Barbrow

NATIONAL BUREAU OF STANDARDS REPORT

8626

Semiannual Technical Report
July 1, 1964 to December 31, 1964

Infrared Optical Measurements

Progress and Status as of December 31, 1964

Metrology Division
National Bureau of Standards
Washington, D. C.

Supported in part by the
Advanced Research Projects Agency

ARPA Order 376-62
Project Code No. 7300

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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* NBS Group, Joint Institute for Laboratory Astrophysics at the University of Colorado.

** Located at Boulder, Colorado.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT **NBS REPORT**

December 31, 1964 8626

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CONTENTS

Infrared Optical Measurements

1. Objectives:

The Advanced Research Projects Agency, Department of Defense, requested the Metrology Division of the National Bureau of Standards to implement a program of development of standard measurement procedures and measurement of infrared optical materials. The program has as its objectives:

a. The determination of optical scattering values of infrared materials.

b. The determination of the emissivity of optical materials.

c. The determination of refractive index of materials as a function of temperature from -180° to +1000°C and from 1900 Angstroms to 50 microns.

d. The establishment of a refractive index testing and calibration service covering the portion of the spectrum from 1900 Angstroms to 50 microns.

e. The determination of optical homogeneity of infrared materials.

f. The development of wavelength standards for use in the calibration of spectrophotometers.

2. Status:

This is the thirtieth month of this program which began on June 28, 1962; it is financed in part by the Advanced Research Projects Agency; it is coordinated with the Infrared Information Analyses Materials Group under the chairmanship of Mr. William Wolfe, University of Michigan; and with the Committee for target finding and anti-camouflage of the Institute for Defense Analyse; the Infrared Information Symposium; and other committees interested in infrared measurements and standards; such as the Committee on Aerial Survey of crops and animals, National Research Council--National Academy of Sciences.

1. Homogeneity Measurements

by

F. W. Rosberry

The shadowgraph method of observing striae is used for the detection of areas of large change in index of refraction. Photographs were made of samples by this method and gradation of striae content determined by comparison with the striae standards for optical glass at this bureau. Prior to this reporting only visual comparison with the standards were made. During this period, the standards were shadowgraphed and now comparisons can be made by comparing photographs which involves much less handling of the standards. A photograph of the standards is shown in Figure 1. with some detail probably lost in reproduction. Microdensitometer traces of the negative were made but to date a number value has not been determined to represent the various ranges of transmittance values indicated for each grade of glass.

A technique was tried to determine the effect the various grades of samples had on imagery when used as windows in front of a lens. The modulation transfer function of a good lens was determined and samples representing several grades of striae content were each used as a window on the object side of the lens. A new MTF curve was then determined with the lens-sample combination and then compared with the lens-only MTF curve. The correlation between the grade of sample as determined by Δn gradient, and amount of image spoiling was very good out to spatial frequencies of 100 lines/mm. Beyond this point one out of the five samples did not fall in its expected position.

During this period a He-Ne gas laser was obtained as a source for the interferometer. It is constructed to lase at a wavelength of 1.15μ in the IR region. This source gives an irregular light distribution pattern in the interferometer as shown superimposed on the fringe pattern of the sample of silicon shown in Figure 2. This mode structure is not a serious detriment to fringe patterns but has so far proved disastrous to attempts at shadowgraphing samples.

Plans for the I. R. Interferometer are about completed and specifications for components have been sent to three manufacturers with returns received from two. It is planned to buy the optical components and mounts but make the bed and ways and do the assembling here.

Samples of materials observed and examined during this reporting period are shown in Table I.

Table I

Material	Source
Fused Silica Type C-151	General Electric Company
Glass Type 457	Owens-Illinois
Irtran I	Hughes Aircraft Company
Silicon	Hughes Aircraft Company
Silicon	Texas Instruments Company

Figure 1. Shadowgraph of four standards for striae grades in optical glass.

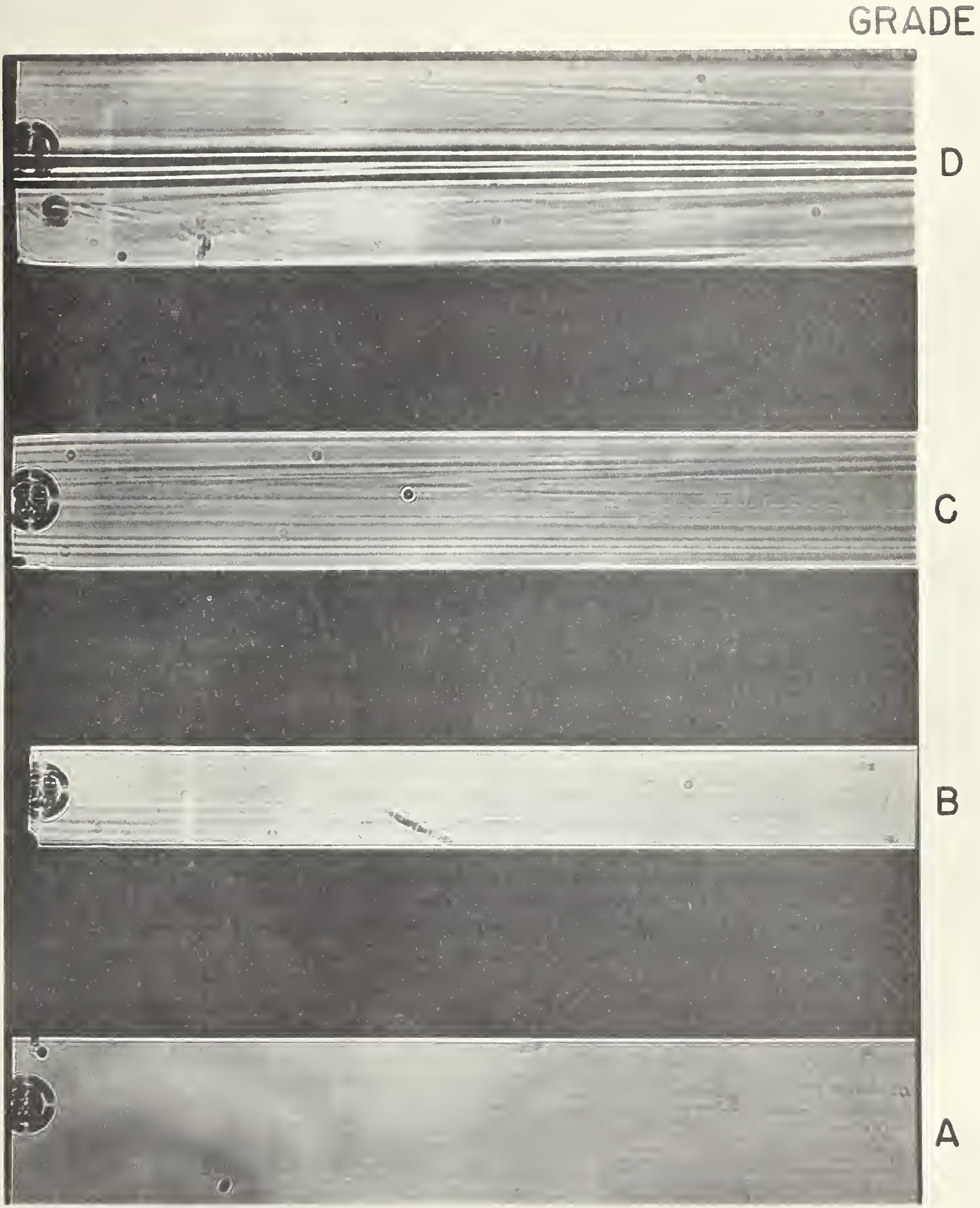


FIGURE I

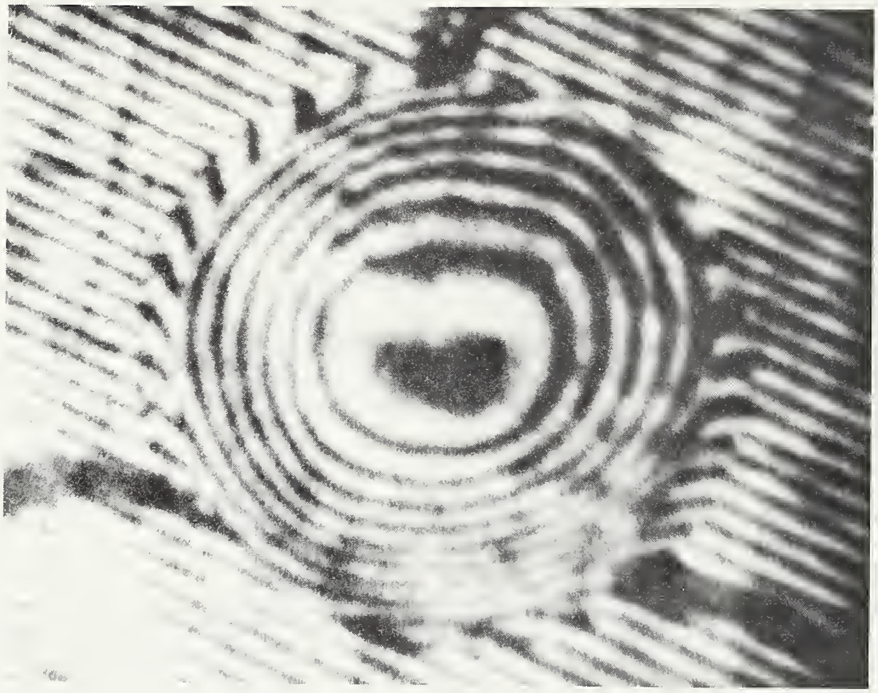


Figure 2. Interferogram of a disc about 8 mm thick of silicon submitted by Hughes Aircraft Co. The sample was not prepared for interferometric examination as evidenced by the spherical shape of the surfaces and the wedge indicating a difference in thickness between lower left and top right of the circular sample.

2. Infrared Hazemeter

by

B. P. Caldwell, D. G. Goebel and H. K. Hammond III

The instrumentation has been refined (see Figs. 3-6) and measurements have een made on three samples of Irtran I (Eastman Kodak material procured in uly, 1964) cut from the same piece in thicknesses of 2, 4, and 8 mm. The hazeeter was equipped with a flame-sprayed, aluminum-coated sphere and this sphere as used for these measurements. Data obtained at 9 wavelengths (.4 to 3.0μ) ith interference filters and lead-sulfide detector are shown in Table II. recision at 0.6 through 2.5 microns with the lead-sulfide detector is estimated o be 0.5%, while above or below these wavelengths the precision is lower because f decreasing detector sensitivity. The instrument has been used regularly with lead-sulfide cell, but it has been modified to use a multiplier phototube to xtend the spectral range to the near ultraviolet.

Table II

Haze and **Percent** Transmittance of Irtran-I Specimens

Wavelength, $\lambda(\mu)$		.4	.5	.6	.7	1.0	1.5	2.0	2.5	3.0
Thickness (mm)										
2	H*	100	99	95	89	65	30	15	8	9
	T_s	0	1	5	11	33	61	75	81	84
	T_d	89	92	92	89	60	27	14	7	8
	T_t	89	93	97	100	94	88	88	89	92
4	H	96	100	100	99	87	51	29	17	18
	T_s	3	0	0	1	11	39	58	70	70
	T_d	63	72	79	84	72	41	24	14	16
	T_t	66	72	79	85	83	81	82	84	85
8	H	99	99	100	100	100	89	68	47	36
	T_s	0	0	0	0	0	7	22	38	49
	T_d	27	35	43	50	59	58	48	34	27
	T_t	28	36	42	50	59	66	71	72	75

*Key: H = haze, T_s = rectilinear (straight-through) transmittance, T_d = diffuse transmittance, T_t = total transmittance.

Figure 3. Overall view of infrared hazemeter.

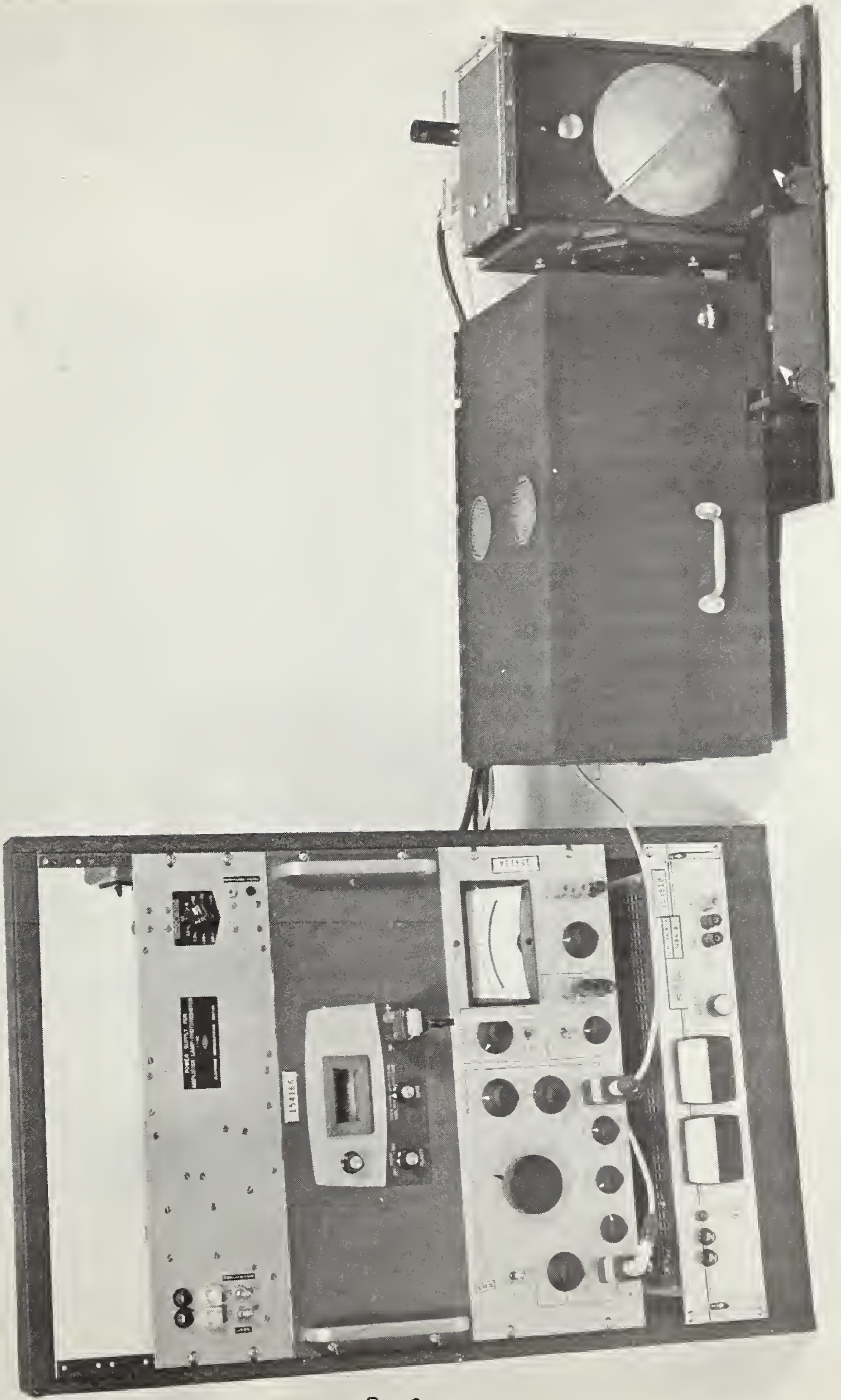


FIG 3
Pg 10

Figure 4. Electronic component rack of infrared hazemeter.

(a) power supplies constructed at NBS for the lead sulfide detector, the preamplifier and the reference lamp.
(b) digital voltmeter.
(c) Princeton Applied Research (PAR) syncronous amplifier.
(d) Sorensen regulated power supply for source lamp.

