T H E U N I V E R S I T Y O F M I C H I G A N

COLLEGE OF ENGINEERING
Department of Aeroanutical and Astronautical Engineering
High Altitude Engineering Laboratory

Technical Report

REFLECTANCE OF KODAK WHITE PAPER

F. L. Bartman
L. W. Chaney
M. T. Surh

Approved by:
L. M. Jones
L. M. Jones, Director
High Altitude Engineering
Laboratory

ORA Project 05863

under contract with:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT NO. NASr-54(03)
GODDARD SPACE FLIGHT CENTER

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

April 1964

engm
UMR0267

ABSTRACT

Data on the spectral directional reflectance and spectral bidirectional reflectance of Kodak white paper (double weight photographic stock) are presented and discussed. It is concluded that Kodak white paper does not have perfectly diffuse (Lambertian) reflectance, and that under certain conditions of use, large errors might result from this assumption. Definitions of spectral and total directional and bidirectional reflection are presented. Data on the reflectance characteristics of Magnesium oxide are presented in the Appendix.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Kodak white paper (regular double weight photographic stock) has been used, along with a calibrated tungsten filament lamp, as a source of radiation for the calibration of the "visible" channels (0.2-5 and 0.55-0.75μ) of the TIROS 5-channel radiometer, both at NASA—Goddard Space Flight Center[1] and at The University of Michigan.

The same technique has been used for calibration of a modified Perkin-Elmer SG-4 grating spectrophotometer and for "in-flight" calibrations of the TIROS radiometer and SG-4 spectrophotometer on a balloon flight test of these instruments.

It has been assumed that Kodak white paper has "ideal diffuse" reflectance (i.e., it is Lambertian). However, this is not the case; the reflectance pattern has a specular component which varies with the angle of incidence and is also a function of wavelength. It is important to consider this specular component in the above-noted calibrations.

The objective of this report is to summarize information on the reflectance of Kodak white paper. Reflectance data is presented after a brief discussion of definitions of reflectance. New data which indicate that Kodak white paper is not a perfect diffuse reflector are then given.

Possible errors in calibration techniques which use Kodak white paper under the assumption that it is a perfect diffuse reflector are then discussed briefly.

The reflectance characteristics of MgO, which is used as a standard of diffuse reflectance for visible light, are summarized in the Appendix.

2. REFLECTANCE

2.1. DEFINITIONS

In Fig. 1, ds is an element of a reflecting surface. (θ_1,ϕ_1) are the

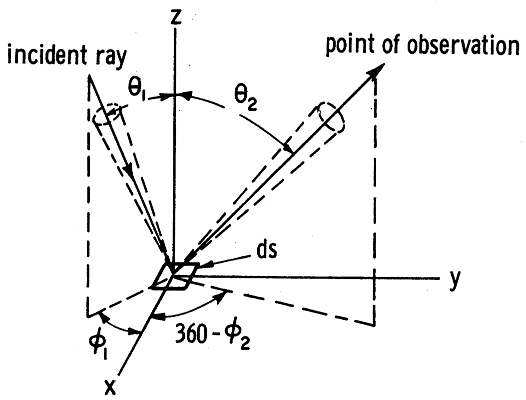

Fig. 1. Element of reflecting surface (ds) showing basic geometry of reflection.

zenith and azimuth angles of the incident ray, and (θ_2,ϕ_2) are zenith and azimuth angles of a reflected ray.

The radiation reflected in the direction (θ_2,ϕ_2) is then given by

$$N_2 = \rho(\theta_1,\phi_1,\theta_2,\phi_2) \text{ Cos } \theta_2 \cdot \frac{H.\cos\theta_1.ds}{R^2} \qquad \text{w-m}^{-2}\text{-ster}^{-1}, \qquad (2.1)$$

where $\rho(\theta_1,\phi_1,\theta_2,\phi_2)$ is the bidirectional reflectance,[2] i.e., the fraction of radiation incident from the direction (θ_1,ϕ_1) which is reflected in the direction (θ_2,ϕ_2).

H is the irradiance from direction (θ_1,ϕ_1) in w-m^{-2}.

ds is the element of reflecting surface area in m^2.

R is the distance in meters from the reflecting surface area to the point of observation.

The total amount of reflected radiation is given by the integral over the hemisphere, i.e.,

$$W = \int_{\phi_2=0}^{2\pi} \int_{\Theta_2=0}^{\pi/2} N_2 . R^2 \sin \Theta_2 \, d\Theta_2 \, d\phi_2 \qquad \text{w-m}^{-2} \tag{2.2}$$

thus

$$W = \int_{\phi_2=0}^{2\pi} \int_{\Theta_2=0}^{\pi/2} \rho(\Theta_1,\phi_1,\Theta_2,\phi_2) \sin \Theta_2 \cos \Theta_2 \, H_1 \cos \Theta_1 ds \, d\Theta_2 \, d\phi_2 \tag{2.3}$$

The directional reflectance $r(\Theta_1,\phi_1)$ defined as the fraction of reflected radiation is

$$r(\Theta_1,\phi_1) = \frac{W}{H \cos \Theta_1 ds} = \int_{\phi_2=0}^{2\pi} \int_{\Theta_2=0}^{\pi/2} \rho(\Theta_1,\phi_1,\Theta_2,\phi_2) \sin \Theta_2 \cos \Theta_2 \, d\Theta_2 \, d\phi_2 . \tag{2.4}$$

If the reflectance is perfectively diffuse (Lambertian), then:

$$\rho(\Theta_1,\phi_1,\Theta_2,\phi_2) = \rho = \text{constant}, \tag{2.5}$$

and, integrating Eq. (2.4), we find

$$r(\Theta_1,\phi_1) = \rho \cdot \pi = r = \text{constant}. \tag{2.6}$$

Thus for perfectly diffuse reflectance, the directional reflectance is equal to π times the bidirectional reflectance, and each of these quantities is a constant, independent of the angle of incidence.

Usually the reflectance quantities are a function of wavelength as well as direction. To indicate this, the subscript λ should be used, i.e., the reflectance quantities above should be written as

$\rho_\lambda(\Theta_1,\phi_1,\Theta_2,\phi_2)$ = spectral bidirectional reflectance
$r_\lambda(\Theta_1,\phi_1)$ = spectral directional reflectance
r_λ = spectral diffuse directional reflectance
ρ_λ = spectral diffuse bidirectional reflectance

Thus, all of the reflectance quantities measured so far may be considered for a given wavelength or for a specified distribution of wavelengths. Such quantities are referred to as "spectral" and "total" reflectances, respectively. "Total" quantities are obtained by integration over the spectral distribution. Thus, for example,

$$r(\Theta_1,\lambda_1) = \int_{\lambda_1}^{\lambda_2} r_\lambda(\Theta_1,\phi_1)\, H_\lambda\, d_\lambda, \qquad (2.7)$$

where λ_1,λ_2 are the limits of the spectral range of the incident radiation. Note that, therefore, the "total" reflectance quantities are a function of the spectral distribution of the incident radiation as well as the nature of the reflecting surface. Thus, total reflectance quantities measured with one spectral distribution cannot necessarily be used as the total reflectance for another spectral distribution.

