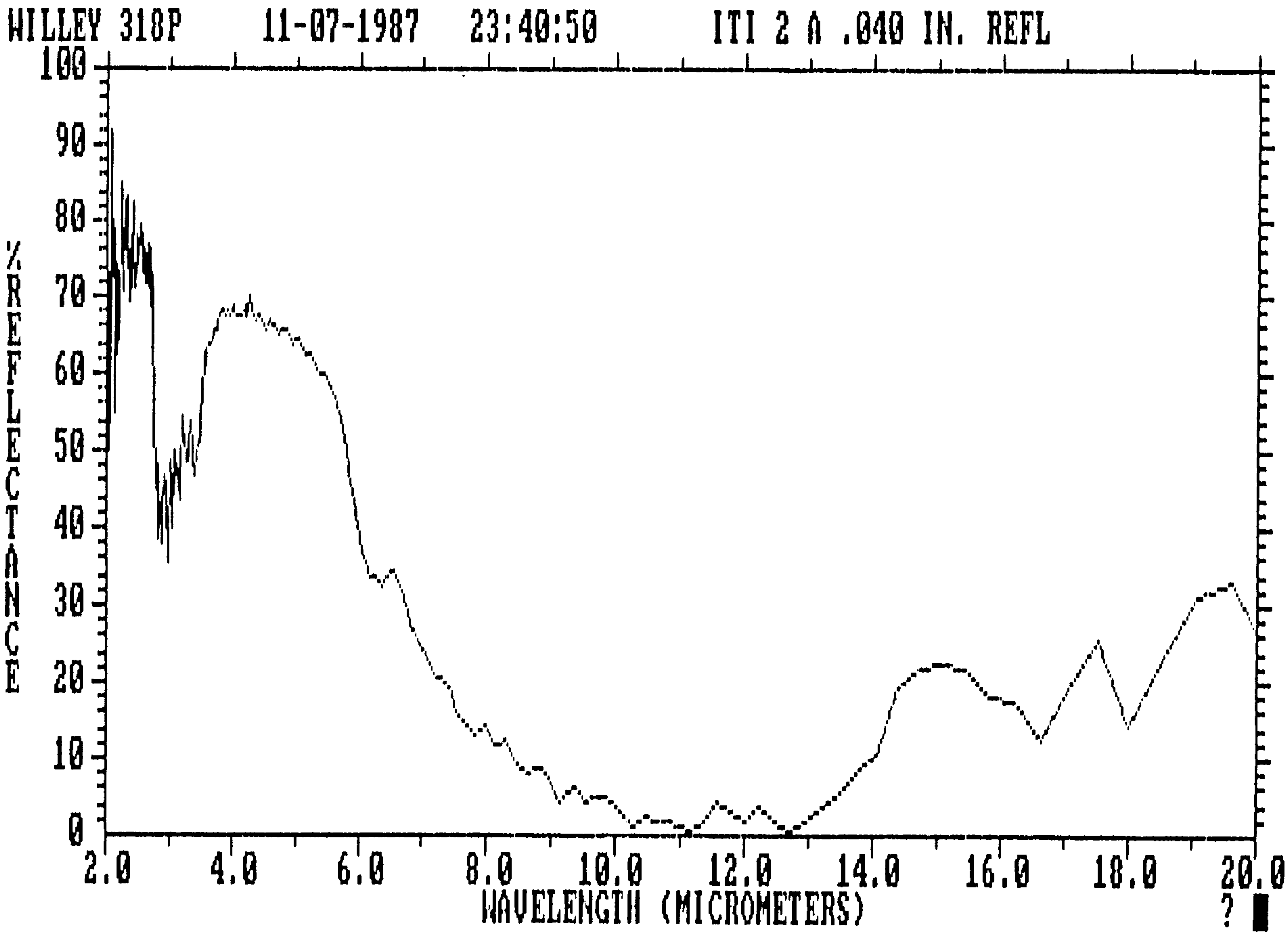

Figure A-2 Unsmoothed Reflectance Spectra of Sample A2

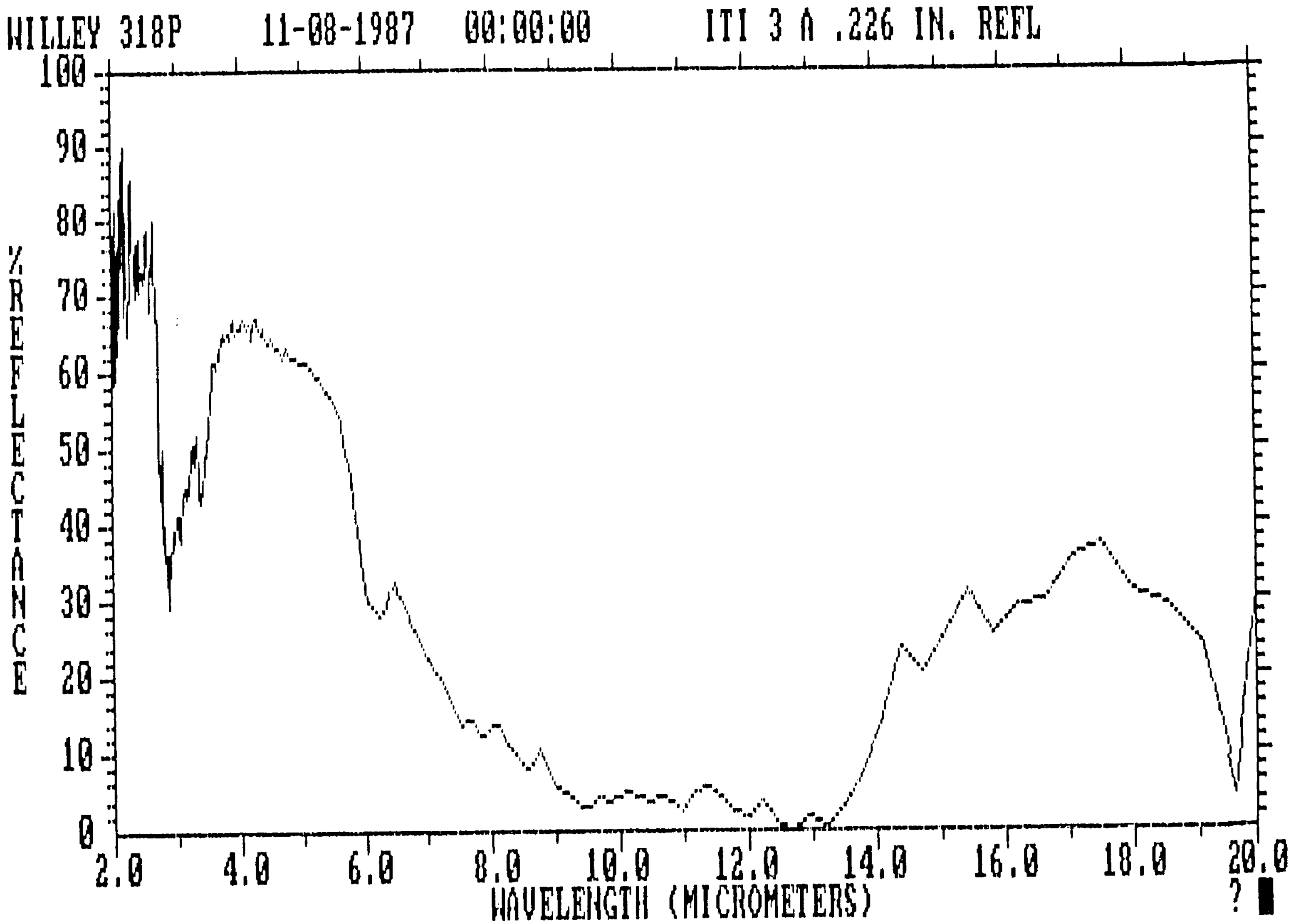

Figure A-3 Unsmoothed Reflectance Spectra of Sample A3

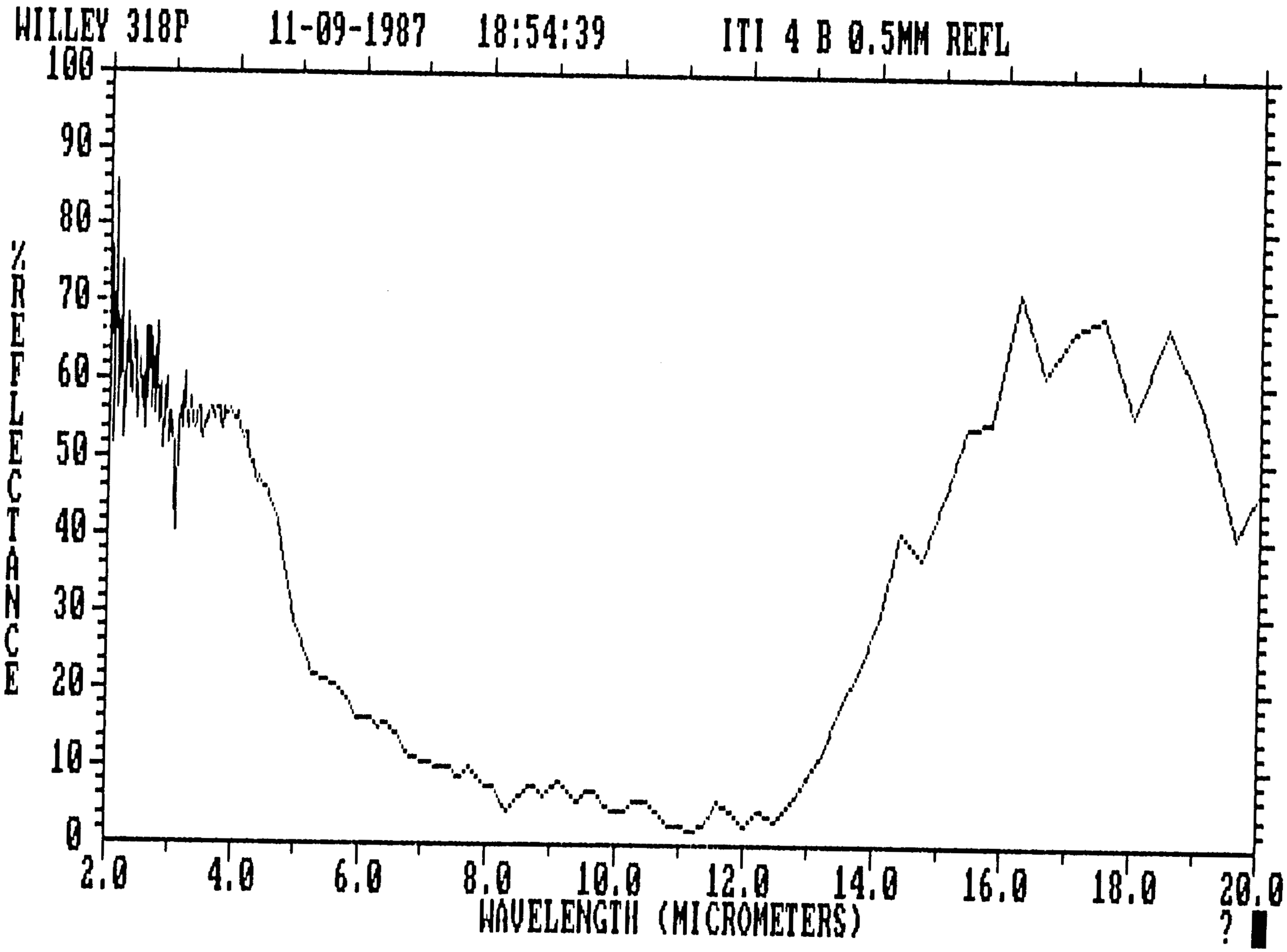

Figure A-4 Unsmoothed Reflectance Spectra of Sample B4

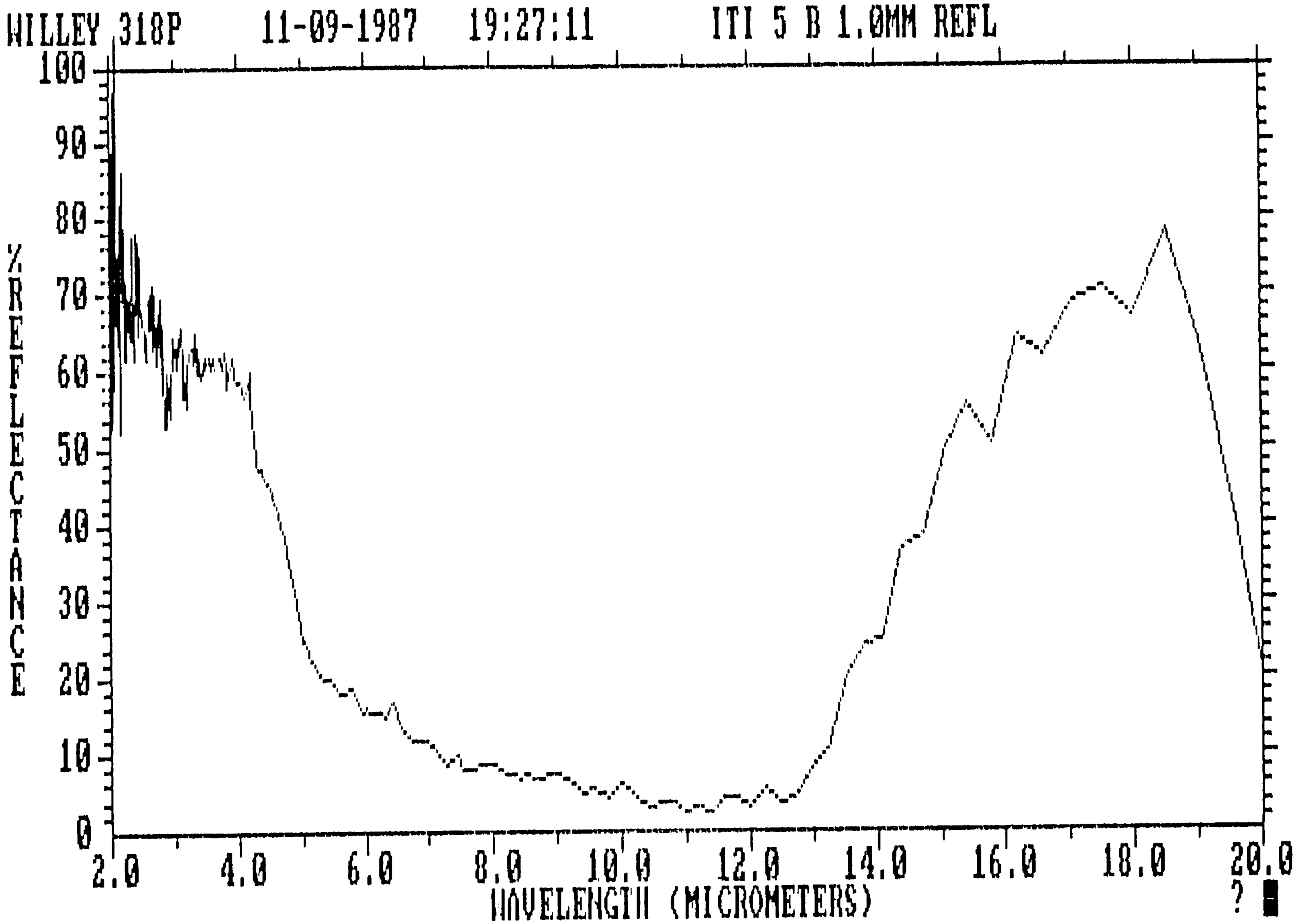

Figure A-5 Unsmoothed Reflectance Spectra of Sample B5

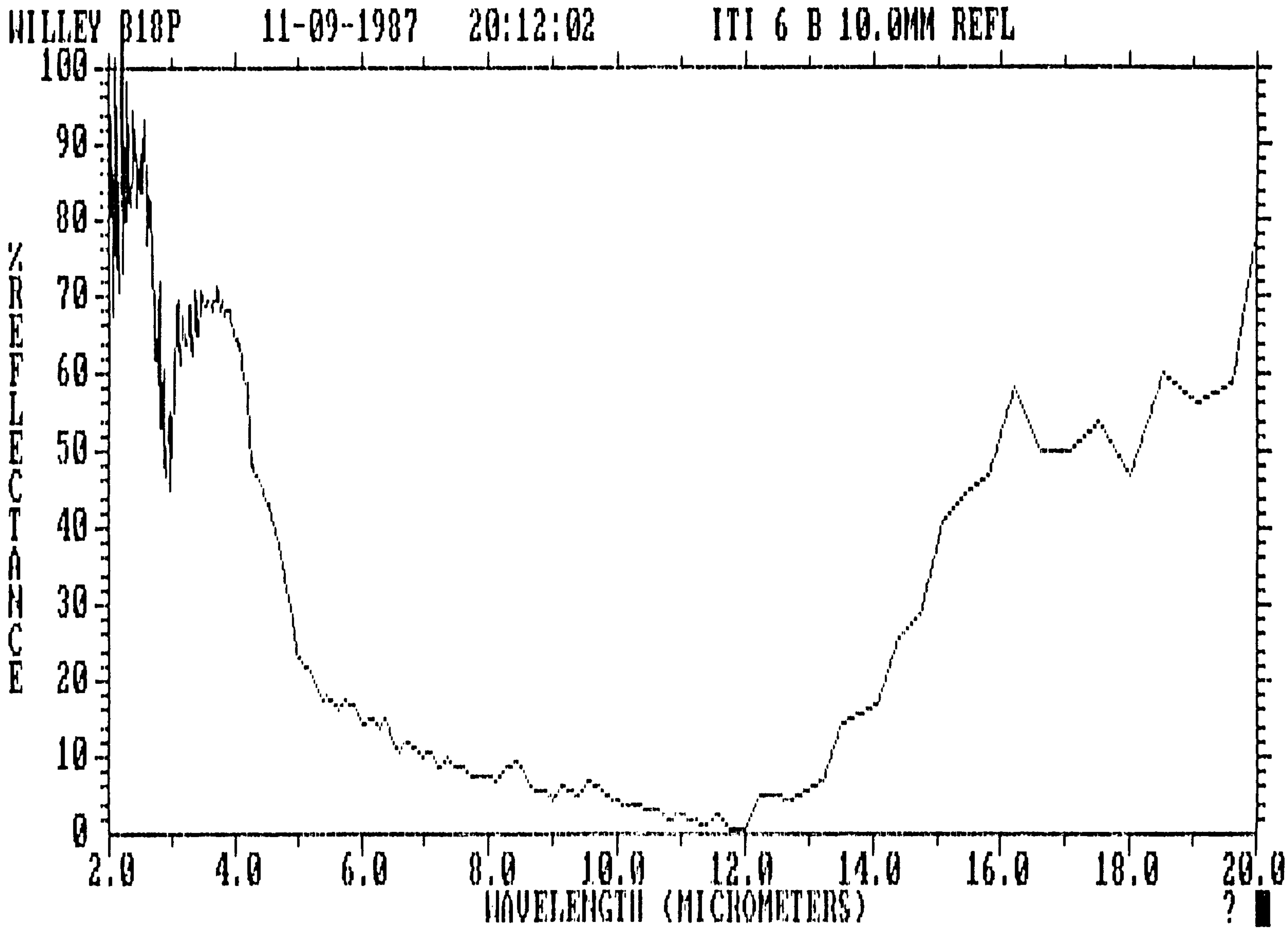

Figure A-6 Unsmoothed Reflectance Spectra of Sample B6

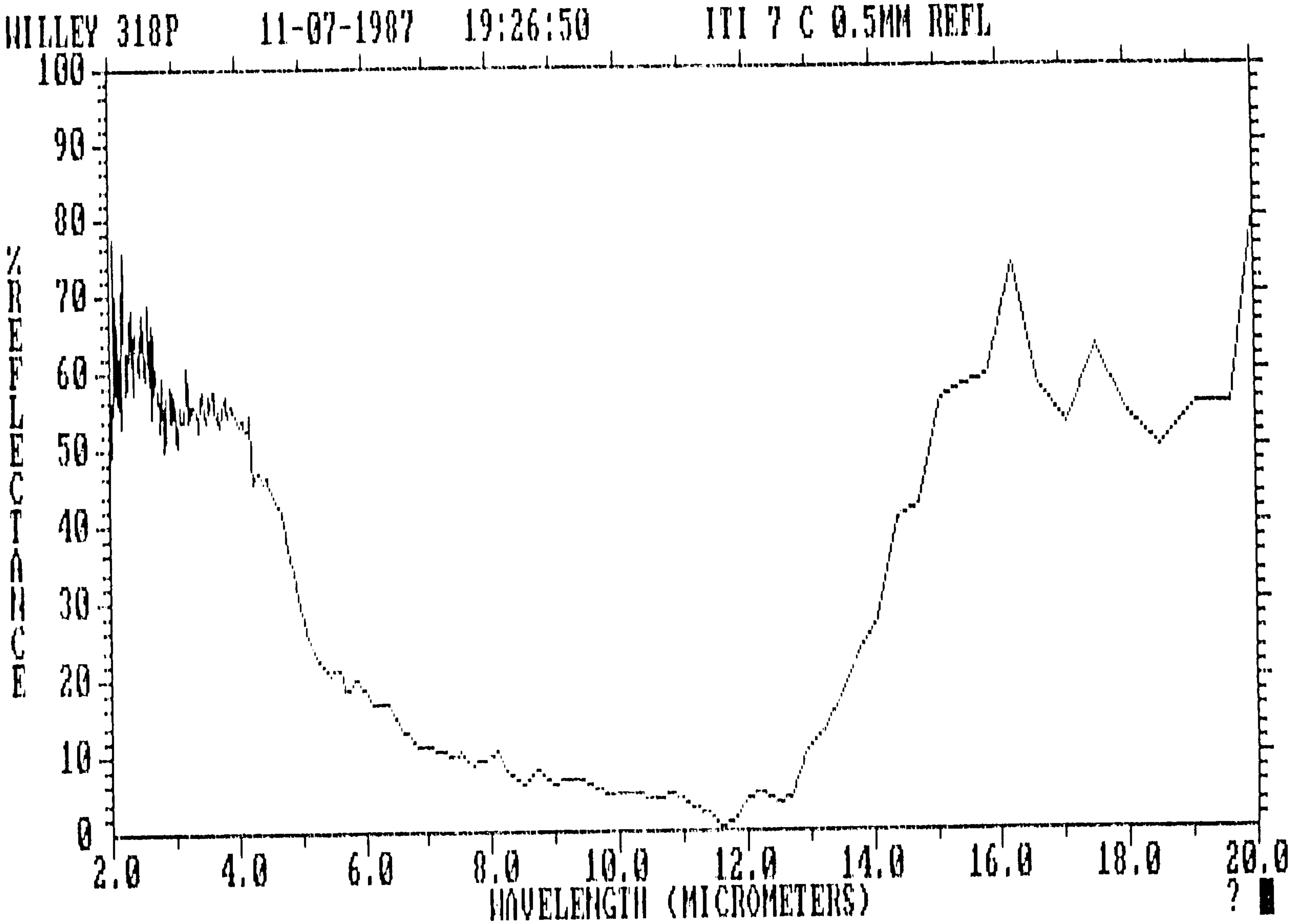

Figure A-7 Unsmoothed Reflectance Spectra of Sample C7

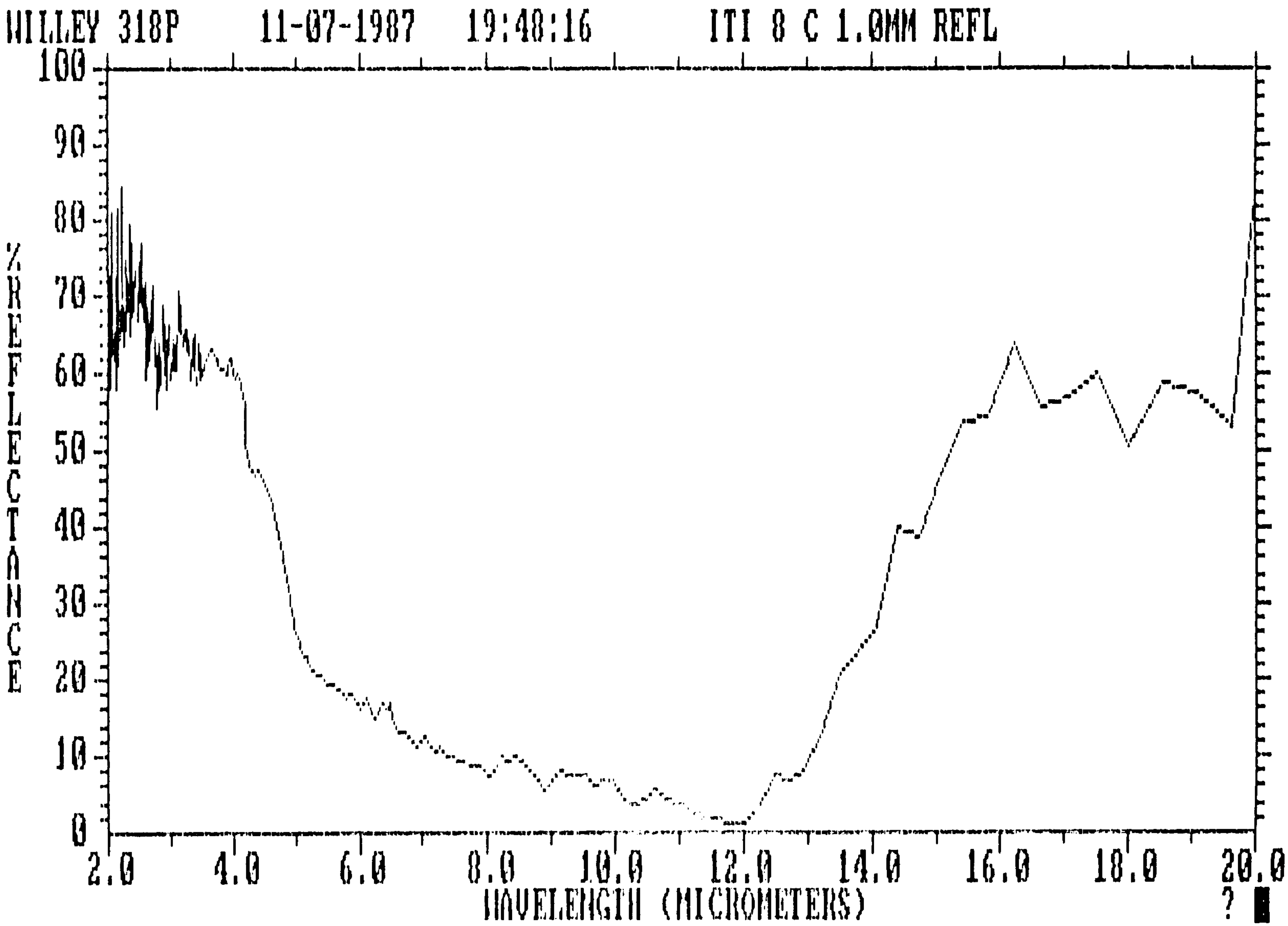

Figure A-8 Unsmoothed Reflectance Spectra of Sample C8

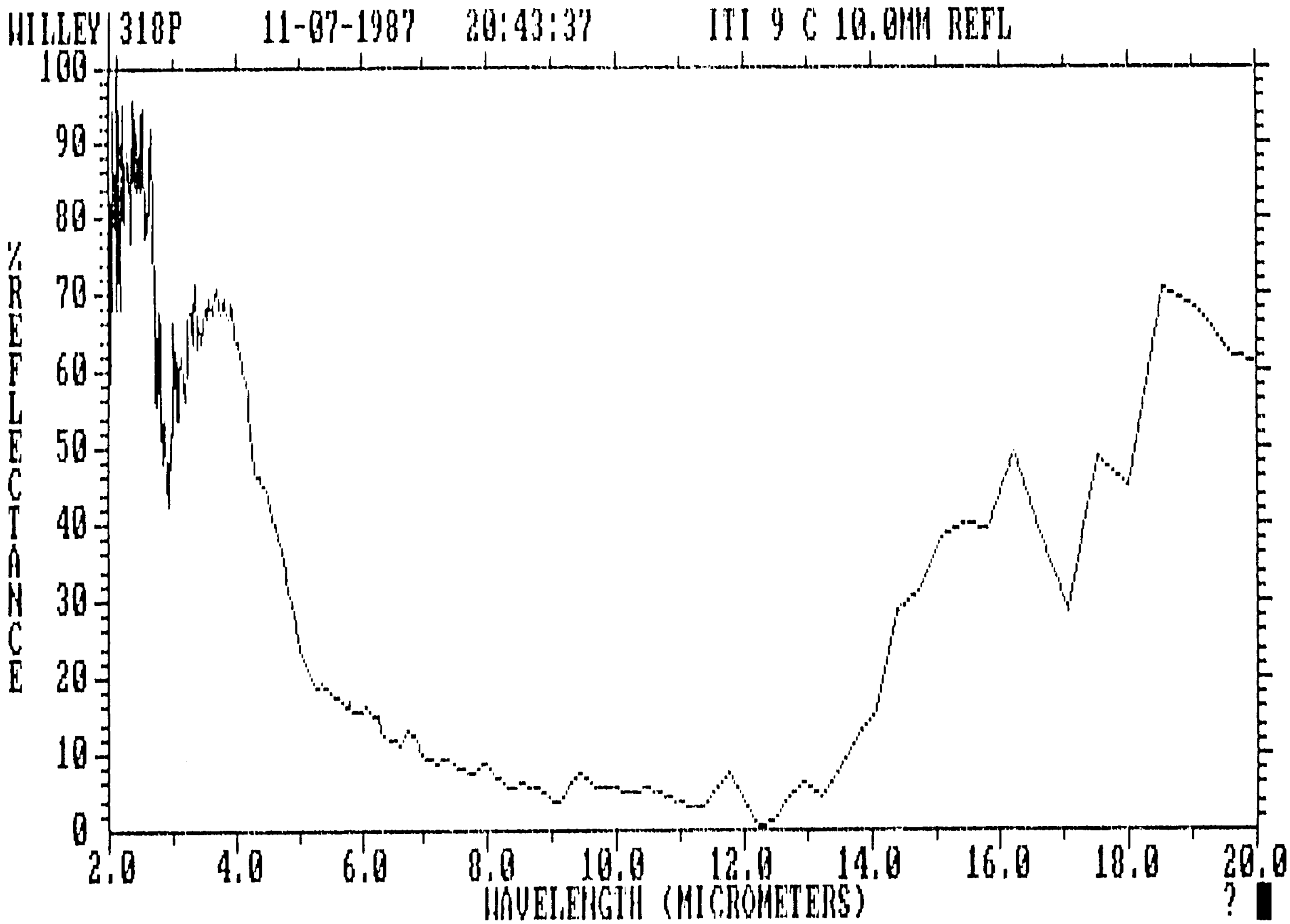

Figure A-9 Unsmoothed Reflectance Spectra of Sample C9

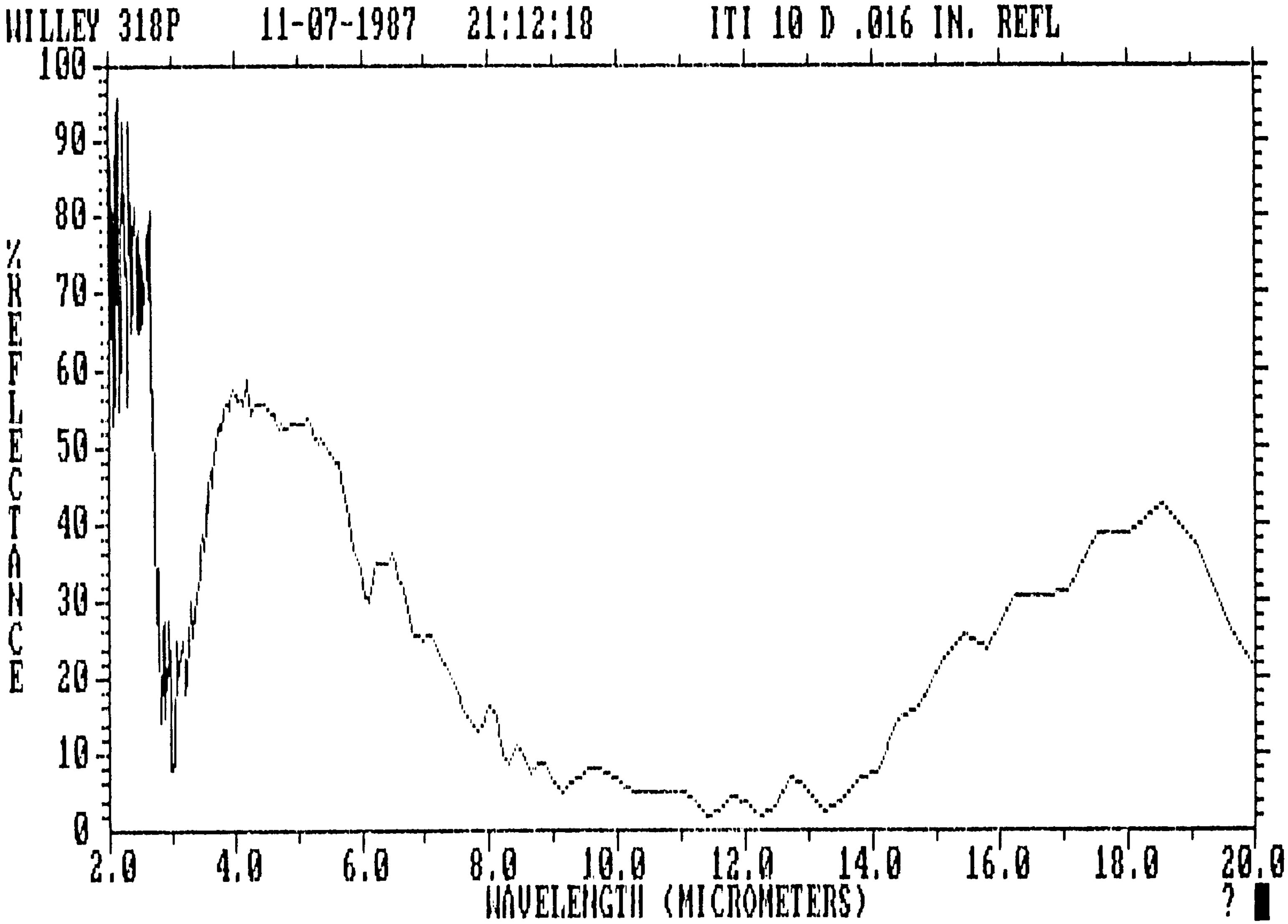

Figure A-10 Unsmoothed Reflectance Spectra of Sample D10

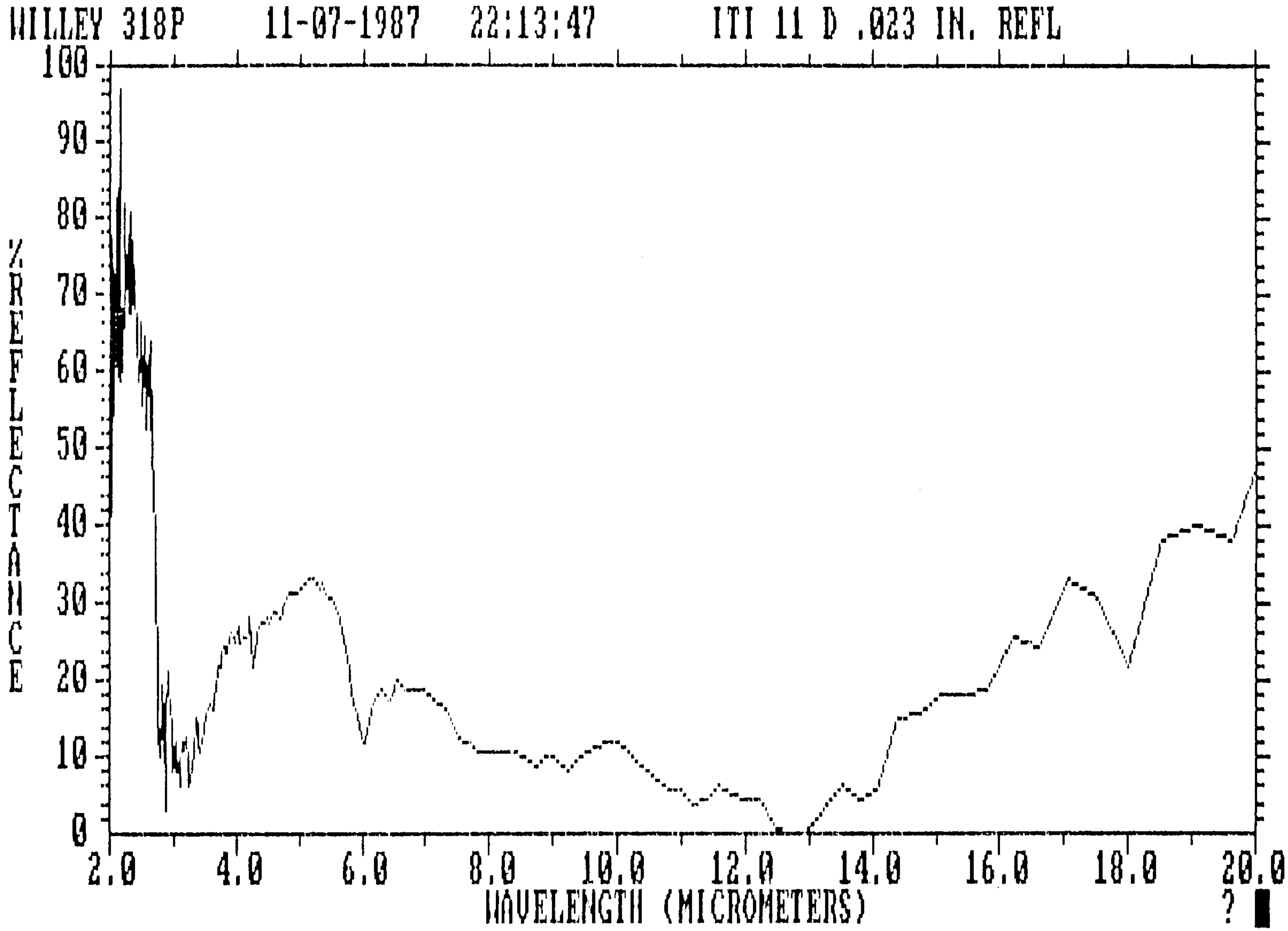

Figure A-11 Unsmoothed Reflectance Spectra of Sample D11

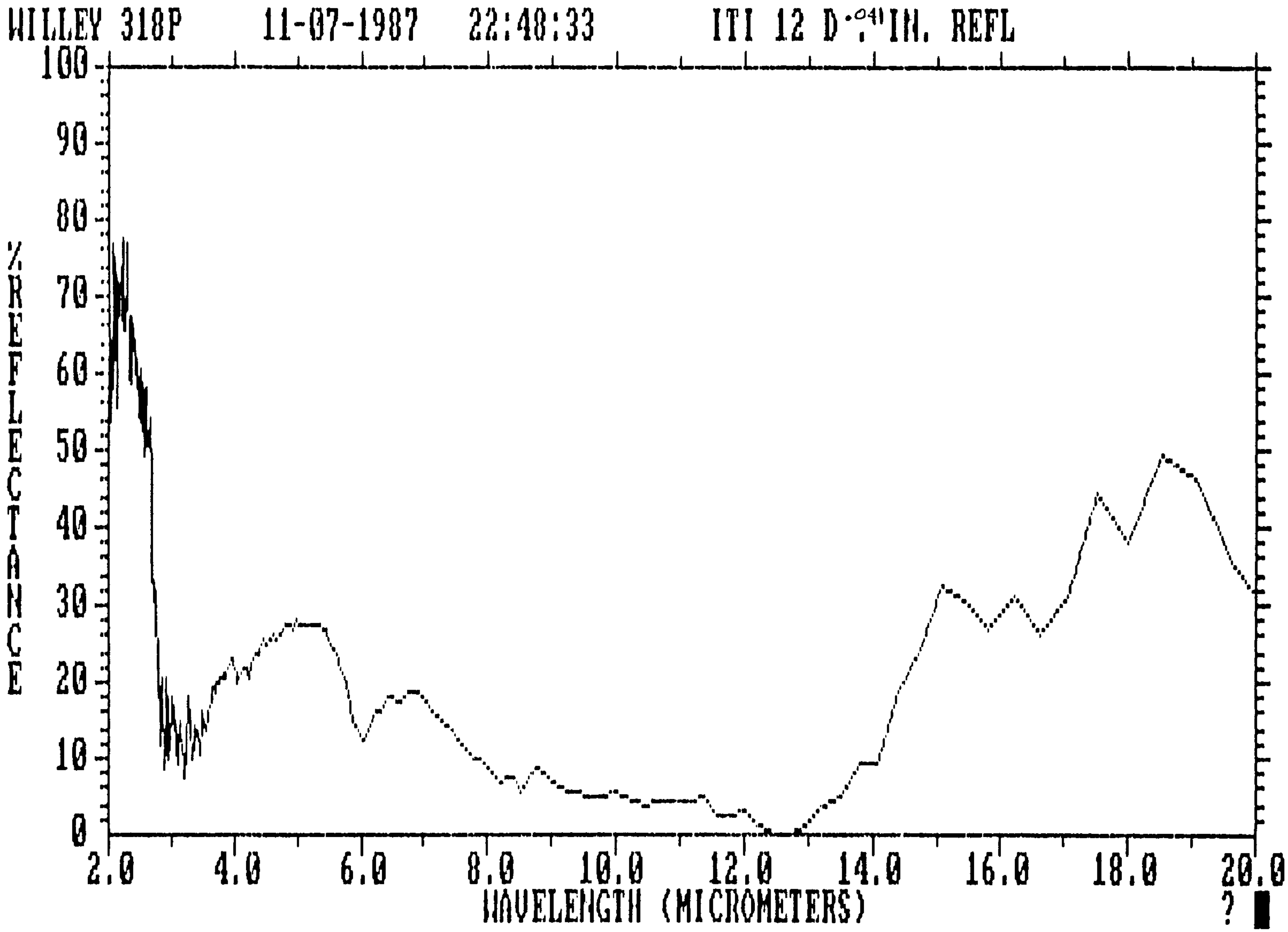

Figure A-12 Unsmoothed Reflectance Spectra of Sample D12

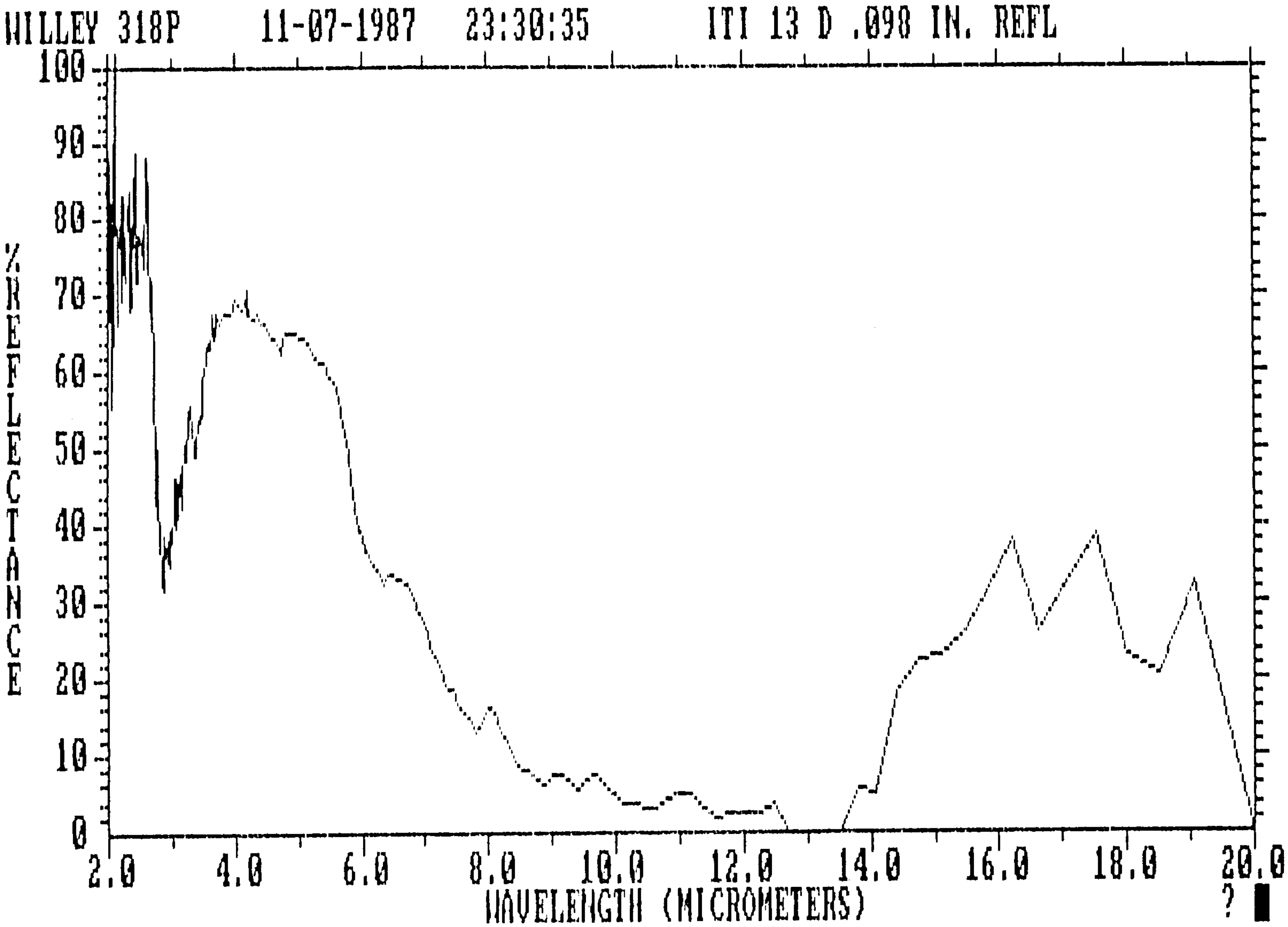

Figure A-13 Unsmoothed Reflectance Spectra of Sample D13

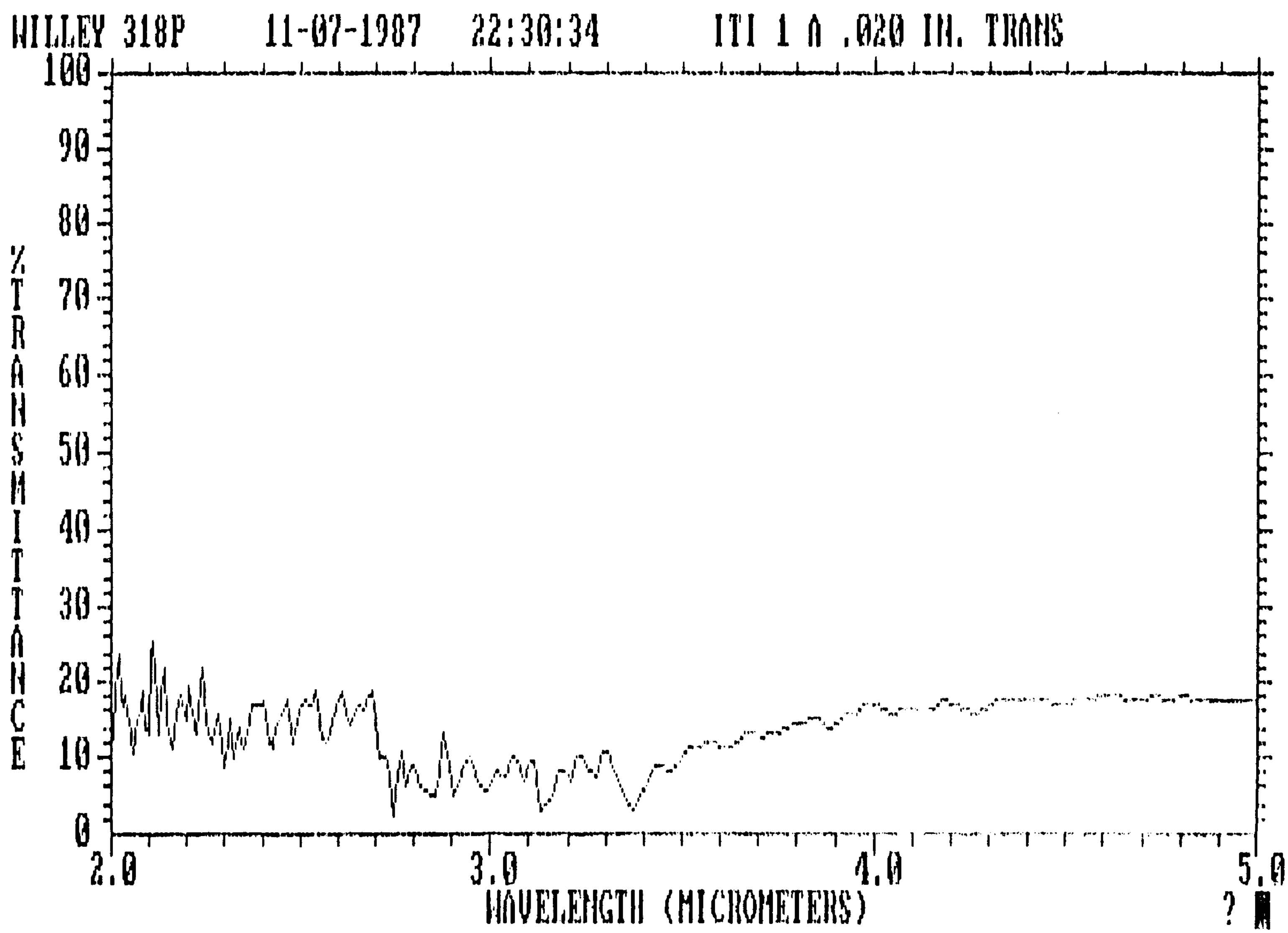

Figure A-14 Unsmoothed Reflectance Spectra of Sample A1

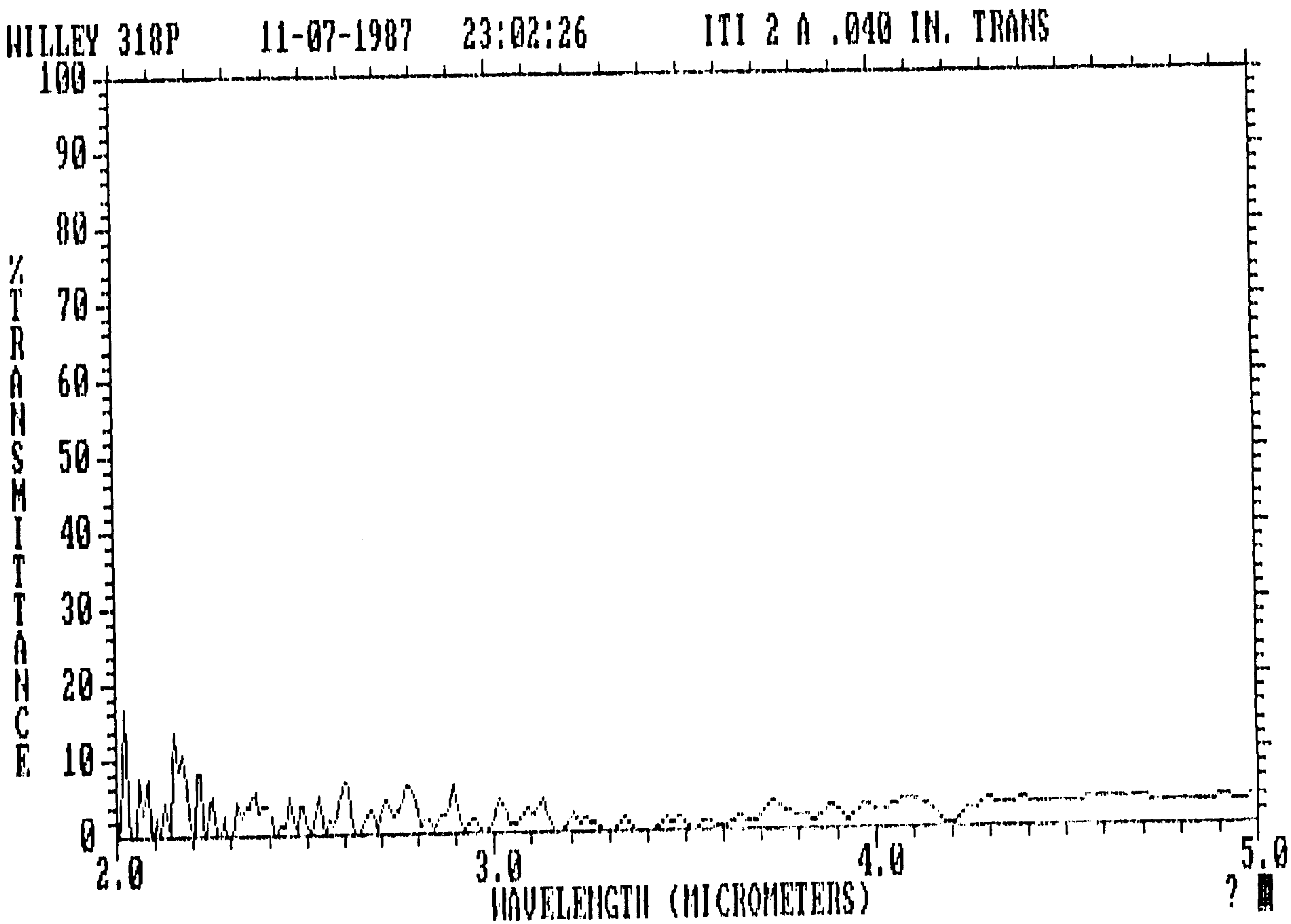

Figure A-15 Unsmoothed Reflectance Spectra of Sample A2

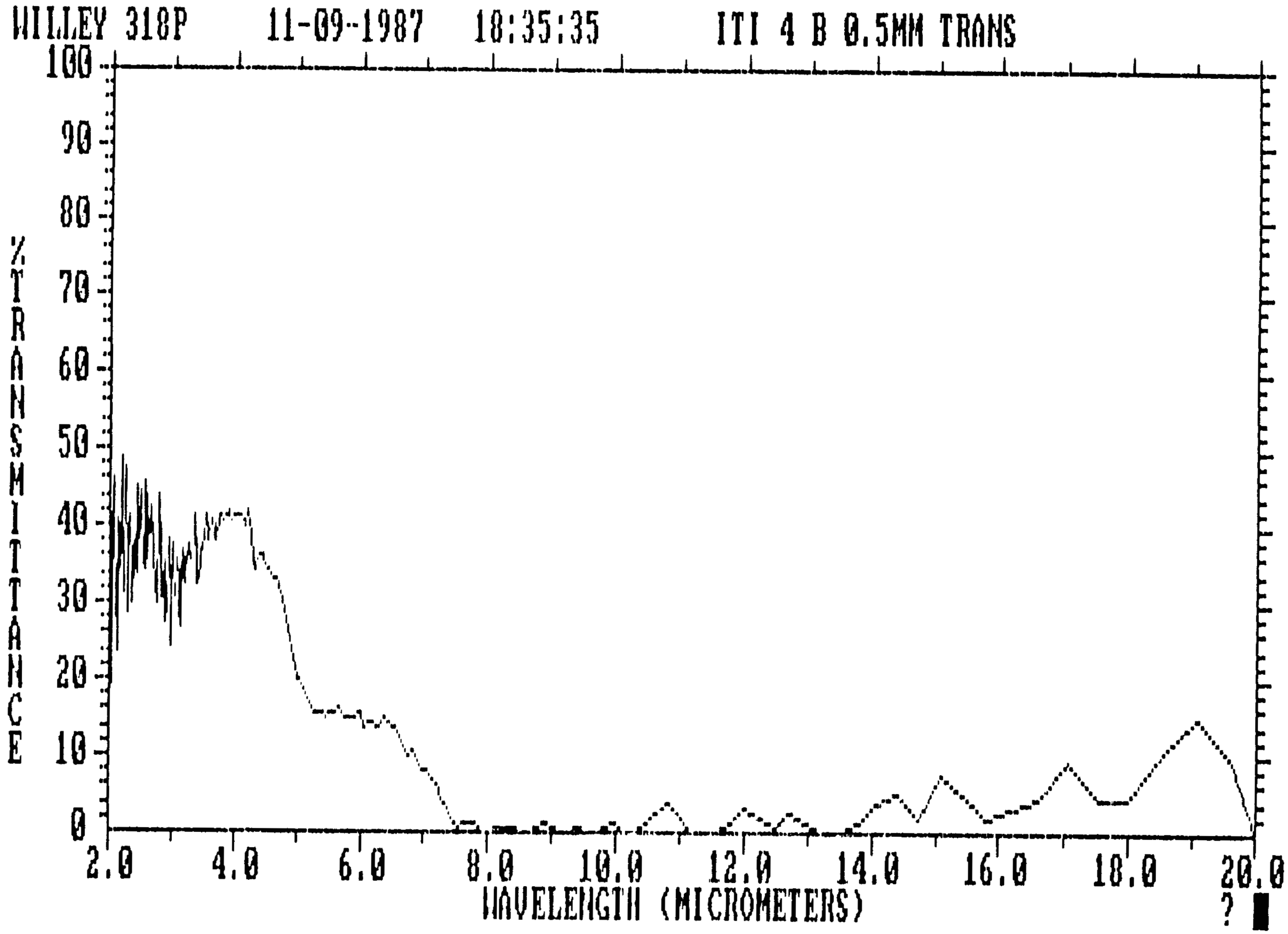

Figure A-16 Unsmoothed Reflectance Spectra of Sample B4

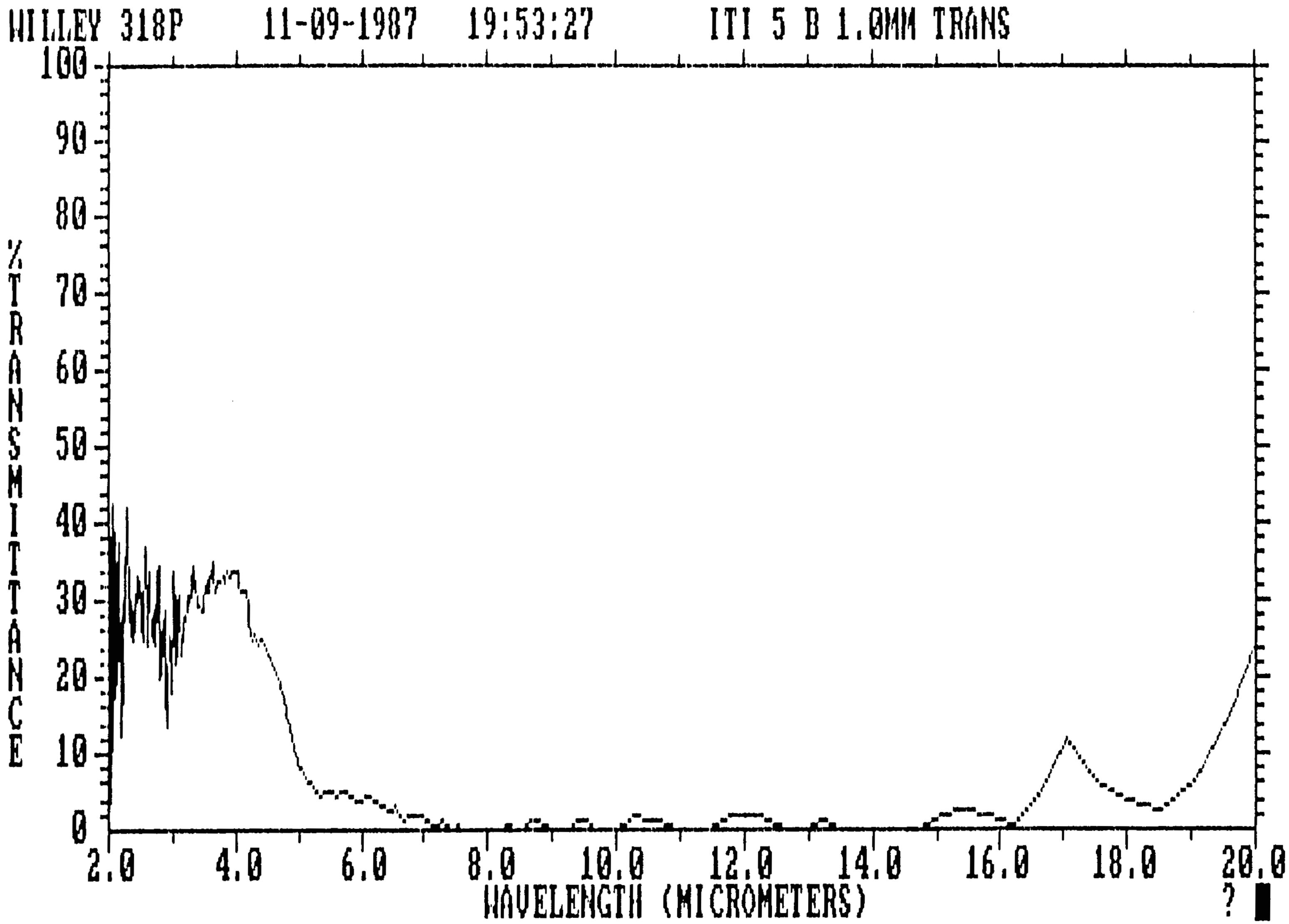

Figure A-17 Unsmoothed Reflectance Spectra of Sample B5

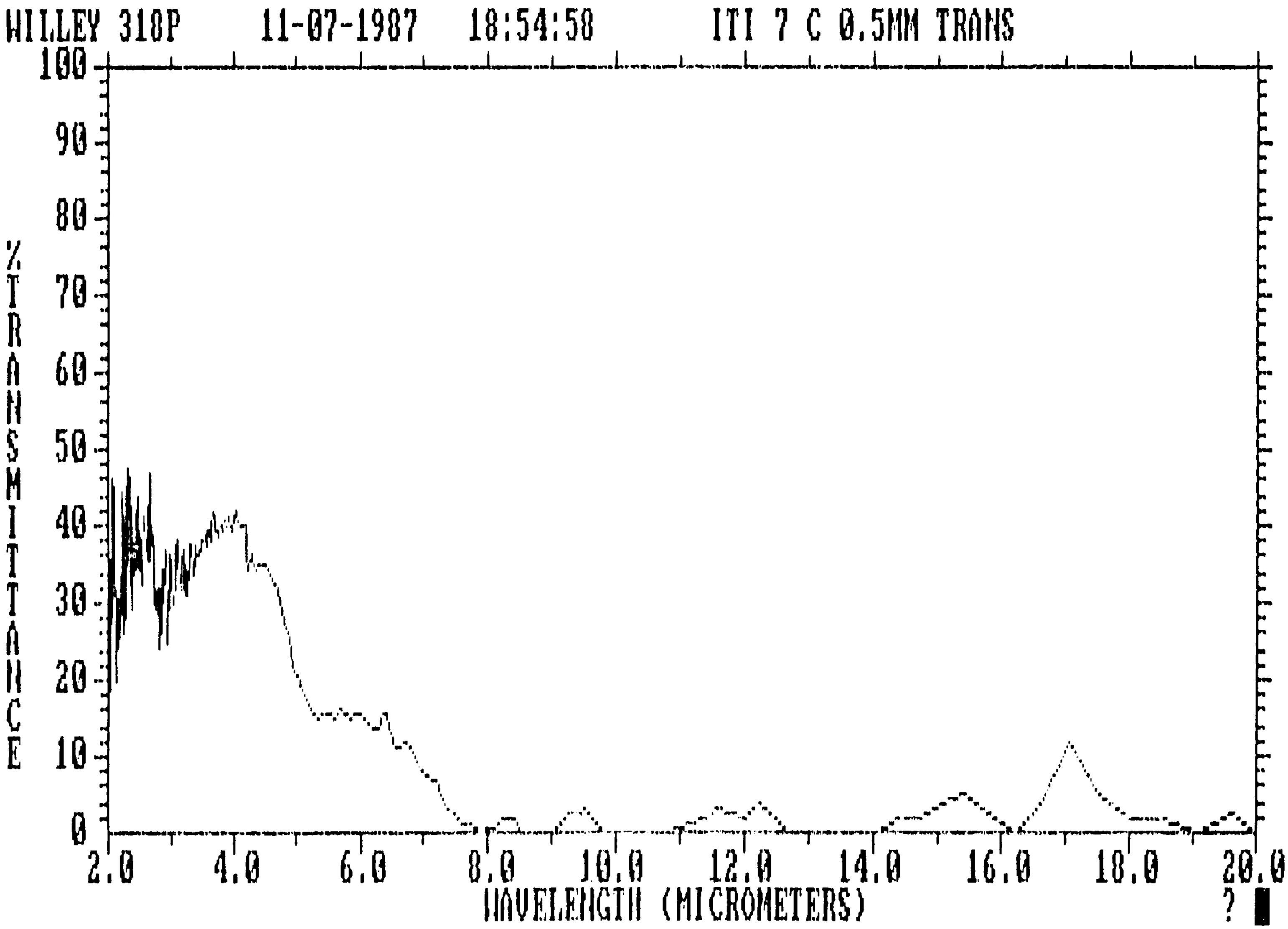

Figure A-18 Unsmoothed Reflectance Spectra of Sample C7

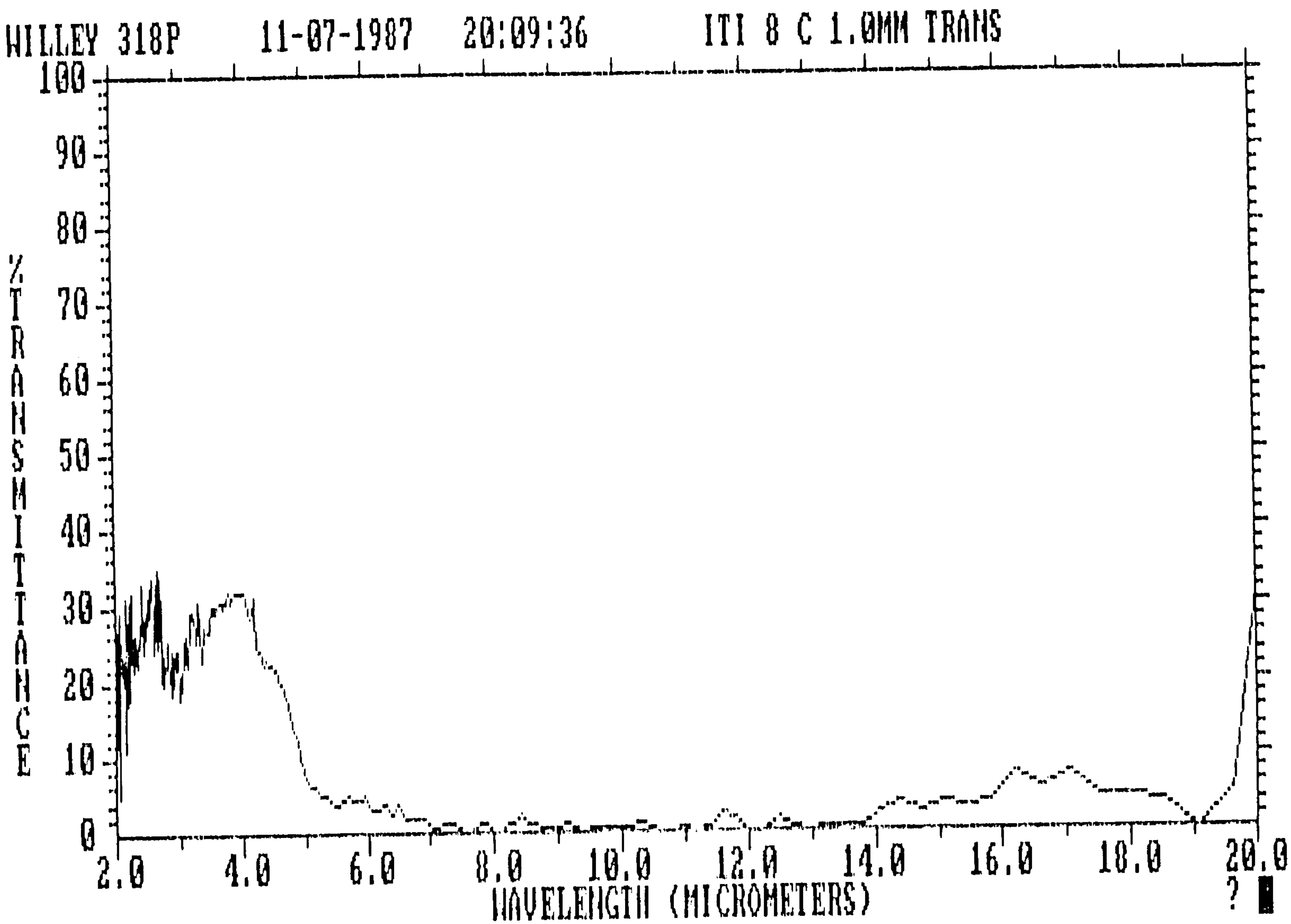

Figure A-19 Unsmoothed Reflectance Spectra of Sample C8

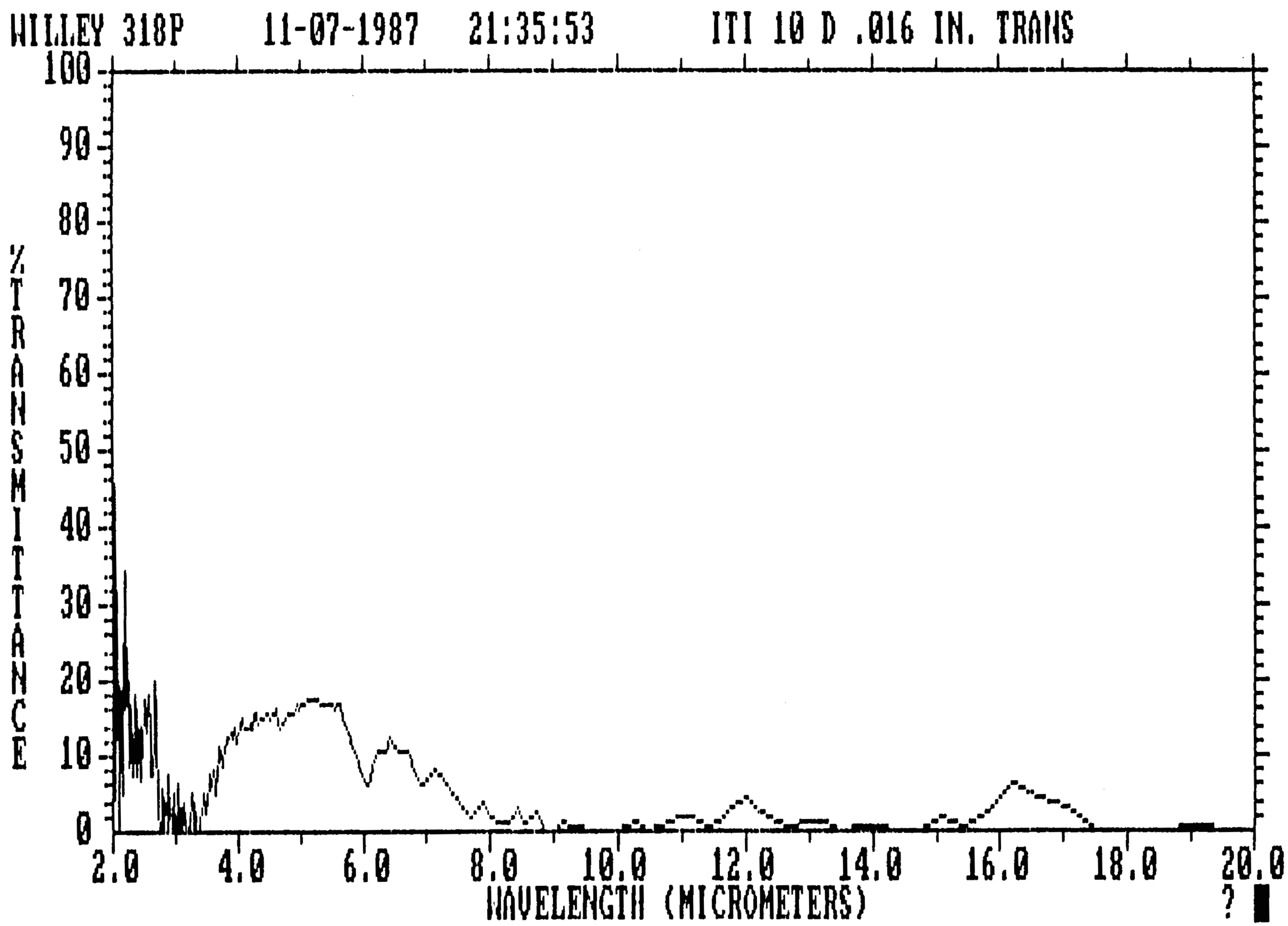

Figure A-20 Unsmoothed Reflectance Spectra of Sample D10

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P.O. Box 85757
San Diego, CA 92186-5757

260. John J. Fedorchak
GTE Products Corporation
Hawes Street
Towanda, PA 18848-0504

261. Jeff T. Fenton
Vista Chemical Company
900 Threadneedle
Houston, TX 77079

262. Larry Ferrell
Babcock & Wilcox
Old Forest Road
Lynchburg, VA 24505

263. Raymond R. Fessler
BIRL
Industrial Research Lab
1801 Maple Avenue
Evanston, IL 60201

264. Michelle Finch
E. I. DuPont de Nemours & Company, Inc.