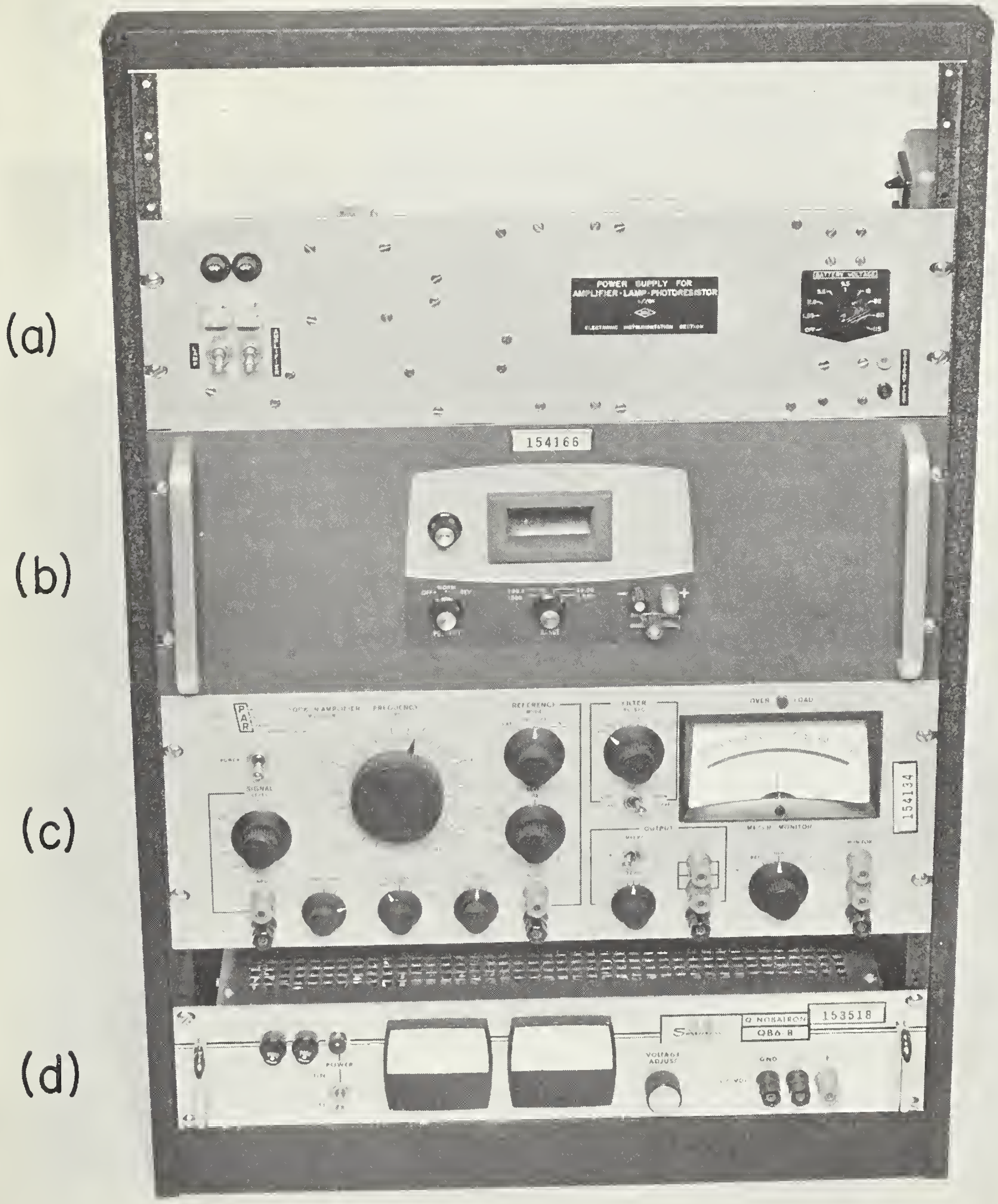

(a)
POWER SUPPLY FOR
AMPLIFIER-LAMP-PHOTORESISTOR
ELECTRONIC INSTRUMENTATION SECTION
BATTERY VOLTAGE
LAMP
AMPLIFIER
(b)
154166
(c)
PAR
LOCK-IN AMPLIFIER
FREQUENCY
REFERENCE
FILTER
OVERLOAD
POWER
SIGNAL
OUTPUT
METER MONITOR
154134
(d)
Q NOBATRON
153518
QB6 B
POWER
VOLTAGE ADJUST
GND
+

FIG 4

Figure 5. Source housing for infrared hazemeter providing chopped collimated flux filtered by interference filters.

- (a) Source lamp (quartz envelope, Iodine vapor, tungsten filament, 60W).
- (b) 30 cps chopper for both source and reference beams (reference lamp and reference detector, a solar cell hidden from view by chopper motor mount).
- (c) Holder for interference filter.

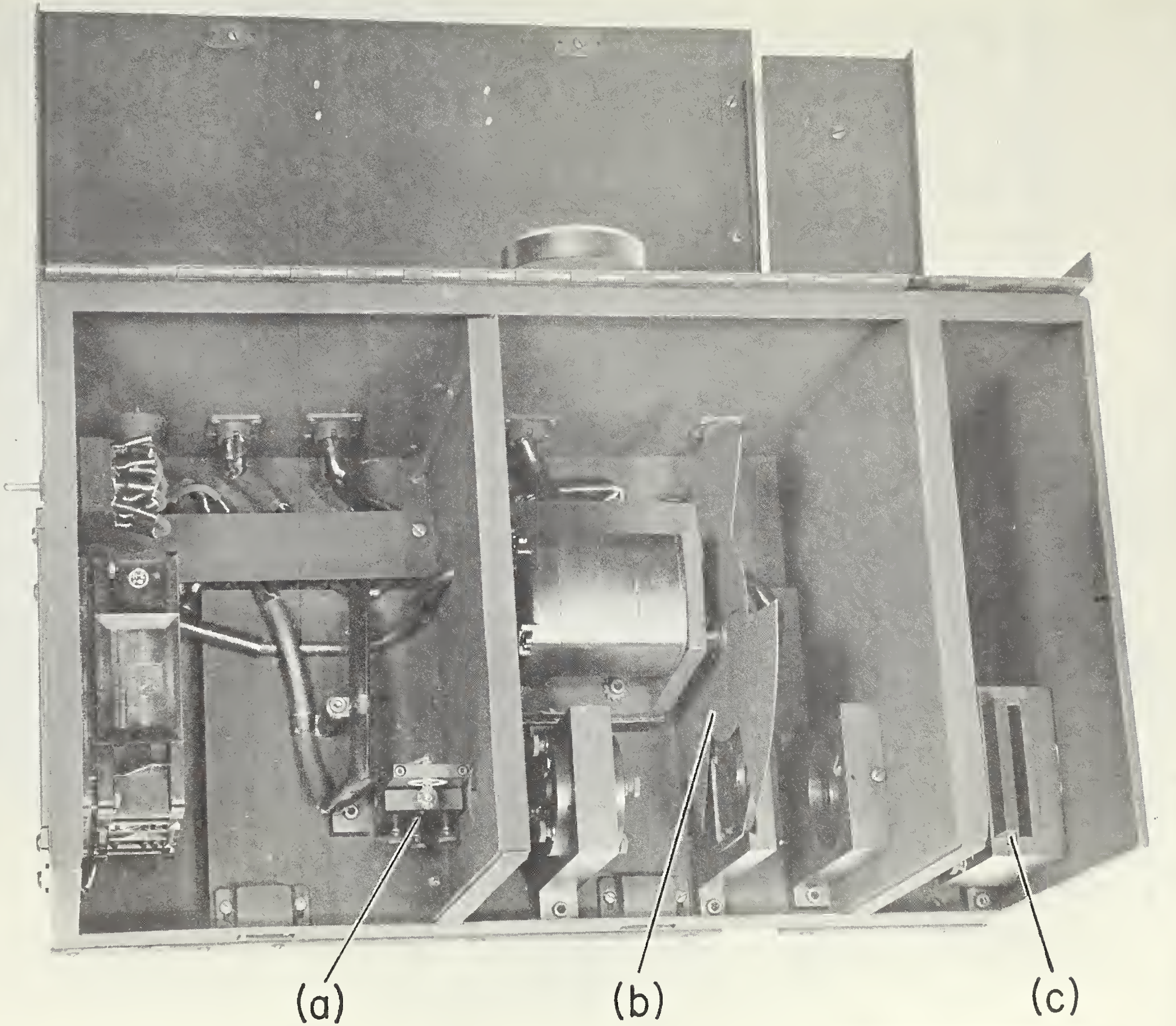


Fig 5

Figure 6. Source unit (See Figure 5); and sphere and detector unit of infrared hazemeter showing:

- (a) sample position
- (b) integrating sphere
- (c) lead sulfide detector housing
- (d) preamplifier constructed at NBS to match lead sulfide detector to PAR syncronous amplifier.

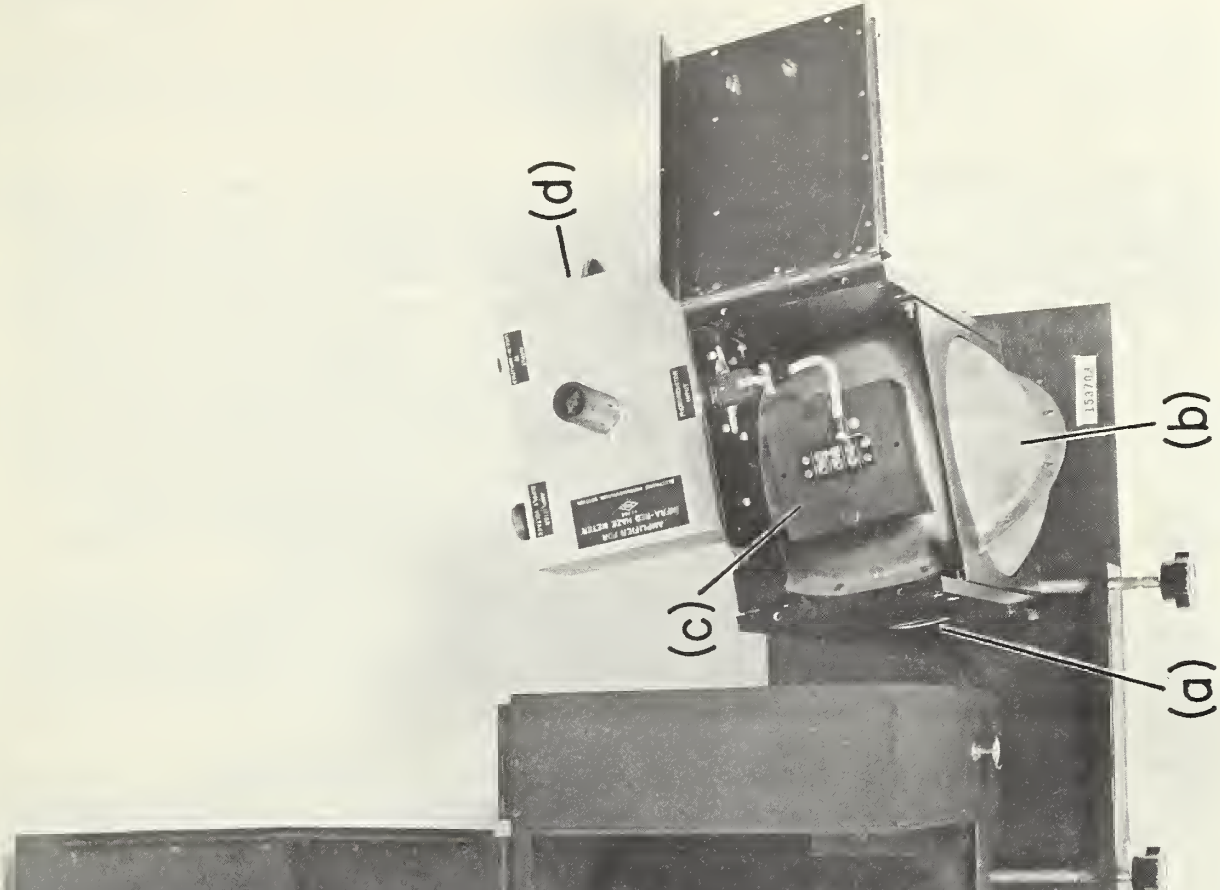


Fig 6

3. Refractive Index Measurements

by

I. H. Malitson
M. J. Dodge

Index of refraction data for high-purity optical quality fused silica (SiO_2) at 20°C were given in the semi-annual report of June 30, 1964. From these data two quantities are obtained that may be used in early stages of optical design as graphical aids (Fig. 7) for estimating the dispersive properties of SiO_2 as a function of wavelength. The quantity $\frac{-dn/d\lambda}{n-1}$ is the ratio of dispersion relative to deviation and serves as a datum for estimating the dispersive power of the material. The shape of the curve shows that the dispersion decreases with increasing wavelength, passes through a minimum near 1.3 microns, then increases again as it approaches the cutoff near 4.0 microns. In fact, SiO_2 is known to be highly dispersive in the 2.0 to 4.0 micron region when compared to other infrared materials. The reciprocal relative dispersion $\left[\frac{-dn/d\lambda}{n-1}\right]^{-1}$ is analogous to the ν-value of the visible region of the spectrum. An increase in this parameter corresponds to a reduction in the contribution to chromatic aberration of a lens made of this material. The curve illustrates that chromatism may be minimized near 1.5 microns.

Specific accomplishments during the present report period are:

(1) The refractive index of one sample of fused silica was re-measured from 0.21 to 3.7 microns at 30°C to determine the thermal coefficient of index, dn/dt. The results are shown graphically in Fig. 8. The coefficients are positive over the measured wavelength range. The value of dn/dt decreases from about 15×10^{6}/°C at 0.21 μ to about 10×10^{6}/°C at 0.4 μ and remains constant at this value through the visible region. The coefficient increases slowly to about 11.5×10^{6}/°C near 2.0μ, then decreases to about 10×10^{6}/°C at 3.7μ. This concludes the investigation of the refractive properties of SiO_2 currently commercially produced in this country. A comprehensive report on the results has been prepared for publication in the Journal of the Optical Society of America.

(2) Refractive index measurements were made on 24 experimental glass formulated by G. W. Cleek of the NBS Glass Section. These are ternary glasses consisting of $BaO-Nb_2O_5-SiO_2$ and transmit to about 5μ for a thickness of 2mm. Index determinations were made with an accuracy of 1×10^{-5} from 0.4 to 1.014μ. The results are shown on Fig. 9 along with computed Abbe number or ν-values.

(3) A number of optical prisms and wedges were tested and calibrated for DOD industrial contractors to determine compliance with contract specifications. The demand for this service has been unusually heavy during this report period, e.g. at the request of Bausch and Lomb Inc., the refractive indices of 13 samples of glass were measured with an accuracy of $\pm 5 \times 10^{-6}$. These are special melts developed for the Air Force and we have been asked not to make public the results of our determinations.

Instrumentation:

The Gaertner Scientific Corp. presented preliminary drawings of a proposed spectrometer using the moire fringe technique for measuring angular displacement. The feasibility of this design is under consideration.

Papers:

"Refractive Index of High-Purity Fused Silica", by I. H. Malitson, published in Proceedings of the Infrared Information Symposia, Vol. 9., No. 3, Sept. 1964.

"Interspecimen Comparison of the Refractive Index of Fused Silica", by I. H. Malitson, presented at October 1964 meeting of the Optical Society of America.

Figure 7. The quantity $\frac{-dn/d\lambda}{n-1}$ defines the dispersion relative to deviation at a chosen wavelength. Contribution to chromatic aberration decreases as reciprocal relative dispersion $\left[\frac{-dn/d\lambda}{n-1}\right]^{-1}$ increases. Dashed portion of the curve indicates region of strong H_2O absorption band.

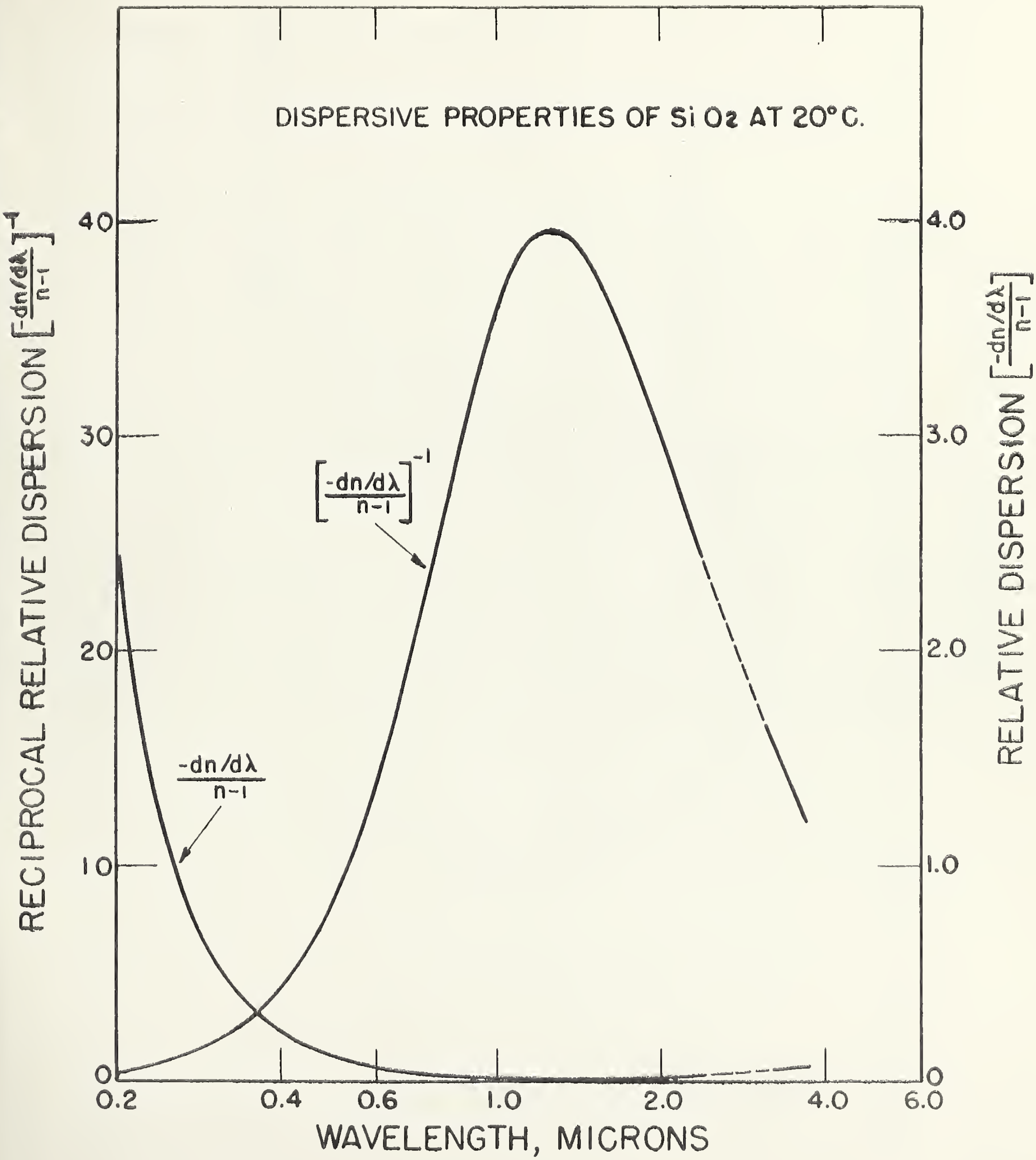

DISPERSIVE PROPERTIES OF Si O2 AT 20°C.
RECIPROCAL RELATIVE DISPERSION $\left[\frac{-dn/d\lambda}{n-1}\right]^{-1}$
RELATIVE DISPERSION $\left[\frac{-dn/d\lambda}{n-1}\right]$
$\left[\frac{-dn/d\lambda}{n-1}\right]^{-1}$
$\frac{-dn/d\lambda}{n-1}$
0
10
20
30
40
0
1.0
2.0
3.0
4.0
0.2
0.4
0.6
1.0
2.0
4.0
6.0
WAVELENGTH, MICRONS

FIG. 7

Figure 8. Thermal coefficient of index for a mean temperature of 25°C.