Figure 2 shows the distribution of reflected radiation for a perfectly

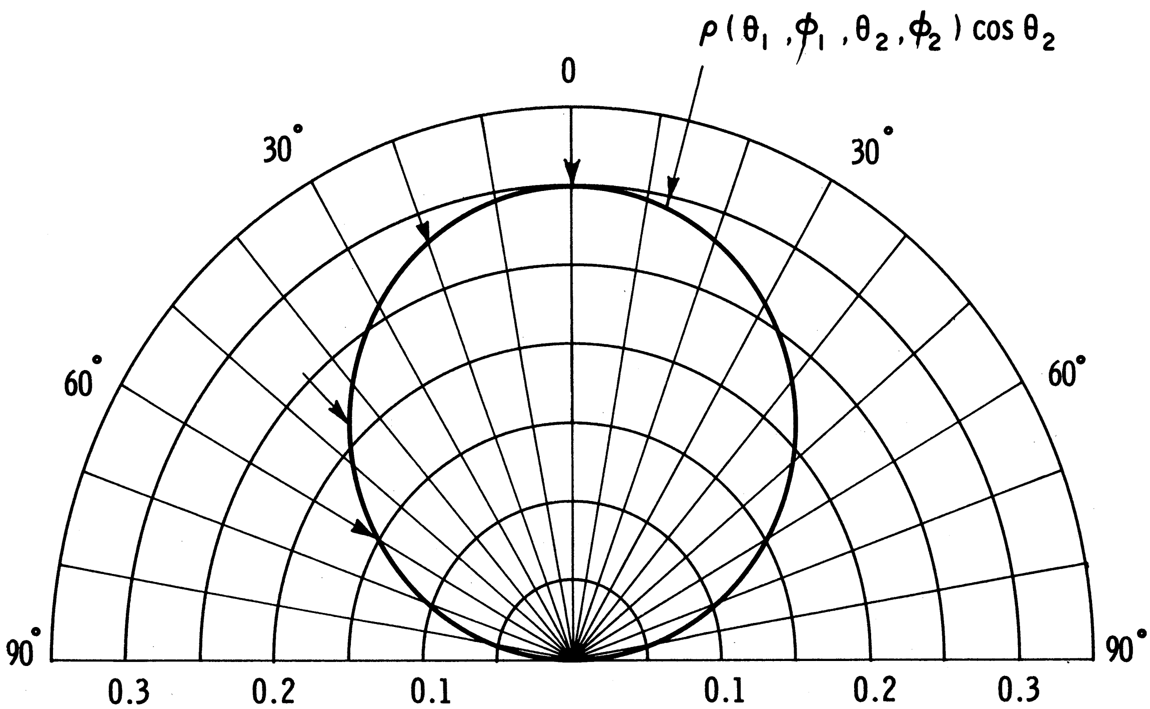

Fig. 2. Distribution of reflected radiation for a perfectly diffuse (Lambertian) reflector.

diffuse (Lambertian) reflector. The quantity plotted is $\rho(\Theta_1,\phi_1,\Theta_2,\phi_2)$.cos Θ_2. Note that the distribution of reflected radiation is the same for all angles of incidence, i.e., $\rho(\Theta_1,\phi_1,\Theta_2,\phi_2) = \rho$ constant. For this illustration, $\rho = 0.3$

and, therefore, the directional reflectance $r(\Theta_1,\phi_1) = \pi.0.3 = .94$.

Figure 3 shows the distribution of reflected radiation for imperfectly

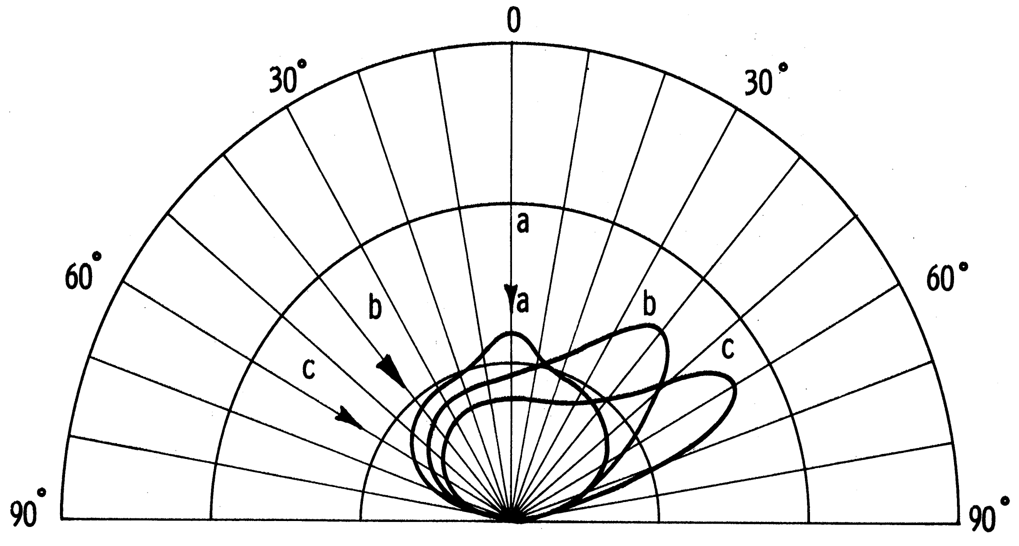

Fig. 3. Distribution of reflected radiation for imperfectly diffuse reflector. $\rho(\Theta_1,\phi_1,\Theta_2,\phi_2).\cos\Theta_2$ is plotted for three angles of incidence: 0°, 40° and 60°.

diffuse reflector. $\rho(\Theta_1,\phi_1,\Theta_2,\phi_2)$ is plotted for three different angles of incidence. In this case, the reflector has a fairly large specular component.

Note that in both Figs. 2 and 3 the distribution of reflected radiation has been shown only for the plane of incidence (the plane determined by the normal to the reflecting surface and the incident ray). Complete specification of the distribution requires similar plots for all vertical planes, i.e., the distribution over the hemisphere.

Such a hemispherical plot should be obtained for each wavelength in the range of consideration. Then, finally, a hemispherical plot of total bidirectional reflectance could be plotted for each spectral distribution considered.