Experimental Station
Information Center E302/301
Wilmington, DE 19898

265. Arthur D. Fine
United Technologies Corporation
Pratt & Whitney Aircraft
400 Main Street
MS:163-10
East Hartford, CT 06108

266. Ross F. Firestone
Ross Firestone Company
188 Mary Street
Winnetka, IL 60093-1520

267. Sharon L. Fletcher
Arthur D. Little, Inc.
15 Acorn Park
Cambridge, MA 02140-2390

268. Thomas F. Foltz
Textron Specialty Materials
2 Industrial Avenue
Lowell, MA 01851

269. Renee G. Ford
Materials and Processing Report
P.O. Box 72
Harrison, NY 10528

270. John Formica
Supermaterials
2020 Lakeside Avenue
Cleveland, OH 44114

271. Jennifer M. Fox
Dyson Refractories Limited
R&D Laboratory
Owler Bar
Sheffield S17 3BJ
UNITED KINGDOM AIR MAIL

272. Edwin Frame
Southwest Research Institute
Division 2
P.O. Drawer 28510
San Antonio, TX 78284

273. Armanet Francois
French Scientific Mission
4101 Reservoir Road, N.W.
Washington DC 20007-2176

274. R. G. Frank
Technology Assessment Group
10793 Bentley Pass Lane
Loveland, OH 45140

275. David J. Franus
Forecast International
22 Commerce Road
Newtown, CT 06470

276. Marc R. Freedman
NASA Lewis Research Center
21000 Brookpark Road
MS:49-3
Cleveland, OH 44135

277. Douglas Freitag
LTV Missiles Division
P.O. Box 650003
MS:WT-21
Dallas, TX 75265

278. Brian R.T. Frost
Argonne National Laboratory
9700 South Cass Avenue
Building 900
Argonne, IL 60439

279. Lawrence R. Frost
Instron Corporation
100 Royall Street
Canton, MA 02021

280. George A. Fryburg
Norton/TRW Ceramics
7A-4 Raymond Avenue
Salem, NH 03079

281. Xiren Fu
Shanghai Institute of Ceramics
Chinese Academy of Sciences
1295 Ding-xi Road
Shanghai 200050
CHINA AIR MAIL

282. John Gahimer
P.O. Box 1302
Dublin, OH 43017

283. J. P. Gallagher
University of Dayton Research Institute
300 College Park, JPC-250
Dayton, OH 45469-0120

284. Tom Garritano
University of Tennessee
Science Alliance
101 South College
Knoxville, TN 37996-1328

285. Joy A. Garwood
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

286. H. Maury Gatewood
Reynolds Metals Company Corporate R&D
Fourth and Canal Streets
P.O. Box 27003
Richmond, VA 23261

287. L. J. Gauckler
ETH-Zurich
Sonneggstrasse 5
CH-8092 Zurich 8092
SWITZERLAND AIR MAIL

288. Peter A. Gaydos
Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201

289. George E. Gazza