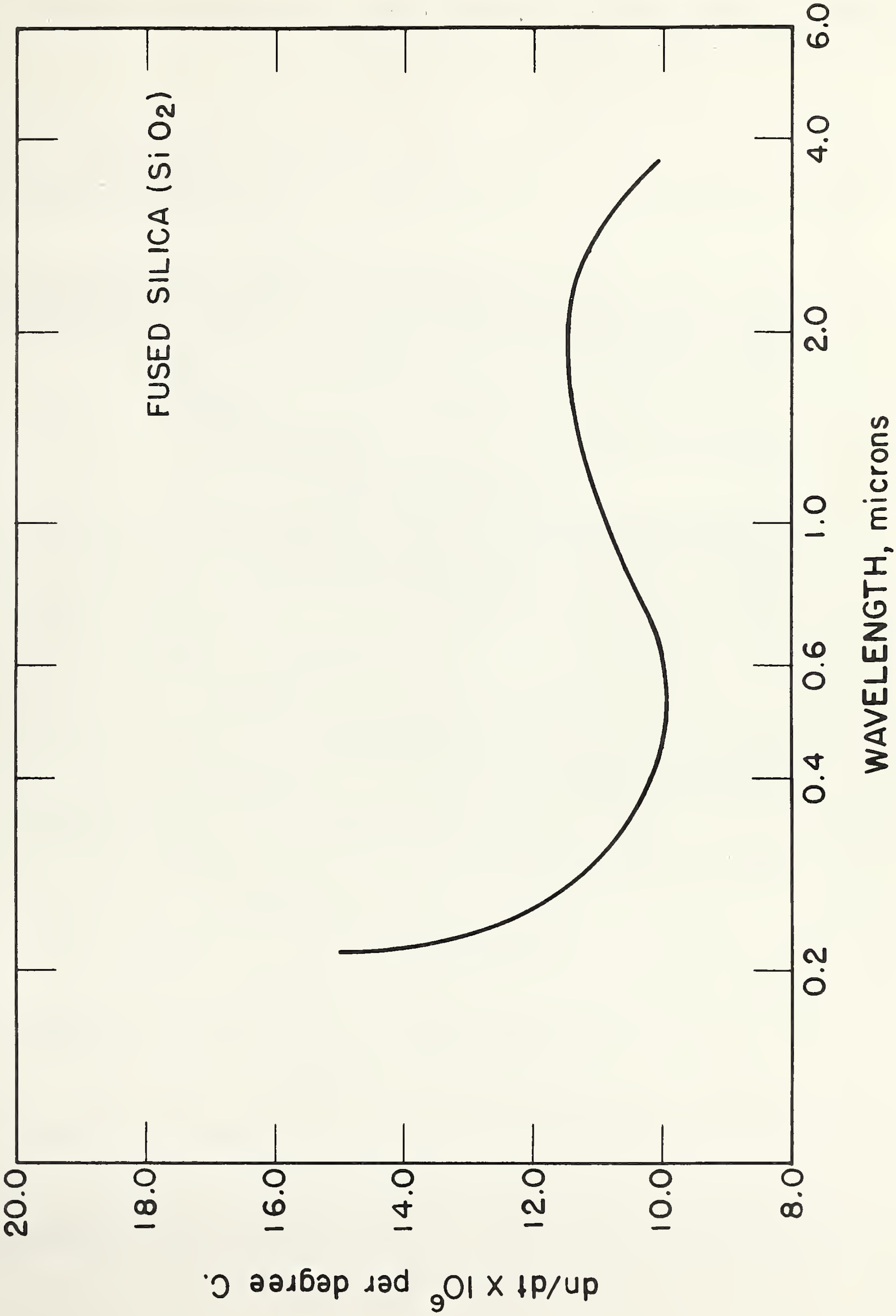

FUSED SILICA (Si O2)
WAVELENGTH, microns
0.2
0.4
0.6
1.0
2.0
4.0
6.0
dn/dt X 10^6 per degree C.
8.0
10.0
12.0
14.0
16.0
18.0
20.0

FIG. 8

Figure 9. Refractive indices and Abbe numbers for glasses consisting of BaO-Nb_2O_5-SiO_2.

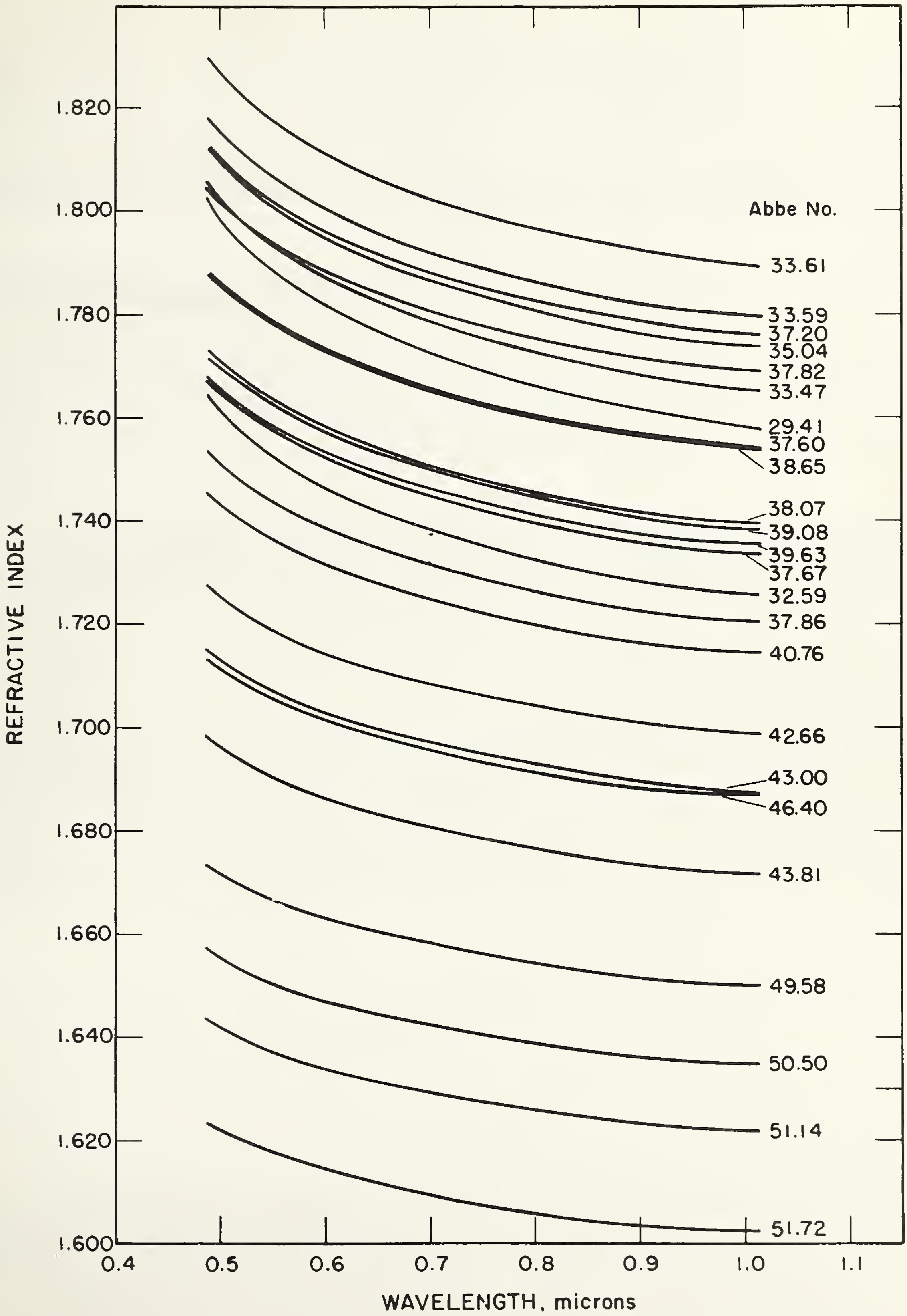

REFRACTIVE INDEX
1.820
1.800
1.780
1.760
1.740
1.720
1.700
1.680
1.660
1.640
1.620
1.600
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
WAVELENGTH, microns
Abbe No.
33.61
33.59
37.20
35.04
37.82
33.47
29.41
37.60
38.65
38.07
39.08
39.63
37.67
32.59
37.86
40.76
42.66
43.00
46.40
43.81
49.58
50.50
51.14
51.72

FIG. 9

4. Spectral Emissivity

by

W. Fussell and J. Geist

I. Instrumentation:

The original Perkin-Elmer thermocouple radiation detector in the Model 112 Infrared Spectrophotometer has been replaced by a more sensitive Reeder thermocouple (Model RP-5W); the improvement in signal-to-noise ratio is a factor of roughly three. (The spectrophotometer is used to compare the spectral radiance of the blackbody and the sample whose emissivity is being measured).

The spectrophotometer, the external mirrors, and the blackbody and sample ovens (of the equipment for measuring emissivity) have been realigned more accurately, and additional optical baffles have been installed. This has reduced the background sample oven radiation (with no sample) to 5%-or less-of the blackbody radiation, an improvement of about a factor of 4 over the previous background levels.

A blackbody with an aperture (5/8 inch diameter) large enough to tolerate small observations and misalignment in the optical system of the spectroradiometric system has been fabricated and tested; as expected, its measured emissivity was slightly higher than that of the previously used blackbody.

II. Measurements:

A. The spectral emissivities of samples of pure germanium from the Valpey Corporation have been measured as follows: (1) Sample thickness approx. 2mm; normal spectral emissivity measured at 200°C at 12, 10, 8, 6, 4 microns wavelength; at 400°C at 12, 10, 8, 6, 4, 2 microns; at 600°C at 14, 12, 10, 8, 6, 4, 2, 1.8, 1.6, 1.4 microns. (2) Sample thickness approx. 8mm; emissivity measured at 300°C at 12, 10, 8, 6, 4 microns; at 400°C at 12, 10, 8, 6, 4, 2, 1.6 microns.

Sample oxidation was noted at 600°C.

At the 2mm thickness, emissivities at all wavelengths invariably increased with temperature (measurements on the 8mm sample are still in progress). Emissivities significantly greater than 1.0 were observed at 600°C at wavelengths of 2, 1.8, 1.6, 1.4 microns. This phenomenon is believed due to infrared fluorescence of the germanium.

B. The spectral emissivities of samples of IR-3 (polycrystalline calcium fluoride) from Eastman Kodak Company and single crystal calcium fluoride from Harshaw Chemical Company have been measured. (Figs. 10 and 11). Sample thicknesses approximated 1, 3, 6mm and normal spectral emissivities were measured at 500 and 600°C at 12, 10, 8, 6, 4, 2 microns wavelength.

Sample deterioration was noted at 600°C. Normal spectral absorption coefficients were computed for IR-3 at 500 and 600°C from the spectral emissivity data and estimated values of the surface reflectance at these temperatures, for

6, 8, 10 microns wavelength. The computed absorption coefficients at 500 and 600°C, and at 8 and 10 microns, were of the order of 10 times the published data on the corresponding spectral absorption coefficients of fluoride at room temperature. The rate of increase of the spectral absorption coefficient of IR-3 with temperature at 8 and 10 microns, based on the published room temperature data for fluoride and the IR-3 emissivity data at 500 and 600°C (assuming the room temperature absorption coefficients of IR-3 to be close to the fluoride values), appears to be linear within the estimated limits of error.

III. Analysis of Data:

J. Geist has developed a mathematical procedure for approximately correcting infrared spectral transmittance data, obtained from a converging beam spectrophotometer, for the possible error introduced by this beam convergence.

IV. Paper:

A paper entitled "Approximate Normal Emissivity Spectra in the Infrared at Elevated Temperatures of Samples of Calcium Fluoride and IR-3," by Fussell and Geist, was delivered at the Fall, 1964 Meeting of the Optical Society of America.

Figure 10. Normal spectral absorption coefficient of single crystal CaF_2 at 600 and 500°C from 6 to 10 microns.

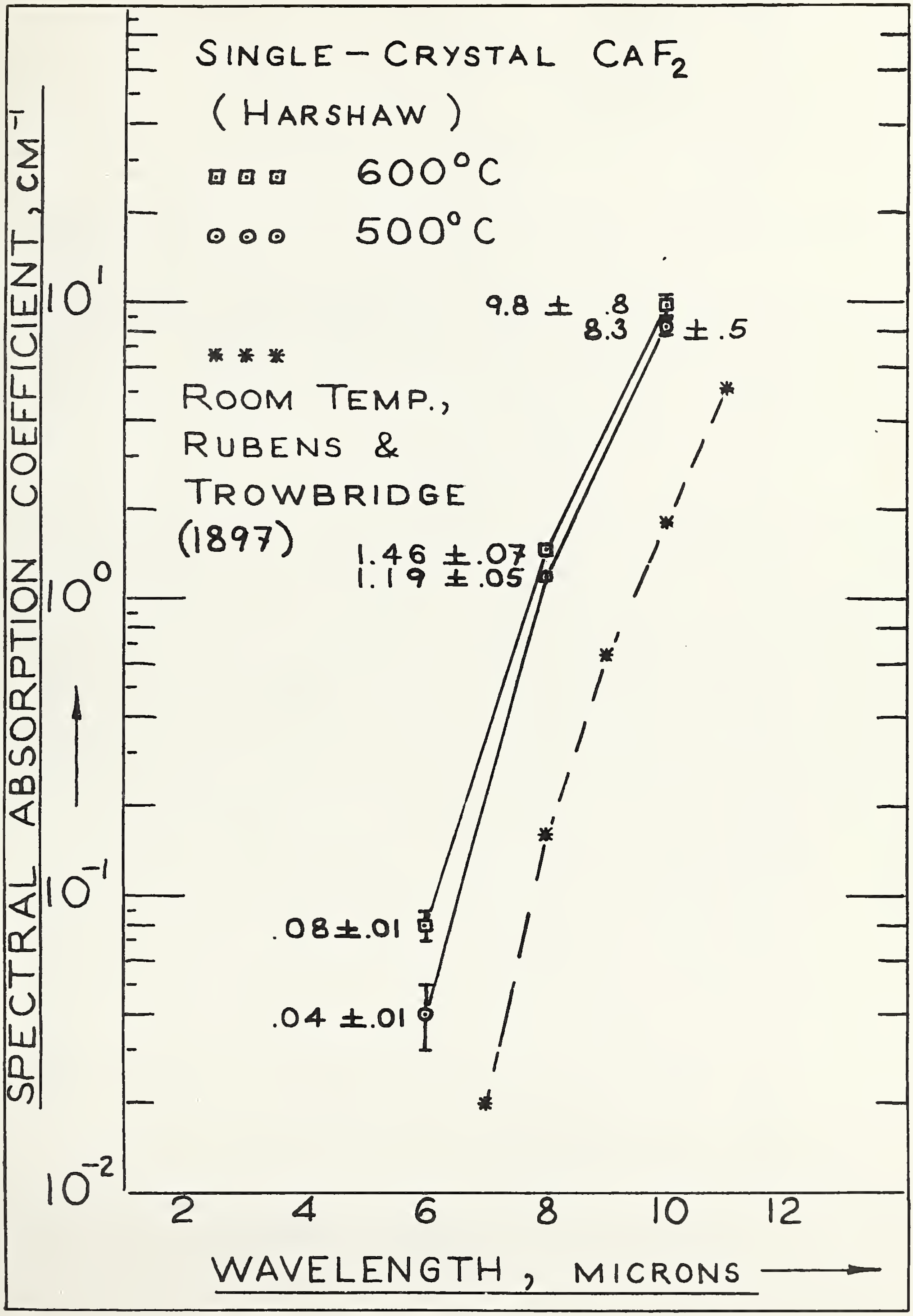

SINGLE-CRYSTAL CaF_2
(HARSHAW)
▫▫▫ 600°C
○○○ 500°C
✱✱✱
ROOM TEMP., RUBENS & TROWBRIDGE (1897)
9.8 ± .8
8.3 ± .5
1.46 ±.07
1.19 ±.05
.08±.01
.04 ±.01
SPECTRAL ABSORPTION COEFFICIENT, CM^{-1}
10^1
10^0
10^{-1}
10^{-2}
2
4
6
8
10
12
WAVELENGTH, MICRONS

Fig 10

Figure 11. Difference between the normal spectral absorption coefficients of IR-3 (polycrystalline CaF_2) and single-crystal CaF_2, at 600 and 500°C, fro 6 to 10 microns.