2.2. EXPERIMENTAL MEASUREMENTS

Measurement of the bidirectional reflectance of a sample can be made by the method shown schematically in Fig. 1. The source and sample would be varied so that a complete set of data existed for all wavelengths, all angles of incidence, and all angles of reflectance. For a sample which has an appreciable specular reflectance component, this is a long and tedious task.

Usually this information is not available. If the sample is known to have almost the ideal "diffuse" reflectance characteristic, the task is easier. A few measurements will determine the essential characteristics of the reflectance properties of the sample.

The directional reflectance of a sample may be measured in an integrating type of reflectance device. The sample is irradiated from a small solid angle and all reflected energy detected. If the sample has perfectly diffuse reflectance, the results will uniquely define the reflectance pattern of the sample. If the sample has a large specular component, this measurement will not determine the reflectance pattern adequately.

If a sample has essentially specular reflectance (mirror-reflection), then a device like the specular reflectance attachment for a spectrophotometer will serve very well. Indeed, such a device will work very well for a sample which is known to have ideal diffuse reflectance characteristics. Again, if the sample is partially diffuse and partially specular, the reflectance pattern is not determined.

To summarize, if a sample is known to have ideal "diffuse" reflectance characteristics or perfectly specular reflectance characteristics, it is not difficult to obtain a measurement which will define these characteristics. However, if the sample has partially diffuse and partially specular reflectance, measurement of the bidirectional reflectance is essential.

3. SPECTRAL DIRECTIONAL REFLECTANCE OF KODAK WHITE PAPER

3.1. BEST ESTIMATE OF SPECTRAL DIRECTIONAL REFLECTANCE OF KODAK WHITE PAPER

Figure 4 shows all of the available data on the spectral directional reflectance, r_λ, of Kodak white paper. The data have been obtained from several sources:

1. National Bureau of Standards (in the wavelength range of 0.5-0.75μ).
2. Naval Research Laboratory (0.25-2.5μ).
3. NASA—Goddard Space Flight Center (0.5-2.6μ).
4. University of Michigan—High Altitude Engineering Laboratory (1.4-5.0μ).

It is believed that all of the data, with the exception of The University of Michigan data, have been obtained by measurement on the integrating type of reflectance attachment, and thus are truly the spectral directional reflectance of Kodak white paper.

The NBS and NRL data have been forwarded to us by NASA—GSFC personnel. Note the excellent agreement between these two sets of datain the range of 0.5-0.75μ.

The NASA data have been normalized to agree with the NBS and NRL data in the range of 0.5-0.75μ. This normalizing factor was then applied to all of the NASA data over the entire range of wavelengths (0.5-2.6μ).

The University of Michigan data in the 1.4-5.0μ region were measured with a specular reflectance attachment on a Perkin-Elmer spectrometer. With this device the spectral reflectance of the Kodak white paper sample is measured relative to a MgO sample for nearly normal angles of incidence and reflectance. This method will yield the correct result if both samples are perfectly diffuse reflectors. If the Kodak white paper has a large specular reflectance component, however, the results would be in error.

The increase in reflectance above 2.8μ should be noted. The shape of this curve in the 2.8-5.0μ region is similar to the increase with wavelength of black or gray body radiance with wavelength. It may be that the radiation emitted by the Kodak white paper is contributing to the readings in this region of the spectrum. This possibility will be examined more closely in the near future.

It is also possible that the increase in reflectance about 2.8μ is due to an increase in specular reflectance. In this case, the interpretation as spectral directional reflectance is incorrect.

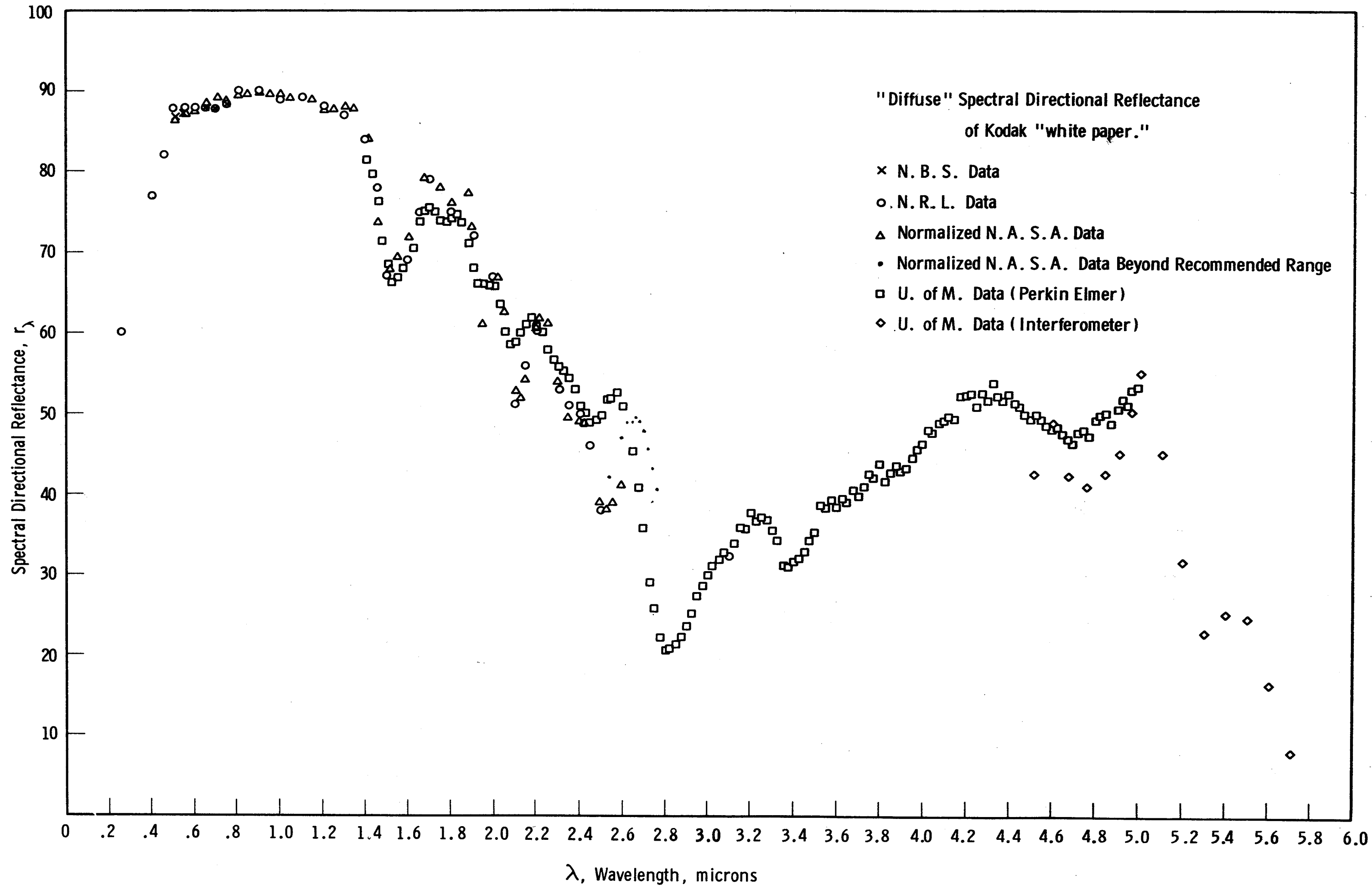

Fig. 4. Spectral directional reflectance data for Kodak White Paper.

