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Spectral Reflectances of Natural Targets for Use in Remote Sensing Studies

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and include laboratory, field, and aircraft	t measureme	nts. A discussion	of the differer	it measurements of
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Introduction

Remote sensing studies devoted to the development of spacecraft sensors have need of a representative selection of spectral reflectances of natural targets in order to determine the optimum number and location of spectral bands and sensitivity requirements. For example, Schappell et al. (1976) utilized reflectances of ground features in the design of a video guidance, landing, and imaging system for space missions; Begni (1982) selected the spectral bands for the SPOT satellite by taking into account both the spectral signatures of ground objects and the modifications introduced by the atmosphere; and Huck et al. (1984) studied spacecraft sensor responses and data processing algorithms for identifying Earth features by using a selection of spectral reflectances taken from the literature. Although several excellent sources of reflectance data are available, such as the agricultural data base from Purdue University Laboratory for Applications of Remote Sensing (Biehl et al. 1982) and the geologic data base from the Jet Propulsion Laboratory (Kahle et al. 1981), these data bases are limited in target selection and are usually available only in computer compatible format. Thus there is a need for a set of reflectance data that is representative of natural targets. The purpose of this report is to present a collection of uniformly digitized spectral reflectances of natural targets in a common format.

The spectral reflectance data were taken from the literature and include laboratory, field, and aircraft measurements. Since the reflectance of most natural targets may be influenced by the measurement technique, the techniques for the measurement of reflectance are discussed with emphasis on their major differences and sources of error. Most of the data have been derived from laboratory or field measurements. There is much interest, however, in the remote sensing of natural targets from both airborne and spaceborne platforms. Therefore, the appendix discusses the changes in apparent reflectance when a target is viewed through the atmosphere.

The target reflectances have been divided into six categories: agriculture; trees; shrubs and grasses; rocks and soils; water, snow, and clouds; and miscellaneous. The 156 reflectance curves included are a representation of what is available in the literature; they are not necessarily the most preferred sets of data for a listing of this kind. There is a similarity among reflectances of many of the targets, and thus a representative reflectance curve for each of the major types is presented along with a discussion of its salient features.

All the data were digitized from copies of doc-

uments and archived on magnetic tape for further processing. Each reflectance curve presented represents the data originally shown by the author. A test of the data transcription method indicated an error of less than 1 percent in the digitization process.

Symbols and Units

- E_d diffuse component of irradiance at the Earth's surface, watts-m⁻²
- E_o solar irradiance at the top of the atmosphere, watts-m⁻²
- E_{os} direct solar component of irradiance at the Earth's surface, watts-m⁻²
- E_s irradiance at the Earth's surface, wattsm⁻²
- FOV field-of-view, deg
- H sensor altitude, km
- IFOV instantaneous field-of-view, deg
- L_B beam radiance component of L_T , wattsm⁻²-sr⁻¹
- L_P path radiance component of L_T , watts- m^{-2} -sr⁻¹
- L_s surface radiance, watts-m⁻²-sr⁻¹
- L_T total radiance measured at the instrument, watts-m⁻²-sr⁻¹
- R bidirectional reflectance factor
- R_r bidirectional reflectance factor of reference
- R_t bidirectional reflectance factor of target
- T transmittance of atmosphere along target-to-sensor path
- TOA top of atmosphere
- V atmospheric visual range, km
- V_{τ} instrument response when viewing reference
- V_t instrument response when viewing target
- θ_i irradiance zenith angle, deg
- θ_r reflected beam zenith angle, deg
- λ wavelength, μ m
- ρ total reflectance; used in the appendix to represent reflectance measurement of the Earth's surface

- ρ_A apparent reflectance of a surface feature when viewed from aloft through the atmosphere
- ρ_b reflectance of background
- ρ_t reflectance of target
- au_A optical depth
- ψ relative azimuth angle, deg
- ϕ_i irradiance azimuth angle, deg
- ϕ_r reflected beam azimuth angle, deg
- ω_o single-scattering albedo

Measurement of Reflectance

Reflectance of a target can be measured in three ways: in the laboratory, in the field, or from an elevated platform such as an aircraft. These three approaches provide different results for several reasons. Illumination conditions are more easily controlled in the laboratory, but then the content of the field-of-view changes from laboratory to field to aircraft (or spacecraft). In studying vegetation, for example, a single leaf may be analyzed in the laboratory, whereas in the field the footprint usually becomes larger with altitude. Thus, depending on its altitude, a narrow-field-of-view instrument may "see" anything from several leaves to a field several hundred meters in diameter. As the footprint becomes larger, the target becomes a composite of leaves, stalks, soil, grasses, weeds, etc., and its reflectance properties are influenced by such factors as wind condition, row geometry, solar zenith, target slope, etc. Also, as altitude increases, atmospheric effects become more important, and scattering and absorption effects on radiance are enhanced. Target radiance is also influenced by scattered radiance from outside the instrument field-of-view. (These two effects are discussed in the appendix.)

Although the three measurement techniques yield different results, each has its place in remote sensing research. When modeling a vegetation canopy, the reflectance of the individual leaves is a required input. The laboratory data in this report do not adequately support canopy modeling; however, they do show spectral variations important in remote sensing. When combining various ratios of vegetation and bare soil to obtain an integrated reflectance, field measurements are required. And lastly, when attempting to correlate target reflectance with satellite measurements, a field measurement with a large footprint is desirable. Since target reflectance is influenced by the manner in which the measurement is

made, each of the three techniques will be discussed separately.

Laboratory Measurements

Total reflectance ρ is the ratio of the reflected radiant flux to the incident flux (Judd 1967). For a given target this quantity can be determined in several ways, but in the laboratory a small sample of the target is usually analyzed using a spectrophotometer with an integrating sphere attachment. Two methods of measuring reflectance with an integrating sphere are possible. In the substitution method, sample and reference (an ideal Lambertian surface) are placed in turn at the sample aperture and the ratio of respective photocell readings is determined. This technique has introduced systematic error of up to 12 percent in the determination of reflectance (Jacquez and Kuppenheim 1955). In the comparison method, both sample and reference are placed in separate apertures, the illuminating beam is switched from one to the other, and the ratio of the respective photocell readings is determined (Vlcek 1972). For a perfect sphere, the error is zero; with a flat sample, the error is about 1 percent. Most of the laboratory data included in the appendix were generated with spectrophotometers that use the comparison method.

Because of the transmittance of leaves, any reflectance measurement of a single leaf is influenced by the background on which the sample is supported (Lillesaeter 1982). When leaves are stacked, it has been found that no further change in reflectance at near-infrared wavelengths occurs beyond a depth of eight leaf layers or more (Allen and Richardson 1968). When comparing laboratory with field measurements, Knipling (1970) found that the visible and near-infrared reflectances from a nearly continuous broad leaf canopy were typically about 40 and 70 percent, respectively, of the laboratory reflectance of a single leaf.

Field Measurements

Spectral reflectance of natural surfaces can be measured in the field by using a radiometer fitted with an integrating sphere as the primary radiation receiver. The aperture of the sphere is pointed at zenith to measure irradiance and then rotated 180° to nadir to measure the target radiance. Since the nadir field-of-view is nearly 180°, a correction is usually applied to compensate for shading by the instrument itself (Coulson and Reynolds 1971). When the integrating sphere technique was used for measuring hemispheric reflectance, Coulson and Reynolds found that the time-varying irradiance field, particularly on hazy days, was responsible for appreciable scatter in

the reflectance determinations because of the sequential nature of the measurements. Duggin and Cunia (1983) compared simultaneous measurements of irradiance and target radiance with sequential measurements and showed that the simultaneous approach dramatically reduced the variation of the reflectance measurements. Large cumulus clouds near the solar disk and thin cirrus clouds are two major causes of varying irradiance (Robinson and Biehl 1979).

A cosine receptor, which usually employs a diffusing optics element or an immersion lens for improved performance, is often used to measure irradiance over a 2π steradian field-of-view. The target radiance measurement at nadir is frequently restricted to a smaller field-of-view, referred to as an "apertured" reflectance measurement (Graetz and Gentle 1982). The more commonly measured parameter, however, is the bidirectional reflectance factor, which requires a reference standard for the irradiance determination. A bidirectional reflectance factor R is defined as the ratio of the radiant flux reflected by the target to that reflected into the same beam geometry by a perfectly reflecting diffuser (Lambertian) identically irradiated (Judd 1967).

The bidirectional nature of $R(\theta_i, \phi_i; \theta_r, \phi_r)$ is illustrated in figure 1 for incident and reflected beams where (θ_i, ϕ_i) and (θ_r, ϕ_r) are the zenith and azimuth angles of the incident and reflected beams. In the field, R can be approximated by taking the ratio of the instrument response when viewing the target V_t to the instrument response when viewing a level reference surface V_r such that

$$R_t(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{V_t}{V_r} R_r(\theta_i, \phi_i; \theta_r, \phi_r)$$
 (1)

where $R_r(\theta_i, \phi_i; \theta_r, \phi_r)$ is the bidirectional reflectance factor of the reference surface; this term corrects for the nonideal reflectance properties of the reference surface. This relation assumes that (1) the instrument response is linear to entrant flux, (2) the diffuse component of irradiance is negligible, (3) the reference surface is irradiated and viewed in the same manner as the target, and (4) the aperture is sufficiently distant from the target.

An attempt to correct for the diffuse skylight component in the irradiance field by subtracting the spectral responses of the shadowed target and shadowed reference introduces an uncertainty in the reflectance determination that is greater than the diffuse skylight effect itself (Bauer et al. 1977). A simulation study on the influence of sky radiance has found the error induced in the estimation of bidirectional reflectance factors to be less than 5 percent for zenith view and Sun zenith angles less than 55° (Kirchner et

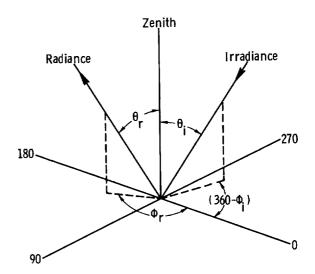


Figure 1. Viewing geometry for bidirectional reflectance factor measurements.

al. 1982). As long as the field-of-view is no greater than 15° to 20°, the term bidirectional reflectance factor is considered to describe the measurements adequately (Bauer et al. 1979).

When field illumination conditions are too variable or the sky is frequently overcast, measurements can be made using an artificial light source (De Boer et al. 1974). In this procedure the target is covered to block out natural light. The technique can also be extended to the laboratory, though it is the usual practice to view potted field plants and not individual leaves (McClellan et al. 1963).

Aircraft Measurements

The measurement of reflectance has thus far involved only a ratio of two instrument readings and a calibrated reference surface (when the reflectance factor is measured). With aircraft measurements, there is the additional complication of atmospheric scattering and absorption effects. Atmospheric scattering is apparent to anyone who has viewed the ground from an aircraft on a hazy day; the scattering produces a bluish turbidity superimposed over the background scene. If a suitable reference surface is available or if the spectral reflectance of selected targets has been established as references using field or helicopter (i.e., low altitude) equipment, aircraft data can also be calibrated (Bauer et al. 1979). The wide scan angle of most aircraft instruments is an additional problem, since the atmospheric path is variable across the scan. Either additional calibrations should be made at selected off-nadir scan angles or the targets of interest should be restricted to nadir viewing.

Surface reflectances can be estimated fairly well without ground support, however, provided that

absolute radiance measurements are obtained and a suitable radiative transfer program is used to correct for atmospheric effects (Bowker et al. 1983). Because of the interest in airborne and spaceborne remote sensing systems, the influence of the atmosphere on radiance measurements from elevated platforms is discussed in the appendix. Two of the reflectance curves presented in this report have been corrected for atmospheric effects using the technique given in the appendix.

General Features of Reflectance Curves

Many natural targets have common features in their spectral reflectance curves, which make the targets difficult to identify or separate. All vegetation, for instance, has a similar reflectance profile, whether it be agricultural crops, trees, shrubs, or grasses. In addition to the subtle differences in reflectances, the reflectances vary with time, at least for vegetation; this often leads to an identification or separation of targets. Several of the major categories of reflectances will be discussed in some detail in this section to show the commonality of features and the manner in which remote sensing may take advantage of minor differences to separate targets. Vane et al. (1982) have summarized the spectral bands useful for remote sensing applications.

Vegetation

Figure 2 is a typical reflectance curve for photosynthetically active vegetation. The spectrum can be broken into three regions according to the major factor responsible for the curve behavior. Below $0.7 \mu m$, absorption is dominated by carotenoid pigments (centered at 0.48 μ m) and chlorophylls (centered at 0.68 μ m). The green peak (centered at approximately 0.56 μ m) is the region of the visible spectrum corresponding to weak absorption. The sharp rise around 0.7 μ m, (called the red edge) marks the change from chlorophyll absorption to cellular reflectance. The near-infrared reflectance from 0.7 to 1.3 μ m is dominated by the cell-wall/airspace interface and, to a lesser extent, by refractive index discontinuities of cellular constituents (Gausman 1974). Beyond 1.3 μ m, reflectance is primarily controlled by leaf water content. The suggested spectral bands given in figure 2 have been successfully used by the researchers; they mostly represent bands that were available on various sensors and are not necessarily optimum-with respect to bandwidth or central wavelength.

During the growth cycle of vegetation the reflectance decreases in the visible wavelength and increases in the near-infrared wavelengths until maximum canopy development is reached. Then, with senescence, the visible reflectance increases while the near-infrared reflectance decreases, although relatively less than the visible increases. Thus, vegetation reflectance usually progresses from a background, such as soil, to full greenness and then returns to the background again.

By analyzing the reflectance spectrum of vegetation in discrete narrow bands, Verhoef and Bunnik (1974) identified about 12 spectral bands relevant for assessing special features of crops. The selection of a few bands and/or wide bands does not give optimum results (Beers 1975). Generally, the selected bands should have low correlation. Using the Landsat MSS bands, Kauth and Thomas (1976) developed a linear transformation (called the "tasseled cap") that defines two orthogonal components called "brightness" and "greenness." The brightness establishes the data space of soils, and the greenness is a measure of green vegetation. The temporal behavior of the greenness can be used to separate some crops (Badhwar et al. 1982). Idso et al. (1980) used a reflectance ratio involving Landsat MSS bands 5 (0.6- $0.7\mu m$) and 6 (0.7–0.8 μm) to estimate grain yields by remote sensing of crop senescence rates. Crops that are stressed for water, which have lowest grain yields, had a longer period of senescence.

The broad absorption areas near 1.4 and 1.95 μ m are also atmospheric water vapor bands and should be avoided in remote sensing. However, the 1.6 and 2.2 μ m regions are useful for distinguishing succulent (average leaf water content of 92 percent) from nonsucculent (average leaf water content of 71 percent) plants (Gausman et al. 1978).

According to Collins (1978) the sharp spectral reflectance rise between the chlorophyll absorption maximum and the cellular reflectance maximum, the red edge, can be very useful in detecting phenologic changes and geochemical stress. In a study of maturation changes of crop plants such as corn, wheat, and sorghum, Collins detected a red-shift (of 0.007 to 0.010 μ m) of the red edge to longer wavelengths (0.690 to 0.700 μ m) associated with the conversion from vegetative growth to reproductive growth (heading and flowering). The red-shift was useful in separating some crop types, particularly the non-grain from the grain crops (the shift is not as pronounced in the non-grain crops).

When plants become stressed, a decrease in chlorophyll productivity causes a shift of the red edge toward shorter wavelengths. This kind of blue-shift has been detected in the reflectance spectrum from a forest canopy growing over copper-lead-zinc sulfide mineralization (Collins et al. 1977).

Just as the detection of the shift in the red edge requires spectral measurements of 0.010-µm

resolution, other regions within the reflectance curve of vegetation may also demand such resolution (Mack et al. 1984). There is an emphasis toward more bands with higher spectral resolution; however, Mack advises using only those bands with an established relevant biophysical and agronomic basis. Knowledge of these spectral characteristics is essential for minimizing data processing costs and time.

Soil

Figure 3 displays five representative spectral reflectance curves for soils. Condit (1970) has classified 160 soil samples from 36 states into three general types according to the shape of their reflectance curves within the 0.4 to 1.0 μ m region of the spectrum. Type 1 curves have rather low reflectances with slightly increasing slope, which gives them their characteristic concave form from 0.32 to about 1.0 μ m. Type 2 curves are characterized by generally decreasing slope to about 0.6 μ m followed by a slight dip from 0.6 to 0.7 μ m, with continued decreasing slope beyond 0.75 μ m. This results in a typical convex shape from the visible to beyond 1.0 μ m. Type 2 soils are better drained and lower in organic matter than type 1 soils. Type 3 curves have a slightly decreasing steep slope to about 0.6 μm followed by a slight dip from 0.62 to 0.74 μ m, with slope decreasing to near zero or becoming negative from 0.76 to 0.88 μ m. Beyond 0.88 μ m (to 1.0 μ m) the slope increases with wavelength. Type 3 soils have moderately high iron content. Condit was able to reproduce these curves (160 in all) with a high degree of accuracy from measurements at five narrow bandwidths (0.02 μ m) centered at 0.40, 0.54, 0.64, 0.74, and $0.92 \mu m$; these wavelengths may not relate to specific physical phenomena. Stoner and Baumgardner (1980) established two more types of soil reflectance curves, similar to type 3, by extending the data out to 1.3 μ m. The type 4 reflectance behavior from 0.88 to 1.3 μm was caused by high iron content and organic material. In type 5, the negative slope from 0.75 to 1.3 μ m resulted from very high iron and low organic concentrations. This was the only type that did not show a strong absorption (water) at 1.45 μ m.

Although reflectances in all spectral regions are negatively correlated with organics, the region around 0.57 μ m (the green peak) is particularly useful for monitoring organic matter in bare soils since it is free of other major disturbances. Stoner and Baumgardner considered measurements at 0.7, 0.9, and 1.0 μ m to be essential for thorough classification of background soil reflectance. Absorptions at 0.7 and 0.9 μ m are produced by ferric iron compounds,

while that at 1.0 μ m is caused by ferrous iron compounds.

The 0.4 to 1.0 μ m region is not useful for monitoring soil moisture content (Reginato et al. 1977), although the entire reflectance curve is generally suppressed with increased moisture. The region centered at 2.2 μ m has the highest correlation with soil moisture; this region was similarly important with vegetation.

The two regions of highest soil reflectance, centered at approximately 1.27 and 1.65 μ m, correlate with many soil properties (Stoner and Baumgardner 1980). With sandy textured soils, a decrease in particle size increased reflectance. However, with medium to fine textured soils, a decrease in particle size decreased reflectance.

Rocks and Minerals

Figure 4 shows spectral reflectance curves for shale and andesite. Rocks are similar to soils in reflectance, which is not surprising since soils are derived from weathered rocks. One major difference between the two is the organic matter present in soils, which tends to decrease reflectance.

With transparent rock particles, reflectance increases with a decrease in particle size, but just the opposite is the case with opaque particles (Salisbury and Hunt 1968). This may explain the behavior of the fine grain soils discussed in the previous section.

The iron absorption bands are very prominent in basic rocks (i.e., igneous rocks with minerals rich in metallic bases). These absorption bands are even prominent in red-stained beach sands.

The strong fundamental OH vibration at 2.74 μ m characterizes the behavior of hydroxyl-bearing minerals. Clays (hydrous aluminum silicates), in particular, show decreasing spectral reflectance beyond 1.6 μ m, and this broadband behavior can be used to identify clay-rich areas associated with hydrothermal alteration zones (Podwysocki et al. 1983). The absorption peaks at 2.17 and 2.20 μ m can be used to identify clay minerals (Goetz and Rowan 1981). The reflectance spectrum of unaltered material is not as complex, particularly in the 2.0 to 2.4 μ m region, as in altered rocks.

The spectral absorption features at 1.4 and 1.9 μ m, as well as at 2.2 μ m, indicate hydration, but these two regions are subject to atmospheric interference.

The detection of vegetation cover and the analysis of the spectral properties of plants to identify conditions present in the soil are also an important area in geologic remote sensing. This subject was mentioned in the vegetation section. A discussion of

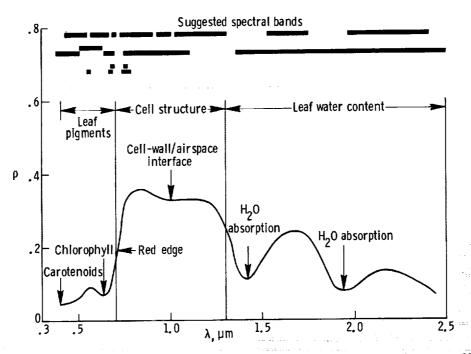


Figure 2. Typical vegetation reflectance curve showing dominant factors controlling leaf reflectance. Vane et al. (1982) attributed the three rows of suggested spectral bands to Wiersma and Landgrebe (top row), Tucker (middle row), and ORI, Inc. (bottom row).

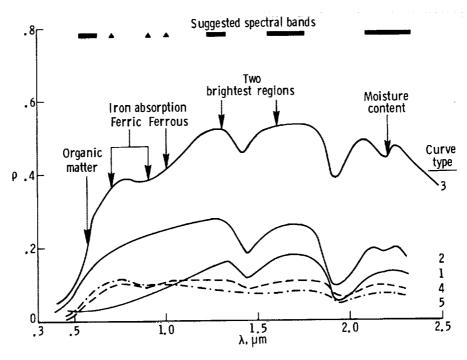


Figure 3. Typical soil reflectance curves for the five major types of curves. Types 1-3 proposed by Condit (1970) and types 4 and 5 by Stoner and Baumgardner (1980). Vane et al. (1982) attributed the suggested spectral bands to Stoner and Baumgardner.

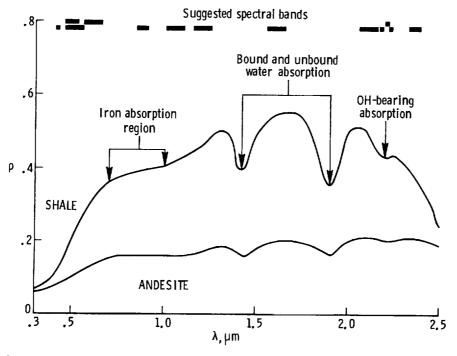


Figure 4. Typical reflectance curves for two rock formations. Vane et al. (1982) attributed the suggested spectral bands to Goetz and Rowan except for the 0.40–0.42 μm and 0.84–0.90 μm bands (ORI, Inc.) and the 0.45–0.52 μm band (Billingsley).

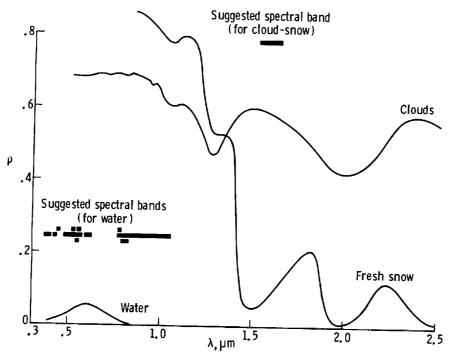


Figure 5. Typical reflectance curves for water, snow, and clouds. Vane et al. (1982) attributed the suggested spectral bands for water to ORI, Inc., except for the 0.47–0.57 μm band (NASA-GSFC). The cloud-snow band is by Crane and Anderson (1984).

the topic has been presented by Goetz et al. (1983). A 10-percent grass cover masks beyond recognition spectral characteristics of such rocks as andesite and limestone that have low reflectances; dry vegetation, on the other hand, has a minimal effect (Siegal and Goetz 1977). Beyond 1.4 μ m, the reflectance of rock tends to become more dominant.

Water, Snow, and Clouds

In the absence of glitter effects, water is easily distinguished from other targets by its low reflectance, particularly in the near-infrared portion of the spectrum. However, high concentrations of suspended sediment, which often occur in shallow reservoirs, can increase reflectance. Surface algal blooms can also change the reflectance properties of water; these are distinguished from high sediment loads by the characteristic chlorophyll absorption in the red area of the spectrum. Monitoring chlorophyll in ocean waters, where reflectance is less than 0.02, has been discussed by Gower et al. (1984).

In figure 5, both snow and clouds are seen to have high reflectance in the visible portion of the spectrum. Clouds are still highly reflective in the near-infrared wavelengths, while snow becomes relatively nonreflective beyond 1.4 μ m, particularly in the 1.5 to 1.6 μ m region (Crane and Anderson 1984).

Selection and Formatting of the Spectral Reflectance Data

A literature search for spectral reflectance data retrieved about 300 spectral curves. From these, 156 were selected based on the following criteria: (1) the importance of the target, (2) the data collection mode, and (3) the quality of the data. Priorities for the remote sensing of agricultural crops have been established by Bowker (1985). For the other areas, however, selection was guided by availability and the desire to present a variety of targets. Field measurements made with a high-resolution scanning spectrophotometer were preferred. This type of data was limited, so that laboratory spectral measurements often had to be selected. It is important to note that laboratory measurements are sometimes required because of vegetation cover of natural targets in the field, for example, soils. Of the 156 data sets, 59 represent laboratory measurements. Most of these occur in either the tree or the rocks and soils category. (As previously mentioned, the laboratory and field data are not compatible since they represent entirely different environments.) Finally, the quality of the reflectance data, which was judged somewhat arbitrarily, was used to eliminate some of the data. The

preferred data were well documented with a discussion of error sources.

The targets were grouped into six major categories: agriculture; trees; shrubs and grasses; rocks and soils; water, snow, and clouds; and miscellaneous targets. Each reflectance curve was presented by its author as being representative of a given target; this report has simply standardized all of the data to a common format.

This standardization involved digitizing the curves from the published documents and interpolating to obtain the desired format. The digitization was performed in the following manner. First, a photocopy was made of each spectral reflectance curve chosen for inclusion in the data set. Then, an X-Y digitizer was used to digitize the data from each profile. Each record was archived on magnetic tape. In final processing the data were retrieved, the reflectance curve was machine plotted, and a second-order interpolation was performed to give the uniform spectral intervals and format shown; having a common wavelength interval for each profile helps intercomparison of the data.

Digitizing the data has, of course, introduced some error. All of the data were taken from copies of the original documents. Fortunately, one of the reports (Gausman et al. 1973) contained both graphical and tabular data. This set of data represents the worst case in digitizing since the original figures were only approximately 20 by 45 mm in size. Comparison of reflectance values at 38 coincident wavelengths (taken from two figures in the Gausman report) gave an average error of only 0.0073 units of reflectance. This is an excellent agreement, and the data presented in this report may, therefore, be taken as reliably reporting the original sources.

Spectral reflectances for the 156 selected targets are presented in the common format in the back of this report. The reflectance data for each target are presented in two formats: (1) graphical, with a wavelength interval from 0.3 to 1.2 μm or from 0.3 to 2.5 μ m, and (2) tabular, with a spectral resolution of $0.01~\mu\mathrm{m}$ (0.3 to 1.2 $\mu\mathrm{m}$) or 0.02 $\mu\mathrm{m}$ (0.3 to 2.5 $\mu\mathrm{m}$). The ordinate of the reflectance curves is labeled "reflectance" with a range from 0 to 1. Bidirectional reflectance factor would have been a more appropriate term for most of the field data, but it was not always clear that the assumptions required by equation (1) were valid (see Robinson and Biehl 1979). In several instances data have been included where the ordinate was labeled "relative reflectance" or "albedo." The magnitudes of most target reflectances are known to vary over wide limits, even when the target descriptions are identical. What is most important is the variation of reflectance with wavelength.

Concluding Remarks

A collection of spectral reflectances for 156 natural targets has been presented in a uniform format. Each target is described by both graphical and tabular data. The collection was chosen with some consideration of the relative importance of the targets, and the data presented are representative of what is available in the literature. While the data set was developed to support simulation studies in the development of remote sensing instruments, it may find application in other areas of remote sensing, such as algorithm development and radiative transfer studies.

The data are presented here with a uniform 0.01or 0.02- μ m spacing, even though the spectral resolution of the source data varied widely. Therefore these data are intended for the broad class of applications requiring moderate spectral resolution, and not for those requiring high spectral resolution, such as the detection of the vegetative red-shift; for these high-resolution tasks, other data must be used.