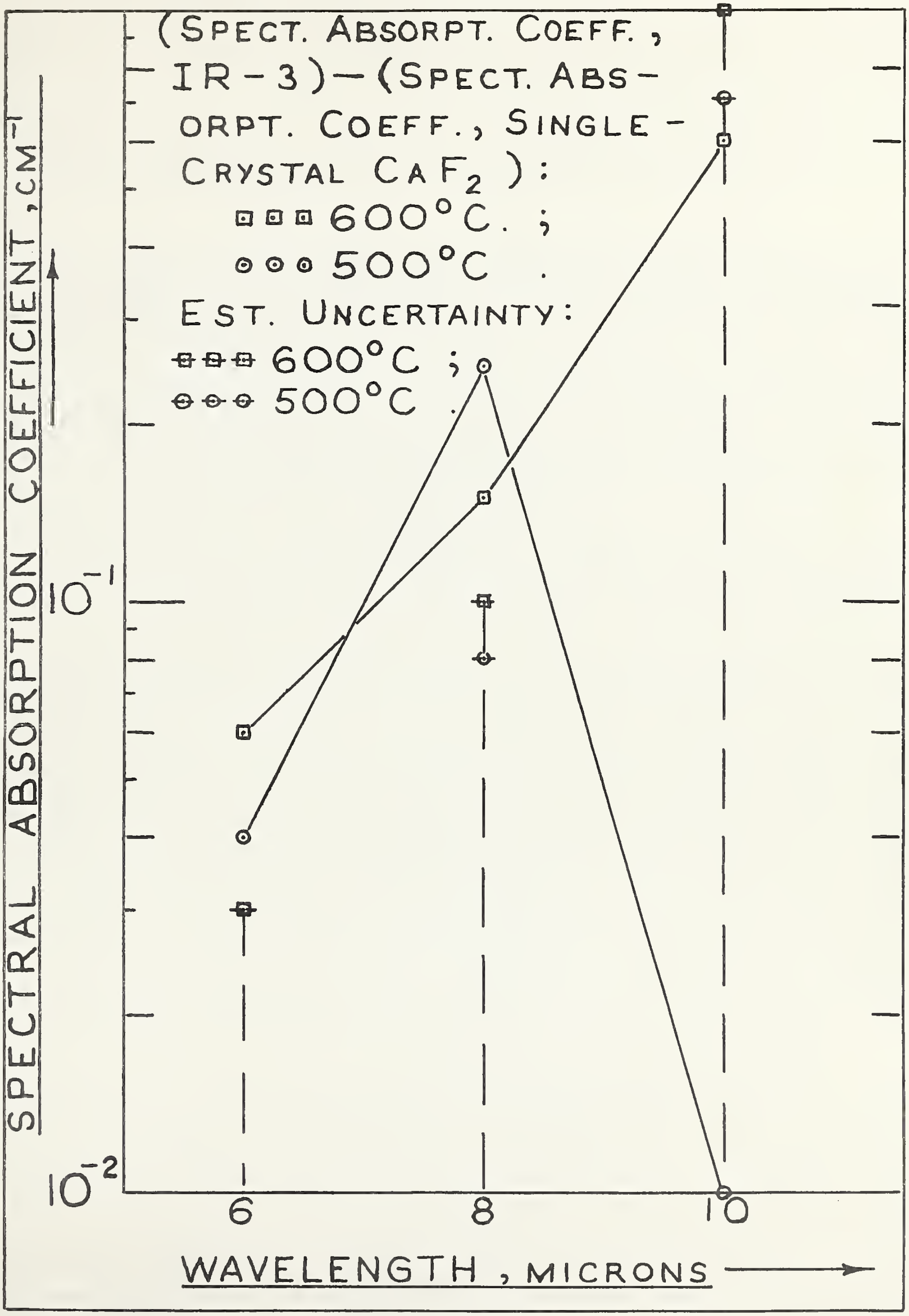

(Spect. Absorpt. Coeff., IR-3)—(Spect. Absorpt. Coeff., Single-Crystal CaF_2):
□□□ 600°C. ;
⊙⊙⊙ 500°C .
Est. Uncertainty:
600°C ;
500°C .
Spectral Absorption Coefficient, cm^{-1}
10^{-1}
10^{-2}
6
8
10
Wavelength, microns

Fig. 11

5. Spectral Properties of Naturally-Occurring and Man-Made Materials

by

J. C. Schleter, V. R. Weidner, and J. D. Kuder

At the request of the Institute for Defense Analyses, The Institute of Science and Technology (University of Michigan), and the Committee on Remote Sensing in Agriculture (NRC-NAS), and with the approval of ARPA, a number of measurements of spectral transmittance or spectral directional reflectance were made of specimens of leaves of both deciduous and coniferous trees, flower blossoms, soils, optical filters, paints, human skin (Figure 12), and various materials which have served as targets in scenes studied by aerial surveillance techniques. In addition to these measurements, a number of measurements of spectral transmittance have been made of optical filters in use at the NBS by others working on the Infrared Optical Measurements Project.

The specimens of naturally-occurring materials which have been measured are listed in Table III and the man-made materials are listed in Table IV, together with instrument used, wavelength region covered, and whether the measurement is of spectral transmittance or spectral directional reflectance.

The measurements of white oak leaves, listed in Table III, are part of a study of seasonal changes in the spectral reflectance of white oak leaves. The study was begun April 17, 1964 and completed November 2, 1964. The spectral directional reflectance and spectral transmittance of the leaves of a white oak tree located on NBS grounds were removed from the tree within 1/2 hour before measurement and measured at intervals of approximately 1 month during the summer months and at weekly intervals during the spring and fall. Measurements were made by means of a General Electric recording spectrophotometer over the wavelength range 0.4 to 1.08 microns and show that the spectral directional reflectance remained the same to within 2% or 3% during the summer months and that the noticeable changes occurred during the spring and fall. The spectral changes in the spring and fall are almost the reverse of each other with respect to the changes in the chlorophyll absorption band in the visible spectrum near 0.68 micron. (Figures 13(a) and (b)). The spectral transmittance data which were taken only during the summer and fall periods have not as yet been analysed.

The measurements of spectral directional reflectance of the needles of red pine and Ponderosa pine (Figures 14), listed in Table III for the indicated spectrophotometers and wavelength ranges, include healthy and treated specimens of red pine needles collected on four different dates during the fall and one set of healthy and diseased needles of the Ponderosa pine. These measurements were financed by the U. S. Department of Agriculture, Forest Service Insect Laboratory and the data are being analysed by their personnel.

The sample of gold-plated-stainless-steel mesh, listed in Table IV, has a Mylar backing. Measurements of spectral directional reflectance were made for the conditions of both included and excluded specular component on both the front surface (gold-plate-stainless-steel) and the back surface (Mylar). No complete analysis of the data has as yet been made. The reflectance of the front surface is approximately 20% from 0.26 to 0.5 micron, then increases to about 75% at 0.8 micron, and then increases slowly to about 90% at 2.5 microns. The Mylar backing has a reflectance of about 20% from 0.26 to 0.5 micron, then increases to only about 50% at 0.8 micron, then increases to about 60% at 2.0 microns, and then decreases to about 45% at 2.5 microns. Between 2.1 and 2.5 microns, there are numberous absorption bands due to the Mylar. These same results are found for either included or excluded specular component.

It should be noted that a number of the specimens listed in Tables III and IV have also been measured by means of the Cary-White 90 over the wavelength range 4000 to 400 cm^{-1} (2.5 to 22.2 microns). These measurements are described elsewhere in this Semiannual Technical Report.

The NBS Test Reports issued during this half-year period are listed in Table V by test number and title.

One paper has been published covering a portion of this work, "Spectral properties of plants," by D. M. Gates, H. J. Keegan, J. C. Schleter, and V. R. Weidner, Applied Optics, 4, 11 to 20, (1965).

Table III

Listing of naturally-occurring materials measured for spectral transmittance (T) or spectral reflectance (R) on the indicated recording spectrophotometers for the indicated wavelength ranges.

Specimen Identification	Recording Spectrophotometer	
	GE	Cary 14
American larch, needles (Larix laricina)	0.4-1.08μ (R)	0.26-2.5μ (R)
Alluvial soil*	0.4-1.08μ (R)	
Apple (diseased tree), bark	0.4-1.08μ (R)	0.26-2.5μ (R)
Apple (diseased tree), leaf	0.4-1.08μ (R)	0.26-2.5μ (R)
Apple (healthy tree), bark	0.4-1.08μ (R)	0.26-2.5μ (R)
Black spruce, needles (Picea mariana)	0.4-1.08μ (R)	0.26-2.5μ (R)
Blue spruce, needles	0.4-1.08μ (R)	0.26-2.5μ (R)
Bur oak, leaf (Quercus macrocarpa)	0.4-1.08μ (R)	0.26-2.5μ (R)
Clay soil*	0.4-1.08μ (R)	
"Heavenly Blue" morning glory, corolla	0.4-1.08μ (RT)	
Ponderosa pine (diseased tree), needle (Pinus Ponderosa)*	0.4-1.08μ (R)	0.35-2.5μ (R)
Ponderosa pine (healthy tree), needles (Pinus Ponderosa)*	0.4-1.08μ (R)	0.35-2.5μ (R)
Red pine (diseased tree), needles (Pinus resinosa) 4 determinations*	0.4-1.08μ (R)	0.35-2.5μ (R)
Red pine (healthy tree), needles (Pinus resinosa) 4 determinations*	0.4-1.08μ (R)	0.35-2.5μ (R)
Sand	0.4-1.08μ (R)	0.26-2.5μ (R)
Sandy soil*	0.4-1.08μ (R)	
Shell-bark hickory, leaf (carya ovata)	0.4-1.08μ (R)	0.26-2.5μ (R)
Sod	0.4-1.08μ (R)	0.26-2.5μ (R)

*Also measured on the Cary-White 90 over the wavelength range 4000 to 450 cm $^{-1}$ (2.5-22.2μ).

Table III (Continued)

Specimen Identification	Recording Spectrophotometer	
	GE	Cary 14
Sphagnum moss, 2 determinations	0.4-1.08μ (R)	0.26-2.5μ (R)
Sugar maple, leaf (Acer sccharum)	0.4-1.08μ (R)	0.26-2.5μ (R)
White elm, leaf (Ulmus americana)	0.4-1.08μ (R)	0.26-2.5μ (R)
White oak, leaf (Quercus alba)	0.4-1.08μ (R)	0.26-2.5μ (R)
White oak, leaf (Quercus alba) 9 determinations	0.4-1.08μ (RT)	

Table IV

Listing of man-made materials measured for spectral transmittance (T) or spectral reflectance (R) on the indicated recording spectrophotometers for the indicated wavelength ranges.

Specimen Identification	Recording Spectrophotometer	
	GE	Cary 14
Aluminized corrugated roofing*	0.4-1.08μ (R)	0.26-2.15μ (R)
Aluminum painted asphalt roofing*	0.4-1.08μ (R)	0.26-2.15μ (R)
Coated (painted) corrugated roofing*	0.4-1.08μ (R)	0.26-2.15μ (R)
Corning 2540 infrared transmitting glass filter (2 specimens)		0.6-2.65μ (T)
Corning 5860 ultraviolet transmitting glass filter		0.2-2.65μ (T)
Flame sprayed Al_2O_3 (2 specimens)*	0.4-1.08μ (R)	0.26-2.15μ (R)
Gold-plated-stainless-steel mesh with Mylar backing*	0.4-1.08μ (R)	0.26-2.5μ (R)
Green camouflage paint*	0.4-1.08μ (R)	0.26-2.5μ (R)
Interference filters (6 specimens)**		0.2-2.65μ (T)
Interference filters for use on infrared hazemeter (11 specimens)		0.2-2.65μ (T)
IRTRAN 1		0.7-2.65μ (T)
IRTRAN 2		0.6-2.64μ (T)
Plastic dome from total radiometer located at Purdue University ** ***		0.2-2.65μ (T)
Uncoated corrugated roofing*	0.4-1.08μ (R)	0.26-2.15μ (R)
Unweathered asphalt shingles*	0.4-1.08μ (R)	0.26-2.15μ (R)
Weathered asphalt shingles*	0.4-1.08μ (R)	0.26-2.15μ (R)
White-lead coated glass from greenhouse roof*	0.4-1.08μ (R)	0.26-2.15μ (R)
Wratten filters (3 specimens) ** ****		0.2-2.65μ (T)

* Also measured on Cary-White 90, 4000-450 cm^{-1} (2.5-22.2μ)
** Also measured on Beckman IR-4, 1-15μ
*** Also measured on Beckman IR-7, 14.3-40μ
**** Also measured on Beckman IR-9, 2.5-25μ

Table V

Listing of NBS Test Reports issued between July 1 and December 31, 1964.

Test No. 212.11P	Title	Submitted to	Date
13/65	Spectral directional reflectance of one green camouflage paint	H. J. Keegan NBS	8-6-64
14/65	Spectral transmittance of 1 IRTRAN 1 sample and 2 Corning glass filters	R. H. Munis NBS	8-7-64
21/65	Spectral transmittance of 1 IRTRAN 2 sample	R. H. Munis NBS	8-28-64
24/65	Spectral directional reflectance of 10 specimens of target materials	H. J. Keegan NBS	9-21-64
25/65	Spectral directional reflectance of 16 botanical specimens and 1 specimen of sand	H. J. Keegan NBS	9-18-64
30/65	Spectral transmittance of 6 interference filters, 3 Wratten filters, and 1 Corning glass filter	H. J. Keegan NBS	9-24-64
32/65	Spectral transmittance of 1 cellulose acetate dome	H. J. Keegan NBS	9-25-64
33/65	Spectral directional reflectance of 1 sample of rusted iron	H. J. Keegan NBS	10-2-64
36/65	Spectral directional reflectance of 3 botanical specimens	H. J. Keegan NBS	10-7-64
38/65	Spectral directional reflectance of 1 gold mesh sample	H. J. Keegan NBS	10-12-64
41/65	Spectral directional reflectance of 2 samples of flame-sprayed aluminum-oxide	H. J. Keegan NBS	10-13-64
46/65	Spectral transmittance of 11 interference filters	H. J. Keegan NBS	11-3-64
58/65	Spectral directional reflectance and spectral transmittance of 1 blue flower	H. J. Keegan NBS	12-15-64
59/65	Spectral directional reflectance of 1 living lizard	H. J. Keegan NBS	12-15-64
60/65	Spectral directional reflectance of 3 botanical specimens	H. J. Keegan NBS	12-15-64

Table V (Continued)

Test No. 212.11P	Title	Submitted to	Date
61/65	Spectral directional reflectance and spectral transmittance of 9 white oak leaves collected during summer and fall (1964)	H. J. Keegan NBS	12-15-64
62/65	Spectral directional reflectance of human skin	H. J. Keegan NBS	12-15-64
63/65	Spectral directional reflectance of 3 soil samples	H. J. Keegan NBS	12-15-64
66/65**	Spectral directional reflectance of 1 specimen of sand blasted aluminum and 3 specimens of carborundum paper	E. Hilsenrath NASA-Goddard	12-22-64
68/65**	Spectral directional reflectance of 6 specimens of hematite-magnetite	W. A. Hovis, Jr.	12-30-64
G35201-1*	Spectral directional reflectance of 6 samples of red pine needles	USDA Beltsville	10-30-64
G35201-2*	Spectral directional reflectance of 6 samples of red pine needles	USDA Beltsville	10-30-64
G35201-3*	Spectral directional reflectance of 7 samples of Ponderosa pine needles	USDA Beltsville	10-30-64
G35201-4*	Spectral directional reflectance of 6 samples of red pine needles	USDA Beltsville	10-30-64
G35201-5*	Spectral directional reflectance of 6 samples of red pine needles	USDA Beltsville	11-2-64

* Measurements financed by USDA Forest Service, Forest Insect Laboratory, Beltsville, Maryland

** Measurements financed by NASA, Goddard Space Flight Center, Greenbelt, Maryland

Figure 12. Spectral directional reflectance of (1) sphagnum moss and (2) human skin.