In the 4.5-5.7μ region, data were also obtained at The University of Michigan with a modified Block I-4T interferometer. The reflectance was measured relative to radiation from an extended black-body source and relative to the reflectance of magnesium oxide. These data confirm the other University of Michigan data in the 4.5-5.0μ region.

The interferometer was also used to measure the reflectance of MgO relative to an extended black-body source. The results agree with data taken from the literature (see Fig. 8), and so the validity of this technique seems to be confirmed.

The smooth curve of Fig. 5, derived from all of the available data, is given as the best estimate of the spectral directional reflectance of Kodak white paper in the range of 0.2-5.7μ.

If the nature of the reflectance can be shown to be diffuse, then the bidirectional reflectance of any wavelength will be the value shown divided by π. If the reflectance has any appreciable specular component, the interpretation cannot be made without additional information.

3.2. BIDIRECTIONAL REFLECTANCE CHARACTERISTIC OF KODAK WHITE PAPER

Some information on the bidirectional reflectance of Kodak white paper has been obtained at The University of Michigan by the following technique. The Kodak white paper target was placed at a distance of one meter from the source lamp. The power reflected from the paper was measured at 10° intervals in the plane of incidence (the plane normal to the target through the direction of incident radiation) for incidence angles of 0° (normal incidence) and 45°. The acceptance angle of the thermopile (i.e., field of view) was reduced to 11° by an aperture.

The same measurements were also made with a magnesium oxide target substituted for the Kodak white paper target. The ratio of the readings for the white paper and MgO for a given set of angle of incidence and reflectance is the reflectance of the white paper relative to the MgO. The absolute reflectance of the white paper was obtained by multiplying this ratio by the reflectance of MgO.

The results are shown in Fig. 6. The reflectance pattern of the Kodak white paper for normal incidence is an ellipse rather than the circle of the ideal diffuse (Lambertian) reflectance. The departure from the ideal diffuse case is even more obvious in the reflectance pattern of the paper for 45° incidence. In this case, a fairly large specular component is shown.

The validity of this technique has been tested by measureing the bidirectional reflectance of an MgO surface. The result is shown in Fig. 7 together

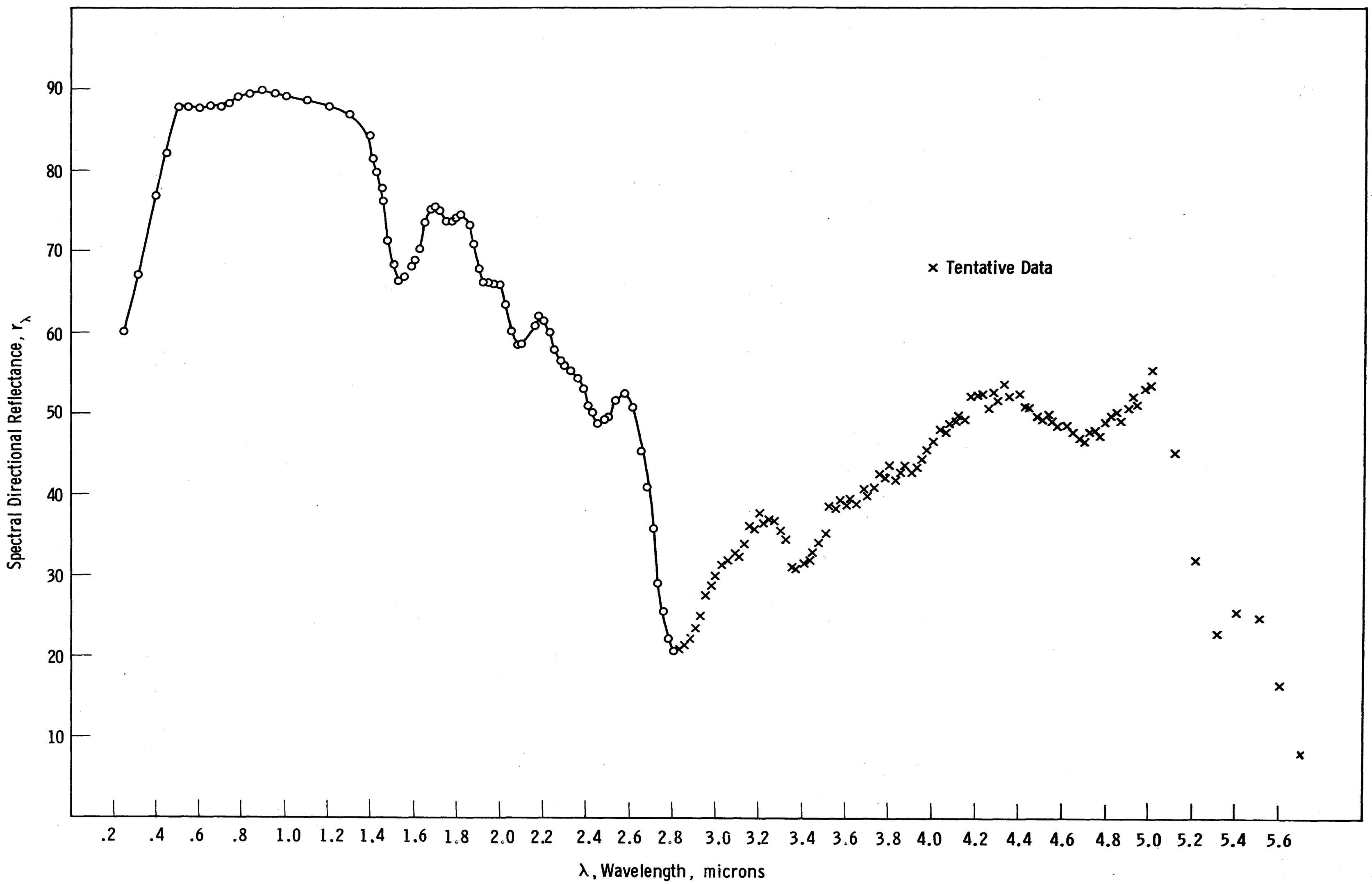

Fig. 5. Best estimate of spectral directional reflectance of Kodak White Paper.