U.S. Army Materials Technology Laboratory
Ceramics Research Division
405 Arsenal Street
Watertown, MA 02172-0001

290. D. Gerster
CEA-DCOM
33 Rue De La Federation
Paris 75015
FRANCE AIR MAIL

291. John Ghinazzi
Coors Technical Ceramics Company
1100 Commerce Park Drive
Oak Ridge, TN 37830

292. Robert Giddings
General Electric Company
Research Laboratory
P.O. Box 8
Schenectady, NY 12301

293. A. M. Glaeser
University of California
Materials Science and Mineral Engineering
Lawrence Berkeley Laboratory
Hearst Mining Building
Berkeley, CA 94720

294. Paul Glance
Concept Analysis
R&D
950 Stephenson Highway
Dupont Automotive Development Building
Troy, MI 48007-7013

295. Joseph W. Glatz
Naval Air Propulsion Center
Systems Engineering Division
P.O. Box 7176, PE24
Trenton, NJ 08628

296. W. M. Goldberger
Superior Graphite Company
R&D
2175 East Broad Street
Columbus, OH 43209

297. Allan E. Goldman
U.S. Graphite, Inc.
907 West Outer Drive
Oak Ridge, TN 37830

298. Stephen T. Gonczy
Allied Signal Research
P.O. Box 5016
Des Plaines, IL 60017

299. Jeffrey M. Gonzales
GTE Products Corporation
Hawes Street
Towanda, PA 18848-0504

300. Robert J. Gottschall
U.S. Department of Energy
ER-131, MS:G-236
Washington, DC 20545

301. Earl Graham
Cleveland State University
Department of Chemical Engineering
Euclid Avenue at East 24th Street
Cleveland, OH 44115

302. William A. Graham
Lanxide Corporation
P.O. Box 6077
Newark, DE 19714-6077

303. Robert E. Green, Jr.
Johns Hopkins University
Materials Science and Engineering Department
Baltimore, MD 21218

304. Lance Groseclose
General Motors Corporation
Allison Gas Turbine Division
P.O. Box 420, MS:W-5
Indianapolis, IN 46206

305. Mark F. Gruninger
Union Carbide Corporation
Specialty Powder Business
1555 Main Street
Indianapolis, IN 46224

306. Ernst Gugel
Cremer Forschungsinstitut GmbH&Co.KG
Oeslauer Strasse 35
D-8633 Roedental 8633
GERMANY AIR MAIL

307. Donald L. Guile
Corning Glass Works
SP-DV-1-9
Corning, NY 14831

308. Bimleshwar P. Gupta
Solar Energy Research Institute
Mechanical and Industrial Technology Division
1617 Cole Boulevard
Golden, CO 80401

309. John P. Gyekenyesi
NASA Lewis Research Center
21000 Brookpark Road, MS:6-1
Cleveland, OH 44135

310. Nabil S. Hakim
Detroit Diesel Corporation
13400 West Outer Drive
Detroit, MI 48239

311. Philip J. Haley
General Motors Corporation