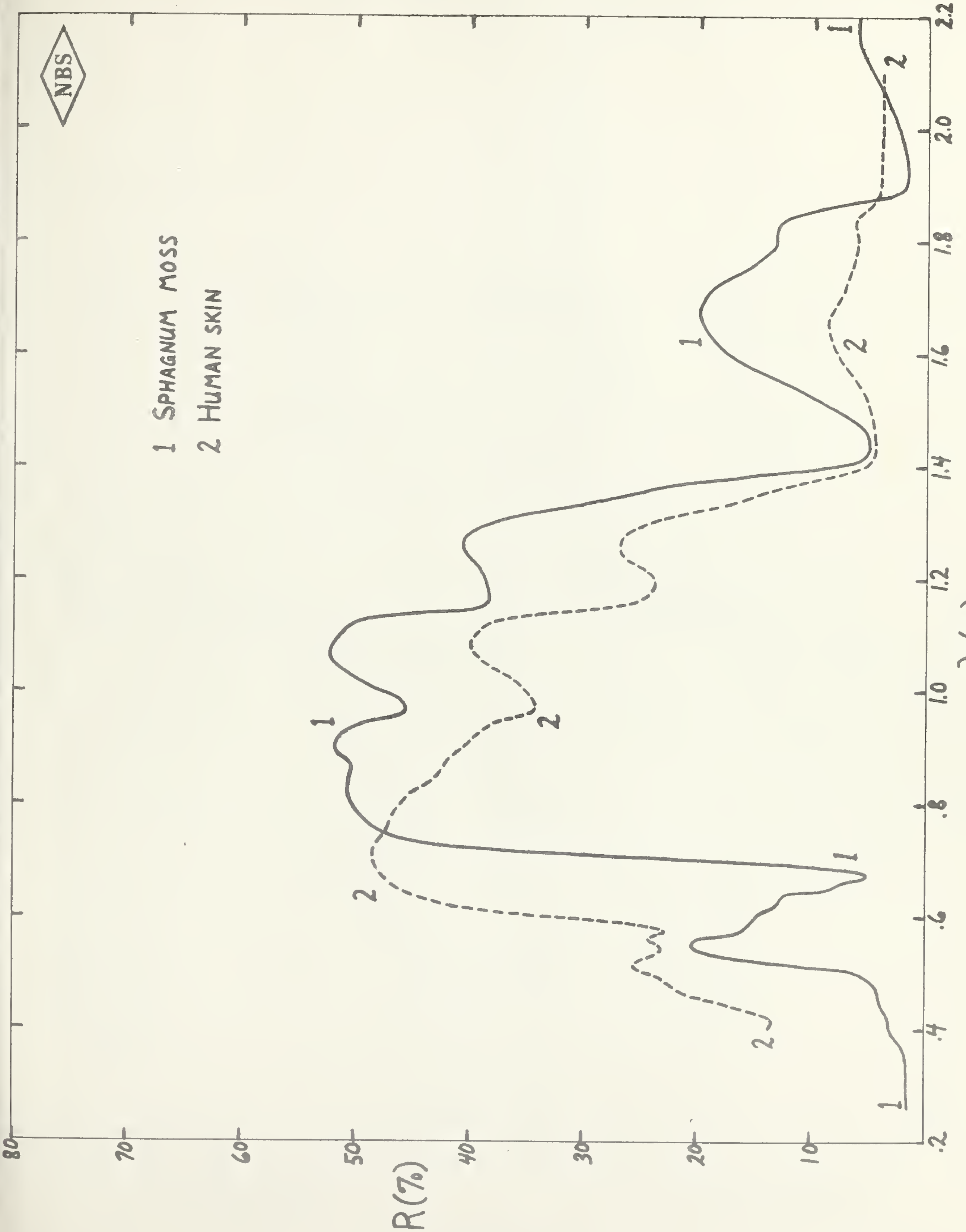
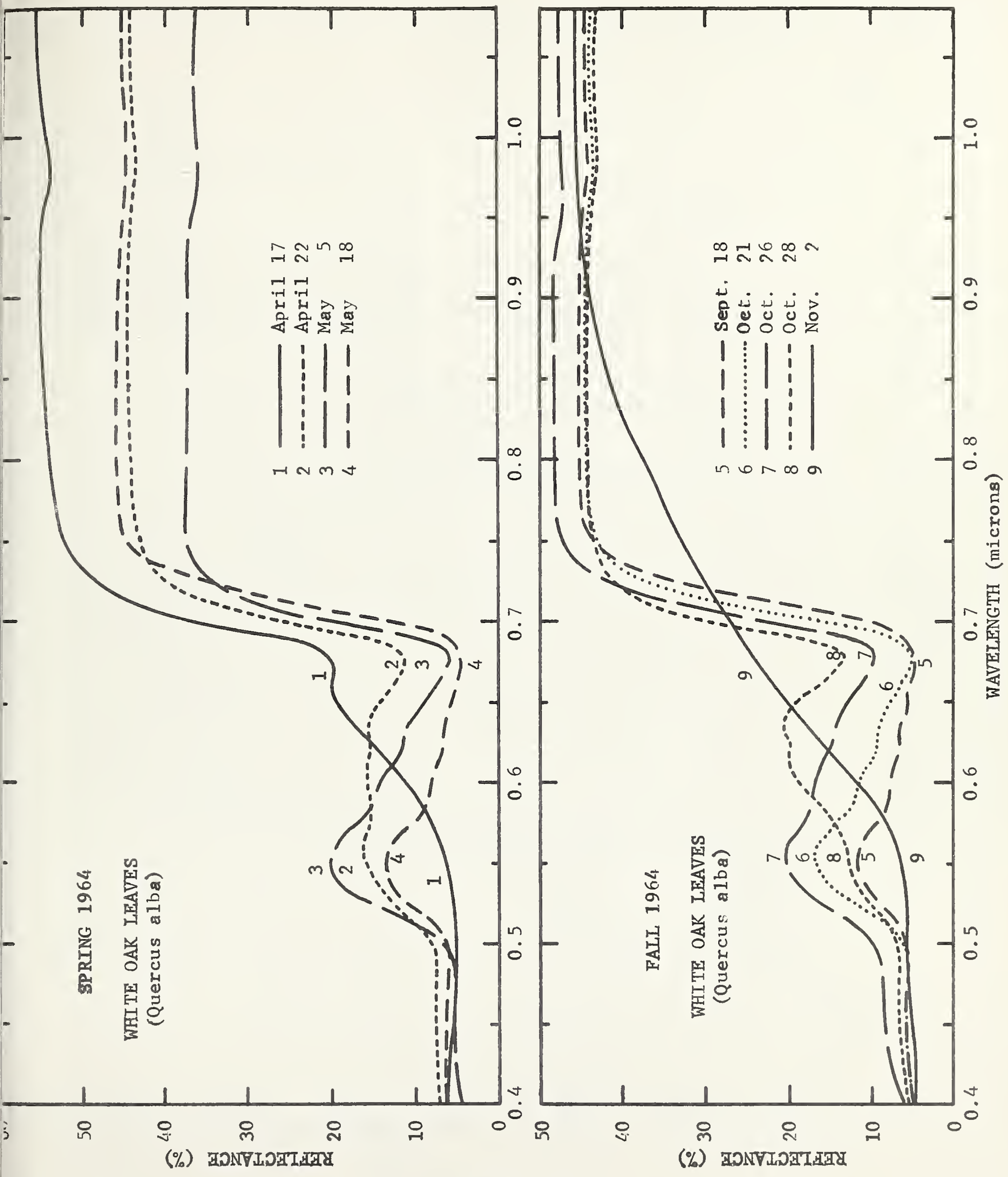

NBS
1 Sphagnum moss
2 Human skin
1
2
R(%)
80
70
60
50
40
30
20
10
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
λ(μ)

FIG. 12

Figure 13. Spectral reflectance of White Oak leaves.
(a) Spring 1964 (b) Fall 1964



(a) Figure 13 (b)

Spectral directional reflectance of white oak leaves (a) spring 1964, (b) fall 1964.

Figure 14. Spectral directional reflectance of (1) healthy and (2 and 3) diseased specimens of Ponderosa pine.

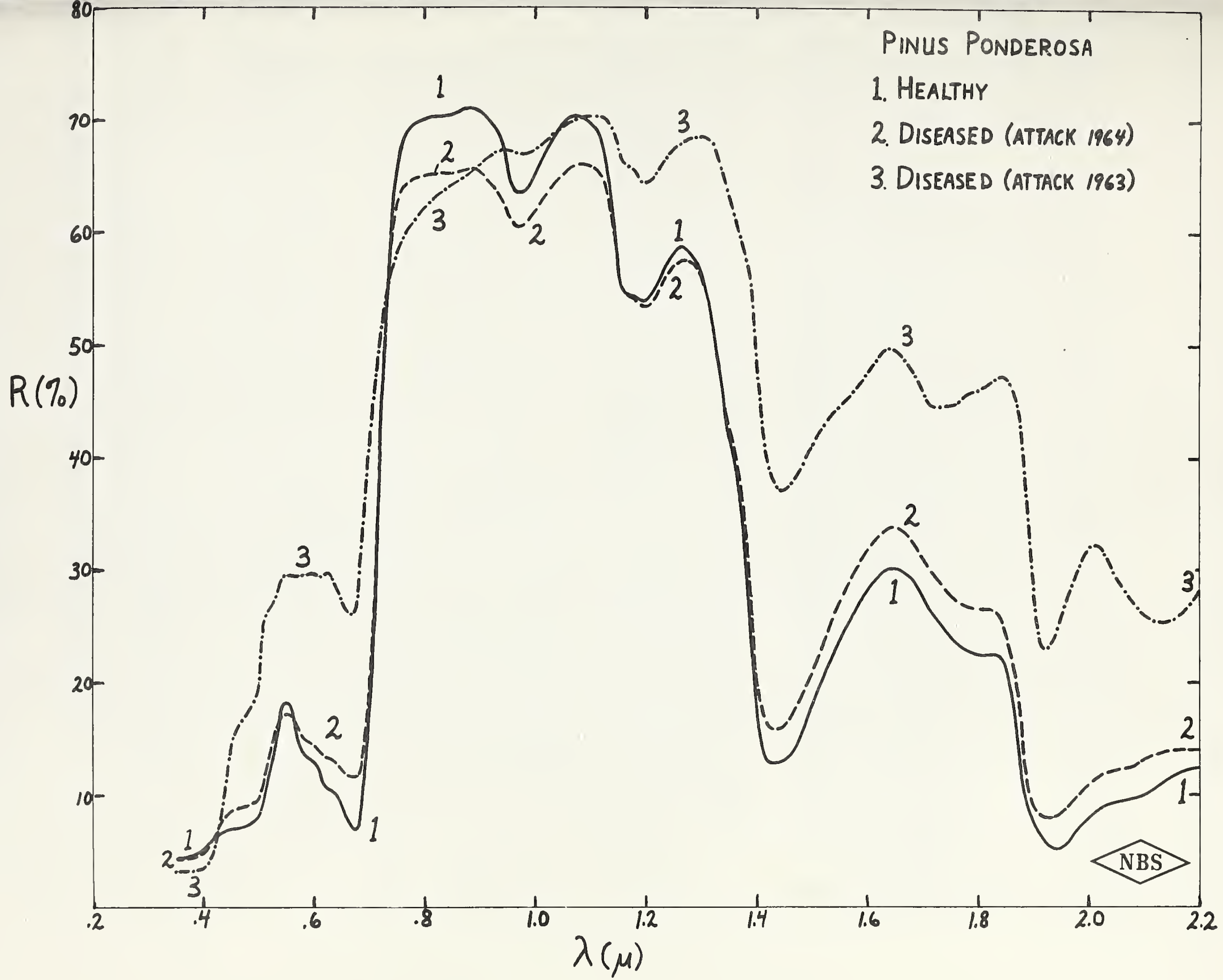

Pinus Ponderosa
1. Healthy
2. Diseased (attack 1964)
3. Diseased (attack 1963)
R(%)
80
70
60
50
40
30
20
10
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
λ(μ)
1
2
3
NBS

Fig 14

6. Use of Cary-White 90 Spectrophotometer

by

V. R. Weidner

I. Standards

(A). Photometric scale standard for total "absolute" spectral reflectance.

The measurement of spectral reflectance on the Cary-White 90 spectrophotometer in terms of "absolute" reflectance for the condition of included specular component can now be accomplished. The equation derived by Dr. Judd, for the calibration and correction of data taken by means of this instrument, has been used successfully for the reduction of data. This equation has been published by the instrument manufacturer, John U. White, in New Method for Measuring Diffuse Reflectance in the Infrared, JOSA 54, 1332, (1964). In using this method, the data are adjusted to an absolute basis by comparing the measured values of an aluminum mirror to the absolute reflectance of an aged aluminum mirror, (H. E. Bennett, J. Silver, and E. J. Ashley, Infrared Reflectance of Aluminum Evaporated in Ultra-High Vacuum, JOSA 53, 1089 (1963).

(B). Photometric scale standard for diffuse spectral reflectance measurements.

The method used in (A) above cannot be employed to calibrate the photometric scale for making measurements where it is desirable to exclude the specular component. At present, no standard exists for this purpose. The ideal standard for this type of measurement would be one which has the following characteristics:

1. High reflectance (80% to 90% or more) throughout the spectral range 2.5 to 22.2 microns.
2. Be a perfect or near perfect diffuser.
3. Have a high stability over a long period of time.
4. Withstand high temperatures.
5. Be reasonably inexpensive.

Metals such as gold and aluminum meet all but the second, and in the case of gold the fifth, requirements without much difficulty. Most of the other materials thus far investigated do not meet the requirements because they are selectively absorbent in one or more regions of the spectral range 2.5 to 22.2 microns.

One promising non-metal materials is flowers of sulfur. This material is very good in that it meets all the requirements but the fourth for the spectral range 2.5 to 10 microns. It has a series of absorption bands between 10 and 22.2 microns. The problem of heat damage can be overcome with flowers of sulfur by reducing the power on the source to less than 100 watts (the maximum is 300 watts).

Since metals are the most promising materials to be used in the solution of this problem a number of ideas are under consideration to meet the second requirement, that of being a perfect diffuser. Several samples of aluminum coated materials have been prepared and will be measured. These consist of aluminum coated glass beads, aluminum coated aluminum beads, and aluminum powders.

Ground gold or gold powder may prove to be a good material for use as a diffuse reflectance standard. Plans include the preparation and testing of pure gold powder.

II. Spectral Measurements.

(A). Spectral properties of plants.

The Cary-White 90 spectrophotometer was successfully used in making spectral reflectance measurements of plants in the spectral range 2.5 to 22.2 microns. These measurements, although of a very limited extent in so far as the number of species examined, indicate that the reflectance of leaves of trees and pine needles in this spectral range is generally less than 5%. The samples measured and the NBS test numbers under which the measurements are reported are given in Table VI.

Table VI

Sample	NBS Test No.	Date
Acer saccharum, (Sugar Maple leaf)	212.11P-25/65	9-18-64
Larix laricina, (American Larch needles)	"	"
Picea mariana, (Black Spruce needles)	"	"
apple leaf	"	"
Cercis canadensis, (Redbud leaf)	212.11P-36/65	10-7-64
" " " "	212.11P-60/65	12-15-64
Quercus Prinus, (Chestnut Oak leaf)	212.11P-36/65	10-7-64
" " " " "	212.11P-60/65	12-15-64
Alopecurus sp. (Foxtail grass)	212.11P-36/65	10-7-64
Cornus Florida, (Dogwood leaf)	212.11P-60/65	12-15-64
Pinus resinosa, (Red Pine needles)	G35201-1,-2,-4, and -5	10-30-64
Pinus Ponderosa, (Ponderosa Pine needles)	G35201-3	10-30-64

The samples listed above were measured in cooperation with the following agencies:

1. The University of Michigan

The measurements made under NBS Test No. 212.11P-25/65 were made in cooperation with the University of Michigan. These measurements were made in an effort to clarify the results of the infrared surveillance studies being made at the University of Michigan. (See Figures 15 and 16.)

2. Dr. David M. Gates, NBS Boulder Colorado Laboratories

The measurements reported to Dr. David M. Gates, (NBS Tests 212.11P-36/65 and 212.11P-60/65) were made in an effort to determine if there were any prominent spectral features in the infrared spectral reflectance of chlorophyll plants which might correlate with findings being made in the studies of the infrared spectra of the planet Mars. In so far as the reflectance measurements made on this instrument are concerned, the leaves measured have reflectances of less than 5% throughout the spectral range 2.5 to 22.2 microns. The one spectral feature found to be prominent for these specimens is the presence of two small reflectance peaks at approximately 3.4 and 3.5 microns. These features appear in a spectral region where many organic materials have strong absorption bands.

3. U. S. Forest Service.

The measurements made under NBS Tests G35201-1, -2, -3, -4, and -5 were made for the U. S. Forest Service Insect Laboratory. The purpose of this study was to determine if there are any differences in the spectral reflectance of diseased and healthy pine trees which might be useful in detecting early stages of damage due to insect infestations. (See Figure 17). The data are being analysed by the Forest Service. This work was financed by the U. S. Department of Agriculture Forest Service under P. O. FI-34-65, dated 9-9-64.

(B). Spectral properties of animals.

1. Human skin

The spectral reflectance of human skin for the infrared spectral range 2.5 to 22.2 microns was measured and reported to Dr. David M. Gates, (NBS Test No. 212.11P-62-65 dated 12-15-64). The results of these measurements show the reflectance to be approximately 2% or less throughout this spectral range.

2. Lizard

The spectral reflectance of a living lizard for the infrared spectral range 2.5 to 22.2 microns was measured and reported to Dr. David M. Gates, (NBS Test No. 212.11P-59-65 dated 12-15-64). The results of these measurements show the reflectance to be less than 4% throughout this spectral range.

(C). Spectral properties of soils and minerals.

1. Soils

The reflectance of three soil samples for the spectral range 2.5 to 22.2 microns was reported to Dr. David M. Gates, (NBS Test No. 212.11P-63/65 dated 12-15-64). The samples consisted of an alluvial soil, a clay-like soil, and a sandy soil. The measurements were made on both wet and dry samples. The soils generally showed a much higher reflectance when dry than when wet, varying by as much as 30% at 2.5 and 4.5 microns.

2. Minerals.

The spectral reflectance of 9 samples of the mineral limonite ($Fe_2O_3.3H_2O$) and 2 soil samples for the spectral range 2.5 to 22.2 microns were measured and reported to Dr. Warren A. Hovis, Jr., NASA, Goddard Space Flight Center, (NBS Test No. 212.11P-57-65 dated 12-14-64).

The spectral reflectance of 6 samples of hematite-magnetite have also been measured for Dr. Hovis and a report is being prepared. These measurements are being made in connection with spectral analysis of materials considered of interest in the study of the planet Mars. The measurements are being analysed by NASA. These measurements indicate a relationship of particle size to reflectance in which the reflectance increases as the particle size decreases. This work is being financed by NASA under Government Order S-75786-G dated 12-7-64.

(D). Spectral properties of man-made materials.

1. Camouflage Paint

The spectral reflectance of a sample of camouflage paint was measured over the spectral range 2.5 to 20.8 microns and reported to Mr. David L. Gee, U. S. Army Engineer Research & Development Laboratories, Fort Belvoir, (NBS Test 212.11P-13/65 dated 8-6-64). This test was financed by ARPA. Future measurements of this nature will be financed by the U. S. Army Engineer Research & Development Laboratories, Fort Belvoir, under Project Order ERDL 50-65 dated 12-11-64.