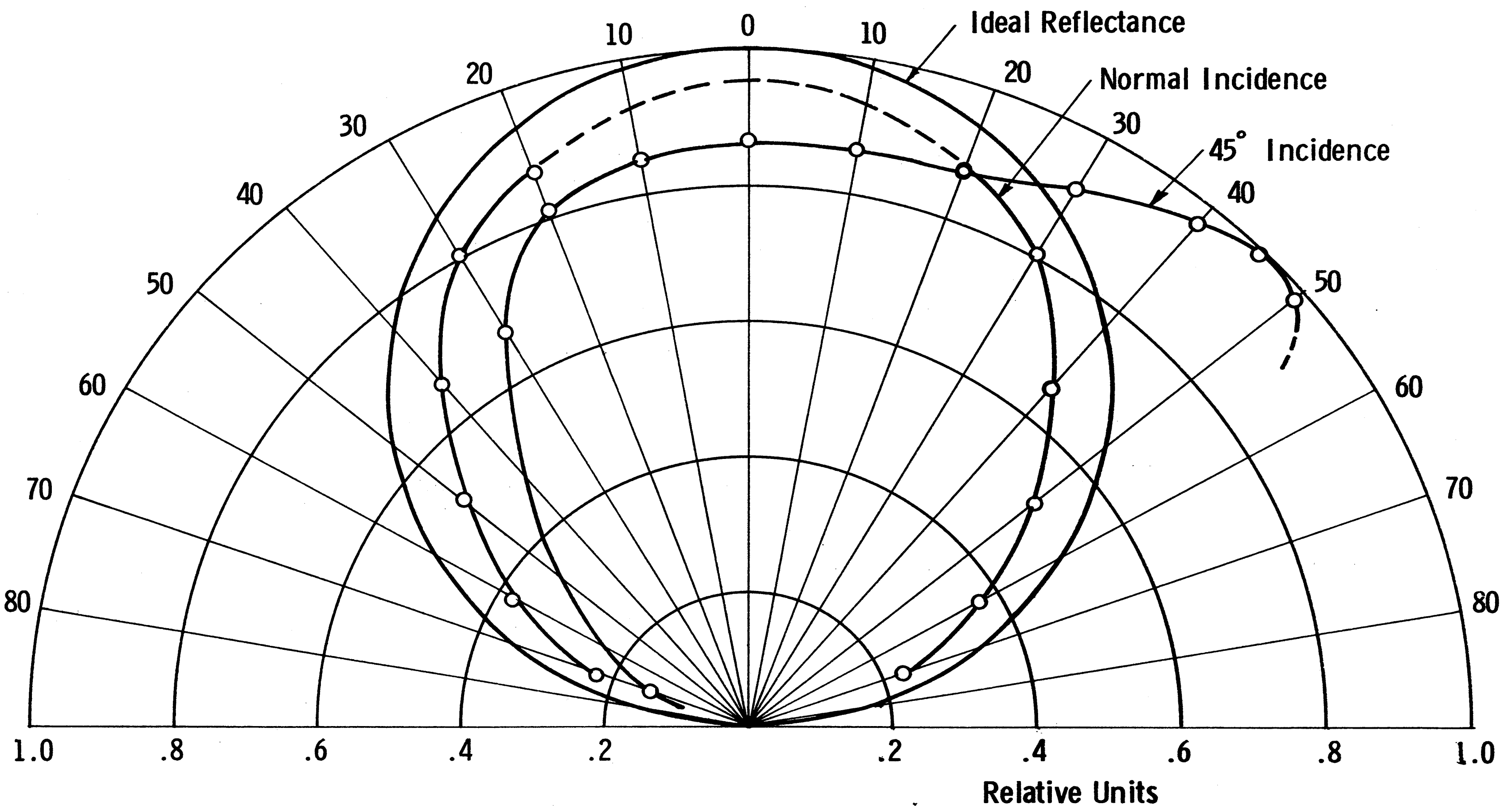

Fig. 6. Bidirectional reflectance patterns for Kodak White Paper.