Vehicular Engineering
P.O. Box 420, MS:T12A
Indianapolis, IN 46236

312. Judith Hall
Fiber Materials, Inc.
Biddeford Industrial Park
5 Morin Street
Biddeford, ME 04005

313. Y. Harada
IIT Research Institute
Nometallic Materials and
Composites
10 West 35th Street
Chicago, IL 60616

314. R. A. Harmon
25 Schalren Drive
Latham, NY 12110

315. Amy Harmon-Barrett
Martin Marietta Laboratories
1450 South Rolling Road
Baltimore, MD 21227

316. Norman H. Harris
Hughes Aircraft Company
P.O. Box 800520
Saugus, CA 91380-0520

317. Alan Hart
Dow Chemical Company
Advanced Ceramics Laboratory
1776 Building
Midland, MI 48674

318. Pat E. Hart
Battelle Pacific Northwest
Laboratories
Ceramics and Polymers
Development Section
P.O. Box 999
Richland, WA 99352

319. Stephen D. Hartline
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

320. Michael H. Haselkorn
Caterpillar, Inc.
Engineering Research Materials
Technical Center, Building E
P.O. Box 1875
Peoria, IL 61656-1875

321. N. B. Havewala
Corning, Inc.
SP-PR-11
Corning, NY 14831

322. John Haygarth
Teledyne WAA Chang Albany
P.O. Box 460
Albany, OR 97321

323. Norman L. Hecht
University of Dayton Research
Institute
300 College Park
Dayton, OH 45469-0172

324. Peter W. Heitman
General Motors Corporation
Allison Gas Turbine Division
P.O. Box 420, MS:W-5
Indianapolis, IN 46206-0420

325. Robert W. Hendricks
Virginia Polytechnic Institute
and State University
Materials Engineering
Department
210 Holden Hall
Blacksburg, VA 24061-0237

326. Wynne Henley
Hertel Cutting Technologies, Inc.
1000 Clearview Court
Oak Ridge, TN 37830

327. Thomas L. Henson
GTE Products Corporation
Chemical & Metallurgical
Division
Hawes Street
Towanda, PA 18848

328. Thomas P. Herbell
NASA Lewis Research Center
21000 Brookpark Road
MS:49-3
Cleveland, OH 44135

329. Marlene Heroux
Rolls-Royce, Inc.
2849 Paces Ferry Road
Suite 450
Atlanta, GA 30339-3769

330. Robert L. Hershey
Science Management Corporation
1255 New Hampshire Ave., N.W.
Suite 1033
Washington, DC 20036

331. Hendrik Heystek
Bureau of Mines
Tuscaloosa Research Center
P.O. Box L
University, AL 35486

332. Wallace C. Higgins
Norwal Unlimited
P.O. Box 1258
Alfred, NY 14802

333. Robert V. Hillery
GE Aircraft Engines
One Neumann Way, M.D. H85
Cincinnati, OH 45215

334. Arthur Hindman
Instron Corporation
100 Royall Street
Canton, MA 02021

335. Jon Hines