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Appendix

Atmospheric Effects on Reflectance Profiles

In the spectral region of interest for this report, 0.3 to $2.5~\mu m$, the sensed energy is almost entirely derived from solar radiation which transits the atmosphere, is reflected by the surface, and is then transmitted to the sensor aloft. In this spectral region, the thermal radiation from the atmosphere itself is negligible in comparison with the solar component, so it will be ignored here. The solar irradiance E_o on top of the atmosphere is shown in figure A1. After passing through the atmosphere, the irradiance impinging on the surface has been attenuated as shown by the lower curve. Both curves here pertain to the Sun at zenith. The atmospheric absorption features shaded on the curve are due to ozone, oxygen, water vapor, and carbon dioxide, as indicated.

The solar irradiance at the surface is composed of both a direct and a diffuse component, as shown in figure A2. For the example shown, the diffuse component amounts to more than 30 percent of the total at the shortest wavelengths. (Slater (1980) states that a diffuse component of 10 to 20 percent is typical for the visual to near-infrared spectral range.) The conditions assumed for figure A2 are an atmospheric visual range of 31.4 km and a surface reflectance of 0.4 at all wavelengths. (For this, and subsequent curves in this appendix, the solar zenith angle θ_i is 20°; all figures here cover the wavelength range from 0.4 to 1.2 μ m.) As will be seen later, varying the visibility and surface reflectance affects the magnitude of the diffuse irradiance.

From the foregoing, it can be seen that the spectral content of the solar irradiance has been modified greatly by the atmosphere even before any reflection takes place. The irradiance at the surface E_s is made up of a direct solar component E_{os} and a diffuse component E_d , so

$$E_s = E_{os} + E_d \tag{A1}$$

Upon reflection by the ground, a surface radiance L_s results which is a function of E_s and ρ , the surface reflectance. If Lambertian (isotropic) reflectance can be assumed (this assumption may not always be justified; see Smith et al. 1980), then

$$L_s = \frac{E_s \rho}{\pi} \tag{A2}$$

All quantities have a spectral dependence, which has been omitted here for clarity of notation. The surface radiance L_s is that radiance which would be measured by an observer at the surface. When the target is viewed from aloft, the total radiance measured at

the instrument L_T is composed of a beam radiance L_B and a path radiance L_P . Thus,

$$L_T = L_B + L_P \tag{A3}$$

The beam radiance L_B is that component of radiance arising from radiation reflected from the surface and transmitted directly to the sensor without scattering, i.e., $L_B = L_s T$. The path radiance L_P is scattered radiation which enters the path between target and sensor. In terms of the surface radiance L_s ,

$$L_T = L_s T + L_P \tag{A4}$$

where T is the transmittance of the atmosphere along the target-to-sensor path. Since the surface reflectance is defined as

$$\rho = \frac{\pi L_s}{E_s} \tag{A5}$$

then the apparent reflectance aloft is

$$\rho_A = \frac{\pi L_T}{E_s} = \frac{\pi}{E_s} (L_s T + L_P) \tag{A6}$$

which differs from the true reflectance ρ according to the magnitudes of T and L_P for the altitude of the sensor. Depending on their magnitudes, ρ_A can be either larger or smaller than the true value ρ .

Figure A3 shows the apparent reflectances of targets with true reflectances of 0.1, 0.4, and 0.7 when the targets are viewed from altitudes of 0.6 km, 3.0 km, and the top of the atmosphere (TOA). In general, viewing through the atmosphere increases the apparent reflectance for low-reflectance objects (e.g., $\rho = 0.1$) and decreases the apparent reflectance for high-reflectance objects (e.g., $\rho = 0.7$). For objects of intermediate reflectance (e.g., $\rho = 0.4$), the effect is minimal and depends on wavelength; ρ_A can be either larger or smaller than the true reflectance ρ .

This distortion in ρ_A is not surprising because only photons in L_s carry information purely concerning the target. Most photons making up L_P have had no interaction with the target. Some of them are derived from multiple-scattered radiation which has never reached the surface. Others are derived from radiation which has been reflected from the surface outside the target area and then, after one or more atmospheric scatterings, has found its way into the field-of-view of the sensor. A small number of photons in L_P have been reflected by the target, but scattered at least once on their way to the sensor (and, thus, are not strictly part of the beam radiance). As the path radiance increases relative to the beam radiance, less information about the target is included in the radiance signal.

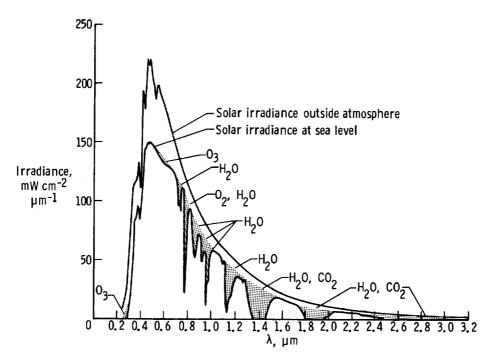


Figure A1. Solar spectral irradiance outside the atmosphere and at the surface, for solar zenith angle of 0°. Features due to principal absorbers are identified.

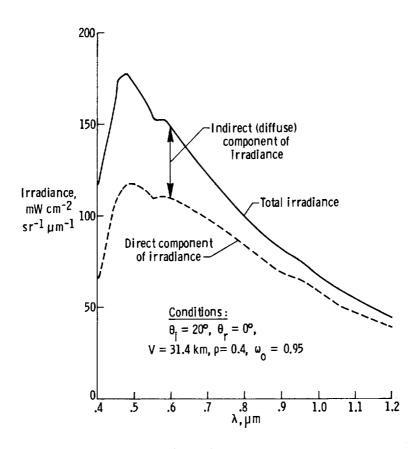


Figure A2. An example of the direct and indirect (diffuse) components of irradiance on a surface with reflectance of 0.4.

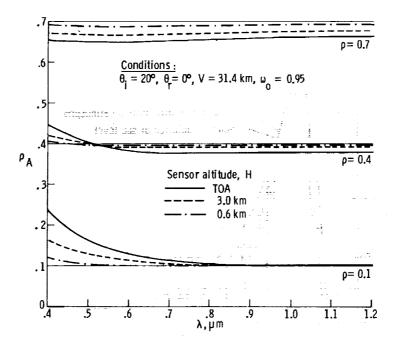


Figure A3. Effect of sensor altitude on apparent surface reflectance.

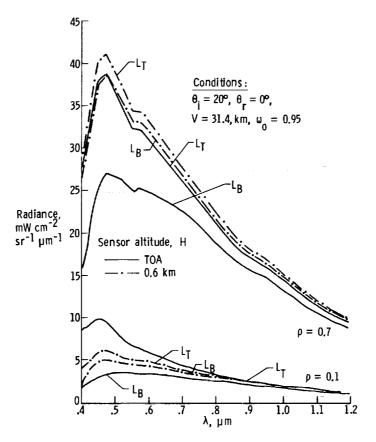


Figure A4. Beam radiance and total radiance at 0.6 km and TOA.

Figure A4 shows the relative strengths of L_T and L_B for reflectances of 0.1 and 0.7, at altitudes of 0.6 km and TOA. Thus, this figure shows the radiance components for the ρ_A plots in figure A3. Note that the absorption features in the radiance curves have been omitted, for clarity. The path radiance is the difference between L_T and L_B . For reflectance of 0.1, the 0.6-km curves lie between the TOA curves. Then, for reflectance of 0.7, the 0.6-km curves lie at or above both TOA curves. This behavior shows that for $\rho = 0.1$, total radiance increases with altitude, but for $\rho = 0.7$, it decreases with altitude. For $\rho = 0.4$ (not shown), the total radiance is nearly constant. Turner (1975) describes in more detail the relative magnitudes of L_T , L_B , and L_P under a variety of conditions.

Factors Affecting Apparent Reflectance Determination

Some introductory examples have just been given of the influence of altitude and surface reflectance on the derived reflectance. In the present section, all the parameters affecting the determination of apparent reflectance will be identified, and their effects described. The parameters are shown on figure A5; they may be grouped as follows:

Viewing geometry:

Solar zenith angle, θ_i Viewing angle, θ_r Azimuthal angle, ϕ_i or ϕ_r Relative azimuthal angle, ψ , where $\psi = \phi_r - \phi_i + 180$ Altitude of sensor, H

Meteorological parameters:

Relative humidity Cloud cover Surface pressure

Atmospheric optical parameters:

Optical thickness, τ_A or Atmospheric visual range, V Aerosol type (phase function) Single-scattering albedo, ω_a

Target and background parameters:

Target size Target reflectance, ρ_t Background reflectance, ρ_b Instantaneous field-of-view, IFOV

The effect of variation in each of these parameters is now discussed.

Viewing Geometry. As θ_i increases, less solar irradiance is incident on the surface, and less is reflected

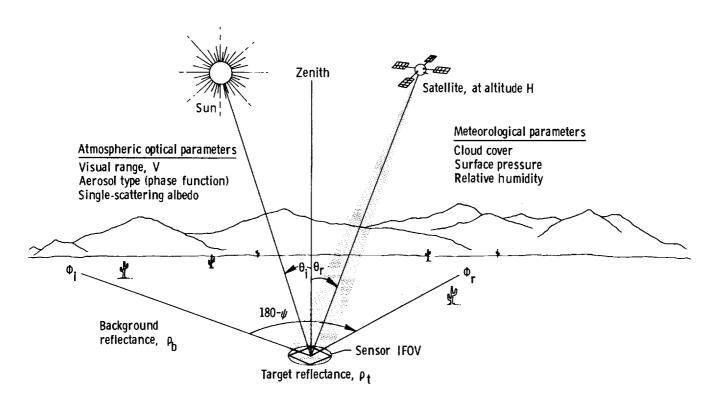


Figure A5. Parameters affecting apparent reflectance.

to the observer. Therefore, failure to account for an increase in θ_i would result in an underestimate of reflectance. (As noted earlier, θ_i should be kept below 55°.) Also, as θ_i increases, there is a higher proportion of multiple scattering in the incident radiation.

Similar effects are noted for θ_r ; as θ_r increases, the path component of radiance increases, and the beam component of radiance passes through a longer atmospheric path and suffers more attenuation through absorption and scattering. Therefore, as θ_r increases, the total radiance depends more heavily on atmospheric influences and less on target characteristics. Thus, target contrast and modulation become reduced with increasing θ_r . In addition to the atmospheric effects, most targets have bidirectional reflectance characteristics that are not isotropic (see, e.g., Smith and Ranson 1979 and Kimes 1983). This behavior needs to be considered in addition to the effects of changing θ_i and θ_r (Holben and Fraser 1984 and Barnsley 1984). A feature's reflectance may be considered to be isotropic only for small instantaneous fields-of-view (IFOV) and over ranges of θ_i and θ_r each smaller than a few degrees (Slater 1980). However, isotropic surface reflectance is assumed in all cases here.

Solar radiation is scattered by both the molecular and the aerosol component of the atmosphere. The molecular component (mostly nitrogen) scatters in a Rayleigh-like fashion with equal amounts of forwardand back-scattering, and smaller amounts at right angles to the incident beam. In a very clear atmosphere, the scattering of radiation approaches this condition. In an aerosol atmosphere, however, scattering is much more anisotropic, with the preponderance of radiation scattered in the forward direction. In most conditions, the scattering phase function shape is a blend of the Rayleigh and aerosol phase function shapes, with considerable departure from anisotropy. For this reason, the magnitude of the radiance reaching the detector depends highly on ψ except when θ_r is zero (i.e., the nadir is being viewed). For molecular scattering, the radiation is scattered approximately as the inverse fourth power of the wavelength. (This accounts for the predominantly blue color of the sky.) For aerosol scattering, the result is less marked, the exponent being on the order of -1.3 (Kiang 1982). Thus, aerosol scattering results in a blue-white "milkiness," rather than a blue coloration. For both of these reasons, the effect of a change in ψ is, again, always most marked at the shortest wavelengths. Figure A6 shows the effect of changing ψ with $\theta_i=20^\circ$ when a surface with reflectance of 0.1 is viewed from satellite altitude for $\theta_r = 5^{\circ}$. For example, at $\lambda = 0.4 \ \mu \text{m}$, ρ_A increases by 0.030 for observations in the direction

of the Sun (relative azimuth angle $\psi=0^{\circ}$) and decreases by 0.014 for observations in the direction opposite the Sun ($\psi=180^{\circ}$), compared with the nadirlooking case, which is denoted by X's on the graph. At $\lambda=0.7~\mu\mathrm{m}$, the increase and decrease are both approximately equal to 0.002.

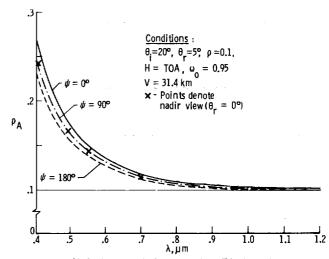


Figure A6. Effect on apparent reflectance of changing relative azimuthal angle when viewing a surface with reflectance of 0.1 at 5° from nadir, from satellite altitude.

Meteorological parameters. Implicit in the foregoing discussion was the assumption of a cloud-free atmosphere and a nominal water vapor profile. Clouds can drastically modulate the amount of energy reaching the surface; they are not modeled here. (For a good discussion of cloud effects, see Duggin et al. 1984.) Changes in the humidity profile change the depth of the water vapor absorption features. A higher level of relative humidity also affects the type of aerosol present, by favoring larger aerosol particles (Shettle and Fenn 1979).

Surface pressure and terrain altitude variability have similar effects on the radiance level. The three-sigma surface pressure variability worldwide is estimated to be equivalent to a surface elevation range from -0.73 to +0.78 km (Bowker et al. 1983). Either a pressure or a surface elevation change modifies the amount of molecular scattering. For most cases, this effect is small.

Atmospheric optical parameters. The amount of aerosol in the atmosphere is usually parameterized by the aerosol optical thickness τ_A where

$$T_A = \exp(-\tau_A) \tag{A7}$$

is the aerosol transmissivity in a vertical path. The value of τ_A can be determined for a locality by viewing the Sun with a photometer over a range of solar

elevation angles (Flowers et al. 1969 and Peterson et al. 1981). The total attenuation is measured and, then, because the molecular scattering and ozone optical thicknesses are known and can be subtracted, the aerosol optical thickness can be determined. The aerosol optical thickness is sometimes expressed as a turbidity, often taken at or near 0.55 μ m wavelength. The optical thickness (or turbidity) at one wavelength can be related to the optical thickness at other wavelengths statistically (Fraser 1975 and Kaufman and Fraser 1983) or analytically (Nicholls 1984).

Another way of quantifying aerosol amount is through visual range in the horizontal at the surface (Elterman 1970). The lower the visual range. the more turbid the atmosphere. This approach has appeal because visibility (which is proportional to visual range (Kneizys et al. 1980)) is a parameter measured at all weather stations, whereas optical thickness is measured at comparatively few sites. The correspondence between optical thickness and visual range is only a rough proportionality, however, because it is possible to have thick layers of aerosol existing aloft with a very clear atmosphere at the surface, as indicated by a surface visibility measurement. For this reason, particularly in remote sensing measurements, for which a target is viewed downward through the atmosphere rather than along a nearsurface path, turbidity is a more reliable measure.

In summary, a decrease in visual range, or an increase in optical thickness, increases the amount of aerosol scattering. Figure A7 shows the effect on apparent reflectance of changing the atmospheric visual range from a very hazy condition (V = 10.5km) through an average condition (V = 31.4 km) to a rather clear condition (V = 62.8 km). The solar zenith angle is 20°, and the nadir is viewed. Three different surface reflectances are simulated. For the low reflectance ($\rho = 0.1$), the effect is an increase in apparent reflectance at all wavelengths, particularly at short wavelengths. Even for the very clear atmosphere (V = 62.8 km), the apparent reflectance at $\lambda = 0.4 \ \mu m$ for $\rho = 0.1$ is around 0.24. At $\lambda = 0.7 \mu m$, the increase in reflectance is only approximately 0.02, even for a very hazy atmosphere. For $\rho = 0.4$, the effect of the atmosphere can be either to decrease or to increase the apparent reflectance, depending on the wavelength and visual There is an increase only at wavelengths smaller than 0.6 μ m; at longer wavelengths, the apparent reflectance decreases, by up to 0.04 for a hazy atmosphere. For $\rho = 0.7$, the effect is a decrease in apparent reflectance for all wavelengths and visual ranges. A more detailed discussion of the effects of

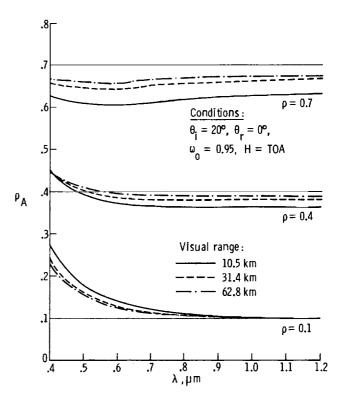


Figure A7. Effect of atmospheric visual range on apparent reflectance, for three surface reflectances.

visual range at solar zenith angles other than 20° may be found in Bowker et al. (1983).

The type of aerosol affects the shape of the singlescattering phase function. Also, the more absorptive the aerosol, the more isotropic the scattering. The single-scattering albedo ω_o determines the amount of radiation scattered, rather than absorbed, at each scattering. A higher ω_o means a higher total radiance level. Remember that the shape of the actual phase function varies with wavelength and is a blend of the Rayleigh and aerosol phase function shapes. Figure A8 shows the effect on ρ_A of changes in the aerosol single-scattering albedo ω_o assumed in the calculations; the effect is shown for three surface reflectances. The apparent reflectance is always highest for the highest value of ω_o and lowest for the lowest value. The effect of a change in ω_o is roughly proportional to the surface reflectance. For darkest scenes, the effect is minimal; for the brightest scene simulated ($\rho = 0.7$), the effect on ρ_A is as much as 0.04 at $\lambda = 0.4 \ \mu m$.

Target and background parameters. If the reflectance of the adjacent surface area differs from that of the target, then light scattered from this surrounding background has a different spectral content from that of the target, and the perceived target re-

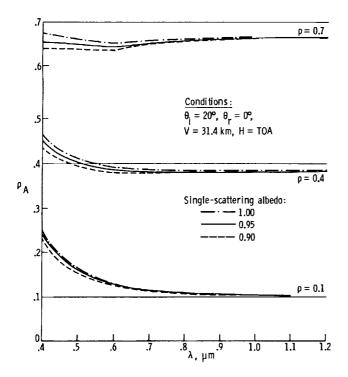


Figure A8. Effect of aerosol single-scattering albedo on apparent reflectance, for three surface reflectances.

flectance will be in error. Figure A9 shows the effect of viewing a target surrounded by a uniform, slightly more reflective background. The figure shows cases with target/background reflectance combinations of 0.1/0.2, 0.4/0.5, and 0.7/0.8. A comparison of these results with those for the uniform-scene reflectances of 0.1, 0.4, and 0.7 in figure A7 shows that in each case the apparent reflectance is higher than that of the target alone, because of additional photons scattered into the path from the background. Even for the slight reflectance differences (0.1) simulated here, the effect is appreciable. Thus, background effects need to be taken carefully into account.

The research area of modeling such "adjacency effects" continues to be an active one. Some recent references are those of Dave (1980), Kaufman and Joseph (1982), Dana (1982), and Kaufman (1984). A good introductory discussion may be found in Slater (1980).

Correction for Atmospheric Effects

Because the factors named above all affect the perceived reflectances of substances, it is of interest

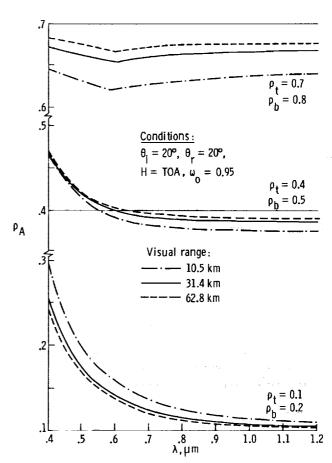


Figure A9. Effect of background radiance on apparent reflectance, when background reflectance is 0.1 higher than target reflectance, for three target reflectances and atmospheric visual ranges.

to ask whether such influences can be estimated well enough to remove their effects and allow the true reflectance profiles to be estimated. Bowker et al. (1983) directly attacked this problem. In that report, the effects of imprecision in the knowledge of each of the quantities noted earlier on derived reflectance are discussed, and the results plotted. Also, a method was developed for estimating spectral reflectance from total radiance values. Figure A10 (from Bowker et al. 1983) shows an example of an alfalfa radiance profile converted to obtain a reflectance profile. When the sky is free of clouds and relatively stable atmospheric conditions prevail, it should be possible to determine reflectance to an accuracy of 10 percent or better, by using local meteorological data. It should be noted, however, that only 2 of the 156 reflectance curves presented in this report have been corrected for atmospheric effects in this manner.

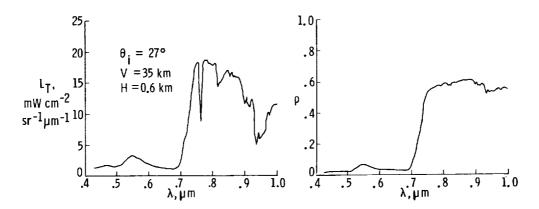


Figure A10. Example of alfalfa field radiance profile that has been converted to spectral reflectance.

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Spectral Reflectance Data

Spectral reflectance data are presented for 156 targets. The targets are grouped into six major categories: agriculture; trees; shrubs and grasses; rocks and soils; water, snow, and clouds; and miscellaneous. Within each category the targets are arranged alphabetically with appropriate adjectives that help to describe the state of the target. Of the 156 data sets, 59 represent laboratory measurements. Most of these occur in either the tree or the rocks and soils category. The laboratory data are identified by the words sample, leaf, or needles. As previously mentioned, laboratory and field data are not compatible, since they represent entirely different environments.

The reflectance data for each target are presented in both a graphical and a tabular format. On each graph the source reference number is given along with the date of measurement and target location, where available, and any other pertinent information concerning the target condition or viewing geometry. The supporting information provided here has been limited to the more commonly measured items, and the reader may refer to the original source when more specific data are needed. Each reflectance curve was presented by its author as being representative of a given target; this report has simply standardized all of the data to a common format.

An index of targets and a numbered list of reference sources precede the spectral reflectance data.

Index of Spectral Reflectance Targets

Agriculture

No.	Target	$\frac{\text{Ref.}}{}$
1	Alfalfa	9
2	Mature Alfalfa	6
3	Dry Alfalfa Hay	37
4	Barley	38
5	Barley	50
6	Stem Extension Barley	3
7	Ripe Barley	6
8	Ripe Barley	3
9	Bean Leaf	26
10	Dehydrated Bean Leaf	26
11	Beans	50
12	Beets	46
13	Cabbage	46
14	Cantaloupe Leaf	20
15	Tall Green Corn	27
16	Silage Corn	27
17	Yellow Corn	27
1 2	Cotton Leaf	15

19	Dehydrated Cott										15
20	Fallow Field .										40
21	Flax				•					•	33
22	Oats										33
23	Oats										50
24	Oats										38
25	Peanuts										33
26	Potatoes					٠					46
27	Potatoes										50
28	Rapeseed										38
29	Sorghum										7
30	Soybeans										29
31	Soybeans										38
32	Sugar Beets .						٠			•	50
33	Sugar Beets .										33
34	Sugarcane Leaf										14
35	Sugarcane Leaf										19
36	Sugarcane										19
37	Sunflower								•		23
38	Tobacco										26
39	Tomatoes										46
40	Tomatoes										33
41	Watermelon Lea	f					•	•			14
42	Wheat										50
43	Seedling Wheat										3
44	Young Wheat										11
45	Booted Wheat								٠		6
46	Mature Wheat									• ,	11
47	Mature Wheat										3
48	Wheat Stubble										40

Trees

No.	Target	Ref.
49	Trembling Aspen	51
50	Birch Leaves	30
51	Redblush Citrus	17
52	American Elm Leaf	24
53	Balsam Fir	57
54	Silver Maple Leaf	24
55	Sugar Maple Leaf	52
56	Burr Oak Leaf	36
57	Live Oak	39
58	Orange Leaf	56
59	Peach Leaf	56
60	Dead Ponderosa Pine Needles	22
61	Ponderosa Pine Needles	22
62	Ponderosa Pine Needles	55
63	Red Pine Needles	36
64	White Pine	51
65	Red Spruce	57
66	Sycamore Leaf	49
67	Dehydrated Sycamore Leaf	49
68	Tulip Tree Leaf	24
	=	

	Shrubs and Grasses		115 Shale	21 47
No.	Target	Ref.	117 Wet Silt Sample	47
—		39	118 Dry Silt	8 45
	Cenizo	4	119 Dry Lacustrine Silt and Clay	43
	Grass	40	120 Soil Sample	43
71 72	Grass	44	121 Soil Sample	25
73	Kentucky Blue Grass	50	122 Soil Sample	18
	Red Fescue Grass	50		8
	Blue Grama Grass	48	124 Dry Pedocal-Type Soil	8
75 76	Perennial Rye Grass	50		8
	Dry Lichen Sample		126 Dry Laterite-Type Soil	24
77	Lichen Mat	12	127 Dry Clay Soil Sample	24
		44	128 Wet Clay Soil Sample	25
79	Manzanita		129 Dry Lake Soil Sample	25
80	•		130 Chilean Nitrate Soil Sample	25
	Honey Mesquite		131 Salt Pool Soil Sample	24
	Dry Sage			24
83	Average Subalpine Slope Leaves	_	133 Wet Sandy Soil Sample	5
	Silverleaf Sunflower		134 Syenite	45
85 86	Burned Forest Surface		135 Dry Glacial Till	1
80	Burned roiest Surface		136 Rhyolite Tuff Sample	1
	Rocks and Soils		Water, Snow, and Clouds	
No.	Target	Ref.	No. Target	Ref.
87	Arkose	. 21		
88	Basalt Sample		137 Altocumulus Clouds	28
89	Red Cinder Basalt Sample		138 Stratus Clouds	28
90	Gray Basalt Sample		139 Cirrostratus Clouds	28
91	Breccia		140 Middle Layer Clouds	34
92	Dry Red Clay Sample		141 Dense Ice Cloud Sample	58
93	Wet Red Clay Sample		142 Hoarfrost Sample	58 E2
94	Quartz Diorite		143 Snow Sample	53
95	Granite		144 Typical Snow Sample	35
96			145 Fresh Snow Sample	35
	Biotite Granite Sample		146 Two Day Old Snow Sample	35
98	Gravel		147 Dry Fresh Snow	23
99	Glaciofluvial Sand and Gravel		148 Wet Snow	23
100			149 Water	40
100	<u> </u>		150 Clear Lake Water	2
101		_	151 Turbid River Water	2
102				
103	• • • • • • • • • • • • • • • • • • •		16' 11	
105	and the contract of the contra		Miscellaneous	
106	· · · · · · · · · · · · · · · · · · ·			ъ.
100			No. Target	$\frac{\text{Ref}}{}$
		~-	152 Asphalt	40
108 109	_ , ~ , ~ 1		153 Blacktop	9
	~ . ~ .		153 Blacktop	40
110	10 10 1	. 10	155 Shingles	40
111			156 Artificial Turf	31
112	Dry Sand		100 Minimial Latt	
1 7 "	Curroum Sand Sample	. 20		

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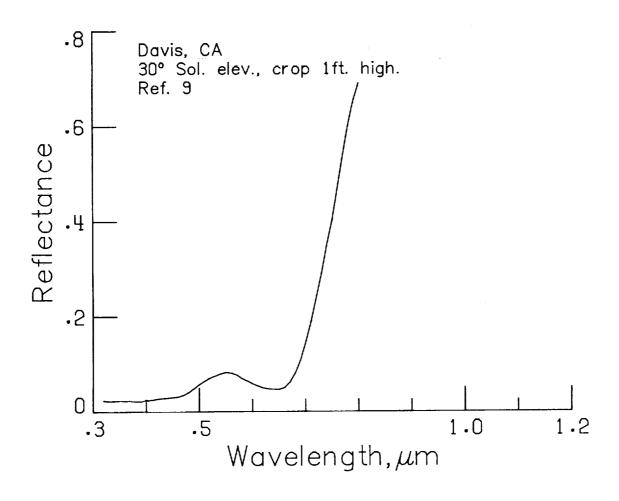
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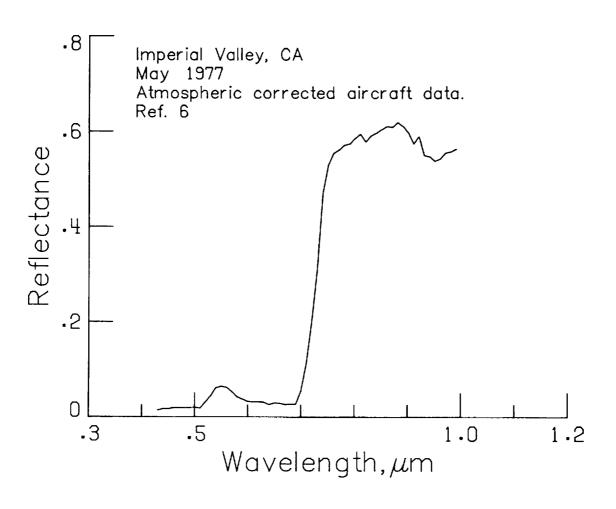
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NO.1 - ALFALFA