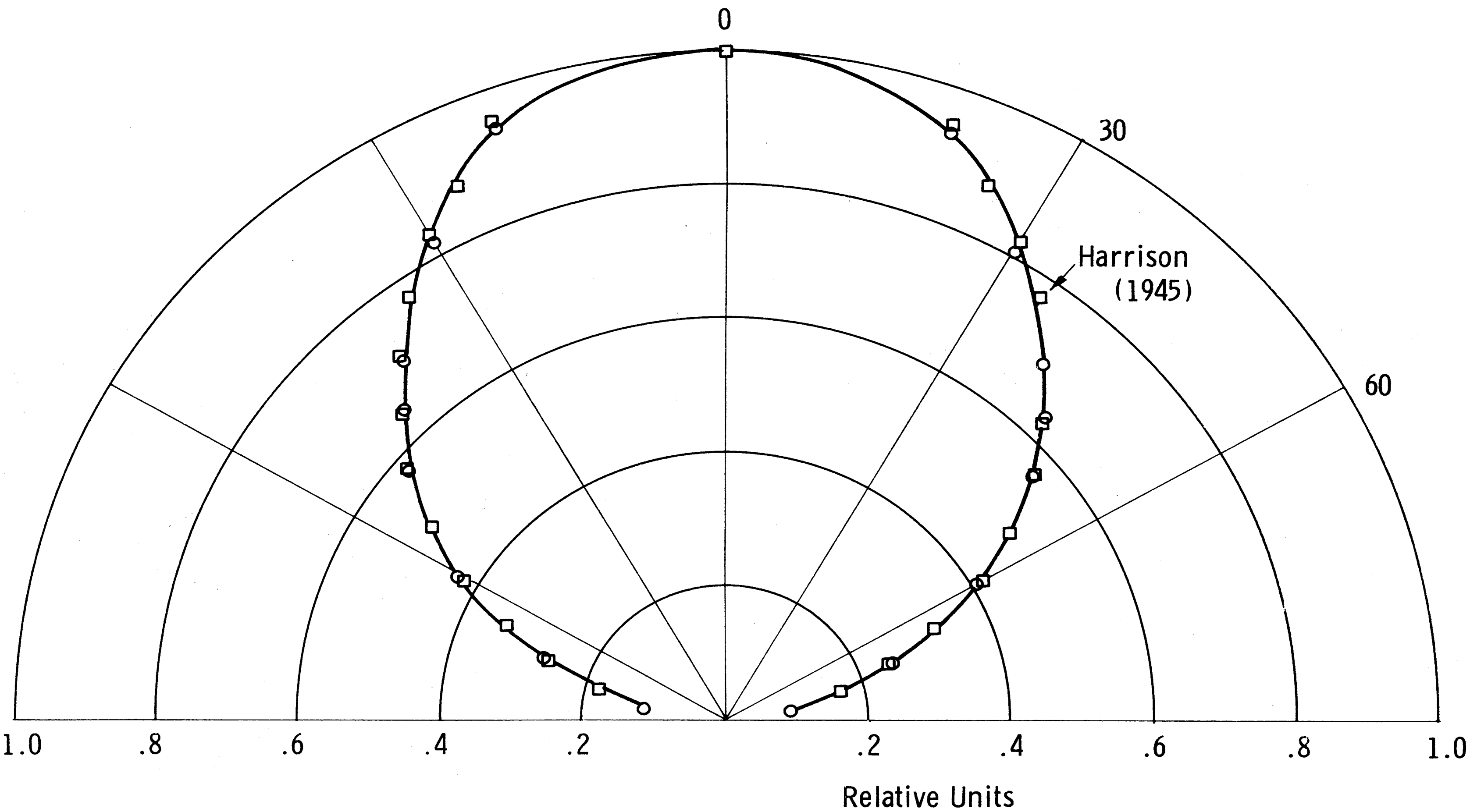

Fig. 7. Bidirectional reflectance pattern for MgO.

with the result of V.G.W. Harrison. The good agreement verifies the accuracy of the technique.

The reflectance patterns shown in Fig. 6 are values integrated over the wavelength range of 0.2-5.0μ. These patterns are not expected to apply for the spectral reflectance at all wavelengths. Evidence for this was obtained by measuring the ratio of spectral reflectance at 45° to that at 0° for an incidence angle of 45°. This ratio is plotted in Fig. 8 for the wavelength range of 0.4-2.4μ.

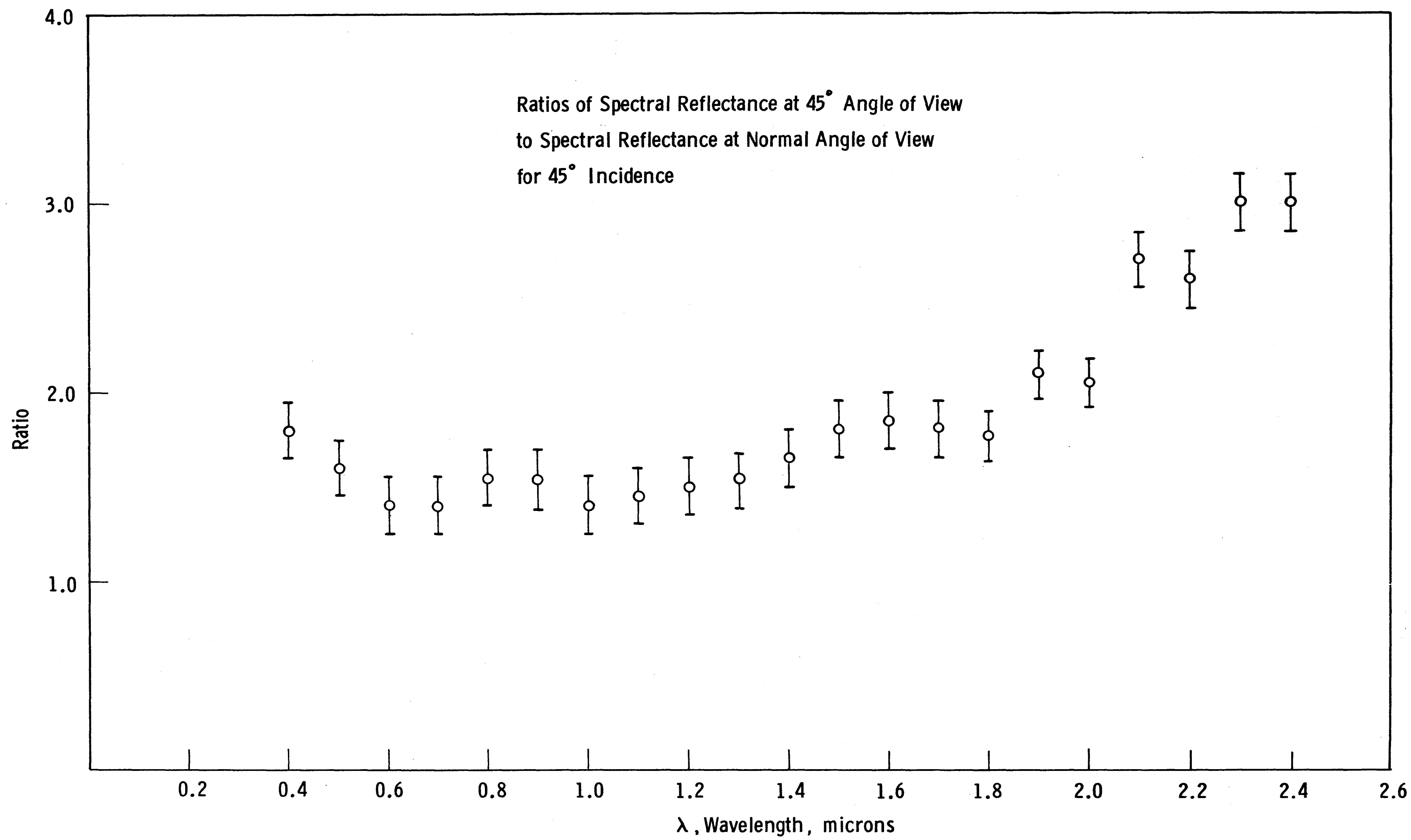

Fig. 8. Curve showing wavelength dependence of bidirectional reflectance of Kodak <u>White Paper</u>.

4. CONCLUSIONS

The data shown in Fig. 5 are the spectral directional reflectance of Kodak white paper. The data are probably quite accurate for wavelengths less than 2.6μ. For wavelengths greater than 2.6μ, the data are probably not quite as reliable. The uncertainty becomes greater with increasing wavelength.

The data of Fig. 6 and 8 indicate that it is not correct to assume that Kodak white paper has prefectly "diffuse" reflectance. This assumption will not lead to large errors if the paper is used at nearly normal angles of incidence and reflectance. For angles of incidence and reflectance greater than 20°, however, it is necessary to consider the bidirectional reflectance characteristics of the paper. Additional data on the bidirectional reflectance are needed for such an application.