American Ceramic Society, Inc.
757 Brooksedge Plaza Drive
Westerville, OH 43081-6136

336. Hans Erich Hintermann
CSEM
Materials and Micromechanics
Division
Rue Breguet 2
Neuchatel 2000
SWITZERLAND AIR MAIL

337. Shinichi Hirano
Mazda R&D of North
America, Inc.
1203 Woodridge Avenue
Ann Arbor, MI 48105

338. Tommy Hiraoka
NGK Locke, Inc.
1000 Town Center
Southfield, MI 48075

339. John M. Hobday
U.S. Department of Energy
Morgantown Energy Technology
Center
Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507

340. Greg Hoenes
Vista Chemical Company
900 Threadneedle
P.O. Box 19029
Houston, TX 77079-2990

341. Clarence Hoenig
Lawrence Livermore National
Laboratory
P.O. Box 808, Mail Code L-369
Livermore, CA 94550

342. Thomas Hollstein
Fraunhofer-Institut fur
Werkstoffmechanik IWM
Wohlerstrabe 11
D-7800 Freiburg
GERMANY AIR MAIL

343. Richard Holt
National Research Council
of Canada
Structures and Materials
Laboratory
Ottawa Ontario K1A 0R6
CANADA AIR MAIL

344. Joseph Homeny
University of Illinois
Department of Materials Science
and Engineering
105 South Goodwin Avenue
Ceramics Building
Urbana, IL 61801

345. A. T. Hopper
Battelle Columbus
Laboratories
Metals and Ceramics Department
505 King Avenue
Columbus, OH 43201-2693

346. Michael Horgan
Materials Engineering Magazine
1100 Superior Avenue
Cleveland, OH 44114

347. Woodie Howe
Coors Technical Ceramics
Company
1100 Commerce Park Drive
Oak Ridge, TN 37830

348. Stephen M. Hsu
National Institute of
Standards and Technology
Gaithersburg, MD 20899

349. Hann S. Huang
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815

350. Gene Huber
Precision Ferrites & Ceramics
5576 Corporate Drive
Cypress, CA 90630

351. M. L. Huckabee
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

352. Harold A. Huckins
Princeton Advanced
Technology, Inc.
56 Finley Road
Princeton, NJ 08540

353. Fred R. Huettic
Advanced Magnetics, Inc.
45 Corey Lane
Mendham, NJ 07945

354. Bill Huffman
Zircar
110 North Main Street
Florida, NY 10921

355. Brian K. Humphrey
Lubrizol Petroleum
Chemicals Co.
3000 Town Center, Suite 1340
Southfield, MI 48075-1201

356. Robert M. Humrick
Dylon Ceramic Technologies
3100 Edgehill Road
Cleveland Heights, OH 44118

357. Lorretta Inglehart
National Science Foundation
Division of Materials Research
1800 "G" Street, N.W.,
Room 408
Washington, DC 20550