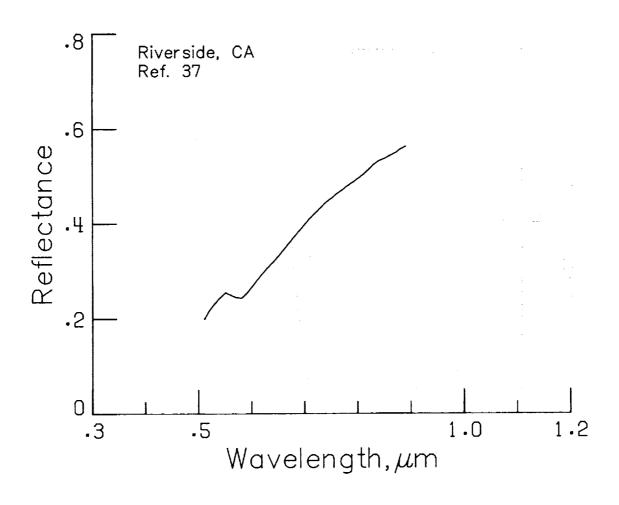
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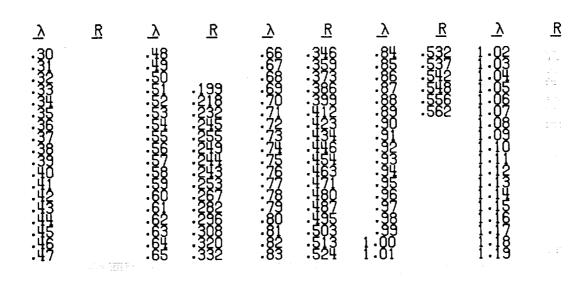
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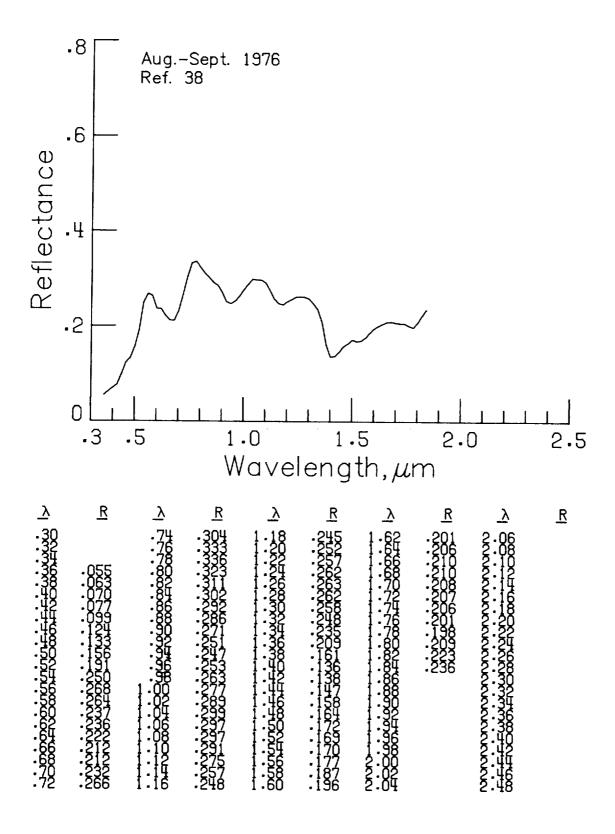
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NO.3 - DRY ALFALFA HAY

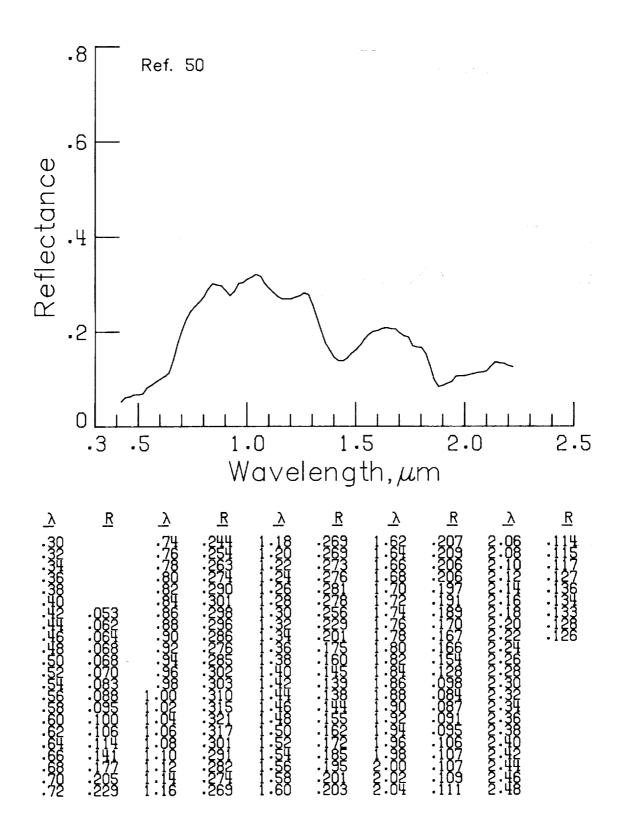




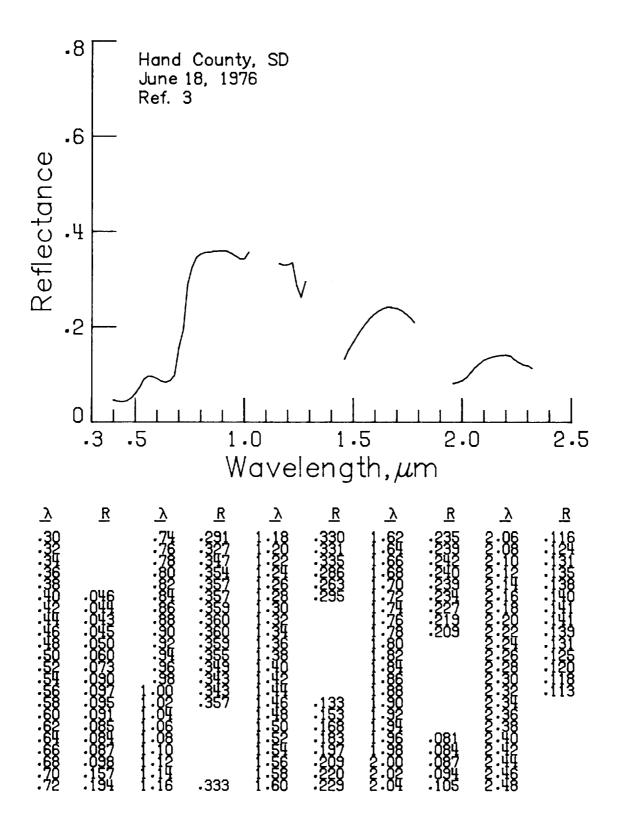
NO.4 - BARLEY



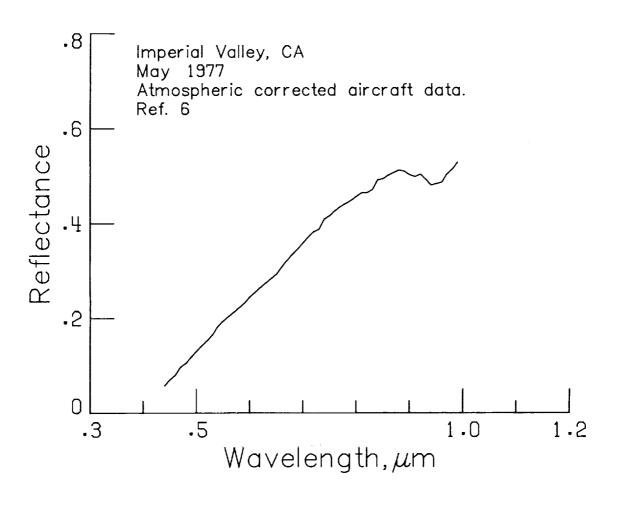
NO.5 - BARLEY



NO.6 - STEM EXTENSION BARLEY

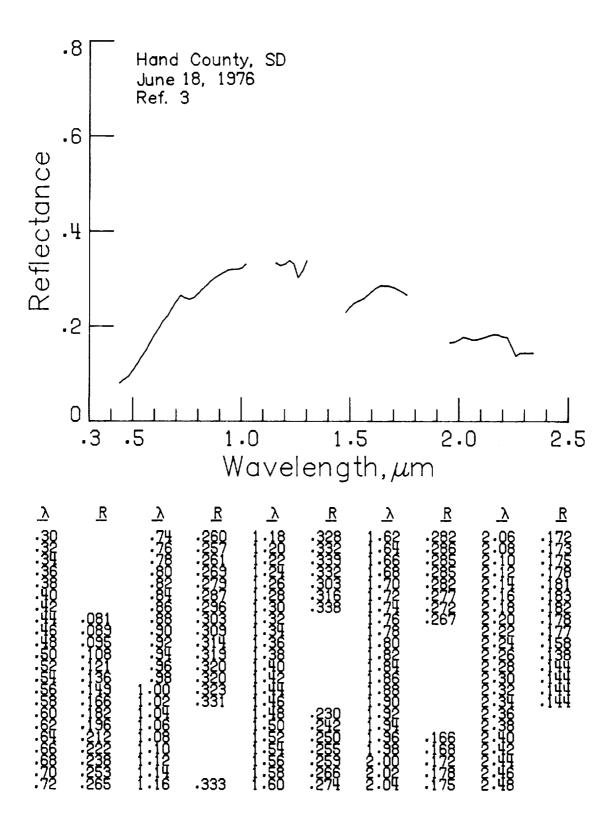


NO.7 - RIPE BARLEY

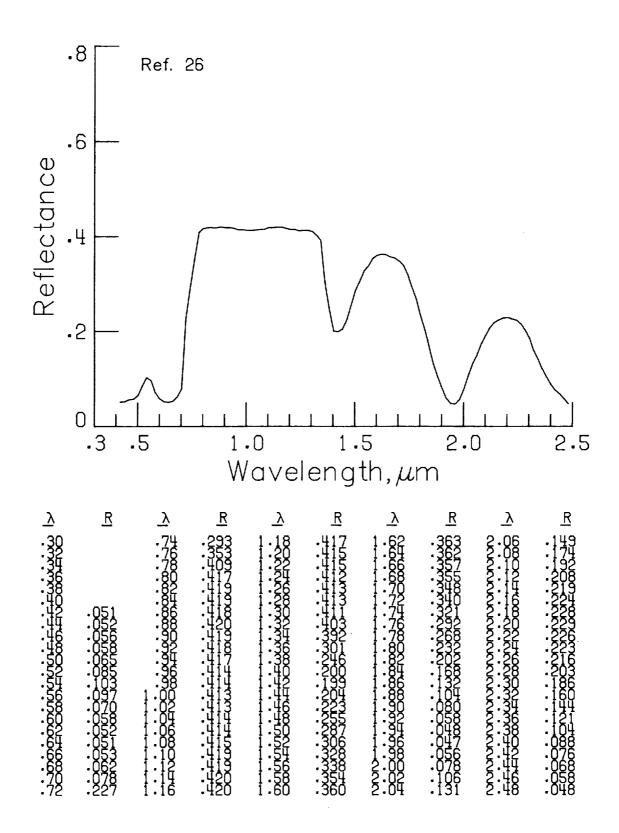


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:49	:097	65	:293	:83	:471	100		1:18	

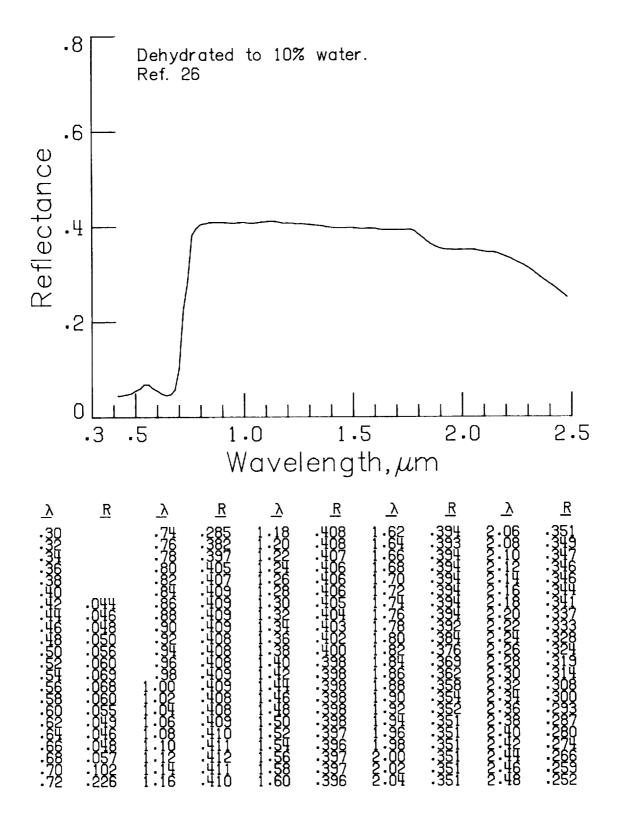
NO.8 - RIPE BARLEY



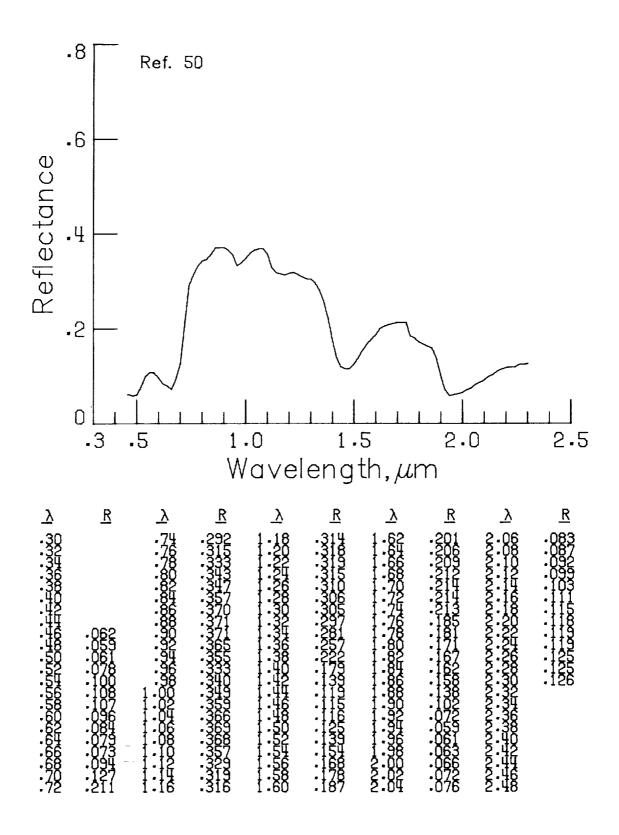
NO.9 - BEAN LEAF



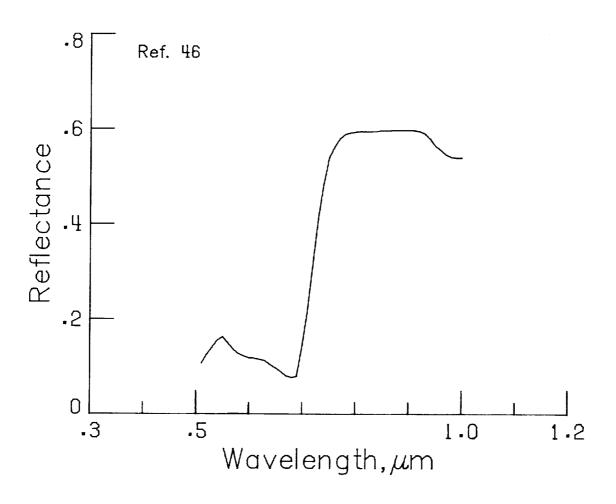
NO.10 - DEHYDRATED BEAN LEAF

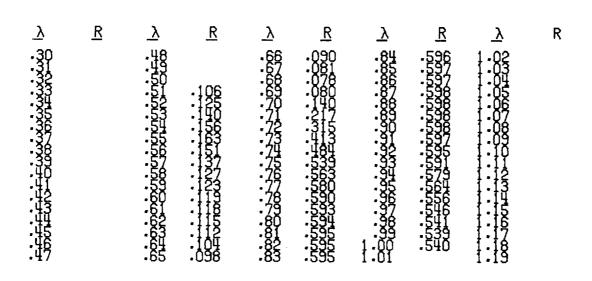


NO.11 - BEANS

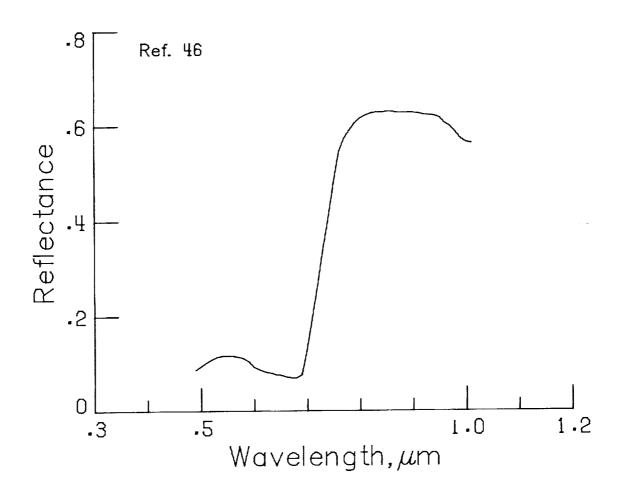


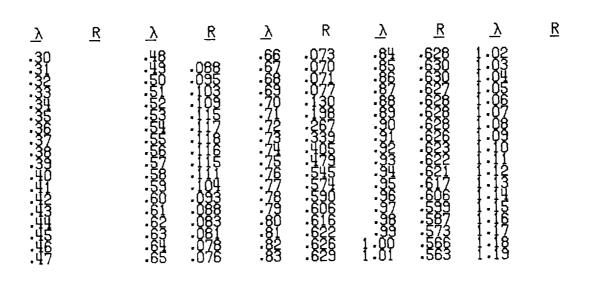
NO.12 - BEETS



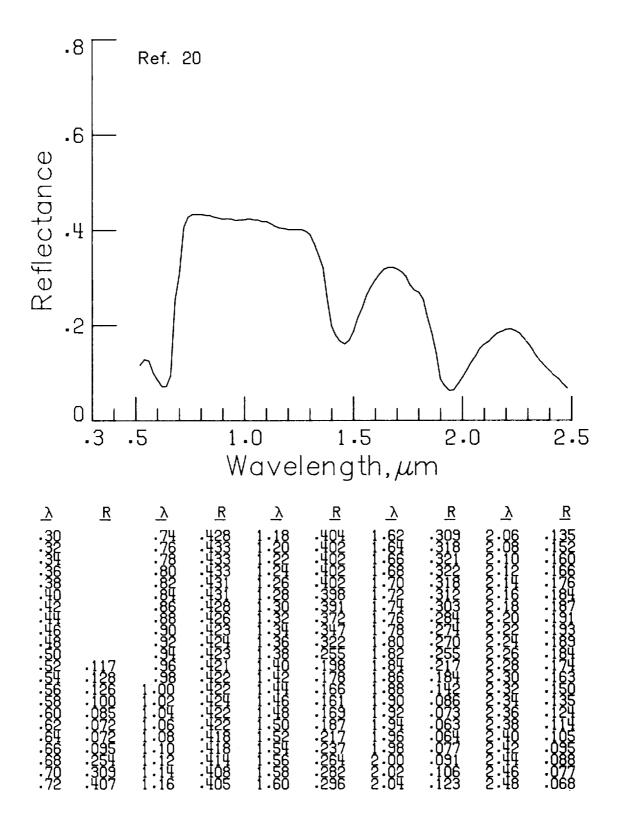


NO.13 - CABBAGE

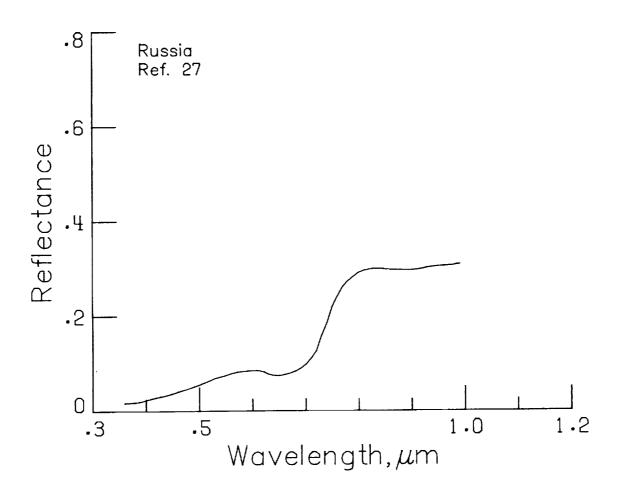




NO.14 - CANTALOUPE LEAF

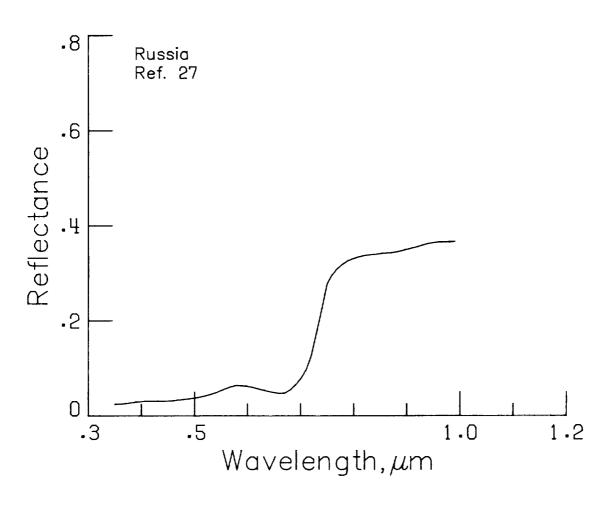


NO.15 - TALL GREEN CORN



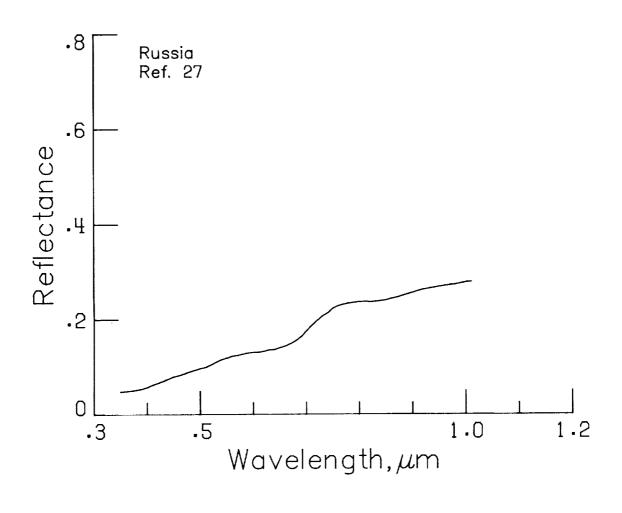
<u>λ</u> ∙30	<u>R</u>	<u>λ</u> .48	<u>R</u> .048	<u>.λ</u> ∙66	<u>R</u> •076	<u>.</u> ∆ :84 :85	<u>R</u> •299	<u>.</u> } 1 ∙82	<u>R</u>
		450 150 1555 150 150 150 150 150 150 150	.051 .055 .069	.67 .68 .70 .71	.079 .083 .089 .097 .110		76666666666666666666666666666666666666	1.04 1.05 1.06	
.367 .389 .40	.017 .018 .020	555558 55558	.072 .075 .079 .082	.723 .775 .76	1255 1255 1250 1250	.9999	.2999 .2999 .303	1.08	
412345 445	.026 .029 .031 .037		.084 .085 .085 .082 .077	.77 .78 .79 .80	.262 .274 .283 .295	9567 9999 1 -00	.305 .305 .306 .307 .309	1.1567	
:蔣	044 044	.64 .65	:874	.82 .83	.298 .299	1:00		1:18	

NO.16 - SILAGE CORN



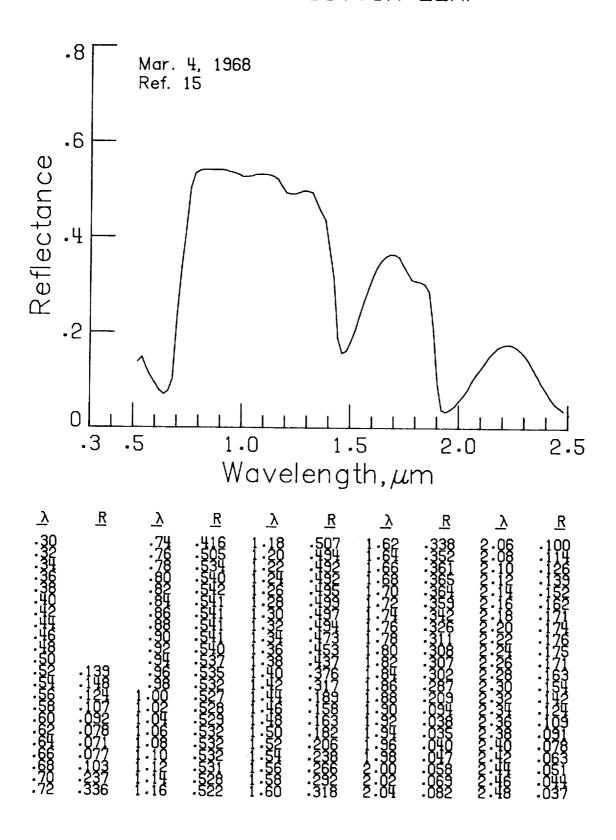
<u>\lambda</u>	<u>R</u>	<u>λ</u>	<u>R</u>	<u>\lambda</u>	<u>R</u>	<u>\lambda</u>	<u>R</u>	<u>λ</u>	<u>R</u>
- - - - - - - - - - - - - - - - - - -		4455555 4890 490 490	.034 .036 .037 .039	.68 .69	.047 .054 .064 .078	85567 8888 8888	339 342 343 344	1.05 1.05 1.06	
.35 .33 .33 .38	.024 .025 .026 .027	33456 3555 3555	045 048 053 057	.71 .72 .73 .74	.096 .127 .176 .226	.99 .90 .92	347 350 353 355	1.07 1.08 1.09 1.10	
39	.029 .030 .031 .031	.57 .559 .60	.061 .064 .062 .061	. 75 . 76 . 77 . 78	.279 .298 .311 .320	995	.359 .364 .365		
134567 134567	.031 .031 .032	566666 578775	.059 .056 .053 .050	.79 .80 .82 .83	.331 .331 .339	.97 .98 .99	.365 .366	1.1567	