5. REFERENCES

1. National Aeroanutics and Space Administration and United States Weather Bureau, TIROS II Data User's Manual." NASA—Goddard Space Flight Center, Greenbelt, Md. August 15, 1961. (Available upon request from the Aeronomy and Meteorology Division, NASA—Goddard Space Flight Center.)

2. Edwards, D. K., "Measurement of Thermal Radiation Characteristics," paper A63-18311 presented at the IES 1963 Annual Technical Meeting, Proceedings, pp. 417-424.

6. APPENDIX:

A REVIEW OF THE REFLECTANCE CHARACTERISTICS OF SMOKED MAGNESIUM OXIDE SURFACES

6.1. INTRODUCTION

Although the reflectance characteristics of a smoked magnesium oxide surface have been investigated extensively, each investigation has dealt with one or two aspects and thus information is widely spread in the literature.

During the past two years, information on smoked magnesium oxide has been gathered at The University of Michigan High Altitude Engineering Laboratory for reference with the use of smoked magnesium oxide as a diffusely reflecting medium. It appears appropriate at this time to summarize the results. This is not intended to be a complete bibliographical survey.

It is recommended that this note be used as a reference in laboratory use and preparation of smoked magnesium oxide.

6.2. METHOD OF PREPARATION

The method of preparing smoked magnesium oxide has been the subject of some controversy; however, there are now two methods which have gained acceptance. In the first method, practiced at the National Bureau of Standards, magnesium turnings are burned in a zirconium dish, the freely burning molten magnesium raked into a block, and the smoke allowed to deposit on the surface. In the second method, a magnesium ribbon is burned in air and the rising stream of smoke allowed to deposit upon the surface. In both cases, the surface is kept away from the flame of the burning magnesium in order to minimize uneven deposit by the turbulent rising stream of smoke.

It has been shown that both methods provide surfaces of a high reflectance, and the two methods are shown to produce surfaces with reflectances which agree to with ±0.3% throughout most of the visible spectrum.[1]

There have been many experiments with various thicknesses of magnesium oxide layer and backing surfaces; however, it is generally agreed that the backing surface be clean and polished or silver-plated, and the minimum thickness of magnesium oxide is considered to be one millimeter, though Preston[2] found 1/3 mm thickness satisfactory and reproducible. G. W. Gordon-Smith[3] however, employed thickness of 1 mm on a silver-plated copper surface. V.G.W.

Harrison,[4] on the other hand, considers layers of 2-mm thickness desirable. Middleton and Sanders[1] also tested the effect of thickness and found that the reflectance in the .45-.65μ wavelength region could be improved from 94% to 97% by further coating. In view of the above it appears that a thickness of not less than 1 mm is required in order to produce a good reproducible surface.

6.3. DETERIORATION DUE TO AGING

One of the disadvantages of a smoked magnesium oxide surface is the fact that the surface deteriorates with time. C. L. Sanders and E.E.K. Middleton[5] measured the extent of deterioration to slow formation of brucite, Mg(OH). They point out, however, that the deterioration at 2.2μ is too large to attribute to the formation of brucite, even though the deterioration in the wavelength region 1.4μ ~ 1.9μ appears to be due to the formation of brucite.

Tests on a 16-month-old surface indicated that the deterioration is very slow after first few days. The tests also showed that the reflectance in the visible spectrum remained practically constant, while in the infrared spectrum the decrease was about 2 to 3%. In the ultraviolet spectral regions, deterioration of about 1% was observed during the first 13-month period. The investigation by Sanders and Middleton[5] was carried out for wavelengths up to 2.4μ and, as of this date, deterioration of reflectance above 2.5μ has not been investigated, although the spectral reflectance in the 1.0μ-15.0μ wavelength region has been measured.

6.4. EFFECT OF UV IRRADIATION

An increase in the reflectance in the spectral region .25-.55μ was observed by Middleton and Sanders[1] when a smoked magnesium oxide surface was exposed to ultraviolet radiation. It is shown that ultraviolet irratiation would increase the reflectance by as much as 3% in the .25-.40μ region. This effect of UV irradiation is considered to be due to bleaching, in which magnesium nitride, formed during the burning of magnesium in air, is slowly decomposed under the influence of ultraviolet radiation.

6.5. REPRODUCIBILITY

A variation in the reflectance between surfaces is expected even though the surfaces may have been prepared in an identical manner. The variation in the spectral reflectance may be due to several causes: unevenness of smoke deposit, thickness, impurities, and so forth. The effect of unevenness of deposit and variation in thickness can be eliminated by coating the surface with a sufficiently thick coating. The effect of impurities is believed to be negligible in view of the result obtained by Middleton and Sanders,[1] and the result obtained by I. G. Priest,[6] who found little change in the relative reflectance in the visible spectrum with grossly contaminated magnesium.

The surface prepared according to the method described by the National Bureau of Standards is considered to have maximum spread in the spectral reflectance of ±0.5%.

6.6. BIDIRECTIONAL REFLECTANCE CHARACTERISTIC

The investigation of the bidirectional reflectance characteristics[4] of a smoked magnesium oxide coating of 2-mm thickness on aluminum showed that for incidence angles up to 60° the patterns were, in general, ellipses. However, at 45° incidence it was found that the ellipses degenerated into a circle, and in this case Lambert's cosine law was obeyed within the accuracy of the measurement.

It was also found that for incidence angles greater than 60°, the reflectance patterns became irregular and at grazing angles, i.e., incidence angles of 80° or more specular components appeared in the reflectance.

The elliptic patterns were sections of a prolate spheroid for the incidence angle from 0° to 45°, and sections of a oblate spheroid for the incidence angles between 45° and 55°. This was in agreement with the early work of Angstrom in 1885.*

6.7. SPECTRAL REFLECTANCE

Spectral reflectance measurements have been made by many investigators for various spectral regions; some of the work is listed below.

A. H. Taylor[6]	.25 - .41μ
F. Benford, et al.[7,8]	.46 - .62μ and .24 - .36μ
E.E.K. Middleton and C. L. Sanders[1]	.25 - .85μ
C. L. Sanders and E.E.K. Middleton[5]	.60 - 2.4μ
J. T. Gier et al.[9]	1.0 -15.0μ

The diffuse spectral directional reflectance of smoked magnesium oxide in the spectral region .24μ-15.0μ is given in Fig. 9. It is noted that the figure represents an average value of various measurements over various spectral regions as listed above. It is also noted that the agreement between various results throughout the spectrum was better than ±2%, although the maximum spread was ±6% in the ultra violet region.

*Angstrom, K., Annals of Physics (Leipzig), Vol. 26, 1885, p. 253.