2. Flamed sprayed aluminum oxide

The spectral reflectance of 2 samples of flame sprayed Al_2O_3 was measured over the spectral range 2.5 to 22.2 microns and reported to Mr. H. J. Keegan, NBS, (NBS Test No. 212.11P-41/65). Because of its stability, this material was measured to determine whether or not it would be suitable as a standard of reflectance for the spectral range 2.5 to 22.2 microns. It proved to be strongly absorbing in many regions of this spectral range and to have a reflectance not greater than 50% throughout most of the 2.5 to 22.2 microns spectral range. Such properties make it undesirable as a material to be used as a reflectance standard.

3. Target materials (roofing)

The spectral reflectance of 10 specimens of target materials (roofing) was measured over the spectral range 2.5 to 22.2 microns and reported to Dr. Marvin Holter, University of Michigan, (NBS Test No. 212.11P-24/65 dated 10-21-64). This data is being analyzed by Dr. Holter's Group at the University of Michigan. This test was financed by ARPA.

4. Gold mesh

The spectral reflectance of a sample of gold plated stainless steel mesh on a Mylar backing was measured over the spectral range 2.5 to 22.2 microns and reported to Mr. H. J. Keegan, NBS, (NBS Test No. 212.11P-38/65 dated 10-12-64). The purpose of measuring this material was to determine whether or not it is a good diffuse reflector in the infrared reflectance of approximately 80% and 75% throughout the spectral range 2.5 to 22.2 microns for the conditions of included and excluded specular components respectively.

sentence [illegible]

5. Rusted iron

The spectral reflectance of one sample of rusted iron was measured over the spectral range 2.5 to 22.2 microns and reported to Dr. Warren Hovis, Jr. NASA, Goddard Space Flight Center, (NBS Test No. 212.11P-33/65 dated 10-2-64). The measurement, made in connection with the spectral analysis of materials considered of interest in the study of the planet Mars, are said to agree well with the observed observations of the spectral reflectance of Mars in the spectral range 2.5 to 4.0 microns. These observations and measurements are said to support the theory that iron oxides may be present on the surface of Mars. Plans are being made for the measurement of various oxides of iron from different geographical locations in order to gain more knowledge of the spectral reflectance of these materials. The first set of measurements in this study have already been made (see spectral properties of soils and minerals). This work is being financed by NASA under Government Order S-75786-G dated 12-7-64.

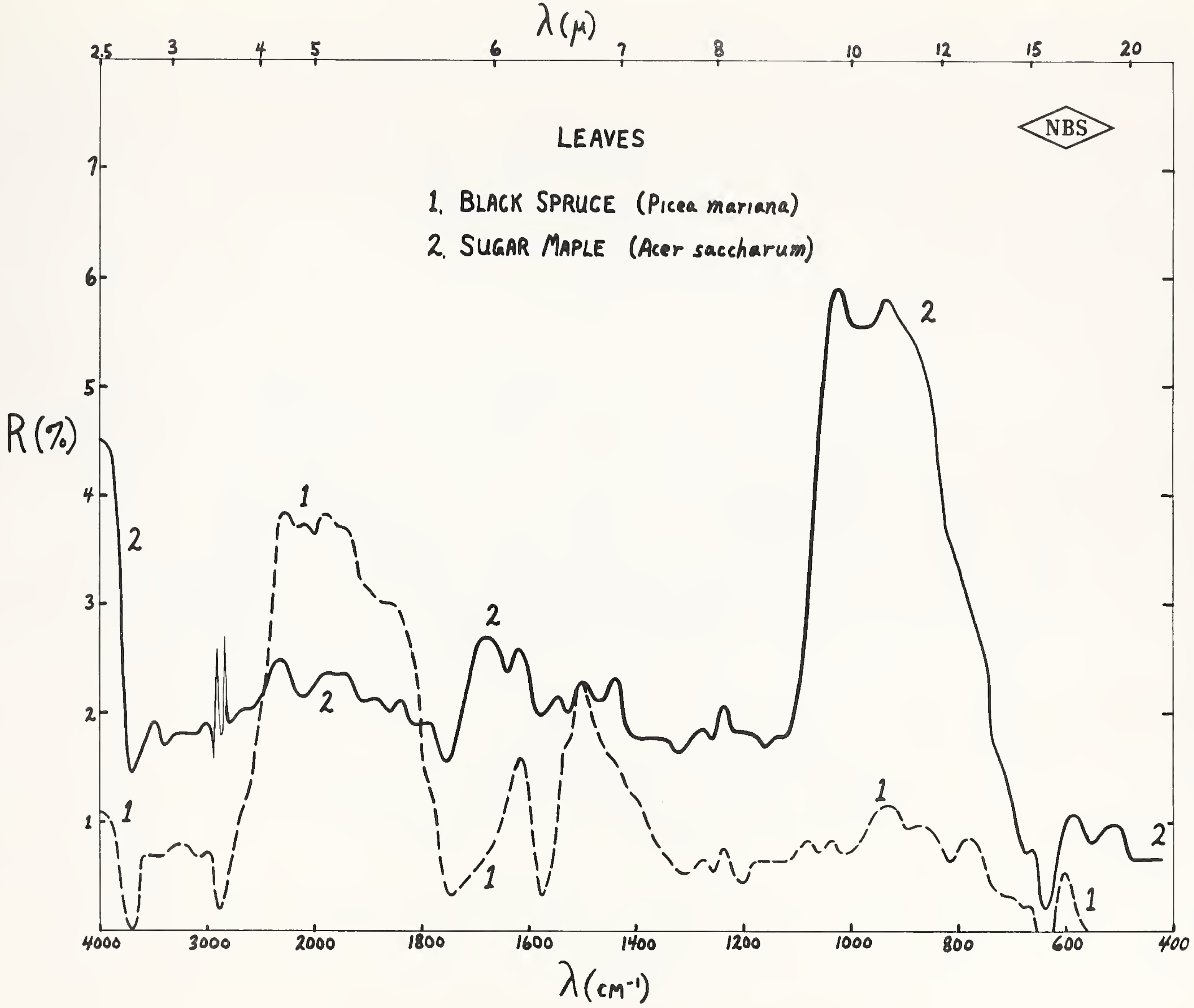
6. IRTRAN 1 and IRTRAN 2, and Pure Germanium

The spectral transmittance and spectral reflectance of IRTRAN 1 and IRTRAN 2 (infrared transmitting materials), and pure germanium were measured over the spectral range 2.5 to 22.2 microns and a report is being prepared to Mr. William Fussel, NBS. This data will be used in connection with the emissivity measurements being made by Mr. Fussel and the data will be analyzed by his group.

7. Sand blasted aluminum and Carborundum paper

The spectral reflectance of sand blasted aluminum and 3 grades of Carborundum paper have been measured over the spectral range 2.5 to 22.2 microns and reported to Mr. Ernest Hilsenrath, NASA, Goddard Space Flight Center, (NBS Test No. 212.11P-66/65 dated 12-22-64). The sand-blasted Al has a spectral reflectance of approximately 60% to 65% throughout this spectral range and is a good diffuser for angles of incidence between zero and 20 degrees. The Carborundum papers have a low reflectance throughout this spectral range. Both the sand blasted aluminum and the Carborundum papers have been coated with evaporated gold and will be measured again in the near future. This work and future work for Mr. Hilsenrath is financed by NASA under Government Order S-75786-G dated 12-7-64.

Figure 15. Spectral directional reflectance of (1) black spruce needles and a (2) sugar maple leaf.


λ(μ)
2.5
3
4
5
6
7
8
10
12
15
20
NBS
LEAVES
1. BLACK SPRUCE (Picea mariana)
2. SUGAR MAPLE (Acer saccharum)
R(%)
7
6
5
4
3
2
1
1
2
2
2
1
1
2
1
2
2
1
4000
3000
2000
1800
1600
1400
1200
1000
800
600
400
λ(cm⁻¹)

(50)

FIG. 15

Figure 16. Spectral directional reflectance of apple leaf (2) and tap water (1) used as a backing material.

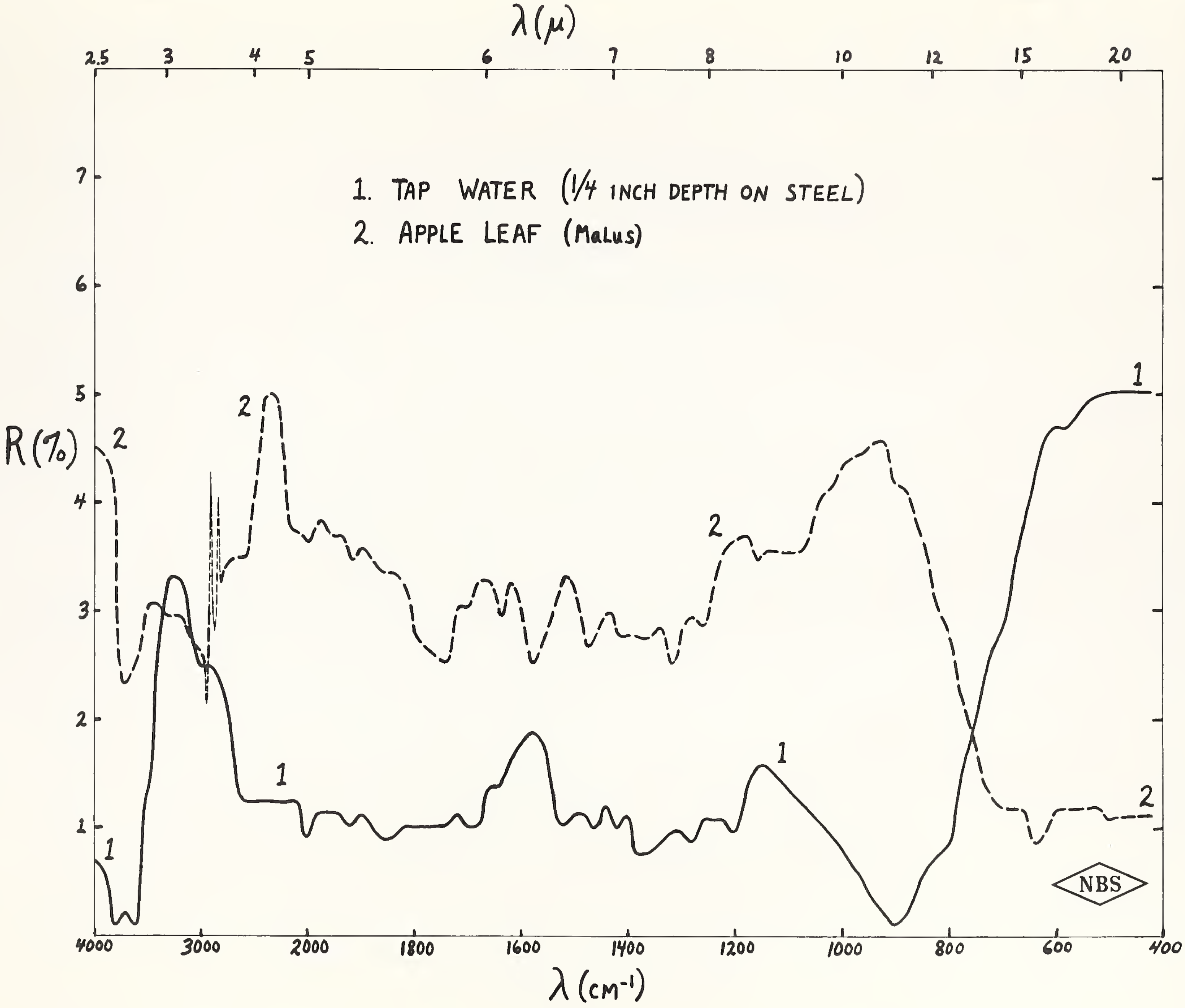

λ(μ)
2.5
3
4
5
6
7
8
10
12
15
20
R(%)
7
6
5
4
3
2
1
1. TAP WATER (1/4 INCH DEPTH ON STEEL)
2. APPLE LEAF (Malus)
1
2
NBS
4000
3000
2000
1800
1600
1400
1200
1000
800
600
400
λ (cm⁻¹)

Fig 16

Figure 17. Spectral directional reflectance of (1) healthy and (2) diseased Ponderosa pine needles.

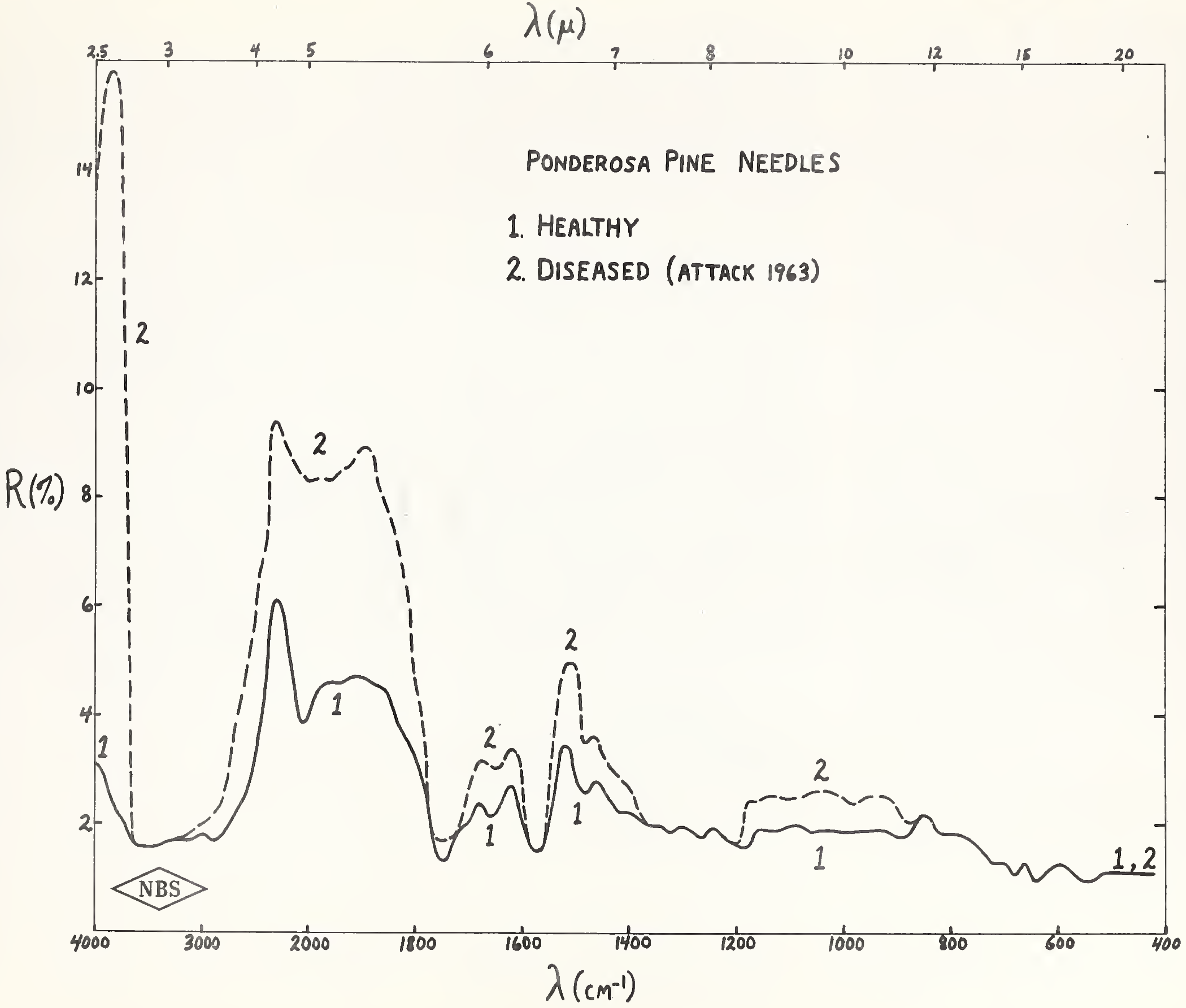

λ(μ)
2.5
3
4
5
6
7
8
10
12
15
20
PONDEROSA PINE NEEDLES
1. HEALTHY
2. DISEASED (ATTACK 1963)
R(%)
14
12
10
8
6
4
2
1
2
1,2
NBS
4000
3000
2000
1800
1600
1400
1200
1000
800
600
400
λ(cm⁻¹)

FIG. 17

7. Wavelength Standards

by

J. C. Schleter and J. D. Kuder

Measurements of spectral transmittance have been started by using the Cary 14 recording spectrophotometer over the wavelength region 0.24 to 2.6 microns to determine the wavelengths of minimum transmittance of 5 glasses (2 silicate base and 3 phosphate base) containing rare-earth oxides. Three of the glasses were prepared in the NBS Glass Section from formulations by Mr. G. W. Cleek and have the following identification, thickness, and contents (in weight percent) of rare-earth oxide: (1) F-1377, 2.36mm, 6% Nd_2O_3, 7% Ho_2O_3, and 7% Sm_2O_3; (2) F-1378, 2.34mm, 10% Nd_2O_3 and 10% Sm_2O_3; and (3) F-1379, 2.33mm, 10% Ho_2O_3 and 10% Yb_2O_3. The spectral transmittance curves of these three glasses were shown in the Semiannual Technical Report, January 1 to June 30, 1964 (NBS Report 8528). The remaining two glasses are commercially available Corning glasses designated Corning 5120 (didymium) and Corning 3130 (holmium).