NO.17 - YELLOW CORN

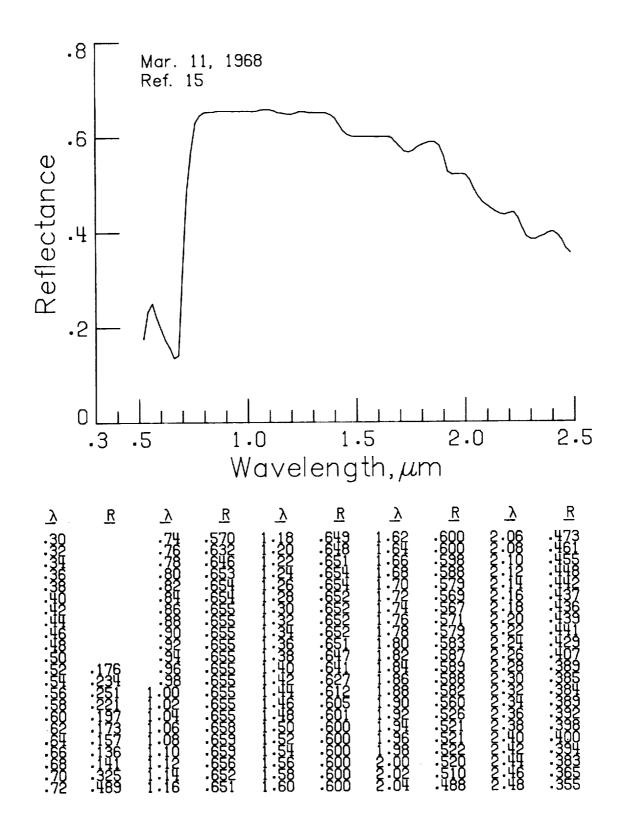


<u>R</u> <u>\lambda</u>	<u>R</u>	<u>\lambda</u> .84	<u>R</u> -239	<u>\lambda</u> 1.02	<u>R</u>
.097 .6 .100 .6 .105 .7	8 -155 9 -164 0 -176	.85 .86 .88	240 250 250	1 .03 1 .05 1 .06	
.116 .7 .116 .7 .123 .7	1 -188 2 -198 3 -208 4 -214	.89 .90 .92 .92	.2556 .2560 .2663	1 .07 1 .08 1 .09 1 .10	
· 124 · 7 · 130 · 7 · 131 · 7	22234	33 <u>4</u> 5566	.265 .269 .270	234	
. 131 . 133 . 136 . 136	23.23.7 23.23.7 23.33.6 23.33.6 23.33.6	.97 .98 .99 1.00	.273 .275 .277	1.167	
	- 6666677777777777777777777777777777777	- 667 8890 - 120	- 667 8990 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 0 1 2 3 4 5 6 7 8 9 9 1 2 3 4 5 7 8 9 9 1 2 3 4 5 7 8		