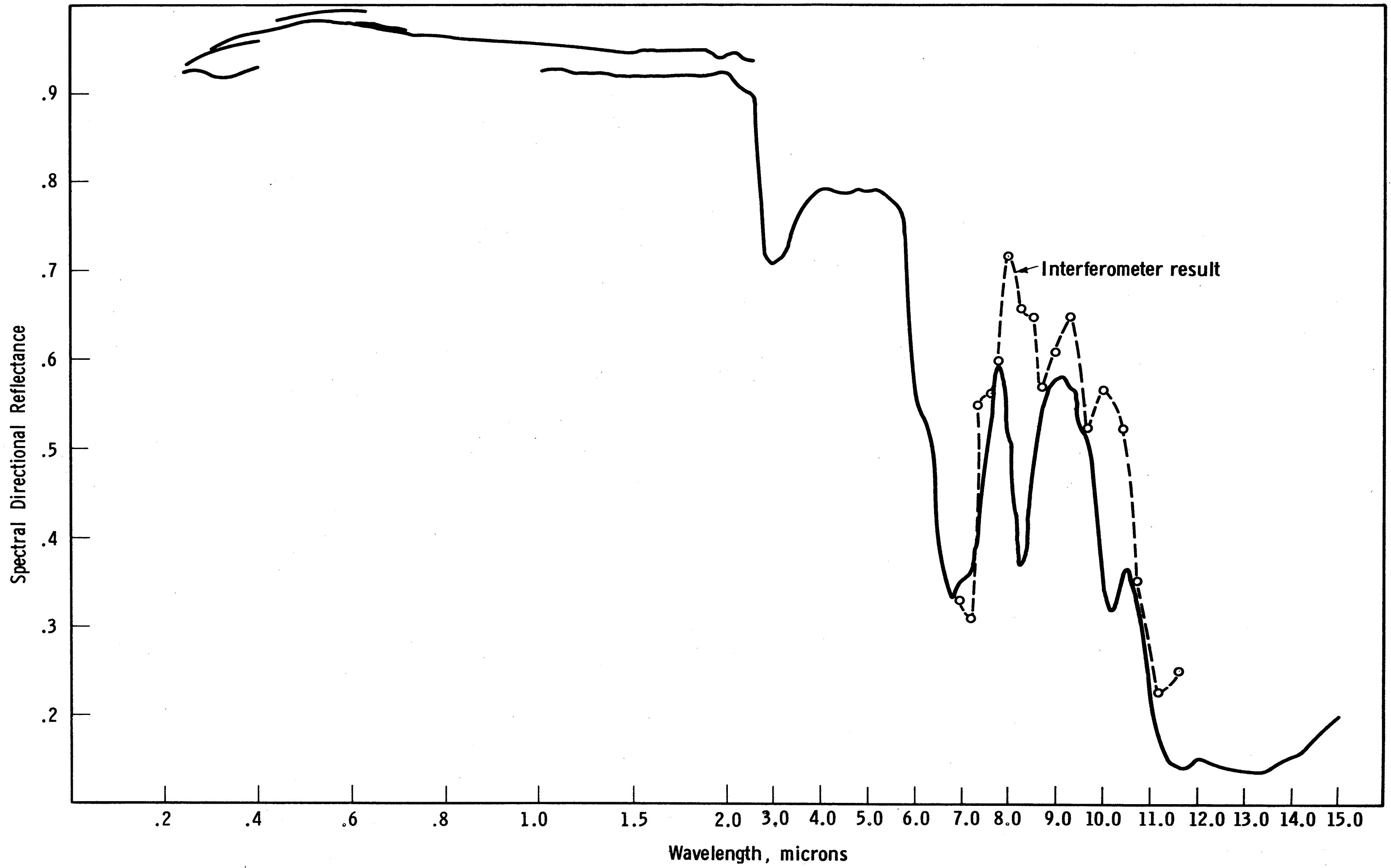

Fig. 9. Spectral directional reflectance of smoked magnesium oxide surfaces.

6.8. DISCUSSION

The thickness of the coating affects the reflectance in the visible and the near-infrared regions, and it appears that the thickness of smoke deposits should not be less than 1 mm to insure the goodness of the surface. In the infrared region between 2.5μ and 15μ, the effect of thickness has not been fully investigated.

Since the amount of magnesium nitride affects the reflectance in ultraviolet, and the amount of magnesium nitride could vary from surface to surface, a maximum fluctuation of approximately ±3% should be expected in the reflectance in the UV region from surface to surface. In the visible portions of the spectrum, however, the reflectance appears to be affected neither by aging nor by UV irradiation. In the near-infrared region, i.e., .8μ-2.4μ, the amount of brucite could cause variations in the reflectance from surface to surface; however, a large variation may be avoided by coating the surface anew whenever the MgO surface is used as a reflecting medium. In the far-infrared region (2.4μ-15μ), the effect of thickness and aging is now known, and a considerable deviation in a particular surface may result from the reflectance values given in Fig. 9.

It is noted that the values of Fig. 1 should be considered as an indication of the reflectance and their limitations should be borne in mind, should it be necessary to use these values.

6.9. REFERENCES

1. Middleton, E.E.K., and Sanders, C. L. "The Absolute Spectral Diffuse Reflectance of Magnesium Oxide" J. Opt. Soc. Amer. 41, 419, 1951.

2. Preston, J. S. "The Reflection Factor of Magnesium Oxide" Trans. Opt. Soc. (London) 31, 15, 1929-30.

3. Gordon-Smith, G. W. "The Spectral Reflection Characteristics of a Smoked Magnesium Oxide Surface" Proc. Phy. Soc. (London) B65, 275, 1952,

4. Harrison, V.G.W. "The Light-Diffusing Properties of Magnesium Oxide" Proc. Phy. Soc. (London) 58, 403, 1946.

5. Sanders, C. L., and Middleton, E.E.K. "The Absolute Spectral Diffuse Reflectance of Magnesium Oxide in the Near Infrared" J. Opt. Soc. Amer. 43, 58, 1953.

6. I. G. Priest and J. O. Riley, J. Opt. Soc. Amer. 20, 178, 1950.

7. Benford, F., Lloyd, G. P., and Schwalz, S. "The Coefficient of Reflection of Magnesium Oxide and Magnesium Carbonate" J. Opt. Soc. Amer. 38, 445, 1948.

8. Benford, F., Schwalz, S., and Lloyd, G. P. "Coefficient of Reflection in the Ultraviolet of Magnesium Carbonate and Oxide" J. Opt. Soc. Amer. 38, 964, 1948.

9. Gier, J. T., Dunkel, R. V., and Bevans, J. T. "Measurements of Absolute Spectral Reflectivity from 1.0 to 15 Microns" J. Opt. Soc. Amer. 44, 558, 1954.