The latter two glasses have been issued for a number of years by the NBS as working standards for checking the wavelength scale of recording spectrophotometers, with certain restrictions. The didymium glass is calibrated for use on the General Electric recording spectrophotometer only for the spectral regions 0.4 to 0.75 micron, with a spectral band pass of 0.01 micron, and 0.73 to 1.08 microns, with a spectral band pass of 0.02 micron. The holmium glass is calibrated for use on recording spectrophotometers having a spectral band pass of less than 0.002 micron for the wavelength region 0.24 to 0.64 micron. The current calibration is intended to determine the wavelengths of minimum transmittance of the didymium glass for use with recording spectrophotometers having a spectral band pass of less than 0.002 micron and also to include absorption bands present in this glass in the wavelength region between 1.08 and 2.6 microns, and also to include absorption bands in the wavelength region between 0.64 and 2.6 microns of the holmium glass. The additional calibrations of these two glasses will partially fill a need of many industrial laboratories who already possess these standards.

Measurements of spectral transmittance have been made over the spectral range 0.24 to 1.07 microns of the following number of absorption bands for the indicated filters: F-1377, 23; F-1378, 26; F-1379, 20; Corning 3130, 19; and Corning 5120, 5 (in the near infrared spectral region only, 0.6 to 1.07 microns); for a total of 93 absorption bands for all glasses. Additional measurements of 17 absorption bands were made for each source-detector combination in wavelength regions in which more than one source-detector combination could be used; for example, between 0.36 and 0.4 micron and between 0.6 and 0.7 micron. Each of these 110 absorption bands was studied for 10 different slit widths ranging from approximately 0.03 to 2.8 millimeters of physical slit width in order to determine the variation of wavelength of minimum transmittance with respect to slit width. Thus, 1100 separate determinations have been made to date. The remaining absorption bands between 1.07 and 2.6 microns will be measured in the next reporting period and the reduction of these data will be started.

A paper on the preparation and spectral properties of the 45 rare-earth glasses in silicate, phosphate, and borate bases, made in the NBS Glass Section, is in preparation by Cleek, Keegan, Schleter, Weidner and Kuder.

The spectral transmittance curves of all of the glasses, on a reduced scale, have been run on the Cary 14 from 0.2 to 2.6 microns. All of the glasses have been measured by Mr. G. Cleek on a Beckman IR-4 infrared spectrophotometer over a wavelength range 1 to 5 microns.

8. Scattering as a Function of Wavelength

by

M. W. Finkel

This is a brief description of an infrared instrument designed to measure scattering as a function of wavelength. Figure 18 shows the optical schematic of the instrument including the source, the monochromator, the Cassegrain collimator, the ellipsoidal collector, the sample and the detector. The source is a quartz envelope zirconium concentrated-arc lamp with a useful spectral range out to about 4.5 microns. The source diameter is 1.6mm, which is essentially the diameter of the image at the exit slit of the monochromator. This point-like source with its relatively high color temperature (3200°K) is much more satisfactory than the previously used globar (1200°K) and has proven to be an "ideal" source for one's purposes. To extend the spectral range, a sapphire window was inserted into the envelope of this lamp, which resulted in transmission out to about 6.5 microns.

The monochromator, a Perkin-Elmer single pass, NaCl prism instrument, has a usable range of 0.2 to 17 microns.

There are at least two reasons for employing a Cassegrain system. To begin, a collimated beam is more compatible with the geometry of the instrument. Furthermore, most theoretical models assume a monochromatic, collimated incident beam. In its present state of design, the Cassegrain should collect as much as 75%, which should be more than ample. However, further modifications to improve performance are being incorporated. Temporarily, therefore the Cassegrain has been replaced by two long focal length spherical mirrors which act as a condensing system.

The radiation is chopped at 990c.p.s., which approachs the optimum frequency for our detector.

The optical path of the incident beam is indicated by the solid line. The incident beam can be monitoried by rotating mirror, m_3, into position and adjusting mirror, m_4, so that both optical paths are equivalent. The scattered flux is collected by a 16" diameter elliptical reflector whose primary and secondary foci are 5 and 20 inches respectively. The sample and detector are placed at these conjugate foci. The exit aperture has a half-angle of about 3 degrees. Back scattering is measured by passing the incident beam through the exit aperture. The reflectivity of the reflector is 94% at 1 micron, rising to 99% at 2 microns, and remaining so out to 20 microns.

A 1-cm-diameter photovoltaic Indium Antimonide detector is employed. At liquid nitrogen temperatures, it has a D* equal to 1.27×10^{10} and a recommended range out to 5.5 microns. *

The instrument, of course, is not limited by considerations of single or multiple scattering. For that matter, neither does it concern itself with questions of distribution, homogeneity, or interference (etc). That it does so without tedious scanning followed by a laborious integration is perhaps

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*The system is completed by a hushed transistor pre-amplifier, a P.A.R. lock-in amplifier, and a Leeds and Northrup speedomax recorder.

its chief virtue. If effectively integrates I_t, the total intensity of the scattered radiation. It does so in two parts,

$$(1.)\quad I_F = \int_0^{2\pi}\int_0^{\pi/2} I(\theta,\varphi)\,\sin\theta\,d\theta\,d\varphi$$

$$I_B = \int_0^{2\pi}\int_{\pi/2}^{\pi} I(\theta,\varphi)\,\sin\theta\,d\theta\,d\varphi$$

Since multiple scattering would have to account for successive orders, and I_o may become a function of some other variable, let us consider, for simplicity, single scattering.

We can write,

$$(2.)\quad I = F(\theta,\varphi)\,I_o / k^2R^2$$

where I and I_o refer to the scattered and incident intensity, $F(\theta,\varphi)$ is a dimensionless function and k is the wave number. Integrating the above, we can define the scattering cross section as, $C_{sca} = 1/k^2 \int_0^{2\pi}\int_0^{\pi} F(\theta,\varphi)\,d\omega$ Since our instrument determines I_t, one need only to divide by I_o to evaluate C_{sca}.

We have the additional option, by using a series of apertures, of investigating the angular distribution of I_F and I_B. By this procedure, one can evaluate the ratio $I(\theta)/I_T$ which for a conservative system with axial symmetry determines the amplitude function $S(\theta)$. The amplitude functions are of central importance to both the Stokes parameters and the Mie theory. This can be clearly expressed by restating equations 2. For linear, perpendicular polarization

$$I(\theta) = i_1(\theta)/k^2R^2\, I_o$$

and for linear, parallel polarization

$$I(\theta) = i_2(\theta)/k^2R^2\, I_o$$

and for random polarization

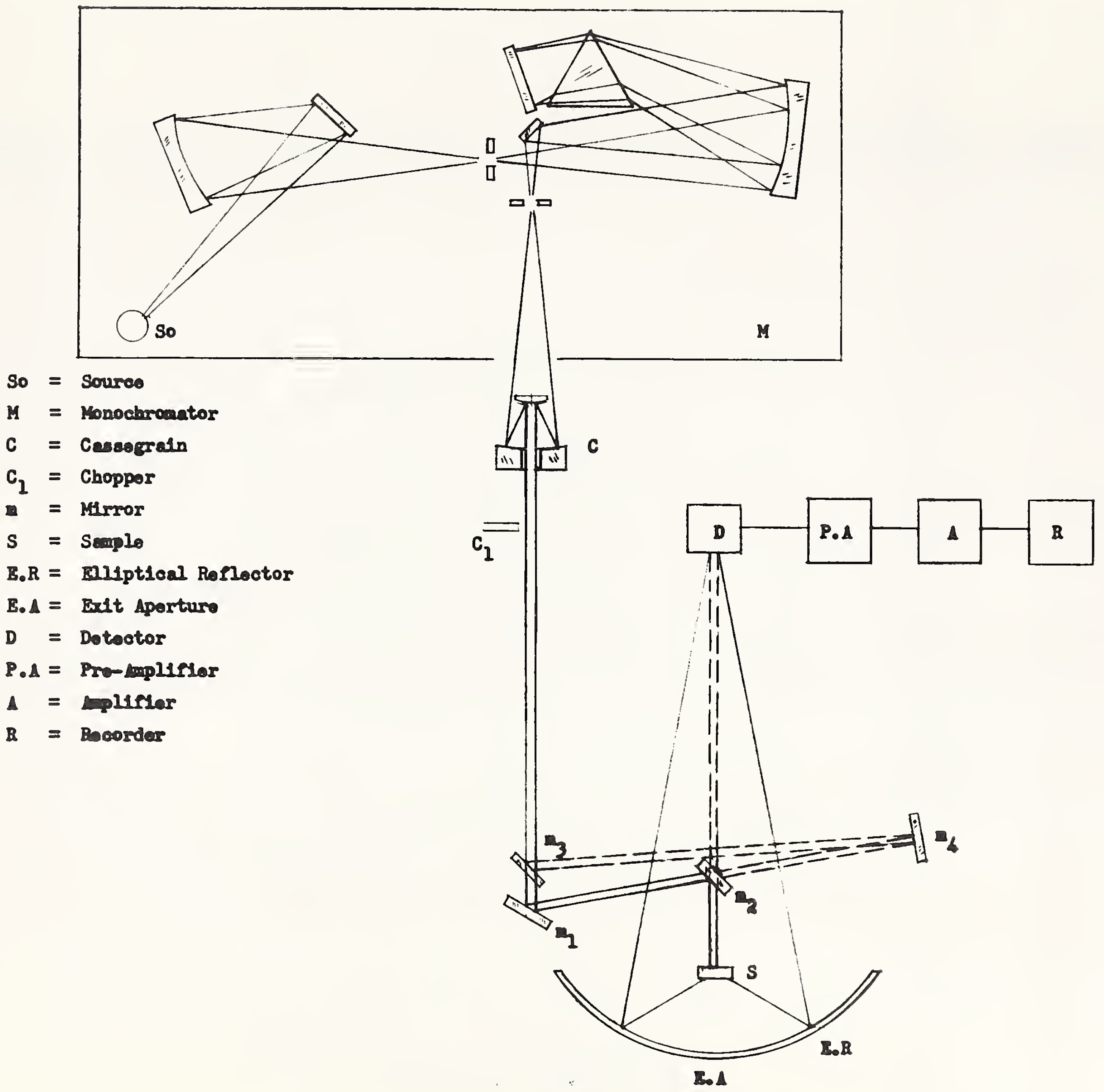
$$I(\theta) = 1/2\,(i_1+i_2)/k^2R^2\, I_o$$

$i_1(\theta)$ and $i_2(\theta)$ may be expanded as a series of Legendre polynomials,

$$i = \sum_{n=0}^{\infty} A_n P_n(\cos\theta)$$

But perhaps more important from an experimental point of view is the fact that $i_1(\theta)=|S_1(\theta)|^2$ and $i_2(\theta)=|S_2(\theta)|^2$. These comments are made as an indication of the versatility of this instrument. Regrettably, the detector did not arrive until the latter part of November, and since its arrival, I have been almost constantly harassed by electronic failures, and stray light problems. What is reported in figures 19, 20, and 21 is the percent decrease in incident energy due to forward scattering. That is I_F/I_{in}, and as such relates to the scattering coefficient. These measurements appear to be quite compatible with the transmission and absorption data. IRTRAN 1 is suggestive of dipole scattering, where the peak occurs at $\lambda = R$. Moreover, there is an indication of a λ^{-4} dependence. Since the m–x domain, where m is the index of refraction and $x = 2\pi R/\lambda$, is more extensive for small angle scattering, it is conceivable that the Rayleigh-Gans theory applies here. The dotted curve was included merely to indicate the "Relative" intensity of the forward scattering. Substantial reflection occurred with IRTRAN 4. For this reason back scattering data is being withheld in this report. IRTRAN 3 is a weak scatterer and demonstrates the advantage of 180° collection. The slit width for IRTRAN 1 was 0.2mm and 0.4mm for IRTRAN 3 and 4. In all cases, the slits could have been further reduced. IRTRAN 2 exhibited a rather unexpected phenomenon. Once irradiated, the entire sample appeared to be bathed in a warm glow. Apparently, this can be attributed to multiple scattering compounded by internal reflections. This contention is supported by a high refractive index and extreme inhomogeneity. Consequently, the detector saw a strong central image surrounded by a faint, somewhat larger image. By placing some collecting system at the secondary foci, we should successfully be able to treat such media.

The difficulty in distinguishing between the incident and the scattered waves at $\theta = 0$, are inherent in all such instruments. Actually, we are collecting between $3° < \theta < 177°$. We intend to attack this problem by methods previously suggested. There remains the problem of determining the angular dependency and surface uniformity of the detector. Finally, we intended to validate this instrument by a straight forward application of the conservation of energy principle.



So = Source
M = Monochromator
C = Cassegrain
C_1 = Chopper
m = Mirror
S = Sample
E.R = Elliptical Reflector
E.A = Exit Aperture
D = Detector
P.A = Pre-Amplifier
A = Amplifier
R = Recorder

FIG. 18

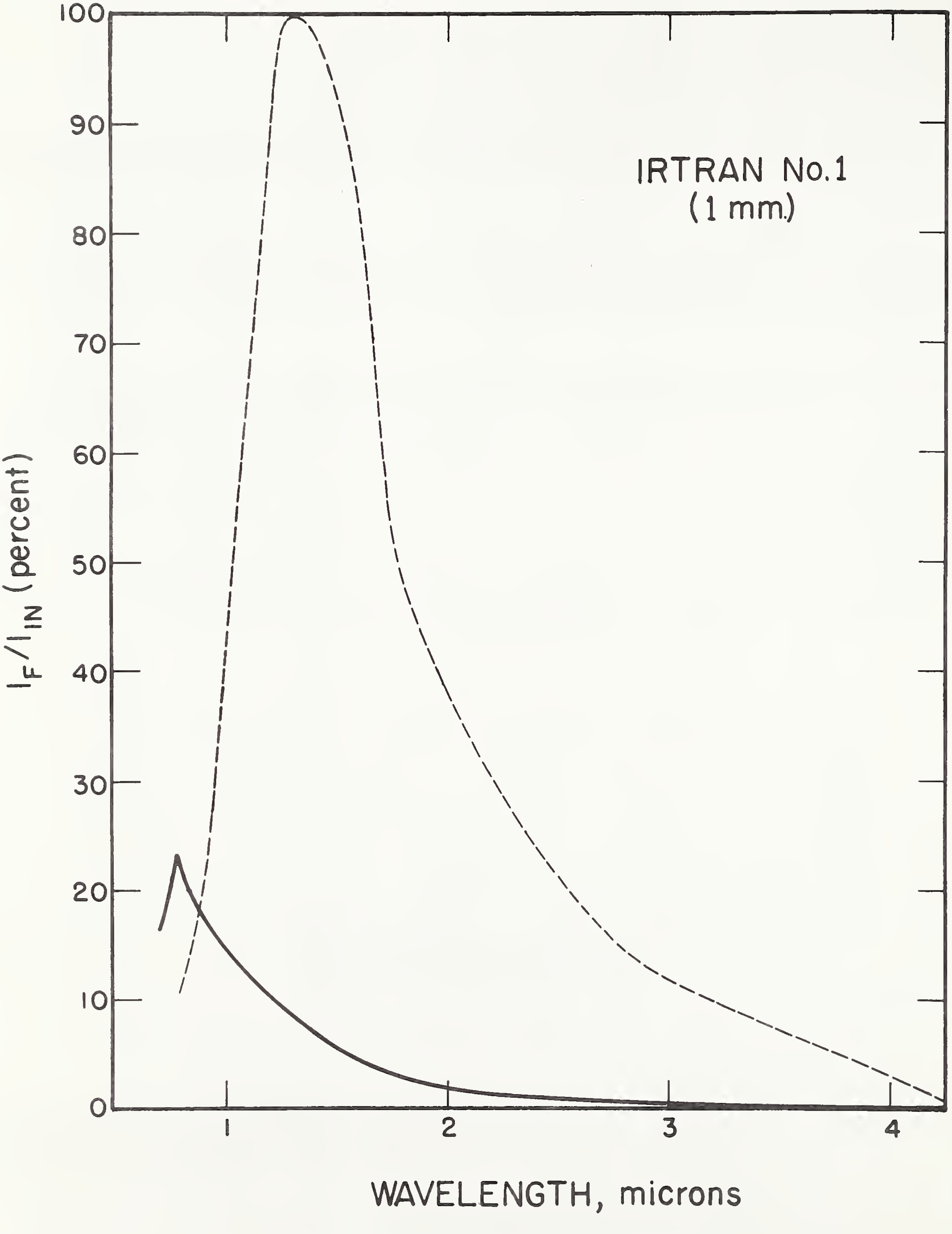

IRTRAN No.1
(1 mm.)
I_F/I_{IN} (percent)
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
WAVELENGTH, microns