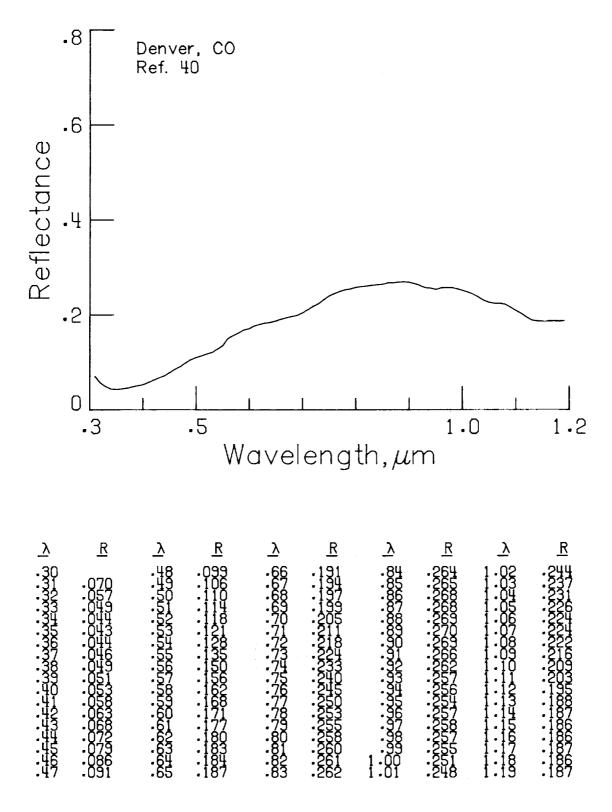
NO.18 - COTTON LEAF



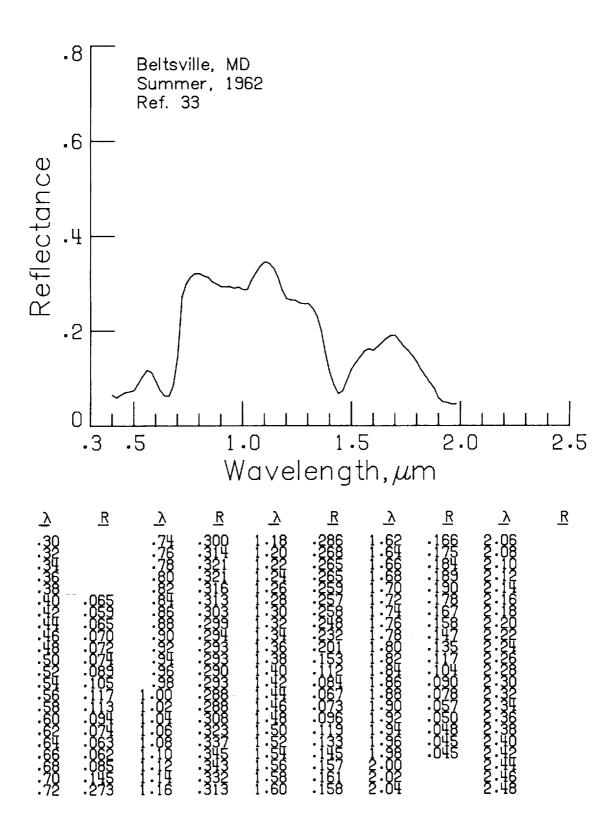
NO.19 - DEHYDRATED COTTON LEAF



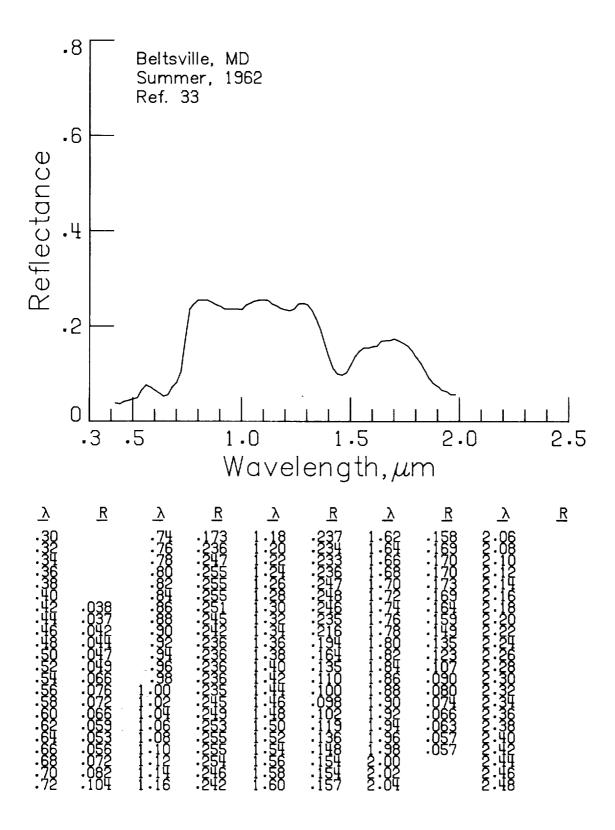
NO.20 - FALLOW FIELD



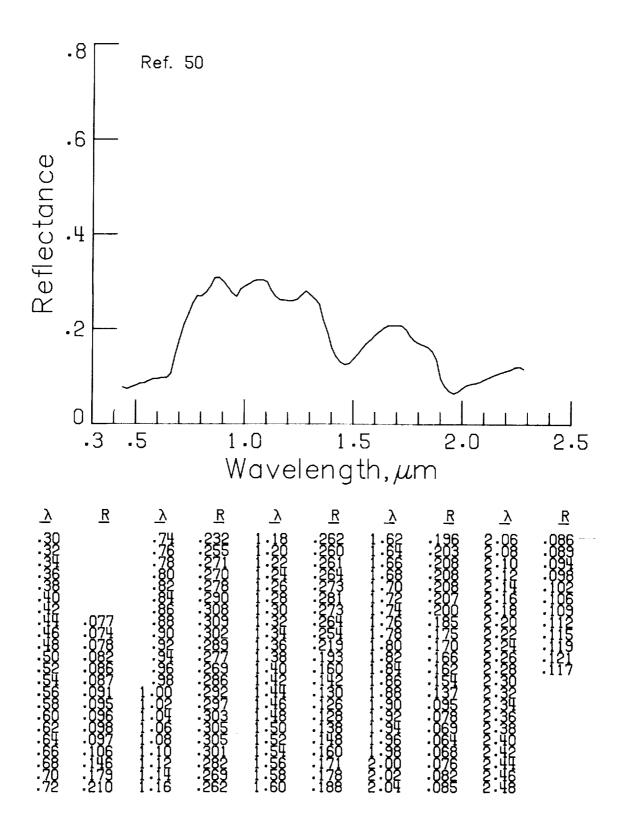
NO.21 - FLAX



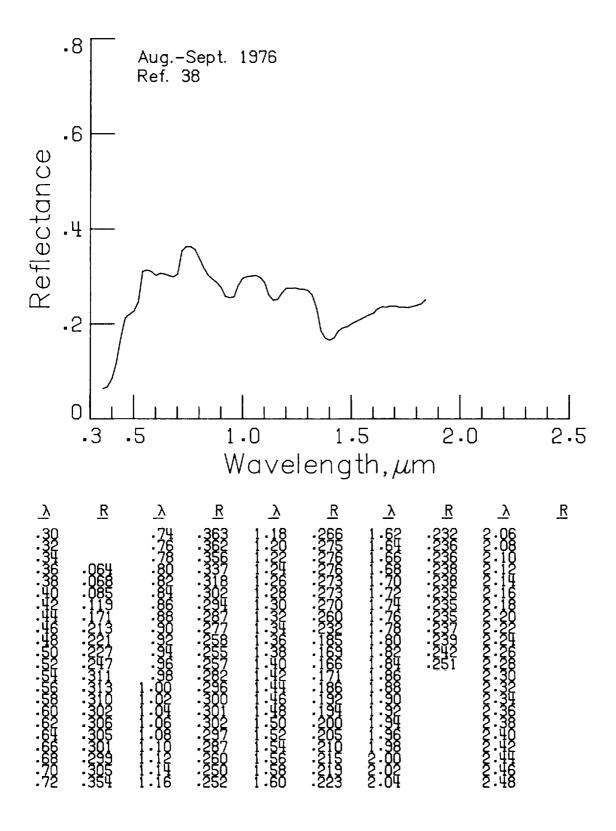
NO.22 - OATS



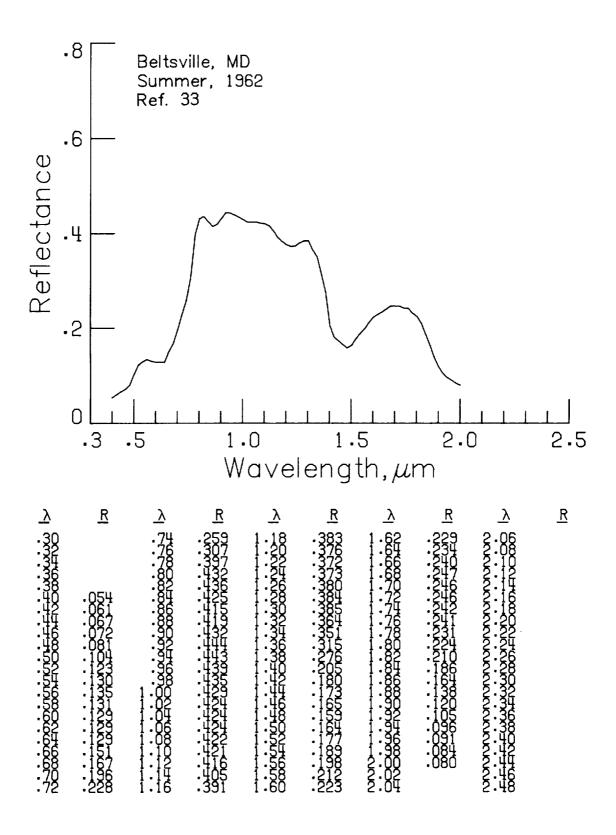
NO.23 - OATS



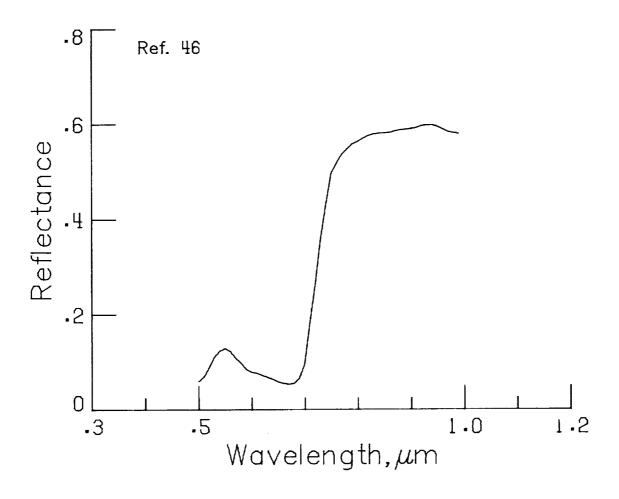
NO.24 - OATS

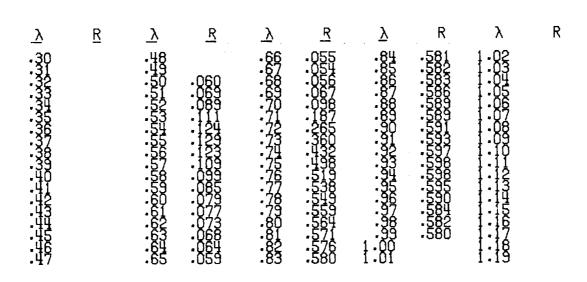


NO.25 - PEANUTS

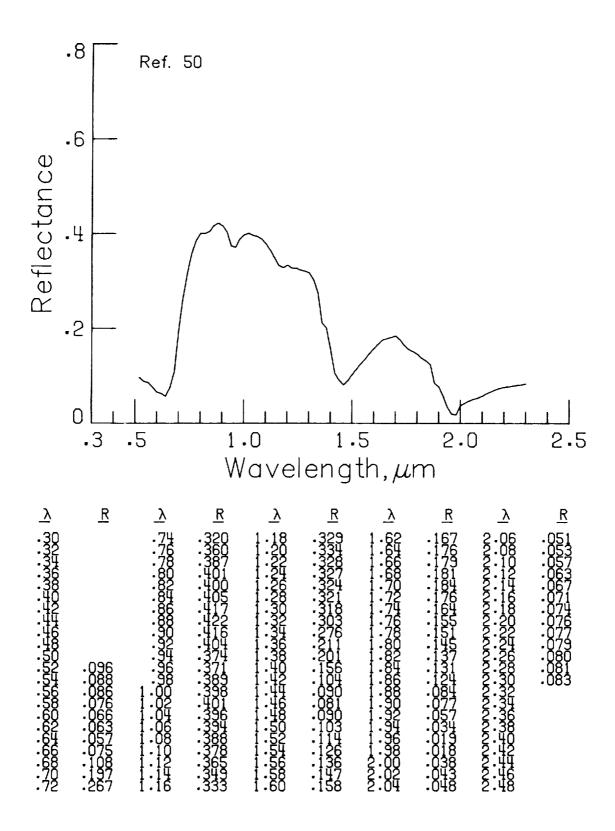


NO.26 - POTATOES

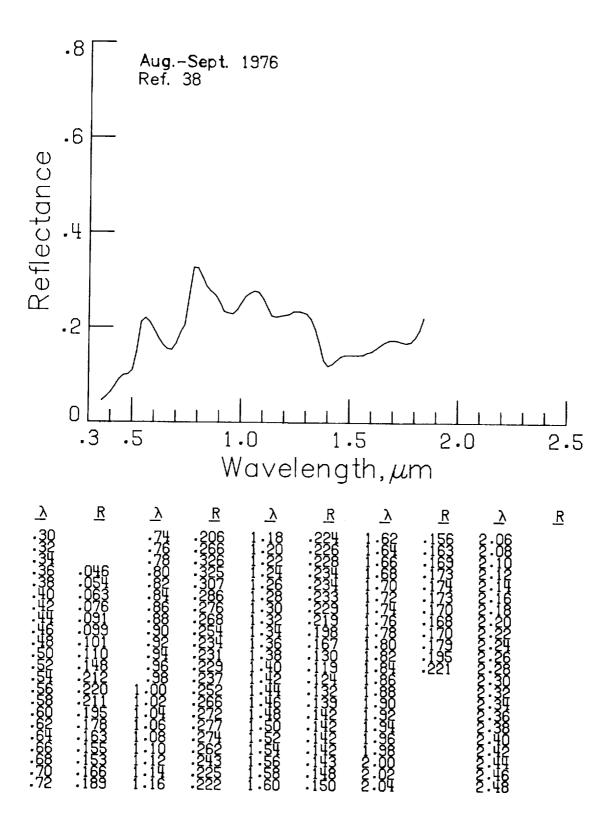




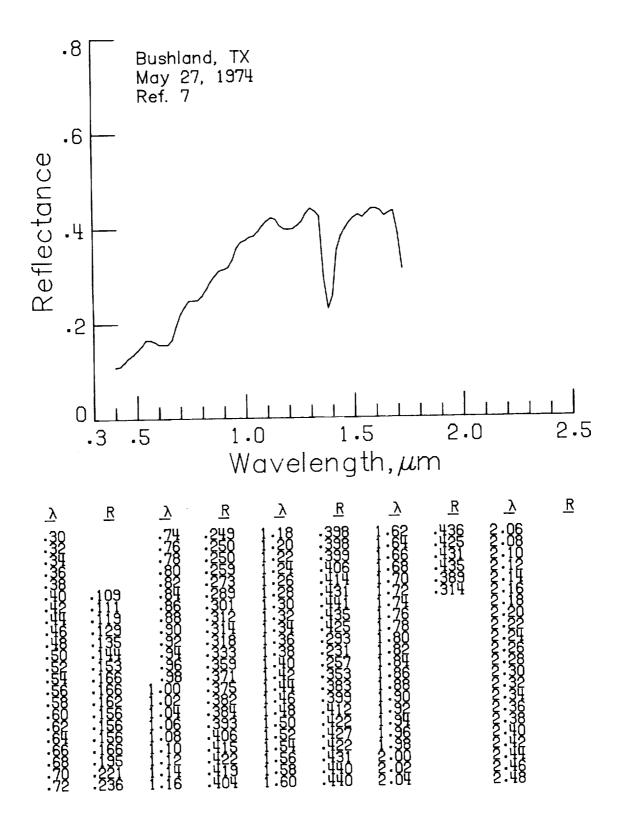
NO.27 - POTATOES



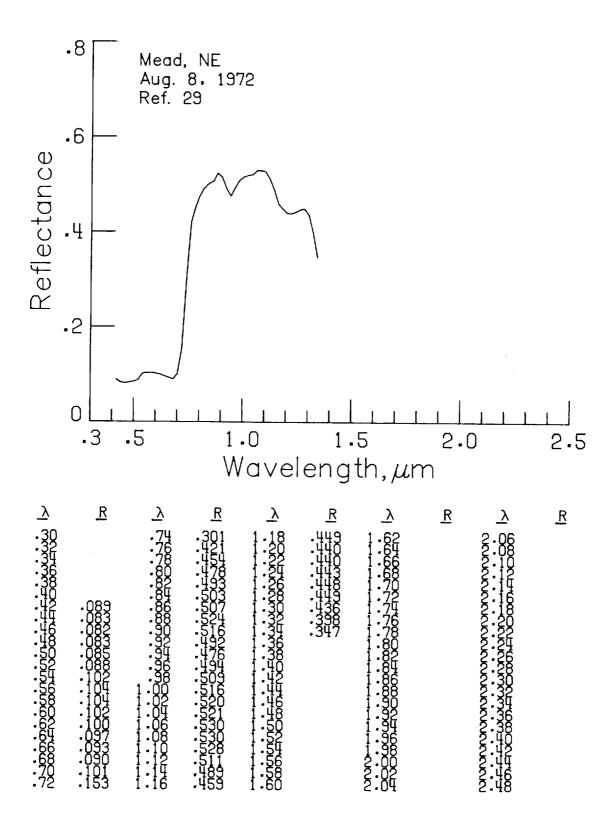
NO.28 - RAPESEED



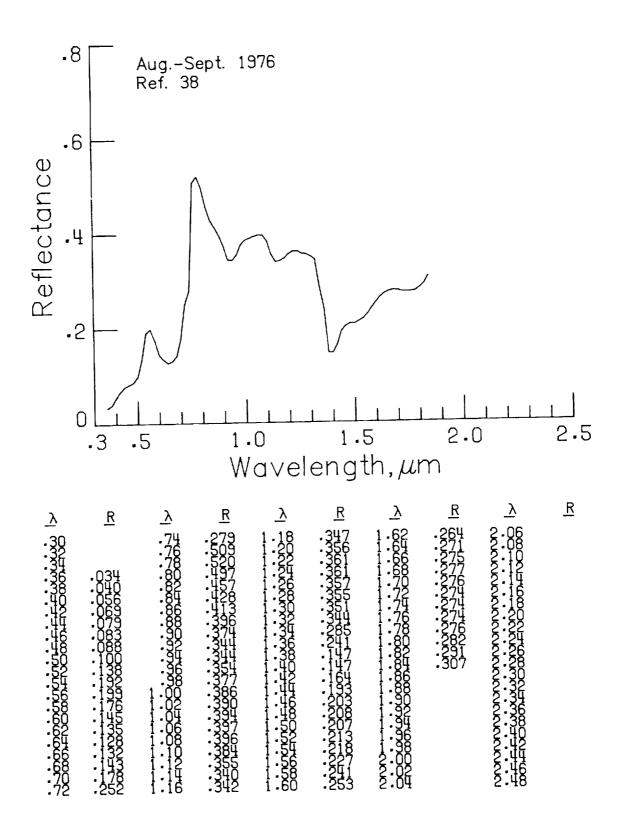
NO.29 - SORGHUM



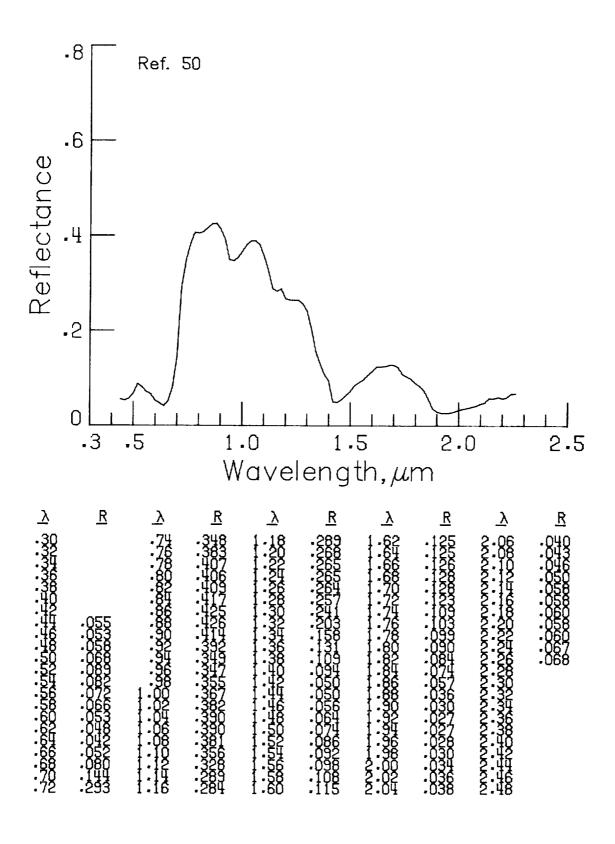
NO.30 - SOYBEANS



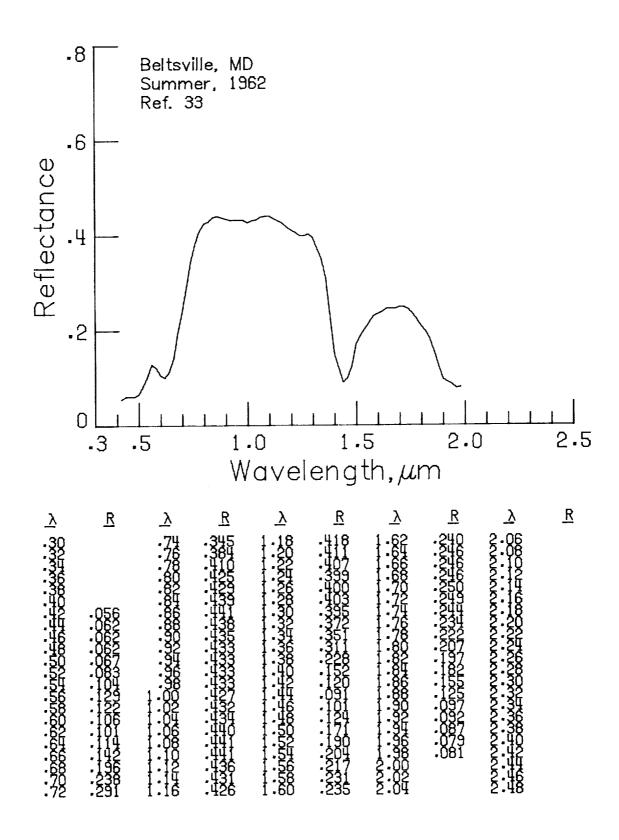
NO.31 - SOYBEANS



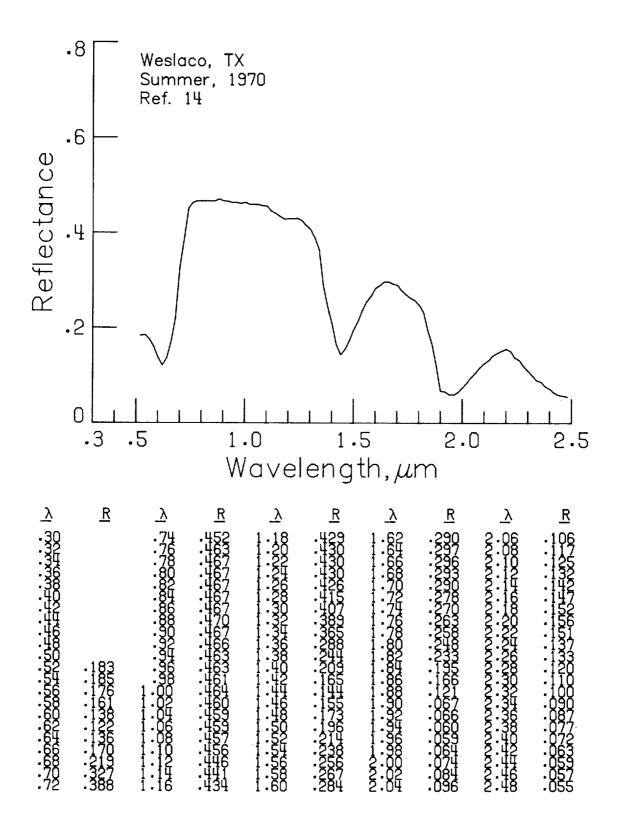
NO.32 - SUGAR BEETS



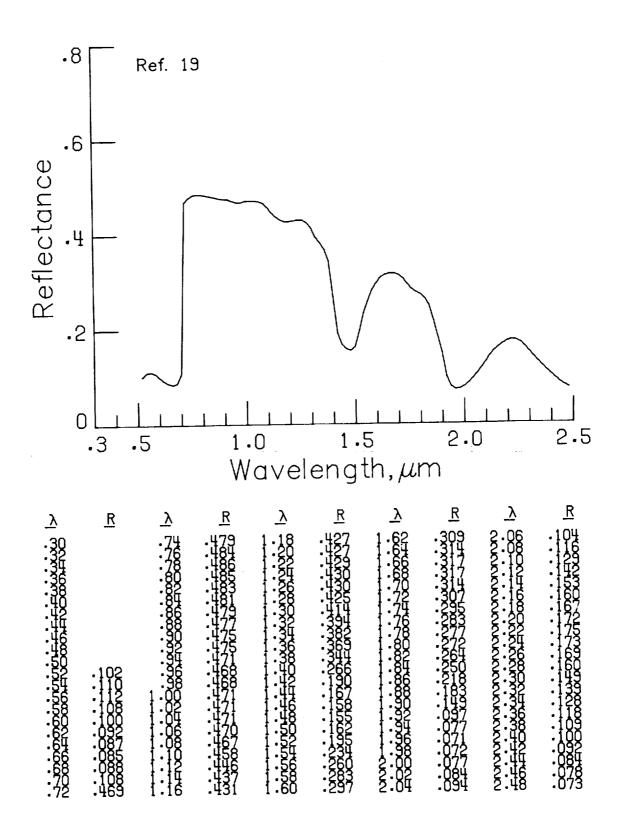
NO.33 - SUGAR BEETS



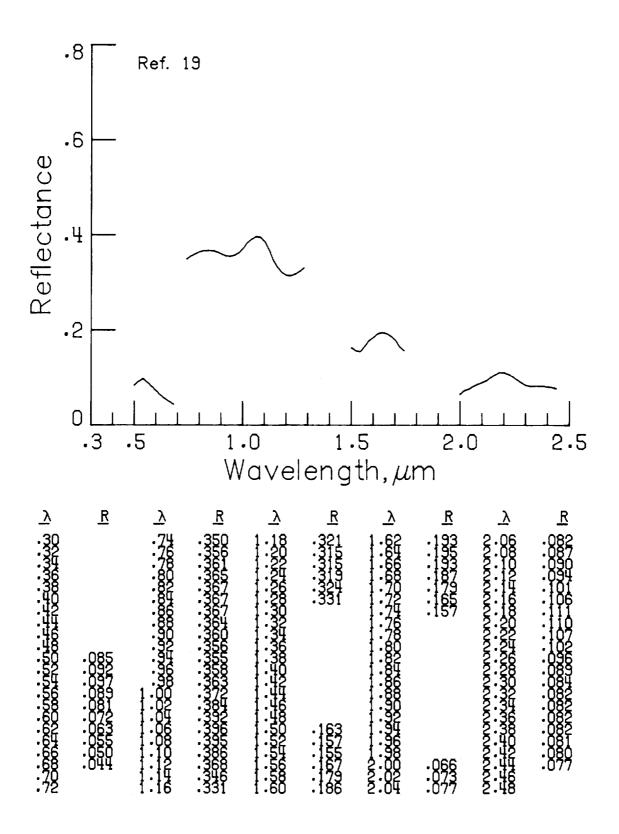
NO.34 - SUGARCANE LEAF



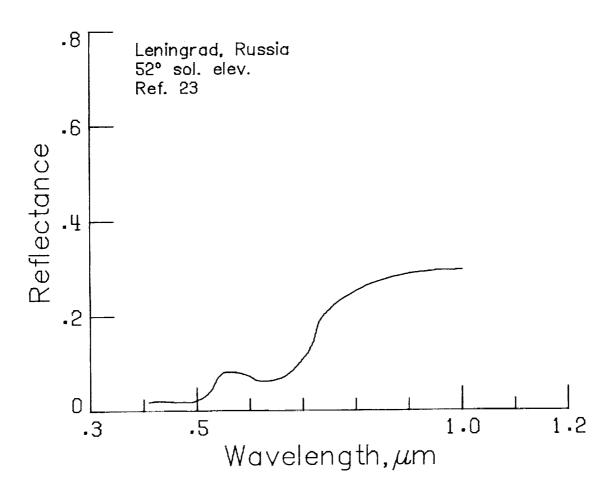
NO.35 - SUGARCANE LEAF

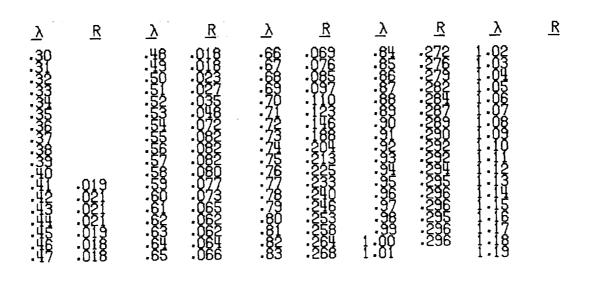


NO.36 - SUGARCANE

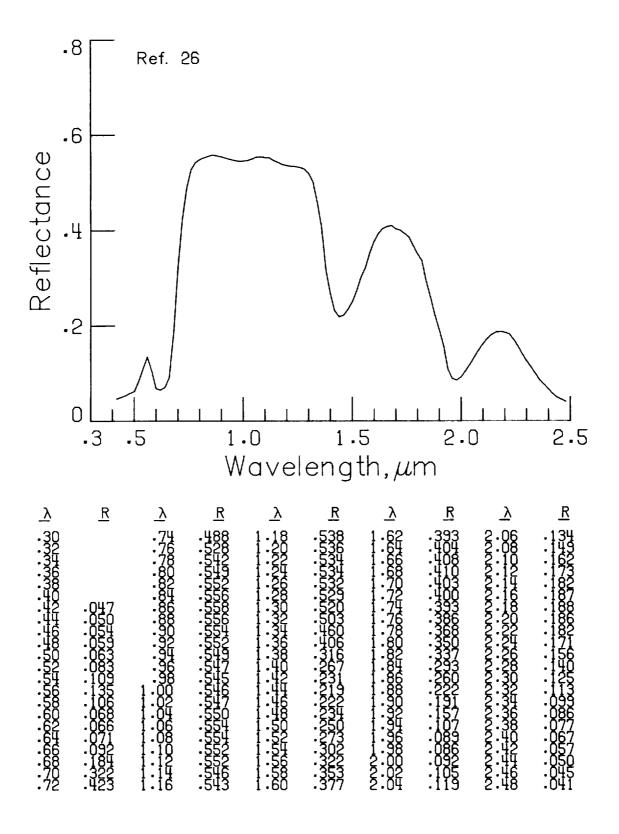


NO.37 - SUNFLOWER

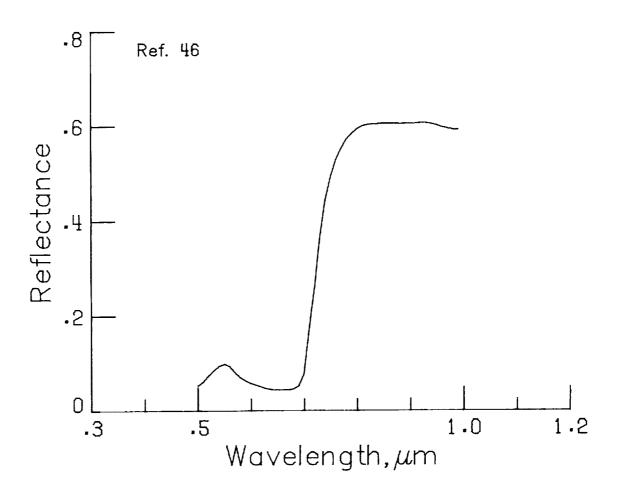


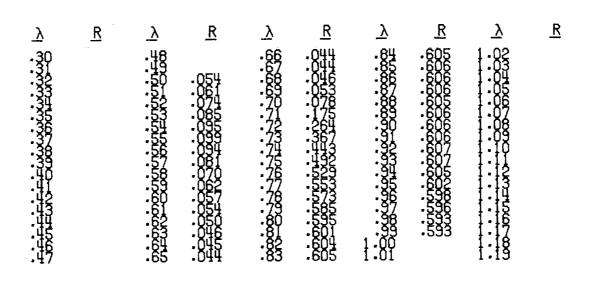


NO.38 - TOBACCO

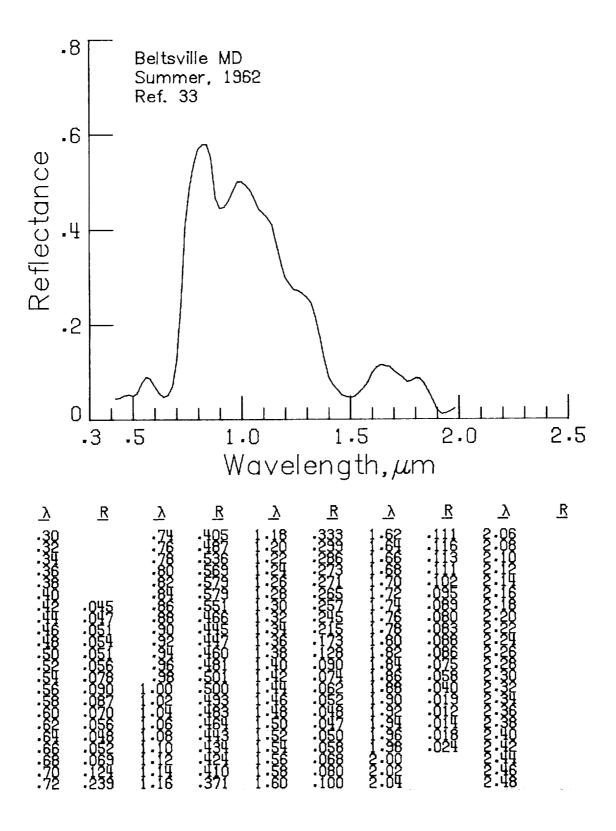


NO.39 - TOMATOES

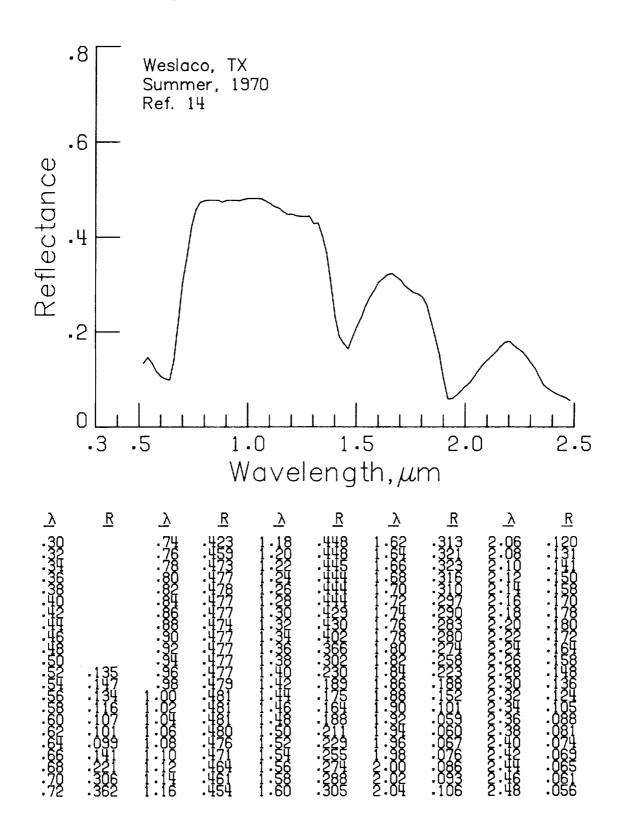




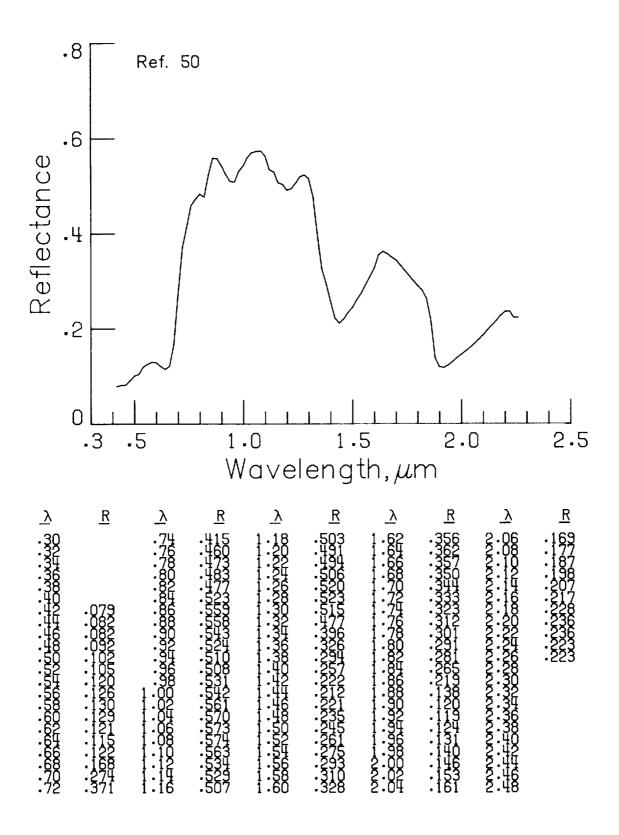
NO.40 - TOMATOES



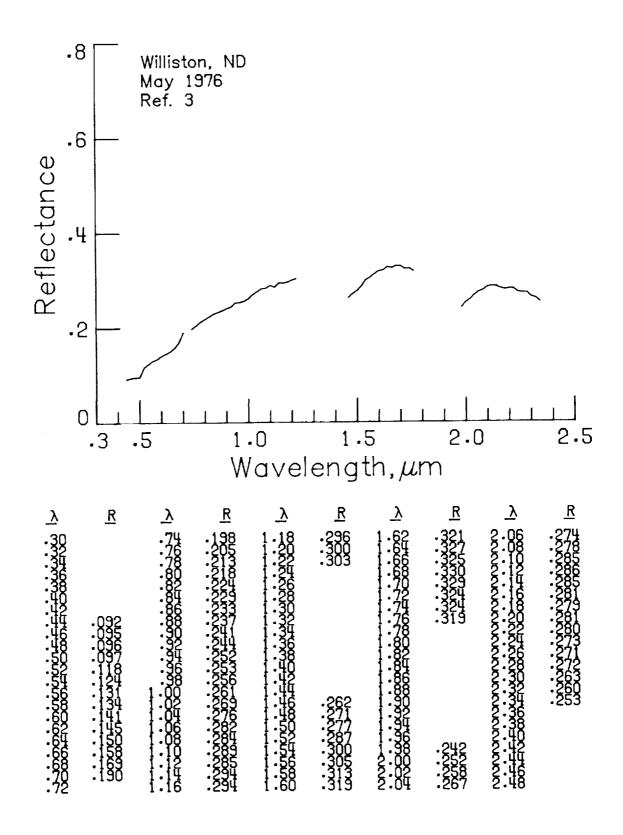
NO.41 - WATERMELON LEAF



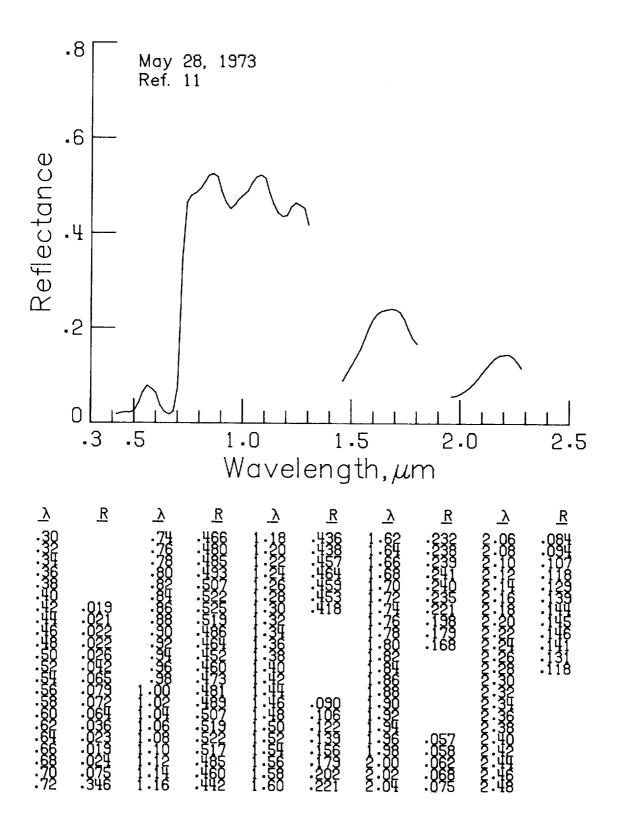
NO.42 - WHEAT



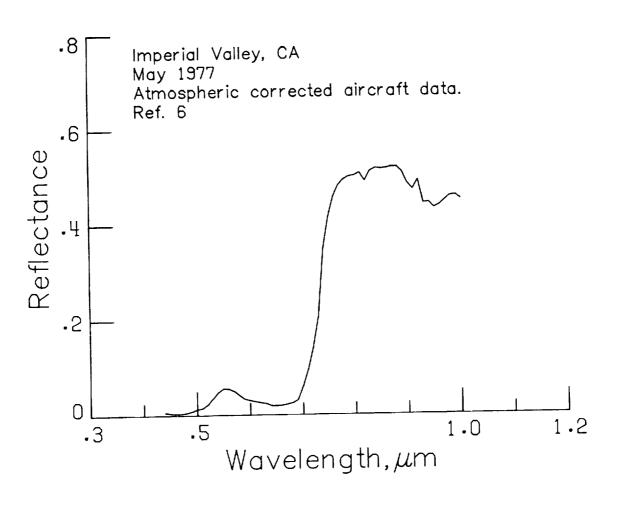
NO.43 - SEEDLING WHEAT

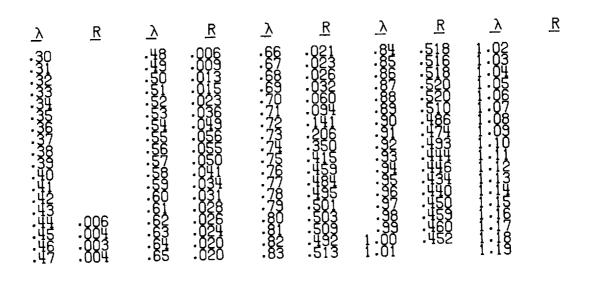


NO.44 - YOUNG WHEAT

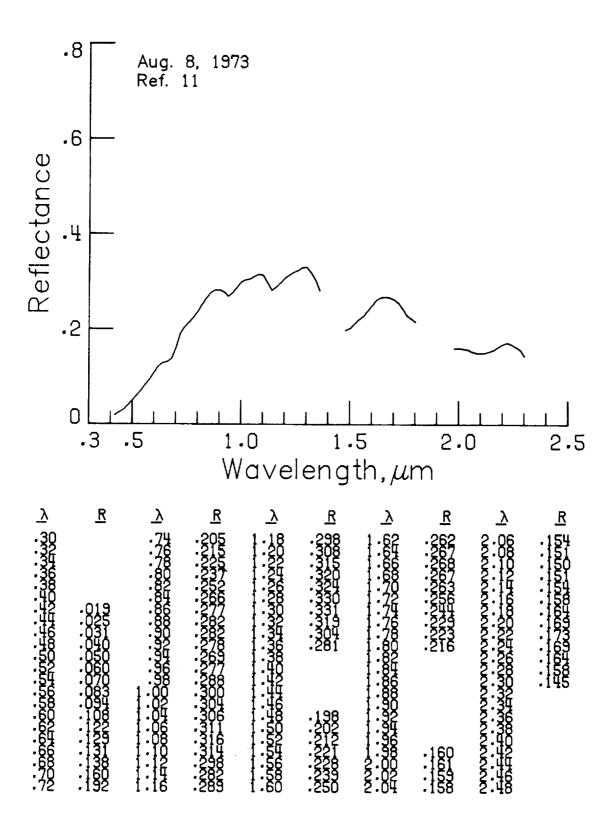


NO.45 - BOOTED WHEAT

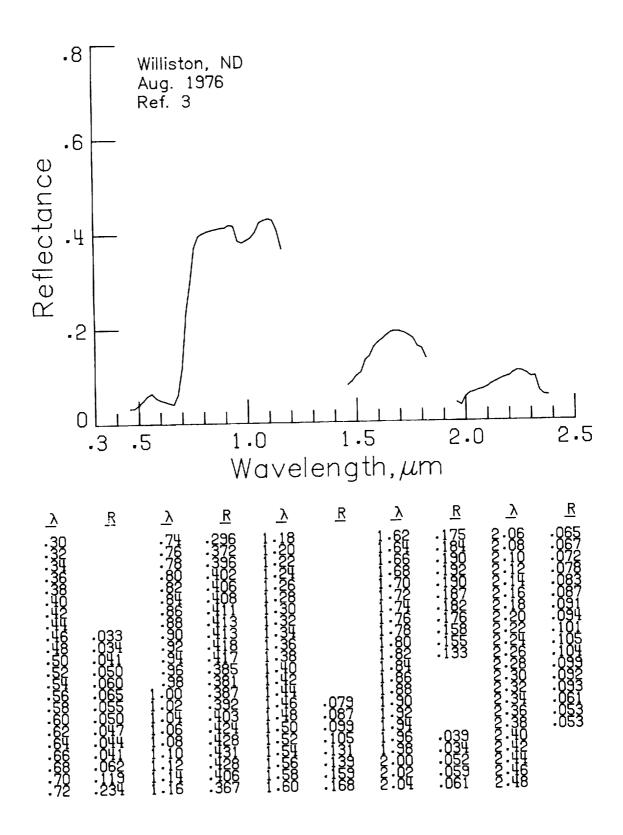




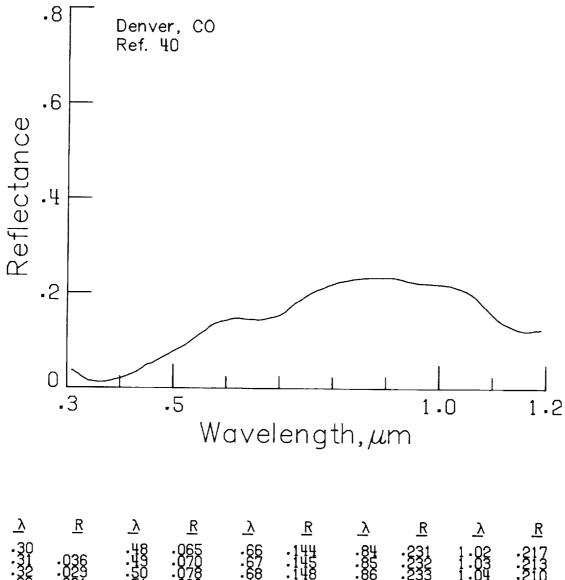
NO.46 - MATURE WHEAT



NO.47 - MATURE WHEAT

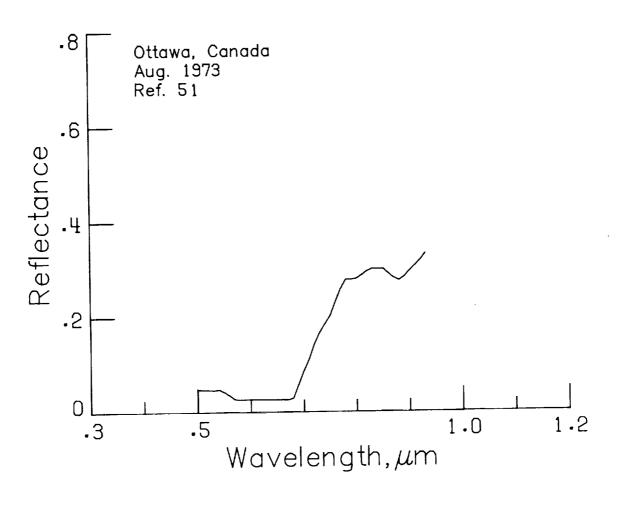


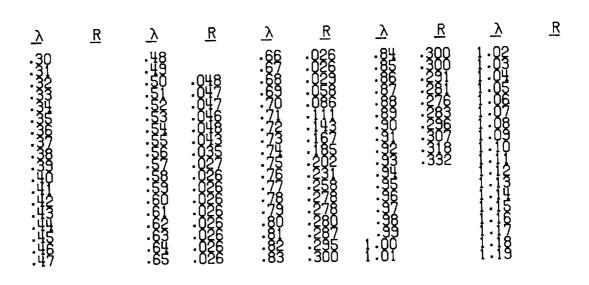
NO.48 - WHEAT STUBBLE



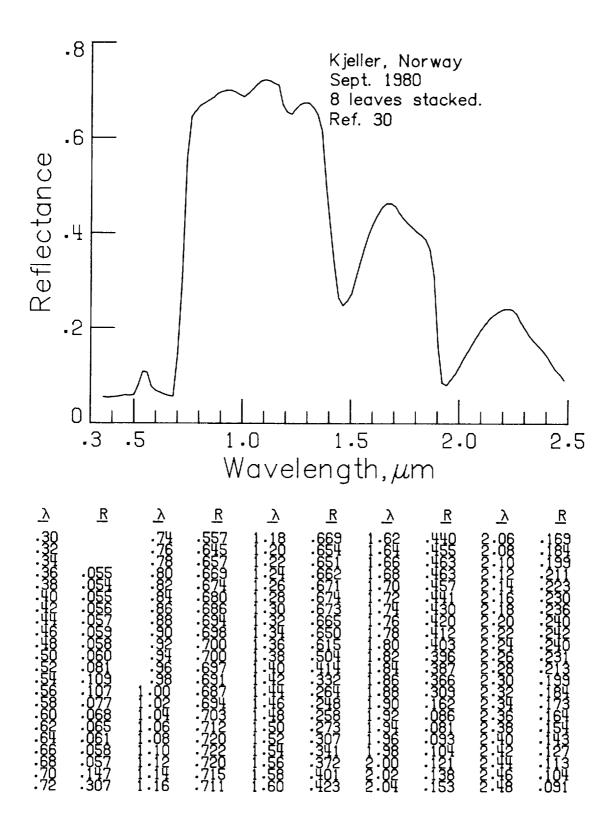
<u> </u>	<u>R</u>	<u>_</u> \cdot	<u>R</u>	<u> </u>	<u>R</u>	<u> </u>	<u>R</u>	<u>_\delta</u>	<u>R</u>
	00000000000000000000000000000000000000	######################################	500000111171-7-3600555	6678901234567890123	458040-074-7-60468 444556788990022000	#567@90-\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\	NAVANAVANAVANAVANAVANAVANAVANAVANAVANAV	20000000000000000000000000000000000000	7905907765898989-245