358. Michael S. Inoue
Kyocera International, Inc.
KII Library
8611 Balboa Avenue
San Diego, CA 92123-1580

359. Osama Jadaan
University of Wisconsin-
Platteville
General Engineering Division
1 University Plaza
Platteville, WI 53818

360. Curtis A. Johnson
General Electric Company
Corporate R&D
Room MB-187
P.O. Box 8
Schenectady, NY 12301

361. Sylvia Johnson
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

362. Thomas A. Johnson
Lanxide Corporation
1300 Marrows Road
P.O. Box 6077
Newark, DE 19714-6077

363. W. S. Johnson
Indiana University
One City Centre, Suite 200
Bloomington, IN 47405

364. Jill E. Jonkouski
U.S. Department of Energy
9800 South Cass Avenue
Argonne, IL 60439-4899

365. L. A. Joo
Great Lakes Research
Corporation
P.O. Box 1031
Elizabethton, TN 37643

366. A. D. Joseph
SPX Corporation
700 Terrace Point
Muskegon, MI 49443

367. Adam Jostsons
Australian Nuclear Science &
Technology Organization
Lucas Heights Research
Laboratories
New Illawarra Road
Lucas Heights New South Wales
AUSTRALIA AIR MAIL

368. Matthew K. Juneau
Ethyl Corporation
451 Florida Street
Baton Rouge, LA 70801

369. Hartmut Kainer
Didier-Werke AG
Anlagentechnik Wiesbaden
Abraham-Lincoln-Str. 16
D-62 Wiesbaden
GERMANY AIR MAIL

370. Tom Kalamasz
Norton/TRW Ceramics
7A-4 Raymond Avenue
Salem, NH 03079

371. Lyle R. Kallenbach
Phillips Petroleum Company
R&D
Mail Drop:123AL
Bartlesville, OK 74004

372. Nick Kamiya
Kyocera Industrial Ceramics
Corporation
2700 River Road
Des Plaines, IL 60018

373. Roy Kamo
Adiabatics, Inc.
3385 Commerce Park Drive
Columbus, IN 47201

374. S. Kang
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

375. Chih-Chun Kao
Industrial Technology Research
Institute
Materials Research
Laboratories
195 Chung-Hsing Road, Sec. 4
Chutung Hsinchu 31015 R.O.C.
TAIWAN AIR MAIL

376. Keith R. Karasek
Allied-Signal, Inc.
Engineered Materials Research
Center
50 East Algonquin Road
P.O. Box 5016
Des Plaines, IL 60017-5016

377. Robert E. Kassel
Ceradyne, Inc.
3169 Redhill Avenue
Costa Mesa, CA 92626

378. Allan Katz
Wright Laboratory
Metals and Ceramics Division
WL/MLLM
Wright-Patterson AFB, OH 45433

379. R. Nathan Katz
Worcester Polytechnic Institute
Dept. of Mechanical Engineering
100 Institute Road
Worcester, MA 01609

380. Ted Kawaguchi
Tokai Carbon America, Inc.
375 Park Avenue, Suite 3802
New York, NY 10152

381. Noritsugu Kawashima
TOSHIBA Corporation
Mechanical Engineering Laboratory
4-1 Ukishima-Cho
Kawasaki-Ku Kawasaki 210
JAPAN AIR MAIL

382. Lisa Kempfer
Penton Publishing
Materials Engineering
1100 Superior Avenue
Cleveland, OH 44114-2543

383. Frederick L. Kennard, III
General Motors Corporation
AC Rochester
Department 32-24, EB
1300 North Dort Highway
Flint, MI 48556

384. David O. Kennedy
Lester B. Knight Cast Metals Inc.
549 West Randolph Street
Chicago, IL 60661

385. George Keros
Photon Physics
3175 Penobscot Building
Detroit, MI 48226

386. Pramod K. Khandelwal
General Motors Corporation
Allison Gas Turbine Division
P.O. Box 420, MS:W05
Indianapolis, IN 46206

387. Jim R. Kidwell
Allied-Signal Aerospace Company
Garrett Auxiliary Power Division
P.O. Box 5227
Phoenix, AZ 85010

388. Han J. Kim
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

389. Shin Kim
Korea Institute of Machinery & Metals
66 Sangnam-dong, Changwon
Kyungnam 641-010
KOREA AIR MAIL

390. W. C. King
Mack Truck, Z-41
1999 Pennsylvania Avenue
Hagerstown, MD 21740

391. Carol Kirkpatrick
MSE, Inc.
CDIF Technical Library
P.O. Box 3767
Butte, MT 59702

392. Tony Kirn
Caterpillar, Inc.
Defense Products Department, JB7
Peoria, IL 61629

393. James D. Kiser
NASA Lewis Research Center
21000 Brookpark Road, MS:49-3
Cleveland, OH 44135

394. Max Klein
Gas Research Institute
Thermodynamics
8600 West Bryn Mawr Avenue
Chicago, IL 60631

395. Richard N. Kleiner
Coors Ceramics Company
4545 McIntyre Street
Golden, CO 80403

396. Stanley J. Klima
NASA Lewis Research Center
21000 Brookpark Road
MS:6-1
Cleveland, OH 44135

397. Chris E. Knapp
Norton Advanced Ceramics
of Canada Ltd.
8001 Daly Street
Niagara Falls, Ontario L2G 6S2
CANADA AIR MAIL

398. Albert S. Kobayashi
University of Washington
Mechanical Engineering
Department
MS:FU10
Seattle, WA 98195

399. Shigeki Kobayashi
Toyota Central Research
Labs, Inc.
Nagakute Aichi 480-11
JAPAN AIR MAIL

400. Richard A. Kole
Z-Tech Corporation
8 Dow Road
Bow, NH 03304

401. E. Kostiner
University of Connecticut
Chemistry Department, U-60
Storrs, CT 06269-3060

402. Kenneth A. Kovaly
Technical Insights, Inc.
P.O. Box 1304
Fort Lee, NJ 07024-9967

403. Ralph G. Kraft
Spraying Systems Company
North Avenue at Schmale Road
Wheaton, IL 60189-7900

404. Saunders B. Kramer
U.S. Department of Energy
Advanced Propulsion Division
CE-322, Forrestal Building
Washington, DC 20585

405. Arthur Kranish
Trends Publishing, Inc.
1079 National Press Building
Washington, DC 20045

406. A. S. Krieger
Radiation Science, Inc.
P.O. Box 293
Belmont, MA 02178

407. Pieter Krijgsman
Ceramic Design International
Holding B.V.
P.O. Box 68
Hattem 8050-AB
THE NETHERLANDS AIR MAIL

408. Waltraud M. Kriven
University of Illinois
Materials Science and
Engineering Department
105 South Goodwin Avenue
Urbana, IL 61801

409. Edward J. Kubel, Jr.
ASM International Advanced
Materials & Processes
Materials Park, OH 44073

410. Dave Kupperman
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

411. Oh-Hun Kwon
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

412. W. J. Lackey
Georgia Institute of Technology
Materials Science and
Technology
Atlanta, GA 30332

413. Jai Lala
Tenmat Ltd.
40 Somers Road
Rugby Warwickshire CV22 7DH
ENGLAND AIR MAIL

414. Hari S. Lamba
General Motors Corporation
Electro-Motive Division
9301 West 55th Street
LaGrange, IL 60525

415. Richard L. Landingham
Lawrence Livermore National Laboratory
Ceramics, Corrosion, and Thermochemistry
P.O. Box 808, L-369
Livermore, CA 94550

416. Charles J. Landry
Chand Kare Technical Ceramics
712 Flat Hill Road
Lumenburg, MA 01462

417. Manfred W. Langer
Volkswagen AG
Material Technology
3180 Wolfsburg 1
GERMANY AIR MAIL

418. James Lankford
Southwest Research Institute
Department of Materials Sciences
6220 Culebra Road
San Antonio, TX 78228-0510

419. Stanley B. Lasday
Business News Publishing Co.
Manor Oak One
1910 Cochran Road, Suite 630
Pittsburgh, PA 15220

420. Mark S. Laser
Solar Turbines, Inc.
2211 Erie Street
San Diego, CA 92110

421. S. K. Lau
Carborundum Company
Technology Division
P.O. Box 832, B-100
Niagara Falls, NY 14302

422. Edward A. Lauder
Advanced Composite Materials Corporation
1525 South Buncombe Road
Greer, SC 29651-9208

423. J. Lawrence Lauderdale
Babcock & Wilcox
Contract Research Division
1850 "K" Street, Suite 950
Washington, DC 20006

424. Harry A. Lawler
Carborundum Company
Technology Division
P.O. Box 832
Niagara Falls, NY 14302

425. Jean F. LeCostaouec
Textron Speciality Materials
2 Industrial Avenue
Lowell, MA 01851

426. Benson P. Lee
Interscience, Inc.
9718 Lake Shore Boulevard
Cleveland, OH 44108

427. Burtrand I. Lee
Clemson University
Department of Ceramic Engineering
Olin Hall
Clemson, SC 29634-0907

428. June-Gunn Lee
KIST
Structural Ceramic Lab
P.O. Box 131, Cheong-Ryang
Seoul 130-650
KOREA AIR MAIL

429. Ran-Rong Lee
Ceramics Process Systems Corporation
155 Fortune Boulevard
Milford, MA 01757

430. Stan Levine
NASA Lewis Research Center
21000 Brookpark Road
MS:49-3
Cleveland, OH 44135

431. Alan V. Levy
Lawrence Berkeley Laboratory
One Cyclotron Road, MS:62-203
Berkeley, CA 94720

432. Ai-Kang Li
Materials Research
Laboratories, ITRI
195-5 Chung-Hsing Road, Sec. 4
Chutung Hsinchu 31015 R.O.C.
TAIWAN AIR MAIL

433. Winston W. Liang
Hong Kong Industrial
Technology Centre Co. Ltd.
78 Tat Chee Avenue
4/F, HKPC Building
Howloon
HONG KONG AIR MAIL

434. Robert Licht
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

435. E. Lilley
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

436. Laura J. Lindberg
Allied-Signal Aerospace
Company
Garrett Fluid Systems Division
1300 West Warner
MS: 93-901-1207-4TT
P.O. Box 22200
Tempe, AZ 85284-2200

437. Leonard C. Lindgren
General Motors Corporation
Allison Gas Turbine Division
P.O. Box 420, Speed Code:T-20A
Indianapolis, IN 46206-0420

438. Hans A. Lindner
Cremer Forschungsinstitut
GmbH&Co.KG
Oeslauer Strasse 35
D-8633 Rodental 8866
GERMANY AIR MAIL

439. Ronald E. Loehman
Sandia National Laboratories
Chemistry & Ceramics
Department 1840
P.O. Box 5800
Albuquerque, NM 87185

440. Jeffrey C. Logas
Winona State University
Composite Materials
Engineering
115 Pasteur Hall
Winona, MN 55987

441. Bill Long
Babcock & Wilcox
P.O. Box 11165
Lynchburg, VA 24506

442. William D. Long
Wacker Chemicals (USA), Inc.
ESK Engineered Ceramics
50 Locust Avenue
New Canaan, CT 06840

443. L. A. Lott
EG&G Idaho, Inc.
Idaho National Engineering
Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-2209

444. Raouf O. Loutfy
MER Corporation
7960 South Kolb Road
Tucson, AZ 85706

445. Gordon R. Love
Aluminum Company of America
Alcoa Technical Center
Alcoa Center, PA 15069

446. Lydia Luckevich
Ortech International
2395 Speakman Drive
Mississauga Ontario L5K 1B3
CANADA AIR MAIL

447. James W. MacBeth
Carborundum Company
Structural Ceramics Division
P.O. Box 1054
Niagara Falls, NY 14302

448. H. MacLaren
General Electric Company
Thomson Laboratory, Materials Engineering 36807
1000 Western Avenue
Lynn, MA 01910

449. George Maczura
Aluminum Company of America
Industrial Chemicals Division
670 One Allegheny Square
Pittsburgh, PA 15212

450. David Maginnis
Tinker AFB
OC-ALC/LIIRE
Tinker AFB OK 73145-5989

451. Frank Maginnis
Aspen Research, Inc.
220 Industrial Boulevard
Moore, OK 73160

452. Tai-il Mah
Universal Energy Systems, Inc.
Ceramics and Composites Research
4401 Dayton-Xenia Road
Dayton, OH 45432

453. Kenneth M. Maillar
Barbour Stockwell Company
83 Linskey Way
Cambridge, MA 02142

454. Lorenzo Majno
Instron Corporation
100 Royall Street
Canton, MA 02021

455. S. G. Malghan
National Institute of Standards and Technology
I-270 & Clopper Road
Gaithersburg, MD 20899

456. Lars Malmrup
United Turbine AB
Box 13027
Malmo S-200 44
SWEDEN AIR MAIL

457. John Mangels
Ceradyne, Inc.
3169 Redhill Avenue
Costa Mesa, CA 92626

458. Russell V. Mann
Matec Applied Sciences, Inc.
75 South Street
Hopkinton, MA 01748

459. William R. Manning
Champion Aviation Products Division
Old Norris Road
P.O. Box 686
Liberty, SC 29657

460. Ken Marnoch
Amercom, Inc.
8928 Fullbright Avenue
Chatsworth, CA 91311

461. Robert A. Marra
Aluminum Company of America
Alcoa Technical Center
Advanced Ceramics Center - E
Alcoa Center, PA 15069

462. Chauncey L. Martin
3M Company
3M Center, Building 60-1N-01
St. Paul, MN 55144

463. Steven C. Martin
Advanced Refractory Technologies, Inc.
699 Hertel Avenue
Buffalo, NY 14207

464. Kelly J. Mather
Williams International Corporation
2280 West Maple Road
P.O. Box 200
Walled Lake, MI 48088

465. James P. Mathers
3M Company
3M Center
Building 201-3N-06
St. Paul, MN 55144

466. Marshall Mayer
Instron Corporation
3815 Presidential Parkway,
Suite 100
Atlanta, GA 30340

467. Ron Mayville
Arthur D. Little, Inc.
15-163 Acorn Park
Cambridge, MA 02140

468. F. N. Mazadarany
General Electric Company
Research Laboratory
Building K-1, Room MB-159
P.O. Box 8
Schenectady, NY 12301

469. James W. McCauley
Alfred University
NYS College of Ceramics
Binns-Merrill Hall
Alfred, NY 14802

470. Carolyn McCormick
Allied-Signal Aerospace
Company
Garrett Auxiliary Power
Division
Bldg. 1303-206
P.O. Box 5227, MS:9317-2
Phoenix, AZ 85010

471. Louis R. McCreight
2763 San Ramon Drive
Rancho Palos Verdes, CA 90274

472. Colin F. McDonald
McDonald Thermal Engineering
1730 Castellana Road
La Jolla, CA 92037

473. B. J. McEntire
Norton Company, TRW Ceramics
Goddard Road
Northboro, MA 01532-1545

474. Chuck McFadden
Coors Ceramics Company
600 9th Street
Golden, CO 80401

475. Henry McFadden
Magnetic Bearings, Inc.
Engineering Library
609 Rock Road
Radford, VA 24141

476. Thomas D. McGee
Iowa State University
Materials Science and
Engineering Department
110 Engineering Annex
Ames, IA 50011

477. Carol McGill
Corning Inc.
Sullivan Park, FR-02-08
Corning, NY 14831

478. T. C. McLaren
Cameron Forged Products
Company
P.O. Box 1212
Houston, TX 77251-1212

479. James McLaughlin
Sundstrand Power Systems
4400 Ruffin Road
P.O. Box 85757
San Diego, CA 92186-5757

480. Arthur F. McLean
6225 North Camino Almonte
Tucson, AZ 85718

481. Matt McMonigle
U.S. Department of Energy
Improved Energy Productivity
Division
Forrestal Building,
CE-231
Washington, DC 20585

482. Dennis McMurtry
EG&G Idaho, Inc.
Idaho National Engineering
Laboratory
P.O. Box 1625
Idaho Falls, ID 83415

483. D. B. Meadowcroft
National Power Technology
and Environmental Centre
Kelvin Avenue
Leatherhead Surrey
KT22 7SE
ENGLAND AIR MAIL

484. Jo Meglen
11004 Birdfoot Court
Reston, VA 22091

485. Pankaj K. Mehrotra
Kennametal, Inc.
P.O. Box 639
Greensburg, PA 15601

486. Joseph J. Meindl
Reynolds International, Inc.
6603 West Broad Street
P.O. Box 27002
Richmond, VA 23261-7003

487. Michael D. Meiser
Allied-Signal Aerospace Company
Garrett Ceramic Components
Division
19800 South Van Ness Avenue
Torrance, CA 90509

488. George Messenger
National Research Council of
Canada
Engine Laboratory
Building M-7
Ottawa Ontario K1A OR6
CANADA AIR MAIL

489. D. Messier
U.S. Army Materials Technology
Laboratory
SLCMT-EMC
405 Arsenal Street
Watertown, MA 02172-0001

490. Gary L. Messing
Pennsylvania State University
Ceramic Science and Engineering
Department
119 Steidle Building
University Park, PA 16802