FIG. 19

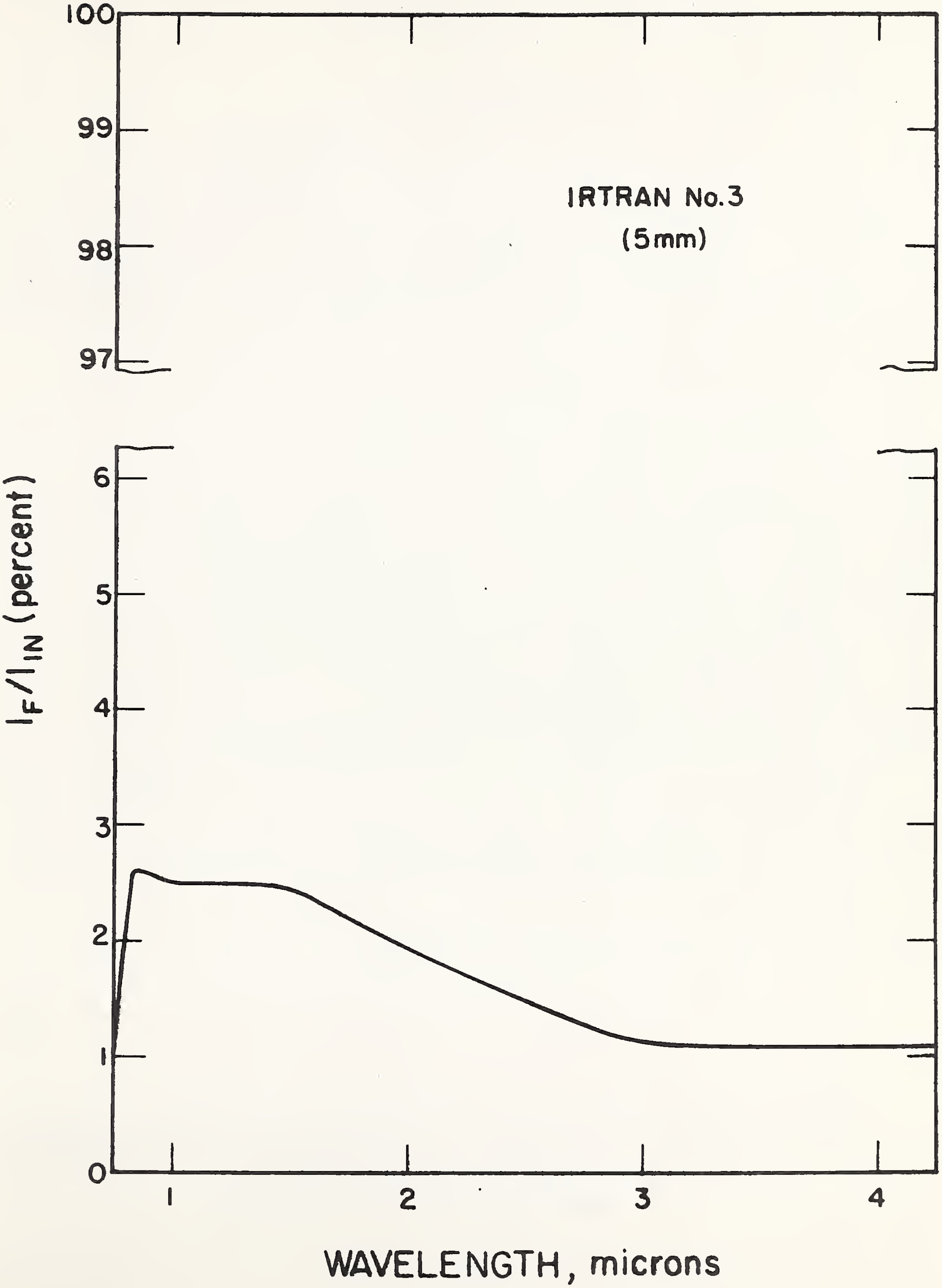

100
99
98
97
6
5
4
3
2
1
0
IRTRAN No.3
(5mm)
I_F/I_{IN} (percent)
1
2
3
4
WAVELENGTH, microns

Fig. 20

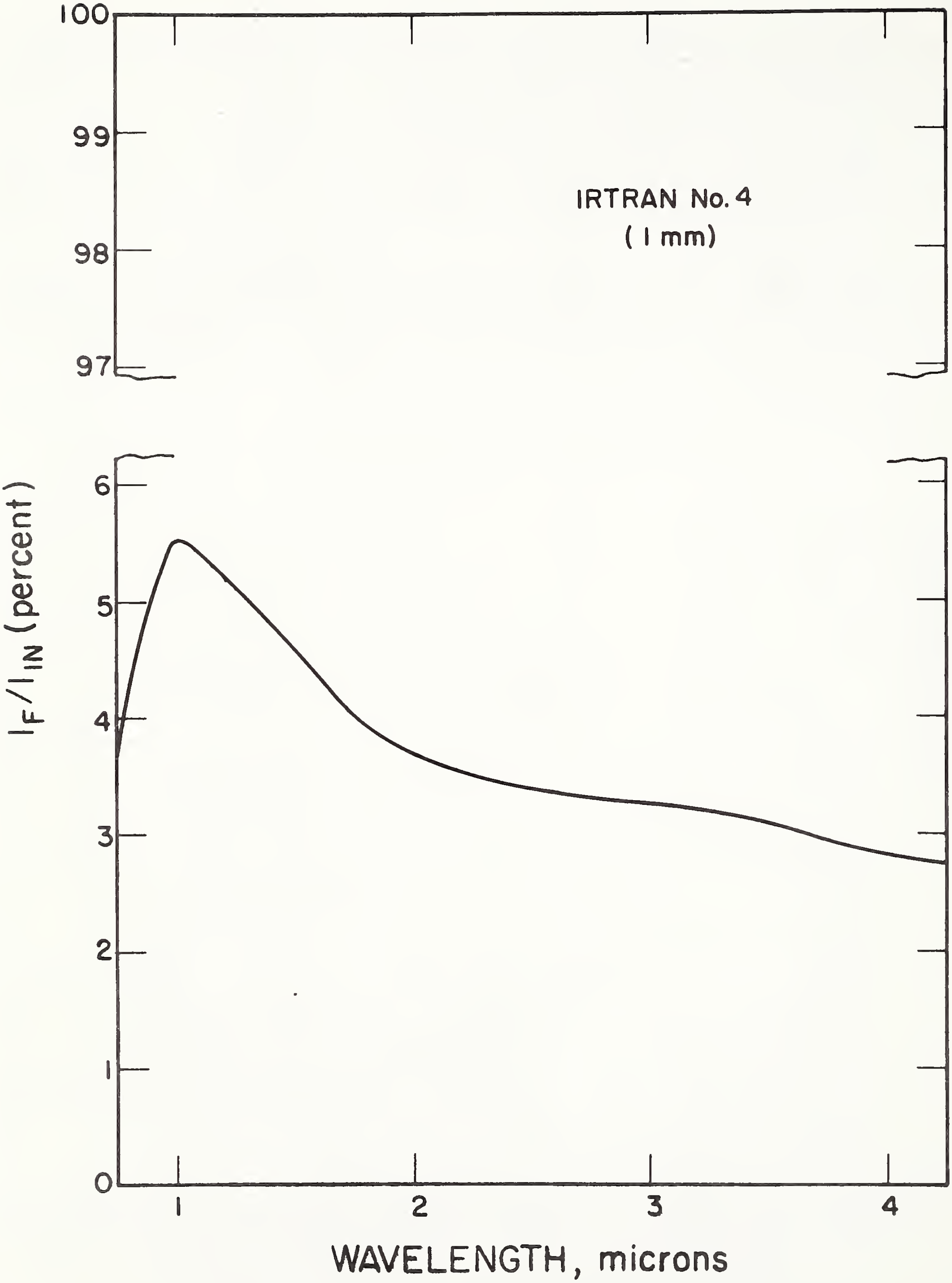

100
99
98
97
IRTRAN No. 4
(1 mm)
6
5
4
3
2
1
0
I_F/I_{IN} (percent)
1
2
3
4
WAVELENGTH, microns

FIG. 21

9. Scattering as a Function of Angle

by

R. H. Munis

An instrument has been designed to measure scattering as a function of angle. Measurements of the same sample were made using two detectors, a photomultiplier with an S20 surface, and a thermocouple. This comparison is shown in Figure 22. The transmission value of both measurements agrees to within 3%. The difference in appearance of the two curves is a result of the two different apertures used to define the field of view. Apparently, the maximum values are displaced from the optical axis not because of the detector misalignment, but because of the non-uniform brightness of the point source across its diameter.

The series of measurements made on the IRTRAN materials shows that all of them are characterized by a strong forward scattering component near 0°. This can be seen in Figure 23, a plot of the ratio of the flux scattered at a angle θ to the flux incident on the material in polar coordinates. It is also obvious that there is symmetry in the scattering pattern about 0° in the forward direction. Thus the next step is to proceed with back-scattering measurements of these materials between the direction of the incident beam and 90°. Shoulejkin[1/] has computed the scattering size parameter $2\pi\rho/\lambda$ for four different values and plotted the intensity of scattered light in polar coordinates in order to show the variations of the scattering pattern due to different particle sizes. He concludes that even at $\rho \simeq \lambda/6$ there is a definite indication of a strong scattering component in the direction of the incident rays.

We are also in the process of depositing films of MgF_2 and ZnS on quartz in order to determine the scattering patterns of the powders in raw form as compared with the data of IRTRAN 1 and IRTRAN 2 whose major chemical constituents are these two powders.

A GaAs laser which emits lines in the 0.80 - 0.90μ region has been constructed for us by Dr. N. Winogradoff of the NBS Electron Devices Section. This laser is ready to be put into operation.

An abstract of a paper entitled "Development of an Instrument to Measure Spectral Angular Infrared Scattering," by R. H. Munis and M. W. Finkel, has been submitted for the program of the spring meeting of the Optical Society of America.

[1/] Shoulejkin, W. "Scattering of light by very big colloidal particles" London, Edinburgh, and Dublin Phil. Mag. and J. Science, <u>48</u> (6th Series) 307-320, August 1924.

Figure 22. Comparison of forward angular scattering measurements using a photomultiplier and a thermocouple.

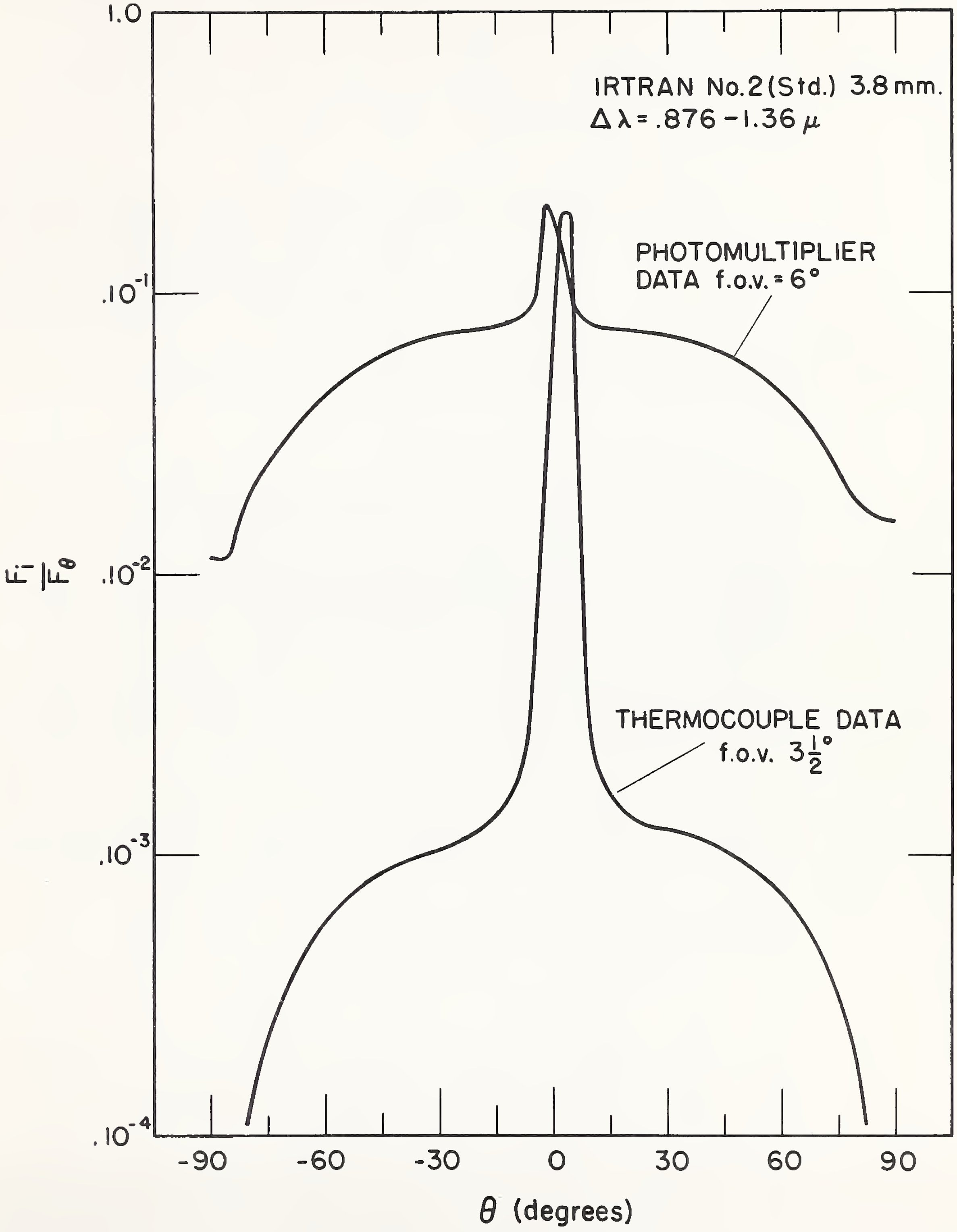

IRTRAN No.2 (Std.) 3.8 mm.
$\Delta\lambda = .876 - 1.36\ \mu$
PHOTOMULTIPLIER DATA f.o.v. = 6°
THERMOCOUPLE DATA f.o.v. $3\frac{1}{2}$°
1.0
$.10^{-1}$
$.10^{-2}$
$.10^{-3}$
$.10^{-4}$
F_i / F_θ
-90
-60
-30
0
30
60
90
θ (degrees)

FIG. 22

Figure 23. Polar plot of flux scattered at angle to that incident on sample.

IRTRAN No.2 (Std.) 3.8mm.

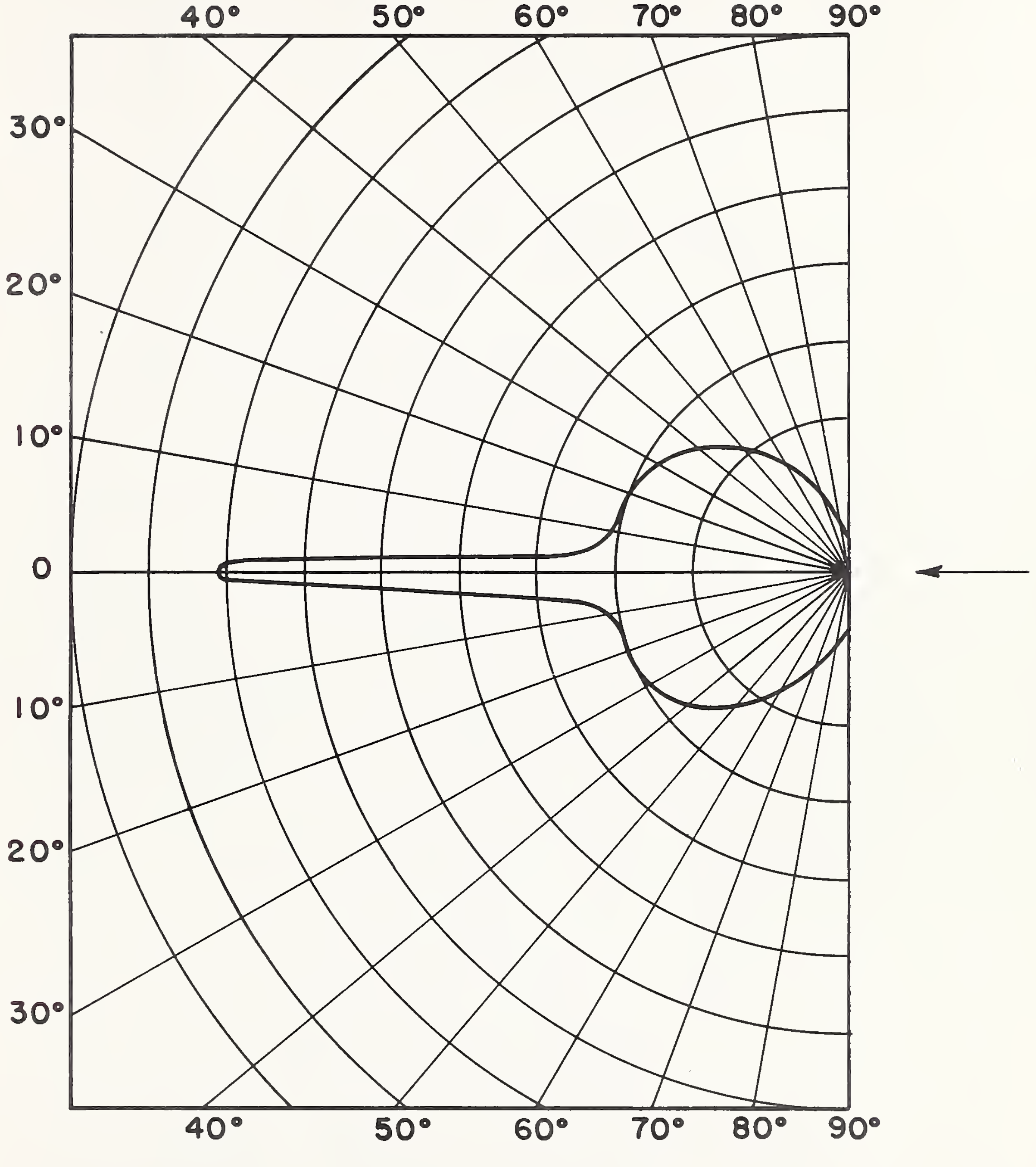


FIGURE No. 23

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