NO.49 - TREMBLING ASPEN

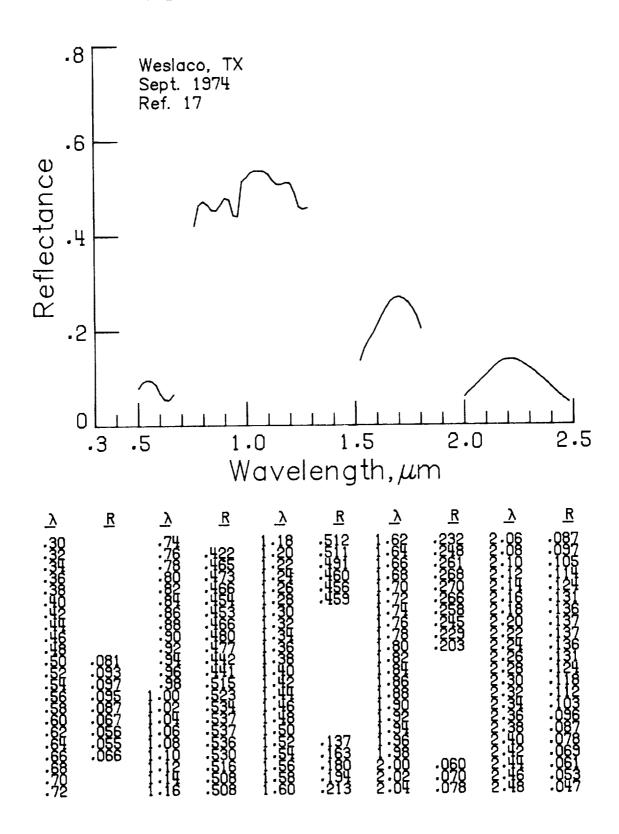




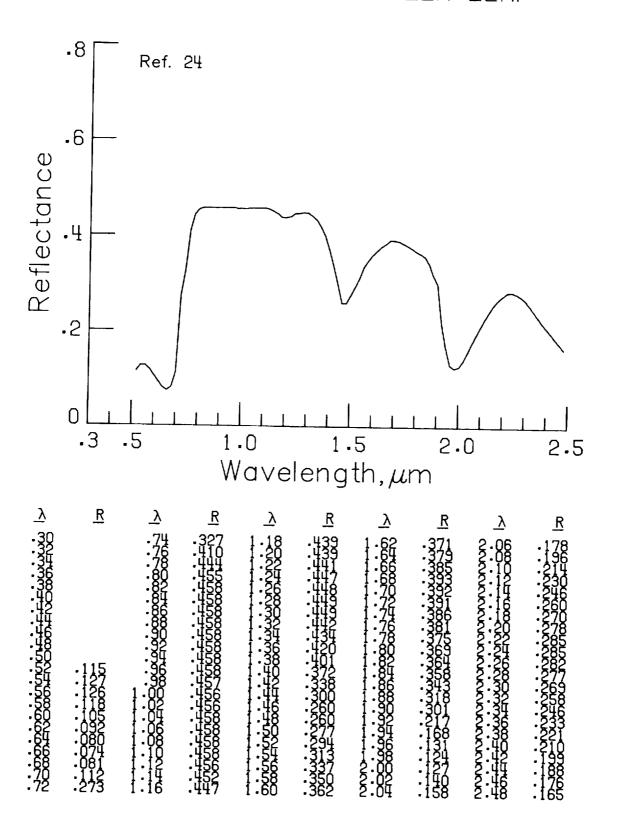
NO.50 - BIRCH LEAVES



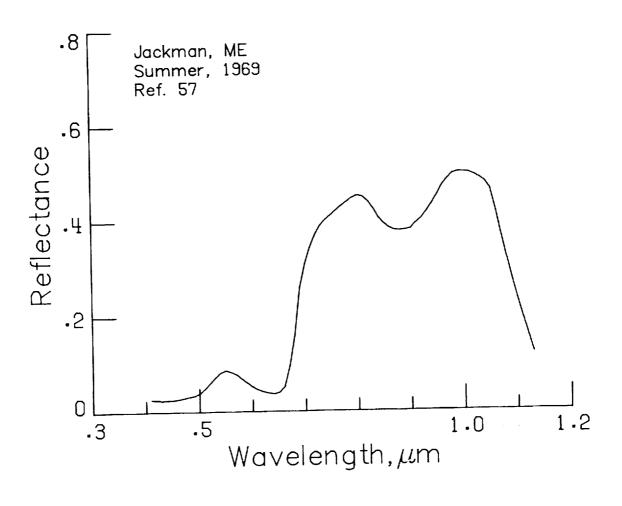
NO.51 - REDBLUSH CITRUS



NO.52 - AMERICAN ELM LEAF

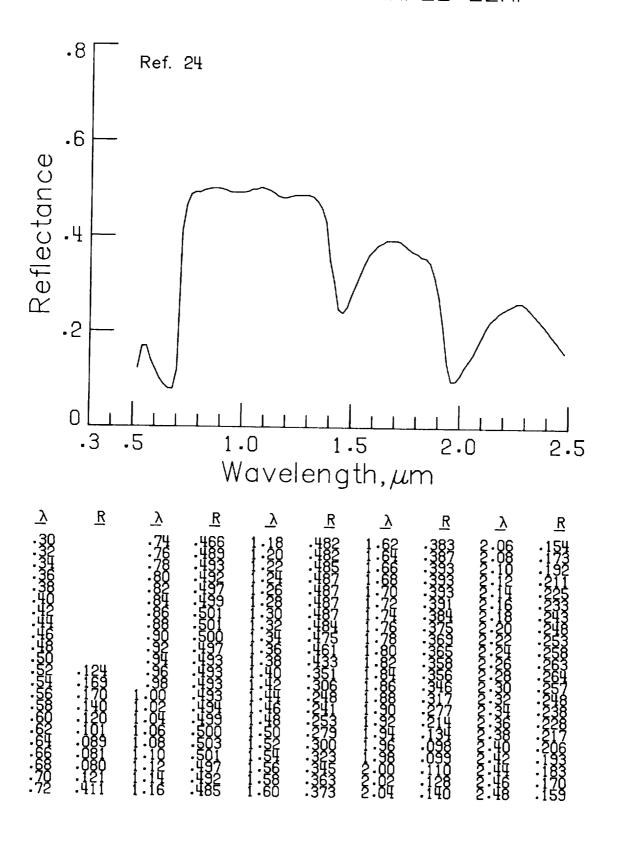


NO.53 - BALSAM FIR

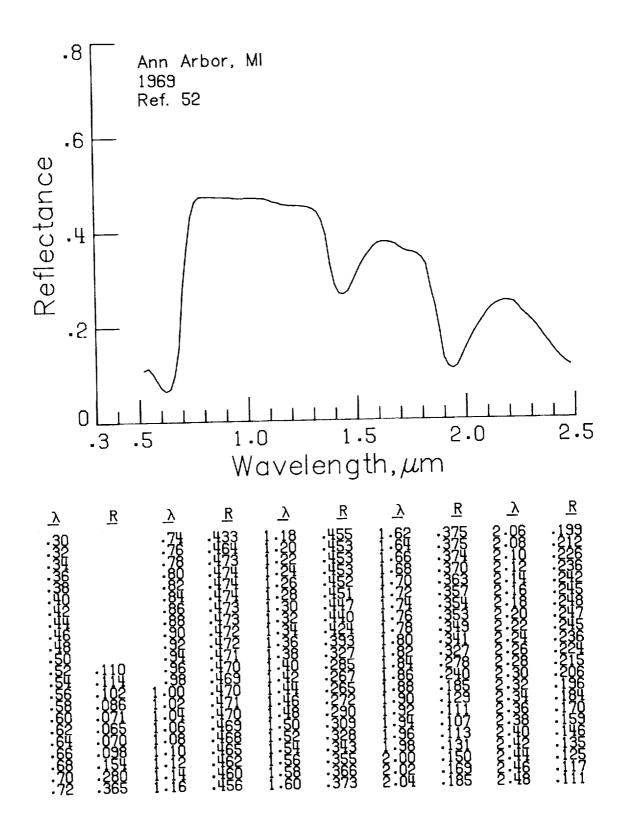


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11111111111111111111111111111111111111	.026 .025 .0225 .0222 .0222 .0229	25000000000000000000000000000000000000	.060 .052 .045 .038 .037 .040	-77 -78 -79 -80 -81 -83	130 145 145 145 145 145	.956 .976 .998 .999 1.00	452 477 487 500 499	20756789	.120

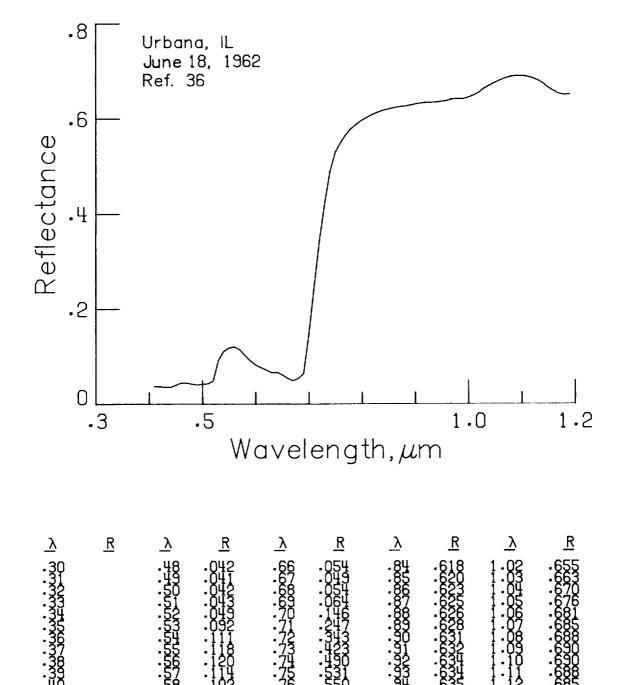
NO.54 - SILVER MAPLE LEAF



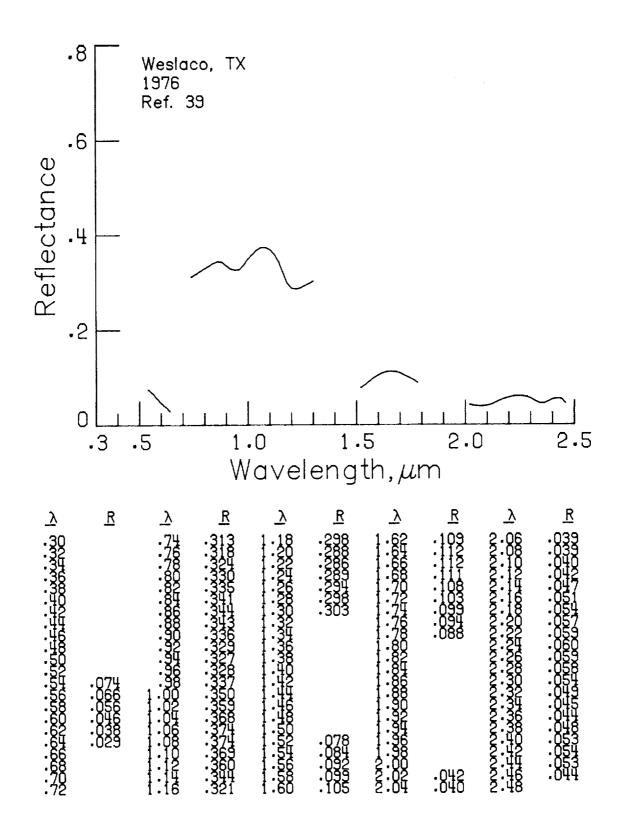
NO.55 - SUGAR MAPLE LEAF



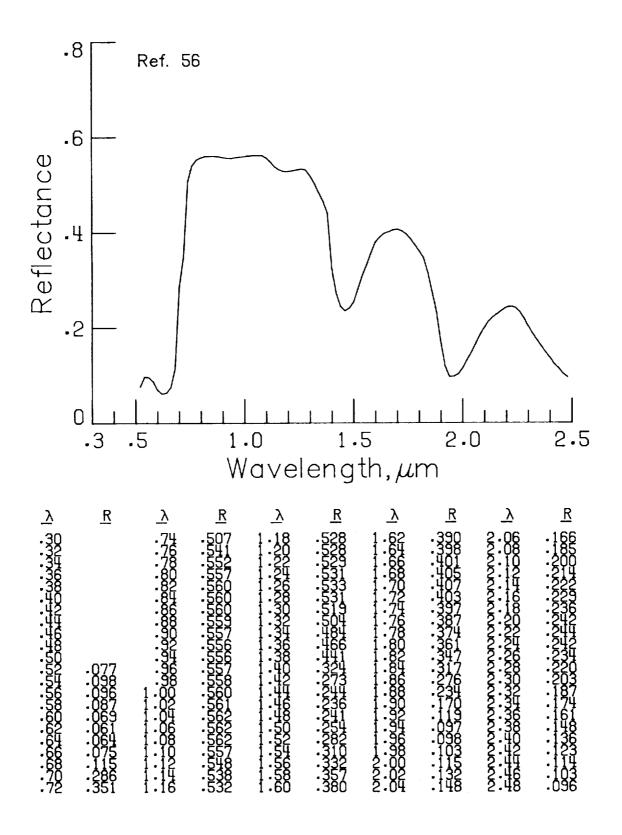
NO.56 - BURR OAK LEAF



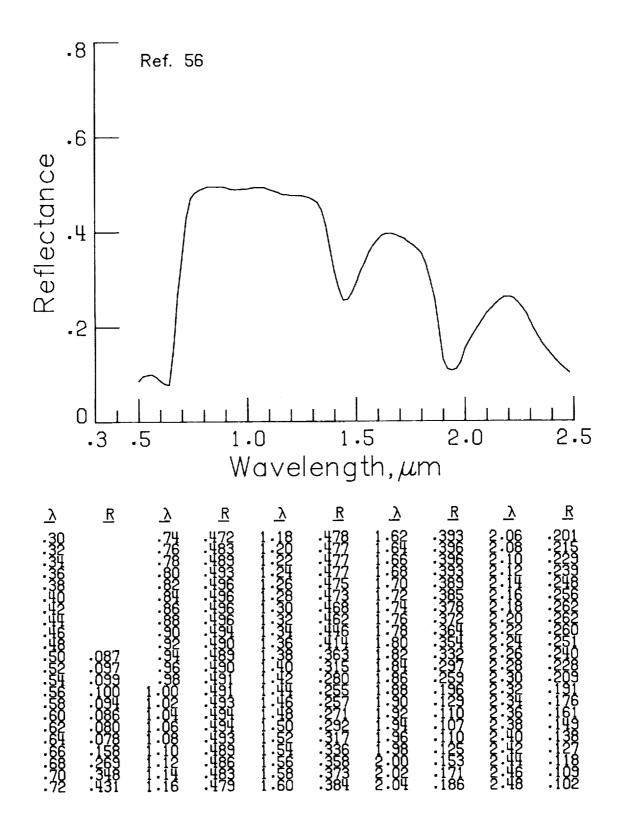
NO.57 - LIVE OAK



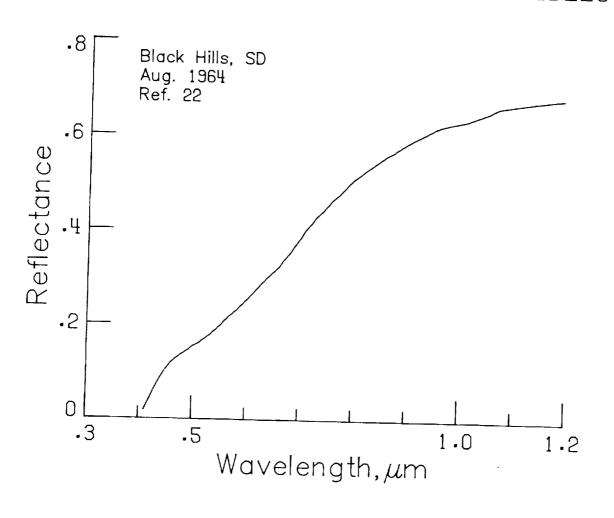
NO.58 - ORANGE LEAF

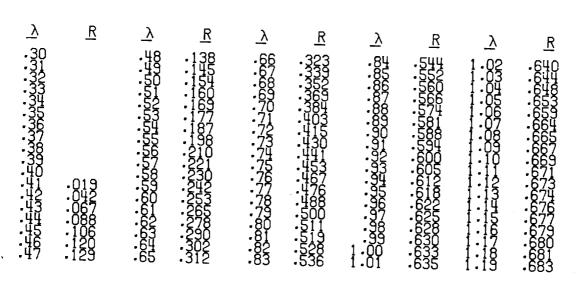


NO.59 - PEACH LEAF

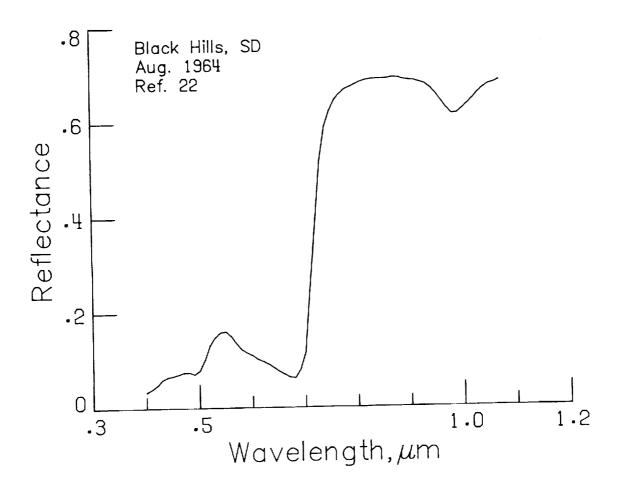


NO.60 - DEAD PONDEROSA PINE NEEDLES



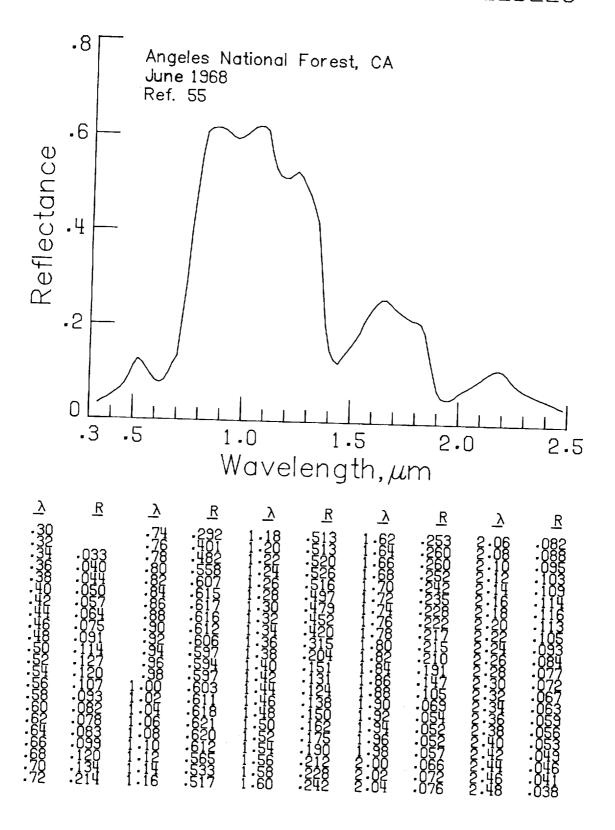


NO.61 - PONDEROSA PINE NEEDLES

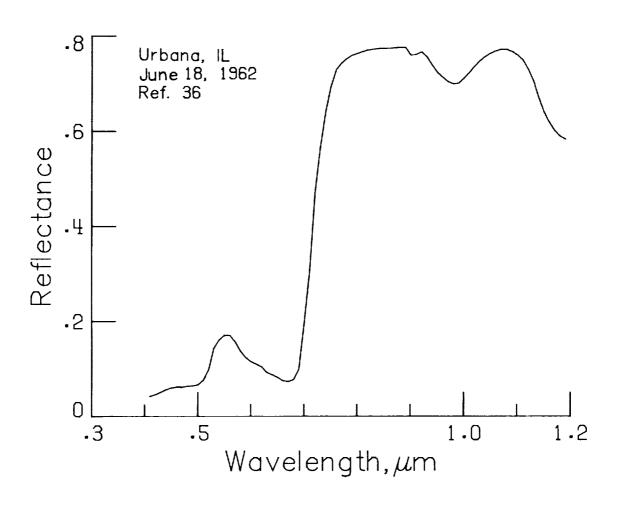


	R #1-90500000000000000000000000000000000000	99999999999999999999999999999999999999	R 51-81-2990005-1591-61-3	入 6678901234567890123 入 666667777777777888888	R 932955569-47094948 0000-235566666666666666666666666666666666666	λ 8888888999999999999999999999999999999	R 001-3287629089755421-22 6666666666666666666666	入 2の4567890-2の456788	R 6999694 6666666
.45 .46 .47	.068 .071 .075	.63 .65	.091 .083 .075	.81 .82 .83	.684 .688 .689	1.00 1.01	.616 .625 .636	1:18	

NO.62 - PONDEROSA PINE NEEDLES

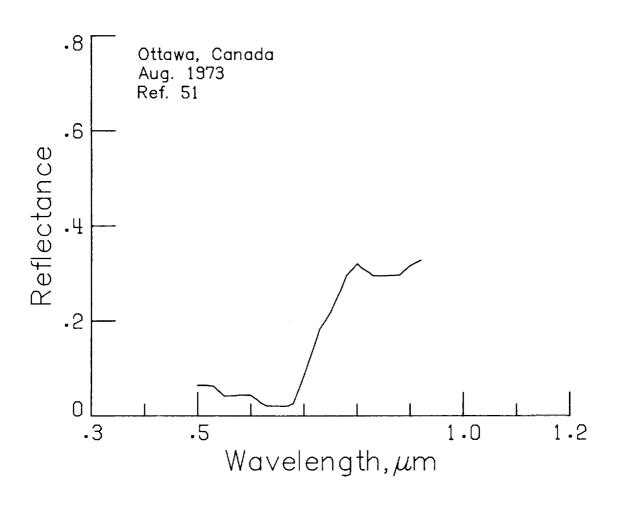


NO.63 - RED PINE NEEDLES



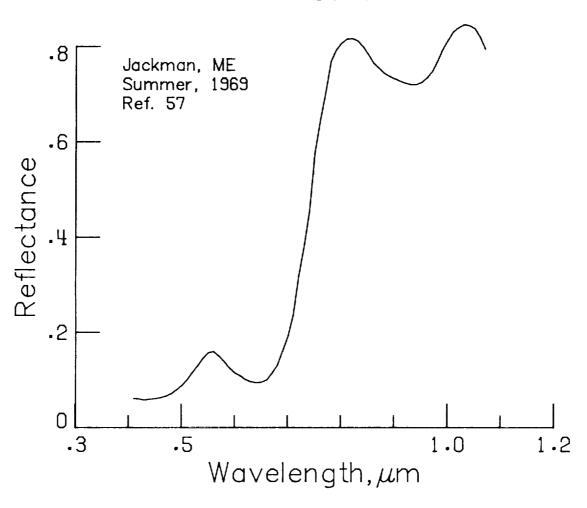
<u> </u>	<u>R</u>	$\vec{\lambda}$	<u>R</u>	<u>\lambda</u>	<u>R</u>	<u> </u>	<u>R</u>	<u> </u>	<u>R</u>
.30 .32		.48 .49 .50	.064 .064 .067	.667 .689 .690	:075 :073 :077	.84 .85 .867	:774 :774 :774	1 -02 1 -03 1 -04	.737 .748 .757
.33 .34 .35		.51 .52 .53	.076 .098 .144	-69 -70 -71	.099 .197 .304	.87 .88 .89	.775 .776 .775	1 · 05 1 · 06 1 · 07	.764 .769 .772
-36 -37 -38		.54 .55 . <u>56</u>	:161 :171	.72 .73 .7 <u>4</u>	.472 .565 .641	.90 .91 .92	.760 .762 .7 <u>6</u> 7	1 -08 1 -09 1 -10	.771 .767 . <u>76</u> 0
.40	-043	•57 •58 •59	: 157 : 137 : 124	.75 .76 .77 .78	: 735 : 744 : 744		.739 .723	1.12	- 750 - 731 - 706
43	.051 .056	970 256666666666666666666666666666666666	:	: / 8 - 80	:760 :764	•35 •97 •98	:704 :699		.640 .618
146 147	.062 .061	.64 .65	.087 .082	.79 .80 .83	: / /71 : 773	1 :00 1 :01	:712 :724		-589 -583

NO.64 - WHITE PINE



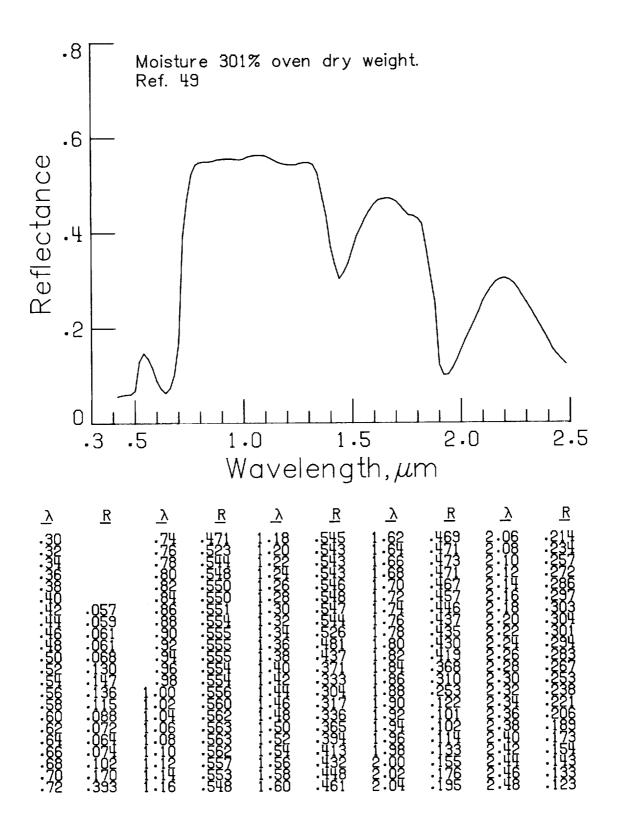
Δ	<u>R</u>	<u>\lambda</u>	<u>R</u>	<u>\lambda</u>	<u>R</u>	<u> </u>	<u>R</u>	<u> </u>	<u>R</u>
.30 .32 .33		.489 .501	.065 .065	.667 .669 .699	.020 .021 .026 .055	845 867 877	55566 555666 555666	1.02 1.03 1.05	
.35 .36 .36 .37		.5555 .5555 .5555	.063 .052 .048	.70 .72 .73	.084 .117 .149 .184	.889	.307 .316 .328	1.05	
.38 .40 .45		.557 .559 .500	.044 .044 .044	: 75 : 76 : 77	.200 .2019 .2067	SOCIOLOGIC NOTIFICACION	•328	1.12	
1445 145 150 150 150 150 150 150 150 150 150 15		.6663 .6633 .673	.036 .027 .021	- 78 - 79 - 80 - 81	.308 .320 .310	.557 .598 .599	÷	1567	
:47		.65	:021	:83	295	1:01		1:18	



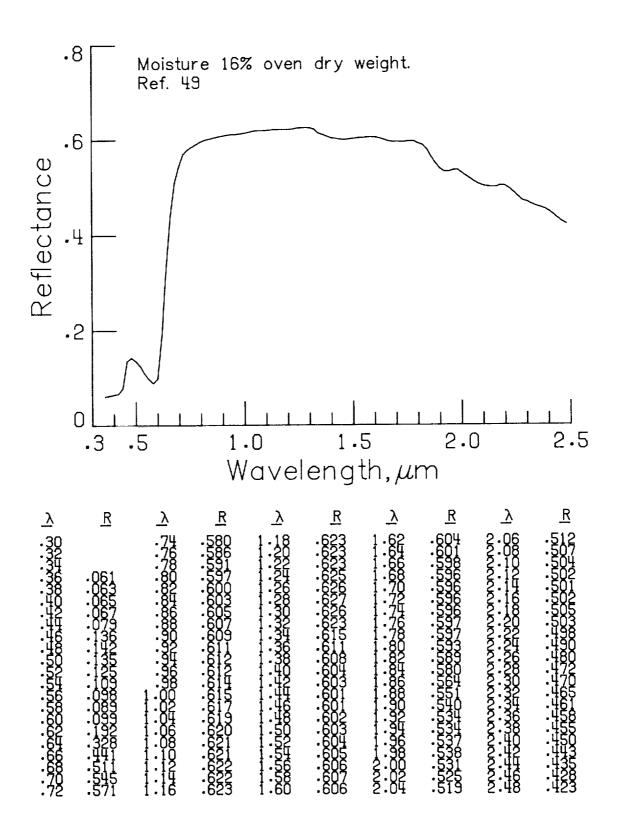


אן משממממממממים -איידודים סיילאים האיידיטטט -סיילאים איידיטט	RI 060560 .00560 .00563	7	R 2091-60570095591-75	λ 66666777777777778888888888888888888888	R 15111782687605867728868	\(\text{\tin}\text{\tex{\tex	R 035554828301547954 876543322222346914	入 234567890-2545678	R 8446 8844 8829 77
:46	.063 .067	.65 .65	.095 .096	.82 .83	.817 .812	1.00 1.01	.814 .832	1 · 18 1 · 19	