491. Arthur G. Metcalfe
Arthur G. Metcalfe and
Associates, Inc.
2108 East 24th Street
National City, CA 91950

492. R. Metselaar
Eindhoven University
Centre for Technical Ceramics
P.O. Box 513
Eindhoven 5600 MB
THE NETHERLANDS AIR MAIL

493. Nancy S. Meyers
U.S. Department of Energy
Transportation Technologies
CE-30, Forrestal Building
6B-094
Washington, DC 20585

494. David J. Michael
Harbison-Walker Refractories
Company
P.O. Box 98037
Pittsburgh, PA 15227

495. Ken Michaels
Chrysler Motors Corporation
Ceramics Development
Metallurgical Processes
P.O. Box 1118, CIMS:418-17-09
Detroit, MI 48288

496. Bernd Michel
Institute of Mechanics
Fracture and Micromechanics
Department
P.O. Box 408
D-9010 Chemnitz
GERMANY AIR MAIL

497. David E. Miles
Commission of the European
Communities
rue de la Loi, 200
B-1049 Brussels
BELGIUM AIR MAIL

498. John V. Milewski
Superkinetics, Inc.
P.O. Box 8029
Santa Fe, NM 87504

499. Carl E. Miller
AC Rochester
1300 North Dort Highway,
MS:32-31
Engineering Building B
Flint, MI 48556

500. Mike Miller
McGraw-Hill Aviation Week
Performance Materials
1156 15th Street, N.W.
Washington, DC 20005

501. Charles W. Miller, Jr.
Centorr Furnaces/Vacuum
Industries
542 Amherst Street
Nashua, NH 03063

502. R. Mininni
Enichem America
2000 Cornwall Road
Monmouth Junction, NJ 08852

503. Michele V. Mitchell
Allied-Signal Aerospace
Company
Garrett Ceramic Components
Division
19800 South Van Ness Avenue
Torrance, CA 90501-1149

504. Howard Mizuhara
GTE - WESGO
477 Harbor Boulevard
Belmont, CA 94002

505. Helen Moeller
Babcock & Wilcox
P.O. Box 11165
Lynchburg, VA 24506-1165

506. Francois R. Mollard
Metalworking Technology, Inc.
1450 Scalp Avenue
Johnstown, PA 15904

507. Phil Mooney
Panametrics
NDE Division
221 Crescent Street
Waltham, MA 02254

508. Thomas Morel
Ricardo North America
645 Blackhawk Drive
Westmont, IL 60559

509. Geoffrey P. Morris
3M Company
3M Traffic Control Materials
Division
Bldg. 209-BW-10, 3M Center
St. Paul, MN 55144-1000

510. Jay A. Morrison
Rolls-Royce, Inc.
Engineering and Information
Center, Overlook 1
2849 Paces Ferry Road,
Suite 450
Atlanta, GA 30339-3769

511. Joel P. Moskowitz
Ceradyne, Inc.
3169 Redhill Avenue
Costa Mesa, CA 92626

512. Brij Moudgil
University of Florida
Material Science and
Engineering
Gainesville, FL 32611

513. Christoph J. Mueller
Sprechsaal Publishing
Group
P.O. Box 2962, Mauer 2
D-8630 Coburg
GERMANY AIR MAIL

514. Thomas W. Mullan
Vapor Technologies Inc.
345 Route 17 South
Upper Saddle River, NJ 07458

515. M. K. Murthy
MKM Consultants International
10 Avoca Avenue, Unit 1906
Toronto Ontario M4T 2B7
CANADA AIR MAIL

516. Solomon Musikant
TransCon Technologies, Inc.
Materials Science & Engineering
1508 Waynesboro Road
Paoli, PA 19301

517. David L. Mustoe
Custom Technical Ceramics
8041 West I-70 Service Road,
Unit 6
Arvada, CO 80002

518. Curtis V. Nakaishi
U.S. Department of Energy
Morgantown Energy Technology
Center
Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

519. Yoshio Nakamura
Faicera Research Institute
2-5-8 Hiyakunin-cho Shinjuku-Ko
Tokyo
JAPAN AIR MAIL

520. K. S. Narasimhan
Hoeganaes Corporation
River Road
Riverton, NJ 08077

521. Samuel Natansohn
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

522. Robert Naum
Applied Resources, Inc.
P.O. Box 241
Pittsford, NY 14534

523. Malcolm Naylor
Cummins Engine Company, Inc.
P.O. Box 3005, Mail Code 50183
Columbus, IN 47202-3005

524. Jeffrey Neil
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

525. Fred A. Nichols
Argonne National Laboratory
9700 South Cass Avenue
MCT - Building 212
Argonne, IL 60439

526. H. Nickel
Furschungszentrum Jüelich (KFA)
P.O. Box 1913
Jüelich 1-5170 BRD NRW
GERMANY AIR MAIL

527. Dale E. Niesz
Rutgers University
Center for Ceramic Research
P.O. Box 909
Piscataway, NJ 08855-0909

528. David M. Nissley
United Technologies Corporation
Pratt & Whitney Aircraft
400 Main Street, MS:163-10
East Hartford, CT 06108

529. Richard D. Nixdorf
ReMaxCo Technologies, Inc.
11317 Snyder Road
Knoxville, TN 37932

530. Bernard North
Kennametal, Inc.
P.O. Box 639
Greensburg, PA 15601

531. Bruce E. Novich
Ceramics Process Systems
Corporation
155 Fortune Boulevard
Milford, MA 01757

532. Daniel Oblas
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

533. Don Ohanehi
Magnetic Bearings, Inc.
1908 Sussex Road
Blacksburg, VA 24060

534. Robert Orenstein
General Electric Company
55-112, River Road
Schenectady, NY 12345

535. Norb Osborn
Aerodyne Dallas
151 Regal Row,
Suite 120
Dallas, TX 75247

536. A. M. Paddick
BP International Limited
BP Research Centre, Main
Library
Chertsey Road
Sunbury-on-Thames
Middlesex TW16 7LN
UNITED KINGDOM AIR MAIL

537. Russell J. Page
Kanthal-Artcor
3001 Redhill Avenue, II-109
Costa Mesa, CA 92705

538. Richard Palicka
Cercom, Inc.
1960 Watson Way
Vista, CA 92083

539. Muktesh Paliwal
GTE Products Corporation
Hawes Street
Towanda, PA 18848

540. Joseph E. Palko
General Electric Company
55-113, River Road
Schenectady, NY 12345

541. Hayne Palmour, III
North Carolina State
University
Materials Science and
Engineering Dept.
Raleigh, NC 27605-7905

542. Joseph N. Panzarino
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

543. Pellegrino Papa
Corning Inc.
MP-WX-02-1
Corning, NY 14831

544. E. Beth Pardue
Technology for Energy
Corporation
One Energy Center
P.O. Box 22996
Knoxville, TN 37933-0996

545. Soon C. Park
3M Company
3M Center
Building 142-4N-02
P.O. Box 2963
St. Paul, MN 55144

546. Hartmut Paschke
Schott Glaswerke
Christoph-Dorner-Strasse 29
D-8300 Landshut
GERMANY AIR MAIL

547. Marina R. Pascucci
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

548. James W. Patten
Cummins Engine
Company, Inc.
Materials Engineering
P.O. Box 3005, Mail
Code 50183
Columbus, IN 47202-3005

549. Robert A. Penty
Eastman Kodak Company
KAD/D73 - 35612
901 Elmgrove Road
Rochester, NY 14653

550. Robert W. Pepper
Textron Specialty Materials
2 Industrial Avenue
Lowell, MA 01851

551. Peter Perdue
Detroit Diesel Corporation
Research Advanced Development
Group
13400 West Outer Drive,
Speed Code A-07
Detroit, MI 48239-4001

552. Bruce Peters
Dow Chemical Company
Building 52
Midland, MI 48667

553. John J. Petrovic
Los Alamos National Laboratory
Group MST-4, MS:6771
Los Alamos, NM 87545

554. Frederick S. Pettit
University of Pittsburgh
Pittsburgh, PA 15261

555. Ben A. Phillips
Phillips Engineering Company
721 Pleasant Street
St. Joseph, MI 49085

556. Richard C. Phoenix
Ohmtek, Inc.
2160 Liberty Drive
Niagara Falls, NY 14302

557. Bruce J. Pletka
Michigan Technological
University
Metallurgical and Materials
Engineering Department
Houghton, MI 49931

558. John P. Pollinger
Garrett Ceramic Components
19800 Van Ness Avenue
Torrance, CA 90501

559. P. Popper
High Technology Ceramics
International Journal
22 Pembroke Drive
Westlands Newcastle-under-Lyme
Staffs ST5 2JN
ENGLAND AIR MAIL

560. F. Porz
Universitat Karlsruhe
Institut fur Keramik Im
Maschinendau
Postfach 6980
D-7500 Karlsruhe
GERMANY AIR MAIL

561. Harry L. Potma
Royal Netherlands Embassy
Science and Technology
4200 Linnean Avenue, N.W.
Washington, DC 20008

562. Bob R. Powell
General Motors Research
Laboratories
Metallurgy Department
30500 Mound Road
Box 9055
Warren, MI 48090-9055

563. Stephen C. Pred
ICD Group, Inc.
1100 Valley Brook Avenue
Lyndhurst, NJ 07071

564. Karl M. Prewo
United Technologies Research
Center
411 Silver Lane
MS:24
East Hartford, CT 06108

565. Peter E. Price
Industrial Materials
Technology, Inc.
P.O. Box 9565
Andover, MA 01810

566. Joseph M. Proud
GTE Laboratories, Inc.
Materials Science Laboratory
40 Sylvan Road
Waltham, MA 02254

567. Vimal K. Pujari
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

568. George Quinn
National Institute of
Standards and Technology
Ceramics Division, Bldg. 223
Gaithersburg, MD 20899

569. Ramas V. Raman
Ceracon, Inc.
1101 North Market Boulevard,
Suite 9
Sacramento, CA 95834

570. Charles F. Rapp
Owens Corning Fiberglass
2790 Columbus Road
Granville, OH 43023-1200

571. Dennis W. Readey
Colorado School of Mines
Department of Metallurgy
and Materials Engineering
Golden, CO 80401

572. Wilfred J. Rebello
PAR Enterprises, Inc.
12601 Clifton Hunt Lane
Clifton, VA 22024

573. Harold Rechter
Chicago Fire Brick Company
R&D
7531 South Ashland Avenue
Chicago, IL 60620

574. Robert R. Reeber
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709

575. K. L. Reifsnider
Virginia Polytechnic Institute
and State University
Department of Engineering
Science and Mechanics
Blacksburg, VA 24061

576. Paul E. Rempes
McDonnell Douglass Missle
Systems Company
P.O. Box 516,
Mail Code:1066086
St. Louis, MO 63166-0516

577. Gopal S. Revankar
John Deere Company
Metals Research
3300 River Drive
Moline, IL 61265

578. K. T. Rhee
Rutgers University
Mechanical Engineering
P.O. Box 909
Piscataway, NJ 08854

579. James Rhodes
Advanced Composite Materials
Corporation
1525 South Buncombe Road
Greer, SC 29651

580. Roy W. Rice
W. R. Grace and Company
7379 Route 32
Columbia, MD 21044

581. David W. Richerson
2093 East Delmont Drive
Salt Lake City, UT 84117

582. Tomas Richter
J. H. France Refractories
1944 Clarence Road
Snow Shoe, PA 16874

583. Michel Rigaud
Ecole Polytechnique
Campus Universite De Montreal
P.O. Box 6079, Station A
Montreal, P.Q Quebec H3C 3A7
CANADA AIR MAIL

584. R. E. Riman
Rutgers University
Ceramics Engineering
Department
P.O. Box 909
Piscataway, NJ 08855-0909

585. Barry Ringstrom
Superior Graphite Company
P.O. Box 2373
Smyrna, GA 30081

586. John E. Ritter
University of Massachusetts
Mechanical Engineering
Department
Amherst, MA 01003

587. Frank L. Roberge
Allied-Signal Aerospace Company
Garrett Auxiliary Power Division
P.O. Box 5227
Phoenix, AZ 85010

588. W. Eric Roberts
Advanced Ceramic Technology, Inc.
990 "F" Enterprise Street
Orange, CA 92667

589. Martha Rohr
U.S. Department of Energy
DOE Oak Ridge Field Office
Building 4500N
P.O. Box 2008, MS:6269
Oak Ridge, TN 37831-6269

590. Y. G. Roman
TNO TPD Keramick
P.O. Box 595
Einhoven 5600 AN
HOLLAND AIR MAIL

591. Mark D. Roos
Carborundum Company
P.O. Box 156
Niagara Falls, NY 14302

592. Michael Rossetti
Arthur D. Little, Inc.
15 Acorn Park
Cambridge, MA 01240

593. Barry R. Rossing
Lanxide Corporation
1300 Marrows Road
Newark, DE 19714-6077

594. Steven L. Rotz
Lubrizol Corporation
29400 Lakeland Boulevard
Wickliffe, OH 44092

595. Bruce Rubinger
Global Competitiveness, Inc.
One Devonshire Place, Suite 1011
Boston, MA 02109

596. Robert Ruh
Wright Laboratory
WL/MLLM
Wright-Patterson AFB, OH 45433

597. Robert J. Russell
17 Highgate Road
Framingham, MA 01701

598. L. William Sahley
Supermaterials Company
24400 Highland Road
Richmond Heights, OH 44143

599. Jon Salem
NASA Lewis Research Center
21000 Brookpark Center
Cleveland, OH 44135

600. W. A. Sanders
NASA Lewis Research Center
21000 Brookpark Road, MS:49-3
Cleveland, OH 44135

601. J. Sankar
North Carolina A&T State University
Department of Mechanical Engineering
Greensboro, NC 27411

602. Yasushi Sato
NGK Spark Plugs (U.S.A.), Inc.
1200 Business Center Drive, Suite 300
Mt. Prospect, IL 60056

603. Maxine L. Savitz
Allied-Signal Aerospace Company
Garrett Ceramic Components Division
19800 South Van Ness Avenue
Torrance, CA 90501

604. Ashok Saxena
Georgia Institute of Technology
Materials Engineering
Atlanta, GA 30332-0245

605. David W. Scanlon
Instron Corporation
100 Royall Street
Canton, MA 02021

606. Charles A. Schacht
Schacht Consulting Services
12 Holland Road
Pittsburgh, PA 15235

607. James Schienle
Allied-Signal Aerospace Company
Garrett Auxiliary Power Division
2739 East Washington Street
P.O. Box 5227, MS:1302-2P
Phoenix, AZ 85010

608. John C. Schneider
San Juan Technologies
P.O. Box 49326
Colorado Springs, CO 80949-9326

609. Gary Schnittgrund
Rocketdyne, BA05
6633 Canoga Avenue
Canoga Park, CA 91303

610. Mark Schomp
Lonza, Inc.
Corporate Headquarters
17-17 Route 208
Fair Lann, NJ 07410

611. Joop Schoonman
Delft University of Technology
Laboratory for Inorganic Chemistry
P.O. Box 5045
2600 GA Delft
THE NETHERLANDS AIR MAIL

612. John Schuldies
Industrial Ceramic Technology, Inc.
37 Enterprise Drive
Ann Arbor, MI 48103

613. Robert B. Schulz
U.S. Department of Energy
Office of Transportation Materials
CE-34, Forrestal Building
Washington, DC 20585

614. Murray A. Schwartz
Materials Technology Consulting, Inc.
30 Orchard Way, North
Potomac, MD 20854

615. Peter Schwarzkopf
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

616. Thomas C. Schweizer
Princeton Economic Research, Inc.
12300 Twinbrook Pkwy., Suite 650
Rockville, MD 20852

617. William T. Schwessinger
Multi-Arc Scientific Coatings
1064 Chicago Road
Troy, MI 48083-4297

618. W. D. Scott
University of Washington
Materials Science Department
Mail Stop:FB10
Seattle, WA 98195

619. Nancy Scoville
Thermo Electron Technologies
74 West Street
P.O. Box 9046
Waltham, MA 02254-9046

620. Brian Seegmiller
Coors Ceramics Company
600 9th Street
Golden, CO 80401

621. T. B. Selover
AICRE/DIPPR
3575 Traver Road
Shaker Heights, OH 44122

622. J. H. Selverian
GTE Laboratories, Inc.
40 Sylvan Road
Waltham, MA 02254

623. Charles E. Semler
Semler Materials Services
4160 Mumford Court
Columbus, OH 43220

624. Thomas Service
Service Engineering Laboratory
324 Wells Street
Greenfield, MA 01301

625. Kish Seth
Ethyl Corporation
R&D Laboratories
P.O. Box 341
Baton Rouge, LA 70821

626. Karleen Seybold
Allied-Signal Aerospace Company
Garrett Auxiliary Power Division
P.O. Box 5227
Phoenix, AZ 85010

627. William J. Shack
Argonne National Laboratory
9700 South Cass Avenue
Building 212
Argonne, IL 60439

628. Peter T. B. Shaffer
Technical Ceramics Laboratories, Inc.
4045 Nine/McFarland Drive
Alpharetta, GA 30201

629. Richard K. Shaltens
NASA Lewis Research Center
21000 Brookpark Road, MS:301-2
Cleveland, OH 44135

630. Robert S. Shane
238 Hemlock Road
Wynnewood, PA 19096

631. Daniel Shanefield
Rutgers University
Ceramics Engineering Department
P.O. Box 909
Piscataway, NJ 08855-0909

632. Ravi Shankar
Chromalloy
Research and Technology Division
Blaisdell Road
Orangeburg, NY 10962

633. Terence Sheehan
Alpex Wheel Company
727 Berkley Street
New Milford, NJ 07646

634. Dinesh K. Shetty
University of Utah
304 EMRO, Dept. of Materials Science and Engineering
Salt Lake City, UT 84112

635. Masahide Shimizu
Ceramic Society of Japan
2-2-503 Takiyama 6-chome
Higashikurume-Shi Tokyo 203
JAPAN AIR MAIL

636. John Shipinski
Toyota Technical Center U.S.A., Inc.
Technical Research Department
2000 Town Center, Suite 500
Southfield, MI 48075