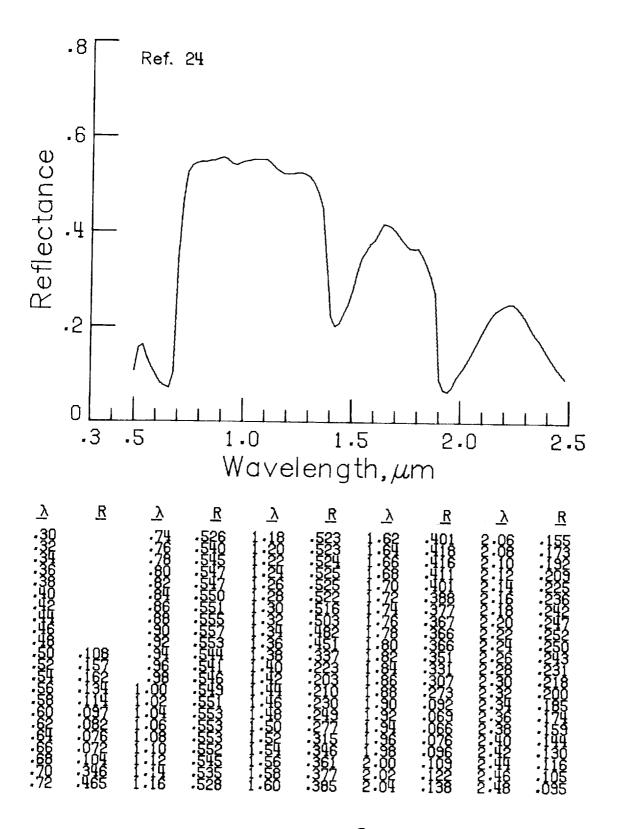
NO.66 - SYCAMORE LEAF



NO.67 - DEHYDRATED SYCAMORE LEAF

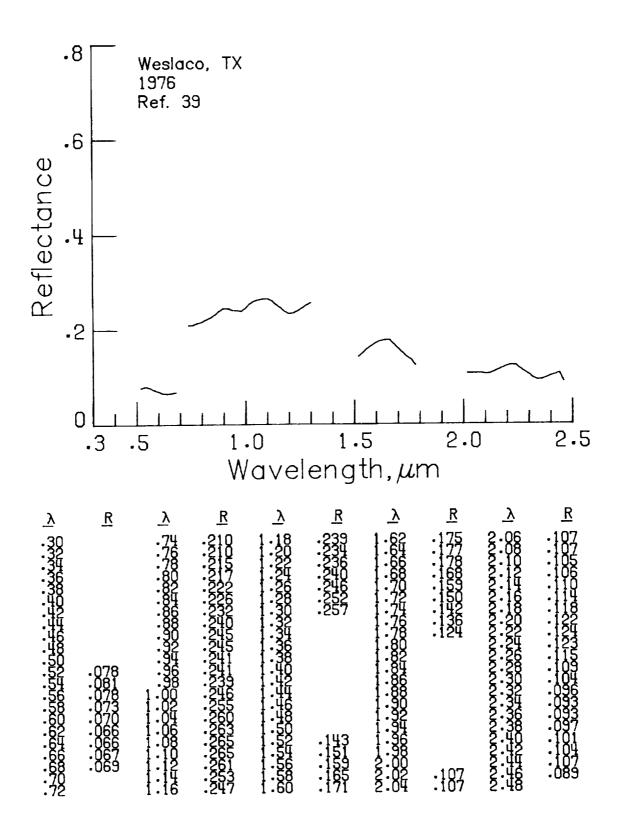


NO.68 - TULIP TREE LEAF

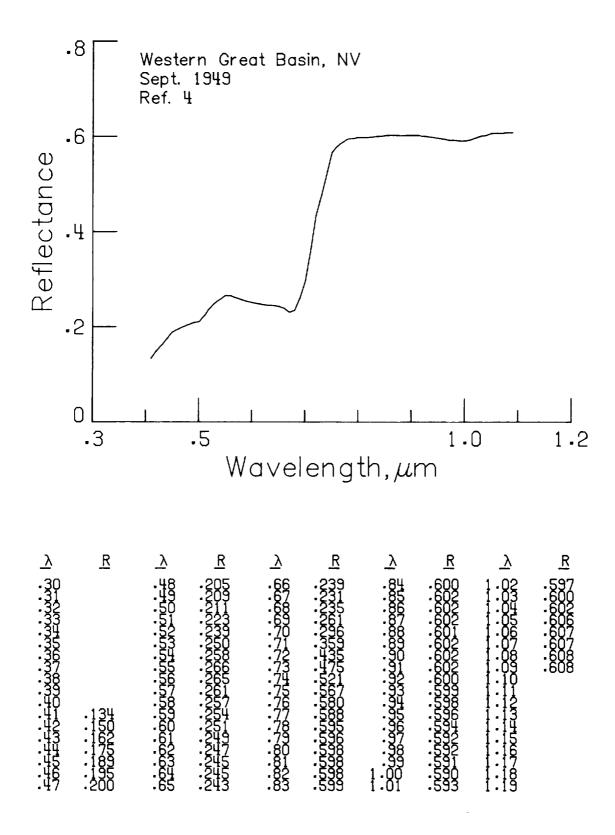


ピーユ

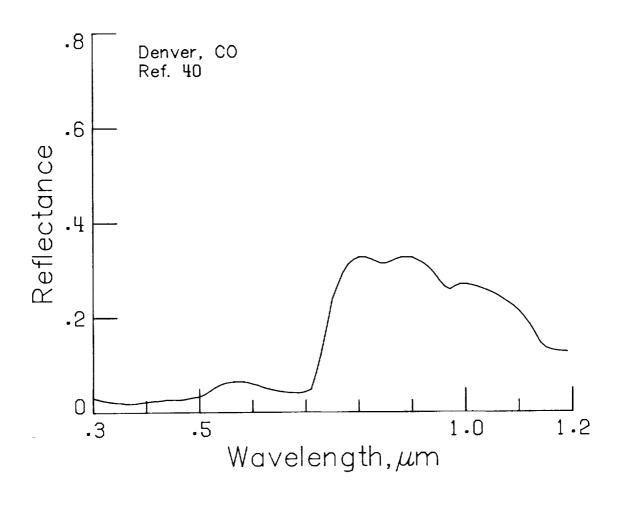
NO.69 - CENIZO



NO.70 - AVERAGE DESERT LEAVES

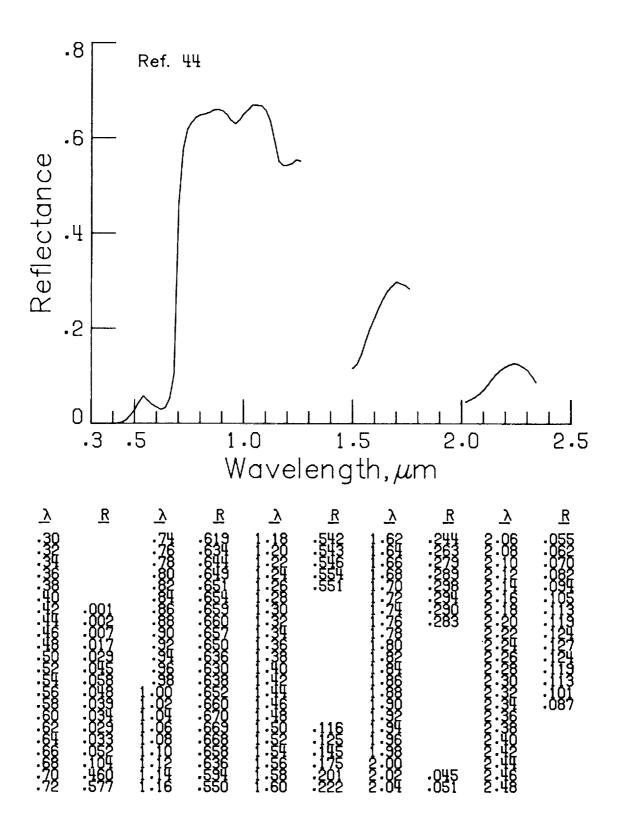


NO.71 - GRASS

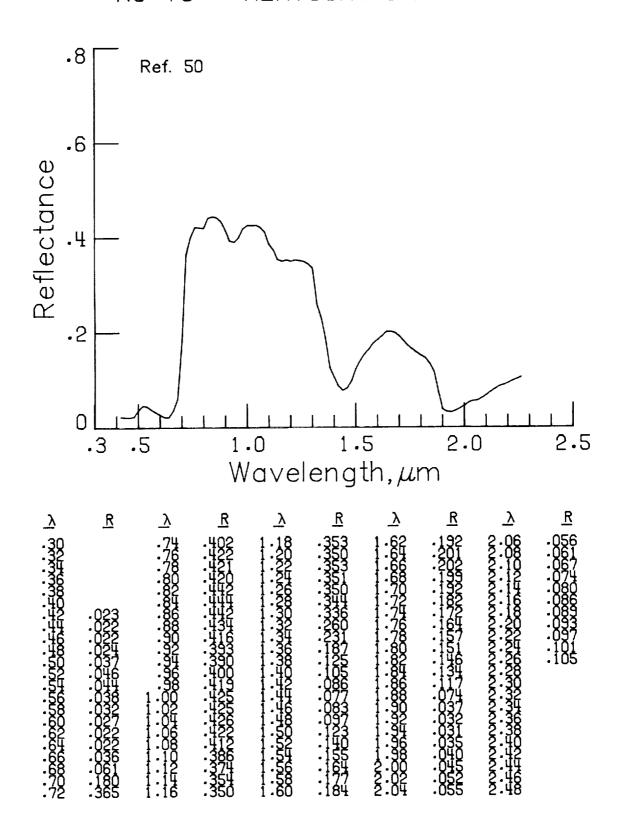


<u> </u>	<u>_R</u>	<u> </u>	<u>R</u>	<u> </u>	<u>R</u>	<u> </u>	<u>R</u>	<u>\lambda</u>	<u>R</u>
.30 .31 .32	.031 .028 .025	.48 .49 .50	.030 .033 .033 .045	.66 .67 .68	.042 .041 .041		314 314 318 303	1.02 1.03 1.04	.264 .260 .256
	.023 .021 .020	##555555 ##555555 ##555555	.038 .045 .053	6678901-2345678901-23	.041 .043 .048	07~000-1~000	327	00000000000000000000000000000000000000	237
.367 .389 .40	.019 .019		.065 .065 .066 .066 .066	: 75 - 74 - 75	.130 .182 .239	.91 .92 .93	.320 .314 .305	1.09	.222 .211 .198
40 42	.022 .024 .025	567890 55555666	.064 .063 .059	.76 .77 .78	.267 .295 .312	.9 <u>4</u> .95 .96	.293 .277 .264	1.12	21-835555-877 21-9864-33222
.43 .45	.026 .027 .027	999999 5699999	.057 .049 .044	- 60 - 81	.327 .327	.98 .99 1.00		1 • 1 /	131
:49	:028	65	:644	.83	:319	1.01	.269 .267	1:18	127

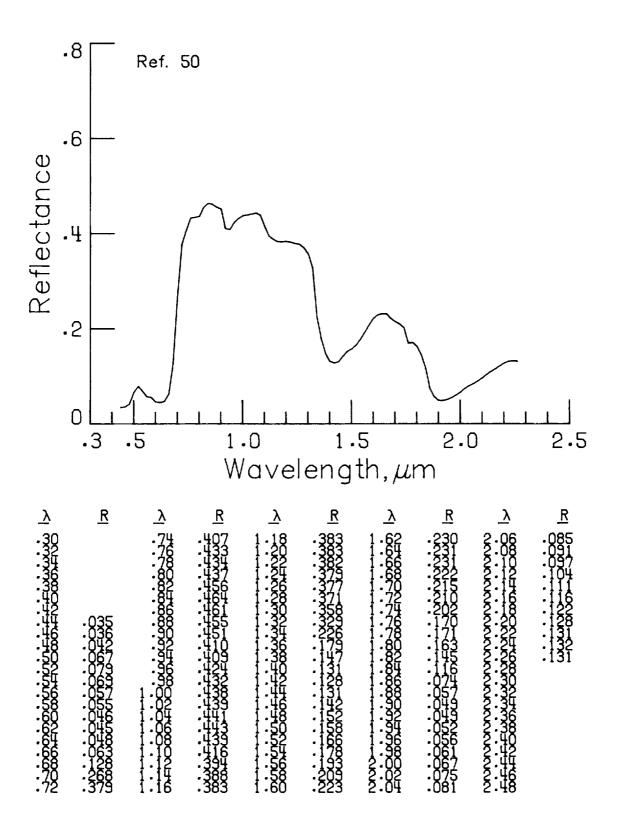
NO.72 - GRASS



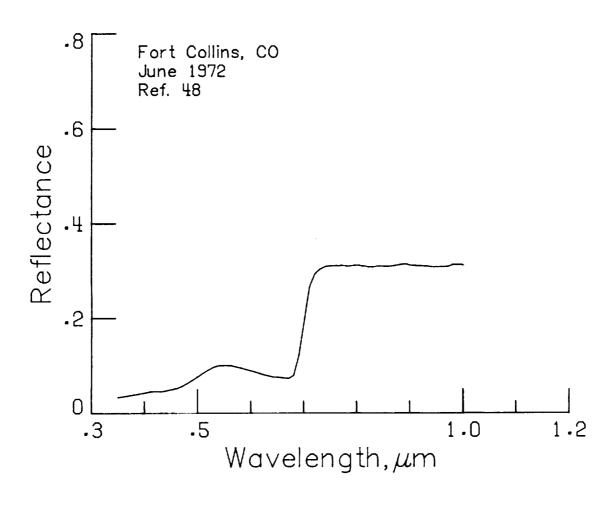
NO.73 - KENTUCKY BLUE GRASS



NO.74 - RED FESCUE GRASS

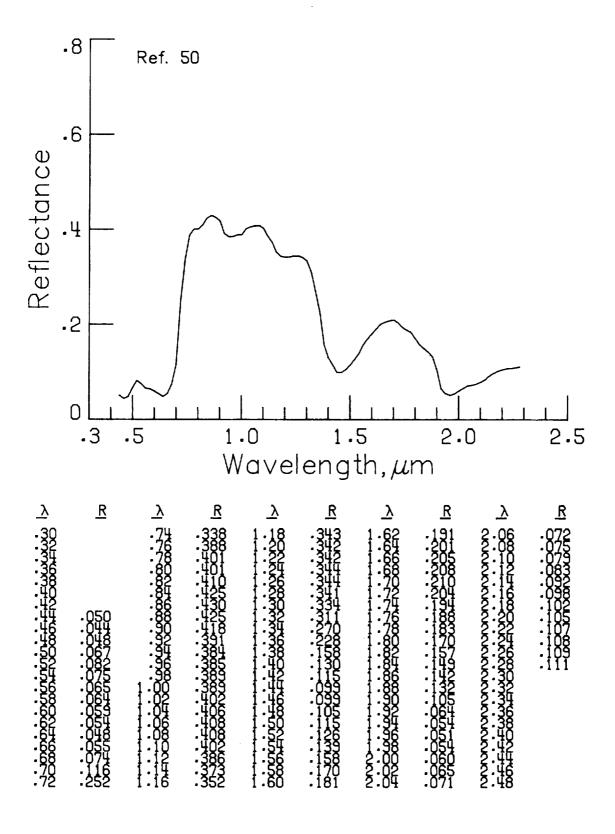


NO.75 - BLUE GRAMA GRASS

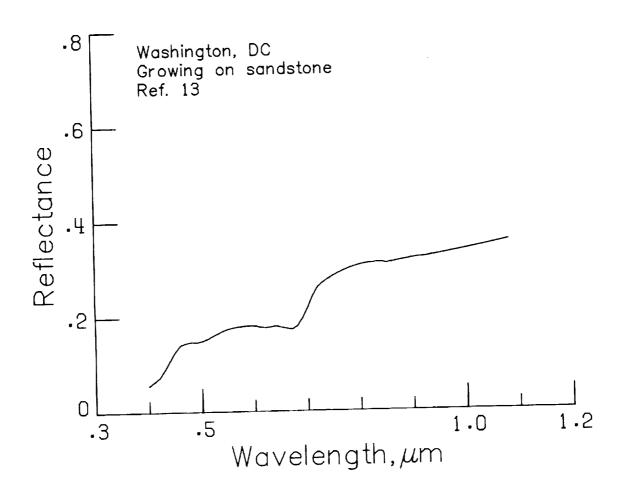


<u>\lambda</u>	<u>R</u>	<u>λ</u>	<u>R</u>	<u>\lambda</u>	<u>R</u>	<u> </u>	<u>R</u>	<u>\lambda</u>	<u>R</u>
.30 .32 .33 .34		490	-053 -070 -077 -085	-667 -689 -70	.079 .079 .121	.855 .887 .88	309	1.05	
.35 .36 .38	.033 .035 .037 .039	55555	.037 .100 .100 .033	71 72 73 74	267 264 309	.90	310	i .07 i .08 i .09 i .10	
39	.043 .043 .045	.57 .59 .60	.097 .094 .092 .089	.75 .76 .77 .78	30000	393565 393565	.309 .308 .308	1.12 2.42 2.42 3.42 3.42 3.42 3.42 3.42 3.4	
.45 .45 .47	.047 .050 .052 .056	- - - - - - - - - - - - - - - - - - -	.081 .079 .076 .075	.83 .88 .83	.310 .308 .308	.98 .99 1.00 1.01	313	367	

NO.76 - PERENNIAL RYE GRASS

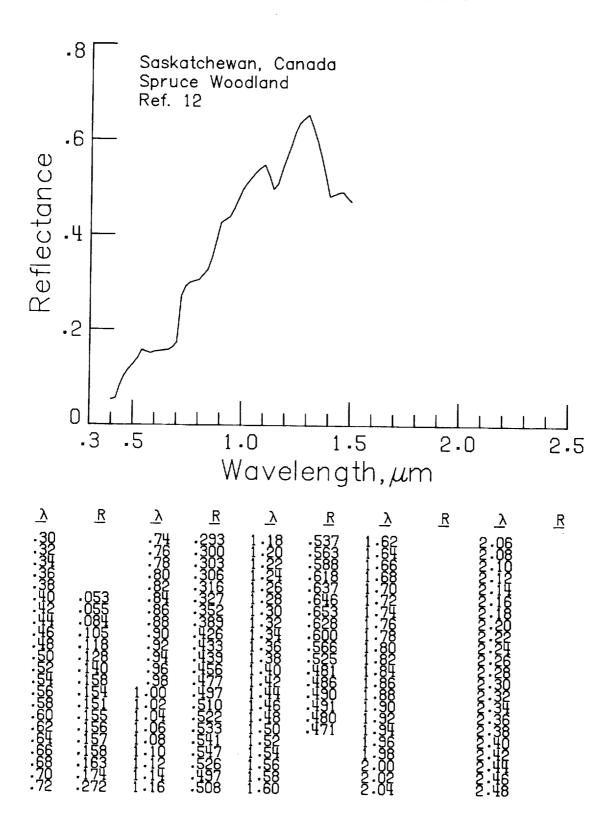


NO.77 - DRY LICHEN SAMPLE

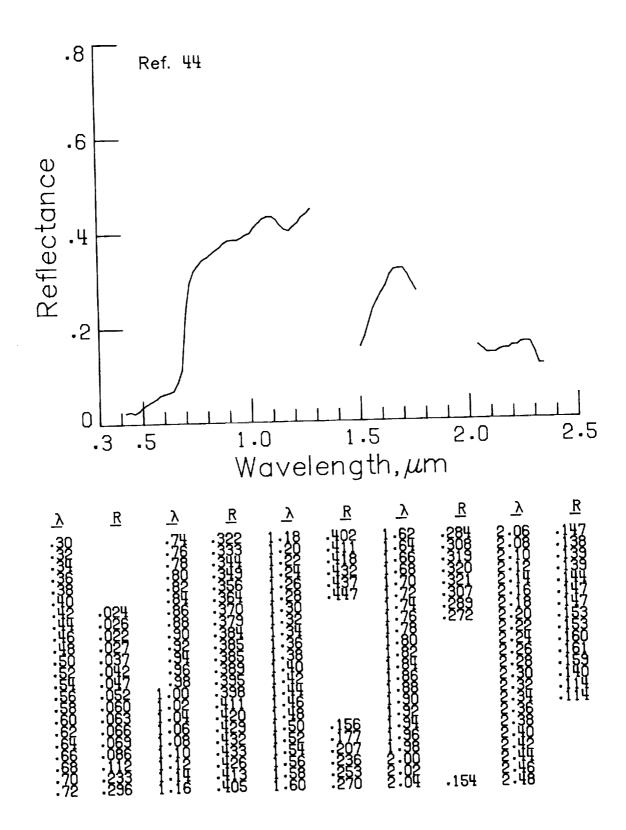


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144567	.074 .091 .129 .146	00 66666666666666666666666666666666666	1'/9	.78 .79 .80 .82 .83	.300 .304 .307 .309 .312		• • • • • • • • • • • • • • • • • • •	1.1567	

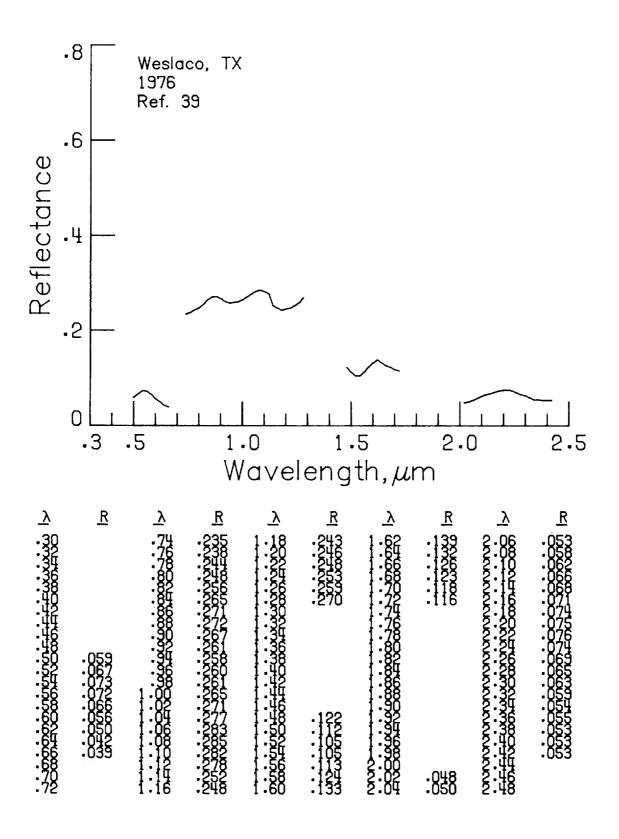
NO.78 - LICHEN MAT



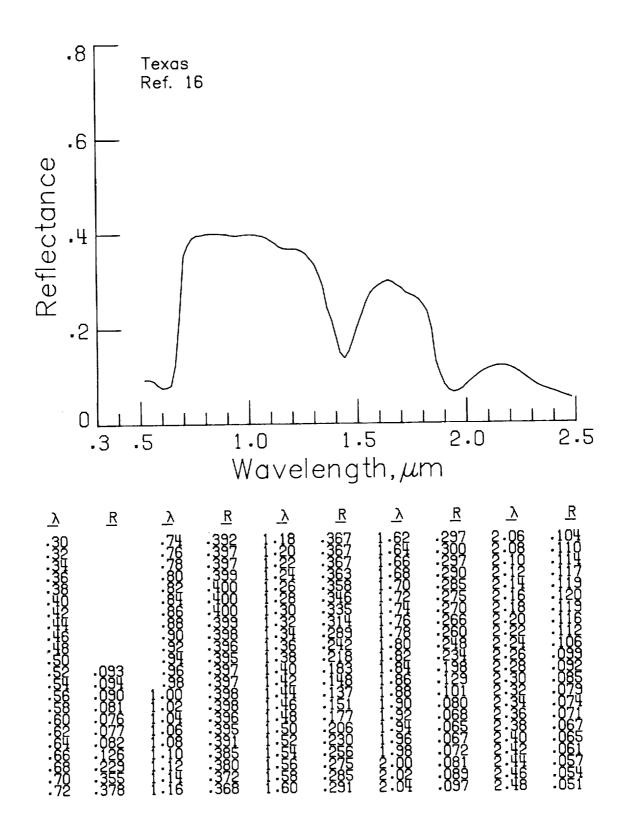
NO.79 - MANZANITA



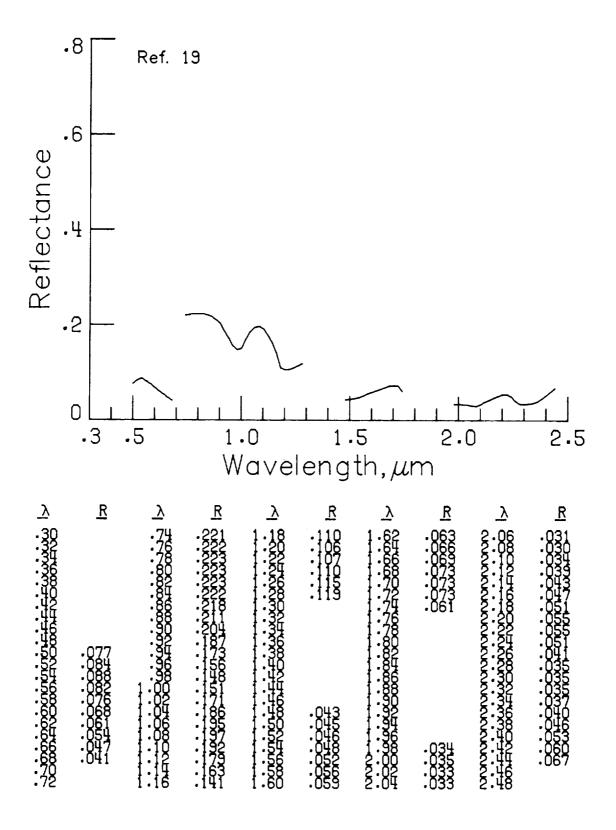
NO.80 - MESQUITE



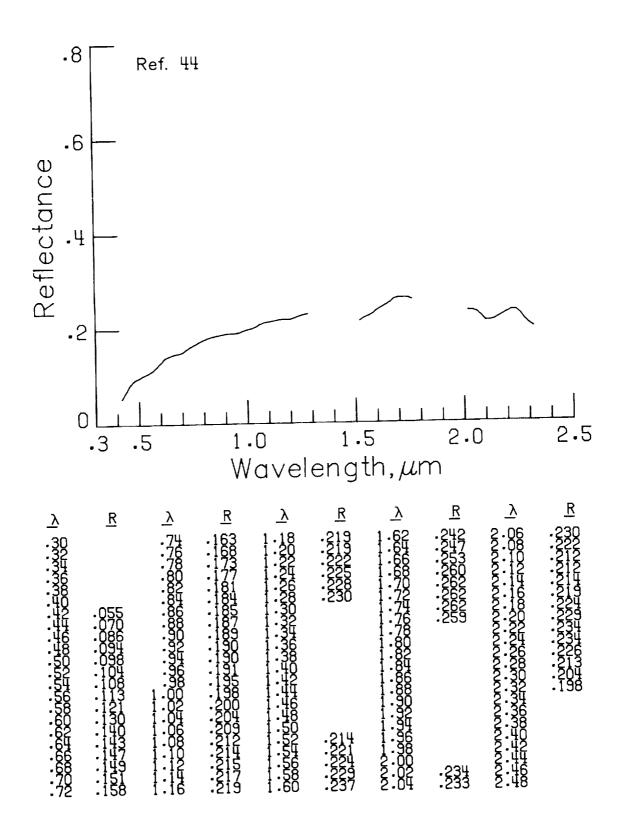
NO.81 - HONEY MESQUITE



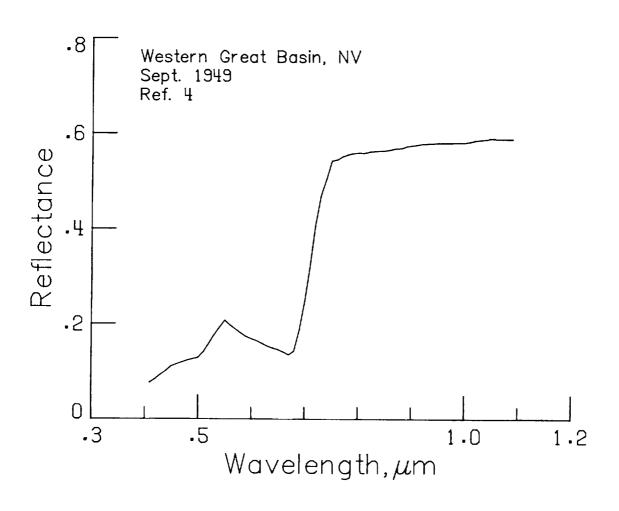
NO.82 - PRICKLY PEAR



NO.83 - DRY SAGE

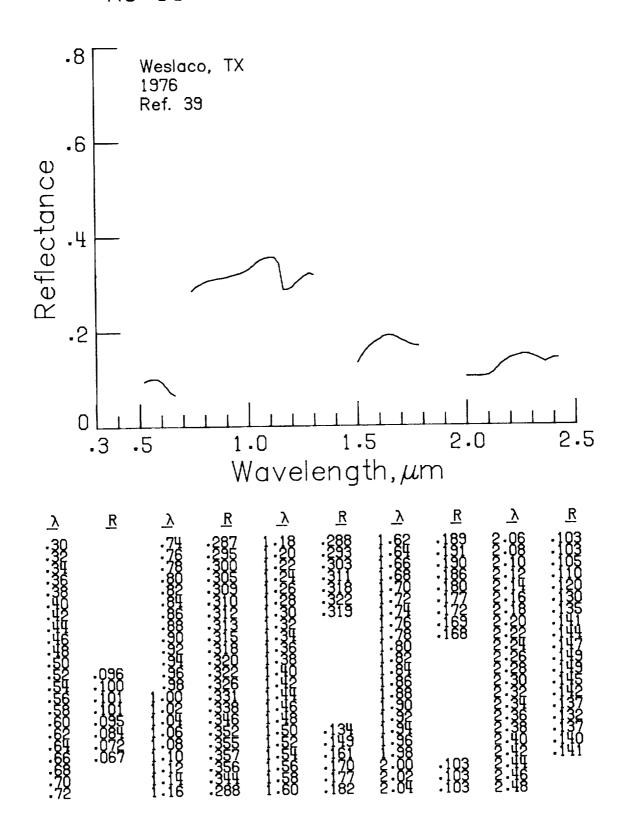


NO.84 - AVERAGE SUBALPINE SLOPE LEAVES

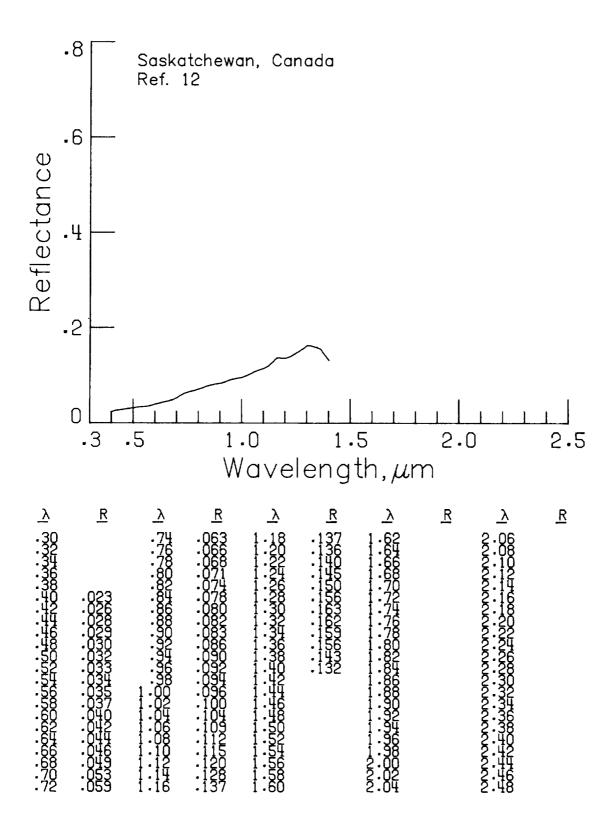


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.47	-120	-65	146	.83	564	1:01	.584	iii	