637. Thomas Shreves
American Ceramic Society, Inc.
Library
757 Brooksedge Plaza Drive
Westerville, OH 43081-2821

638. Jack D. Sibold
Coors Ceramics Company
Contracts for Corporate Technology
4545 McIntyre Street
Golden, CO 80403

705. Janet Wade
Allied-Signal Aerospace Company
Garrett Auxiliary Power Division, Department 93-772
P.O. Box 5227, MS:1303-2
Phoenix, AZ 85010

706. Richard L. Wagner
Ceramic Technologies, Inc.
537 Turtle Creek South Drive, Suite 24D
Indianapolis, IN 46227

707. J. Bruce Wagner, Jr.
Arizona State University
Center for Solid State Science
Tempe, AZ 85287-1704

708. Daniel J. Wahlen
Kohler, Co.
444 Highland Drive
Kohler, WI 53044

709. Ingrid Wahlgren
Royal Institute of Technology
Studsvik Library
S-611 82 Nykoping
SWEDEN AIR MAIL

710. Ron H. Walecki
Allied-Signal Aerospace Company
Garrett Ceramic Components Division
19800 South Van Ness Avenue
Torrance, CA 90501

711. Michael S. Walsh
Vapor Technologies Inc.
2100 Central Avenue
Boulder, CO 80301

712. Chien-Min Wang
Industrial Technology Research Institute
Materials Research Laboratories
195 Chung-Hsing Road, Sec. 4
Chutung Hsinchu 31015 R.O.C.
TAIWAN AIR MAIL

713. Robert M. Washburn
ASMT
11203 Colima Road
Whittier, CA 90604

714. Gerald Q. Weaver
Carborundum Specialty Products
42 Linus Allain Avenue
Gardner, MA 01440-2478

715. Karen E. Weber
Detroit Diesel Corporation
Technology and Planning
13400 West Outer Drive
Detroit, MI 48239-4001

716. R. W. Weeks
Argonne National Laboratory
MCT-212
9700 South Cass Avenue
Argonne, IL 60439

717. Ludwig Weiler
ASEA Brown Boveri AG
Corporate Research
Eppelheimer Str. 82
D-6900 Heidelberg
GERMANY AIR MAIL

718. James Wessel
Dow Corning Corporation
1800 "M" Street, N.W., Suite 325 South
Washington, DC 20036

719. Robert D. West
Therm Advanced Ceramics
P.O. Box 220
Ithaca, NY 14851

720. Thomas J. Whalen
Ford Motor Company
26362 Harriet
Dearborn Heights, MI 48127

721. Ian A. White
Hoeganaes Corporation
River Road
Riverton, NJ 08077

689. L. J. Trostel, Jr.
Box 199
Princeton, MA 01541

690. W. T. Tucker
General Electric Company
Corporate R&D
Building K1-4C35
P.O. Box 8
Schenectady, NY 12301

691. Masanori Ueki
Nippon Steel Corporation
Central R&D Bureau
1618 Ida
Nakahara-Ku Kawasaki 211
JAPAN AIR MAIL

692. Filippo M. Ugolini
ATA Studio
Via Degli Scipioni, 268A
ROMA 00192
ITALY AIR MAIL

693. Donald L. Vaccari
Allison Gas Turbines
P.O. Box 420
Speed Code S49
Indianapolis, IN 46206-0420

694. Carl F. Van Conant
Boride Products, Inc.
2879 Aero Park Drive
Traverse City, MI 49684

695. Marcel H. Van De Voorde
Commission of the European Communities
Institute for Advanced Materials
Joint Research Centre
P.O. Box 2
1755 ZG Petten
THE NETHERLANDS AIR MAIL

696. O. Van Der Biest
Katholieke Universiteit Leuven
Departement Metaalkunde en Toegepaste
de Croylaan 2
B-3030 Leuven
BELGIUM AIR MAIL

697. Michael Vannier
Washington University, St. Louis
Mallinckrodt Institute of Radiology
510 South Kings Highway
St. Louis, MO 63110

698. Stan Venkatesan
Southern Coke & Coal Corporation
P.O. Box 52383
Knoxville, TN 37950

699. V. Venkateswaran
Carborundum Company
Niagara Falls R&D Center
P.O. Box 832
Niagara Falls, NY 14302

700. Dennis Viechnicki
U.S. Army Materials Technology Laboratory
405 Arsenal Street
Watertown, MA 02172-0001

701. Ted Vojnovich
U.S. Department of Energy
Office of Energy Research, ER-42
Washington, DC 20585

702. John D. Volt
E. I. Dupont de Nemours & Company, Inc.
P.O. Box 80262
Wilmington, DE 19880

703. John B. Wachtman
Rutgers University
Ceramics Department
P.O. Box 909
Piscataway, NJ 08855

704. Shigetaka Wada
Toyota Central Research Labs, Inc.
Nagakute Aichi 480-11
JAPAN AIR MAIL

672. Patrick L. Sutton
U.S. Department of Energy
Advanced Propulsion Division
CE-322, Forrestal Building
Washington, DC 20585

673. Willard H. Sutton
United Technologies
Corporation
Research Center, MS:24
Silver Lane
East Hartford, CT 06108

674. Ron Sviben
100 Indel Avenue
Rancocas, NJ 08073

675. J. J. Swab
U.S. Army Materials Technology
Laboratory
Ceramics Research Division
SLCMT-EMC
405 Arsenal Street
Watertown, MA 02172

676. Robert E. Swanson
Metalworking Technology, Inc.
1450 Scalp Avenue
Johnstown, PA 15904

677. Scott L. Swartz
Battelle Columbus
Laboratories
Metals and Ceramics
505 King Avenue
Columbus, OH 43201

678. Steve Szaruga
Air Force Wright Aeronautical
Laboratory
Materials Directorate
WL/MLBC
Wright-Patterson
AFB, OH 45433-6533

679. Yo Tajima
NGK Spark Plug Company, Ltd.
NTK Technical Ceramic Division
2808 Iwasaki
Komaki-shi Aichi-ken 485
JAPAN AIR MAIL

680. Fred Teeter
5 Tralee Terrace
East Amherst, NY 14051

681. Monika O. Ten Eyck
Carborundum Company
Technology Division
P.O. Box 832
Niagara Falls, NY 14302

682. David F. Thompson
Corning Glass Works
SP-DV-02-1
Corning, NY 14831

683. Merle L. Thorpe
Hobart Tafa Technologies, Inc.
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Mercedes-Strabe 136
Stuttgart 60
GERMANY AIR MAIL

685. T. Y. Tien
University of Michigan
Materials Science and
Engineering Department
Dow Building
Ann Arbor, MI 48103

686. Julian M. Tishkoff
Air Force Office of Scientific
Research
AFOSR/NA
Bolling AFB, DC 20332-6448

687. D. M. Tracey
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

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General Motors Corporation
Allison Gas Turbine Division
P.O. Box 420, MS:W-16
Indianapolis, IN 46206-0420

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Madison, NJ 07940

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Technology Assessment and Transfer, Inc.
133 Defense Highway, #212
Annapolis, MD 21401

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Norton Company
Advanced Ceramics Library
Goddard Road
Northboro, MA 01532-1545

642. Gurpreet Singh
Department of the Navy
Internal Combustion & Gas Turbine Engine Division
Code 56X31
Washington, DC 20362-5101

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University of Michigan
Chemical and Metallurgical Engineering
5106 IST Building
Ann Arbor, MI 48109-2099

644. John Skildum
3M Company
3M Center
Building 224-2S-25
St. Paul, MN 55144

645. David P. Smith
Hoskins, Rees & Smith
1910 Cochran Road
Manor Oak II, Suite 658
Pittsburgh, PA 15220

646. Richard H. Smoak
Smoak & Associates
3554 Hollyslope Road
Altadena, CA 91001-3923

647. Jay R. Smyth
Allied-Signal Aerospace Company
Garrett Auxiliary Power Division
2739 East Washington Street
P.O. Box 5227
MS:93-173/1303-207
Phoenix, AZ 85010

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Findlay, OH 44815

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British Petroleum Company
Technical Center, Broadway
3092 Broadway Avenue
Cleveland, OH 44115

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SAC International Ltd.
1445 Bonhill Road, # 13
Mississauga Ontario L5T 1V3
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Nishi Tokyo University
3-7-19 Seijo, Setagaya
Tokyo 157
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Neward, DE 19707

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Advanced Industrial Concepts Division
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Washington, DC 20585

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EA Technology
Capenhurst Chester
CH1 6ES
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Hercules, Inc.
Hercules Plaza
Wilmington, DE 19894

656. Richard M. Spriggs
Alfred University
Center for Advanced Ceramic
Technology
Alfred, NY 14802

657. Charles Spuckler
NASA Lewis Research Center
21000 Brookpark Road
MS: 5-11
Cleveland, OH 44135-3191

658. M. Srinivasan
Material Solutions
P.O. Box 663
Grand Island, NY 14702-0663

659. Gordon L. Starr
Cummins Engine Company, Inc.
Design & Technology
P.O. Box 3005
Mail Code 50182
Columbus, IN 47202-3005

660. Jim Stevenson
Windrock, Incorporated
154 Fairbanks Plaza
Oak Ridge, TN 37830

661. Tom Stillwagon
Allied-Signal Aerospace
Company
Garrett Ceramic Components
Division
19800 South Van Ness Avenue
Torrance, CA 90501

662. Harold L. Stocker
General Motors Corporation
Allison Gas Turbine Division
P.O. Box 420
Indianapolis, IN 46206

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Dow Chemical USA
1776 "Eye" Street, N.W.,
Suite 575
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Technology Division
P.O. Box 337
Niagara Falls, NY 14302-0337

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4 Chittenden Lane
Owings Mills, MD 21117

666. F. W. Stringer
Aero & Industrial
Technology Ltd.
P.O. Box 46, Wood Top
Burnley Lancashire BB11 4BX
UNITED KINGDOM AIR MAIL

667. Thomas N. Strom
NASA Lewis Research Center
21000 Brookpark Road
MS:86-6
Cleveland, OH 44135

668. M. F. Stroosnijder
Institute for Advanced
Materials
Joint Research Centre
21020 Ispra (VA)
ITALY AIR MAIL

669. Karsten Styhr
30604 Ganado Drive
Rancho Palos Verdes, CA 90274

670. T. S. Sudarshan
Materials Modification, Inc.
2929-P1 Eskridge Center
Fairfax, VA 22031

671. M. J. Sundaresan
University of Miami
Mechanical Engineering
Department
P.O. Box 248294
Coral Gables, FL 33124

722. Alan Whitehead
General Electric Company
1 River Road, 55-111
Schenectady, NY 12345

723. Sheldon M. Wiederhorn
National Institute of
Standards and Technology
Building 223, Room A329
Gaithersburg, MD 20899

724. John F. Wight
Alfred University
McMahon Building
Alfred, NY 14802

725. D. S. Wilkinson
McMaster University
Materials Science and
Engineering Department
1280 Main Street, West
Hamilton Ontario L8S 4L7
CANADA AIR MAIL

726. James C. Williams
General Electric Company
Engineering Materials
Technology Labs
One Neumann Way
Mail Drop: H85
Cincinnati, OH 45215-6301

727. Janette R. Williams
Kollmorgen Corporation
PCK Technology Division
150 Motor Parkway, # 262
Hauppauge, NY 11788-5108

728. Steve J. Williams
RCG Hagler Bailly, Inc.
1530 Wilson Boulevard,
Suite 900
Arlington, VA 22209-2406

729. Craig A. Willkens
Norton Company
Advanced Ceramics
Goddard Road
Northboro, MA 01532-1545

730. Roger R. Wills
TRW, Inc.
Valve Division
1455 East 185th Street
Cleveland, OH 44110

731. David Gordon Wilson
Massachusetts Institute of
Technology
Mechanical-Engineering
Department
77 Massachusetts Avenue,
Room 3-455
Cambridge, MA 02139

732. Matthew F. Winkler
Seaworthy Systems, Inc.
P.O. Box 965
Essex, CT 06426

733. Gerhard Winter
Hermann C. Starck Berlin GmbH,
Werk Goslar
P.O. Box 25 40
D-3380 Goslar 3380
GERMANY AIR MAIL

734. W. L. Winterbottom
Ford Motor Company
Material Systems Reliability
Department
20000 Rotunda Drive
SRL, Room E-3182
P.O. Box 2053
Dearborn, MI 48121

735. David G. Wirth
Coors Ceramics Company
600 9th Street
Golden, CO 80401

736. Thomas J. Wissing
Eaton Corporation
Engineering & Research Center
P.O. Box 766
Southfield, MI 48037

737. James C. Withers
MER Corporation
7960 South Kolb Road
Building F
Tucson, AZ 85706

738. Dale E. Wittmer
Southern Illinois University
Mechanical Engineering
Department
Carbondale, IL 62901

739. Warren W. Wolf
Owens Corning Fiberglass
2790 Columbus Road, Route 16
Granville, OH 43023

740. George W. Wolter
Howmet Turbine Components
Corporation
Technical Center
699 Benston Road
Whitehall, MI 49461

741. James C. Wood
NASA Lewis Research Center
21000 Brookpark Road
MS:86-6
Cleveland, OH 44135

742. Marrill Wood
LECO Corporation
Augusta Division
P.O. Box 211688
Augusta, GA 30917-1688

743. Wayne L. Worrell
University of Pennsylvania
Department of Materials
Science and Engineering
3231 Walnut Street
Philadelphia, PA 19104

744. John F. Wosinski
Corning Inc.
ME-2 E-5 H8
Corning, NY 14830

745. Ian G. Wright
Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201

746. Ruth Wroe
ERDC
Metals & Materials Industries
Division
Capenhurst Chester CH1 6ES
ENGLAND AIR MAIL

747. Bernard J. Wrona
Advanced Composite Materials
Corporation
1525 South Buncombe Road
Greer, SC 29651

748. Carl C. M. Wu
Naval Research Laboratory
Ceramic Branch, Code 6373
Washington, DC 20375

749. John C. Wurst
University of Dayton Research
Institute
300 College Park
Dayton, OH 45469-0101

750. Neil Wyant
ARCH Development Corp.
9700 South Cass Avenue
Building 202
Argonne, IL 60439

751. Roy Yamamoto
Texaco Inc.
P.O. Box 509
Beacon, NY 12508-0509

752. John Yamanis
Allied-Signal, Inc.
Ceramics Program
P.O. Box 1021
Morristown, NJ 07962-1021

753. Harry C. Yeh
Allied-Signal Aerospace
Company
Garrett Ceramic Components
Division
19800 South Van Ness Avenue
Torrance, CA 90509

754. Hiroshi Yokoyama
Hitachi Research Lab
4026 Kuji-Cho
Hitachi-shi Ibaraki 319-12
JAPAN AIR MAIL

755. Thomas M. Yonushonis
Cummins Engine Company, Inc.
P.O. Box 3005
Mail Code 50183
Columbus, IN 47202-3005

756. Thomas J. Yost
Corning, Inc.
Technical Products Division,
Main Plant 21-1-2
Corning, NY 14831

757. Jong Yung
Sundstrand Aviation
Operations
Department 789-6
4747 Harrison Avenue
Rockford, IL 61125

758. A. L. Zadoks
Caterpillar Inc.
Technical Center, Building L
P.O. Box 1875
Peoria, IL 61656-1875

759. Avi Zangvil
University of Illinois
Materials Research Laboratory
104 South Goodwin Avenue
Urbana, IL 61801

760. Charles H. Zenuk
Transtech
6529 East Calle Cavalier
Tucson, AZ 85715

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Office of Energy Research,
ER-42
Washington, DC 20585

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Applied Test Systems, Inc.
2571 Mt. Gallant Road
Rock Hill, SC 29730

763. Carl Zweben
General Electric Company
P.O. Box 8555, VFSC/V4019
Philadelphia, PA 19101

764. Klaus M. Zwilsky
National Research Council
National Materials
Advisory Board
2101 Constitution Avenue
Washington, DC 20418

765. Department of Energy
DOE Field Office, Oak Ridge
Assistant Manager for Energy
Research and Development
P.O. Box 2001
Oak Ridge, TN 37831-8501

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