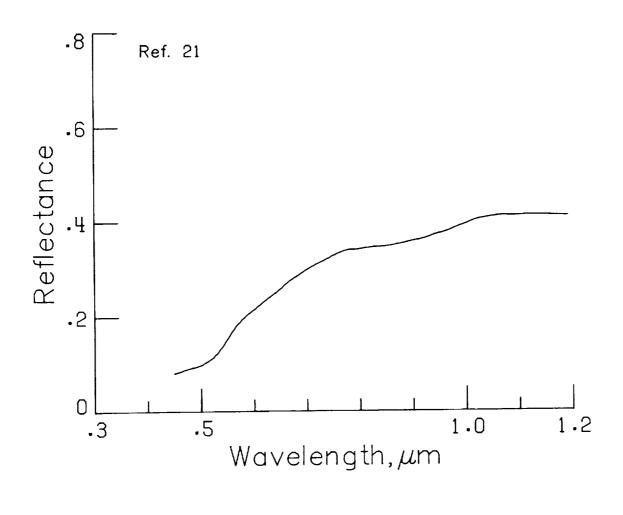
NO.85 - SILVERLEAF SUNFLOWER

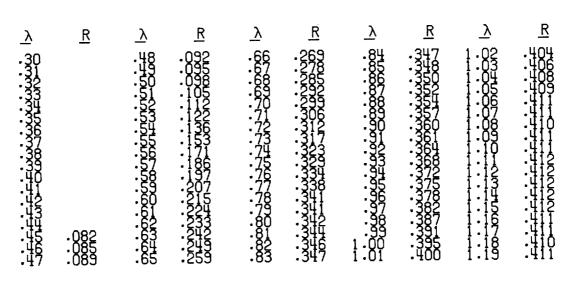


NO.86 - BURNED FOREST SURFACE

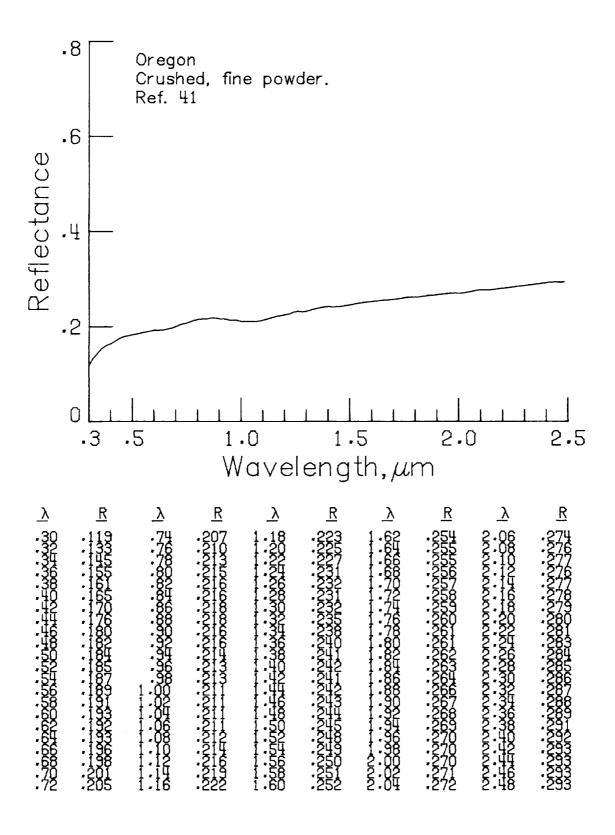


NO.87 - ARKOSE

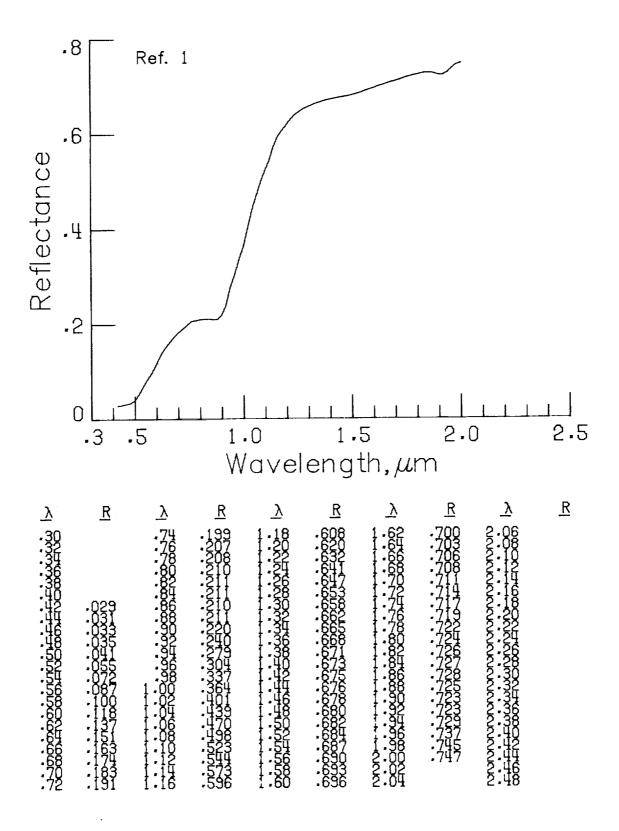




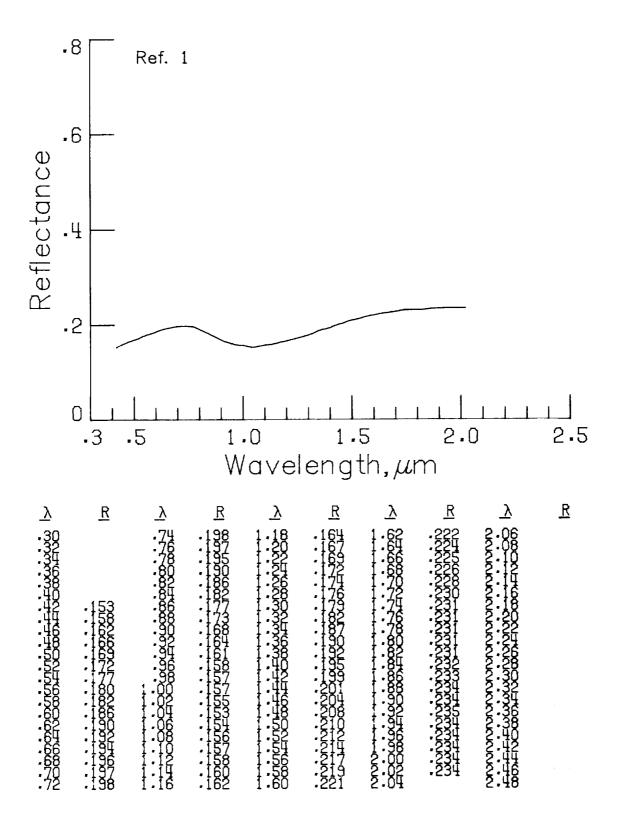
NO.88 - BASALT SAMPLE



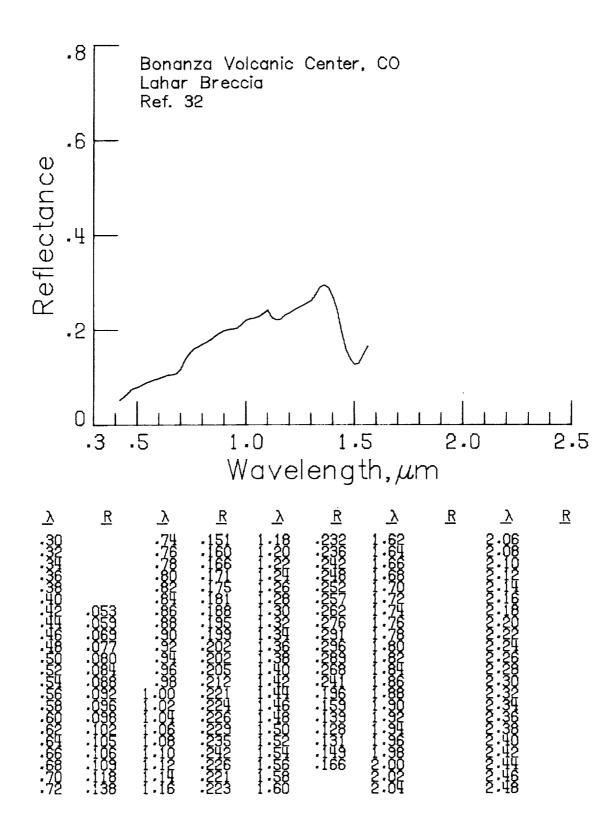
NO.89 - RED CINDER BASALT SAMPLE



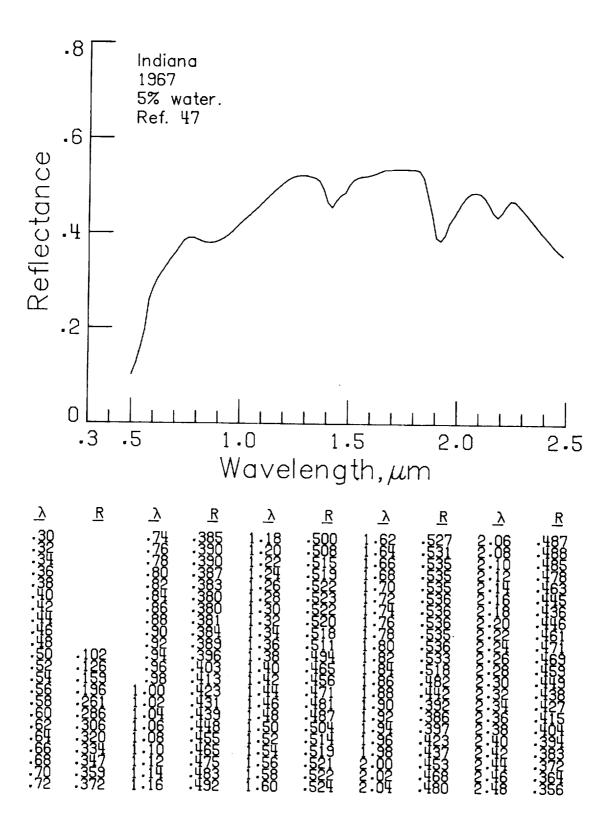
NO.90 - GRAY BASALT SAMPLE



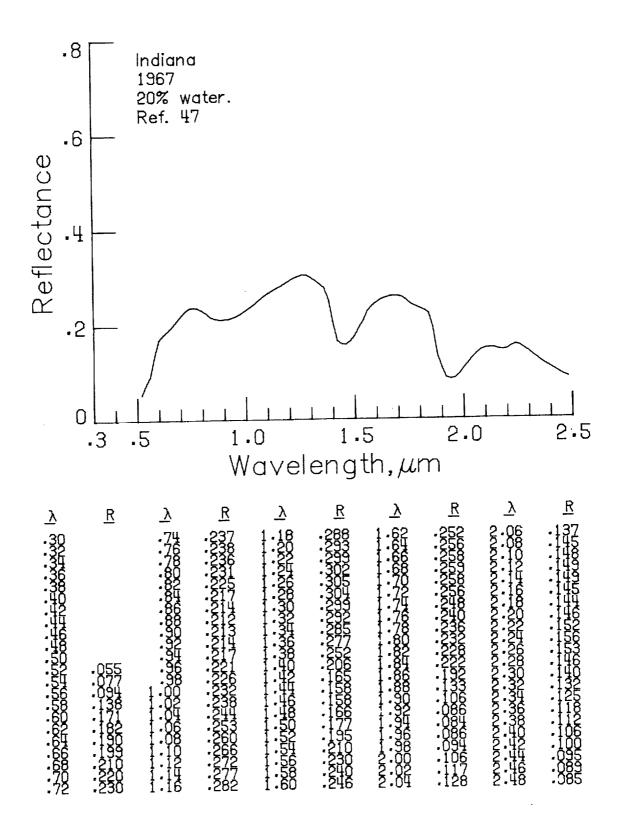
NO.91 - BRECCIA



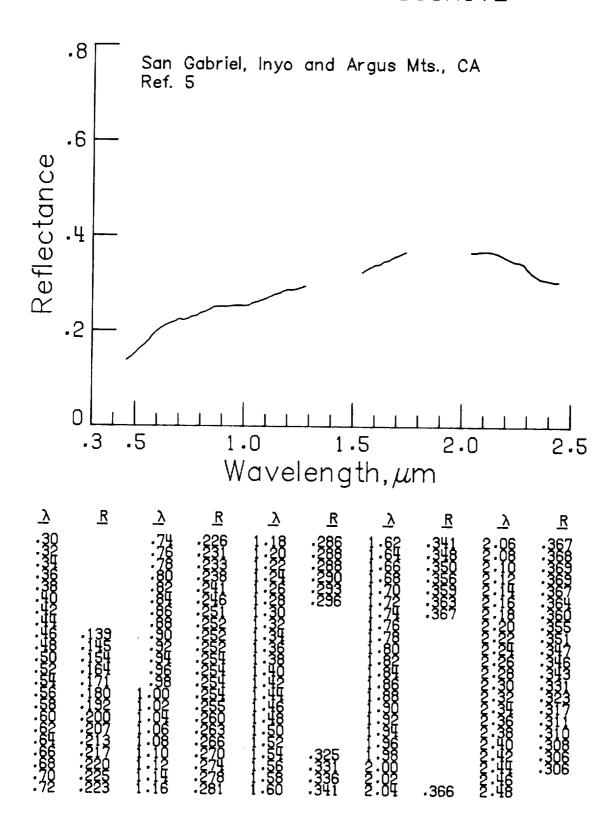
NO.92 - DRY RED CLAY SAMPLE



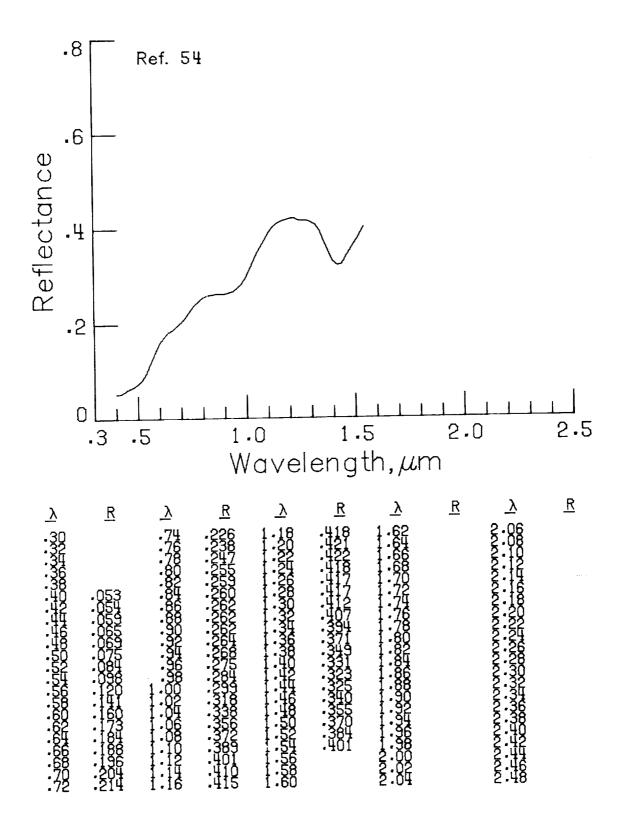
NO.93 - WET RED CLAY SAMPLE



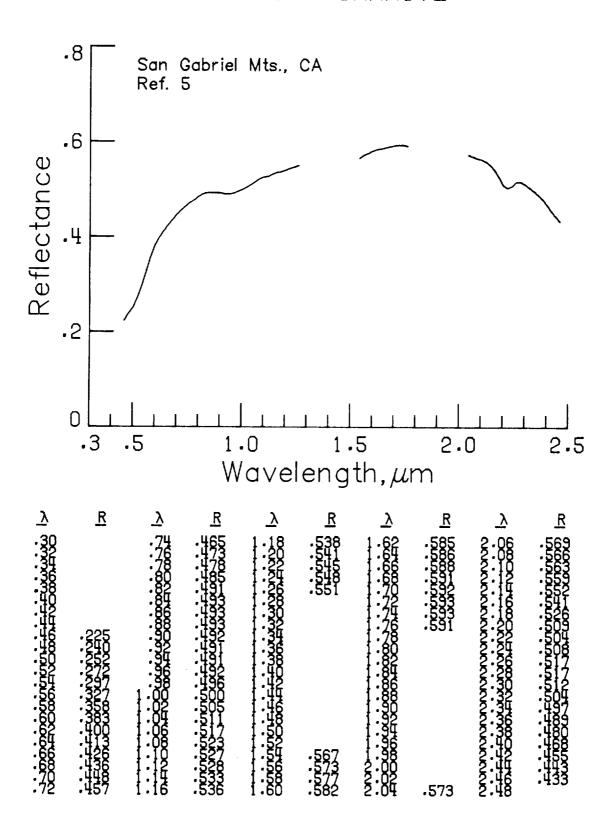
NO.94 - QUARTZ DIORITE



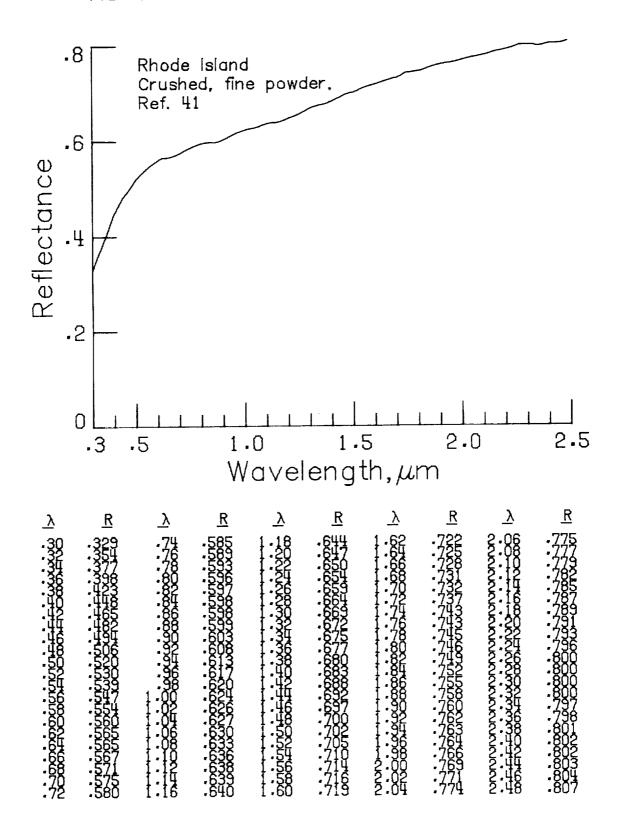
NO.95 - GRANITE



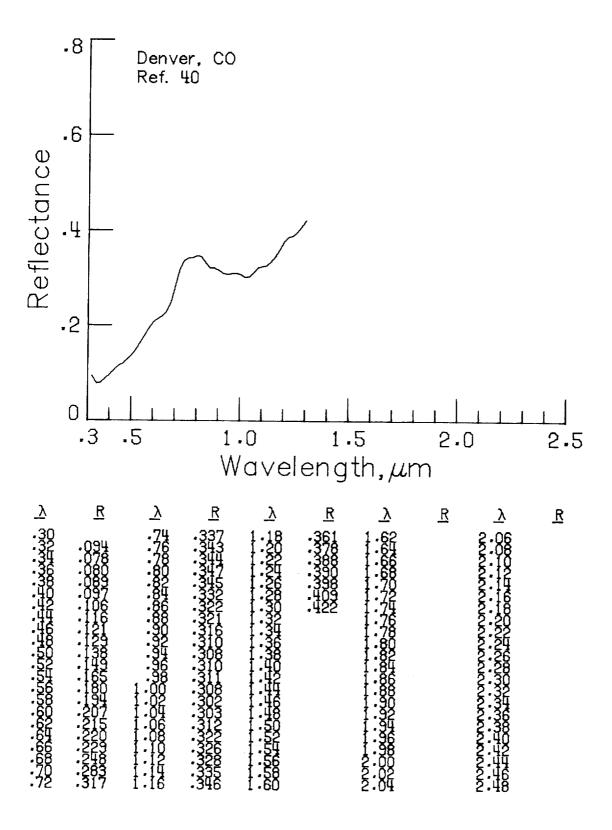
NO.96 - GRANITE



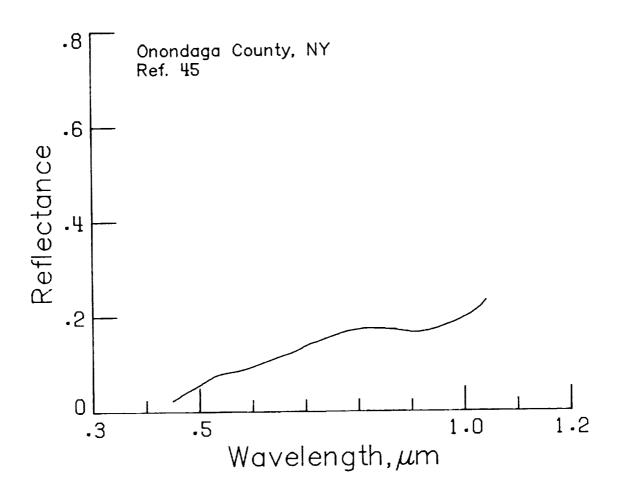
NO.97 - BIOTITE GRANITE SAMPLE

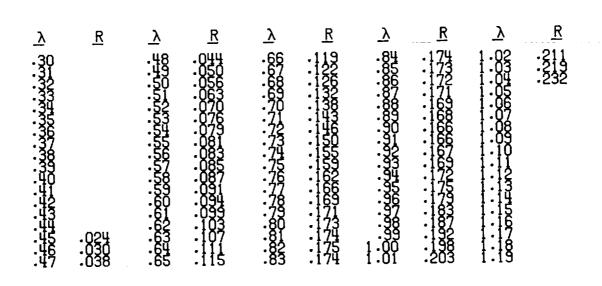


NO.98 - GRAVEL

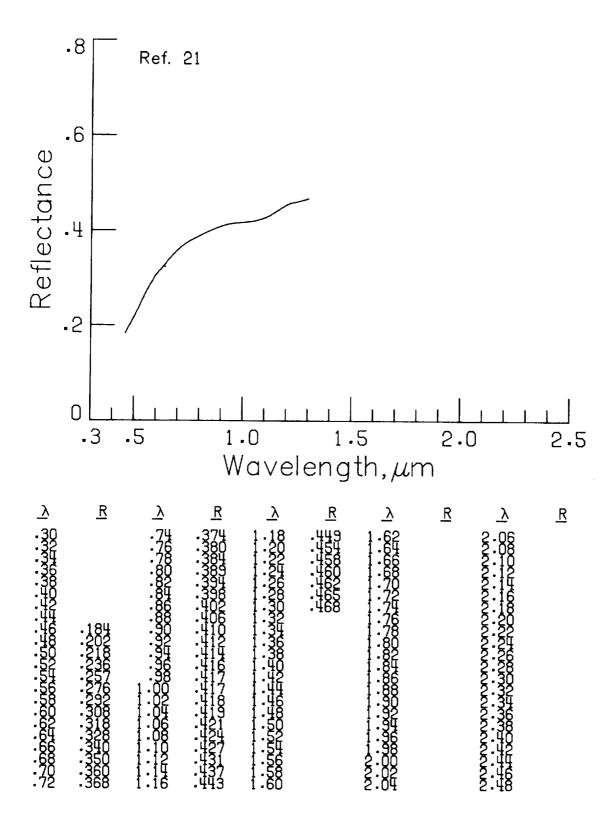


NO.99 - GLACIOFLUVIAL SAND AND GRAVEL

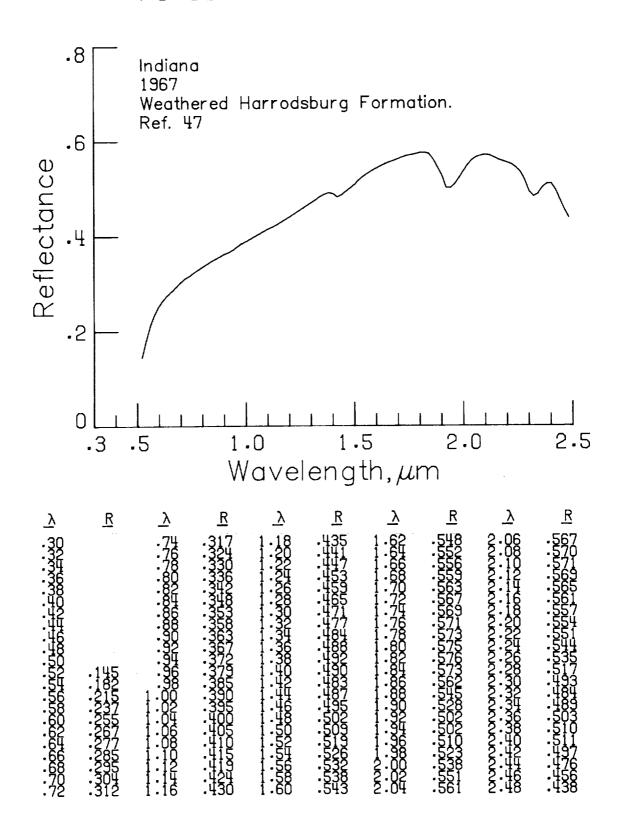




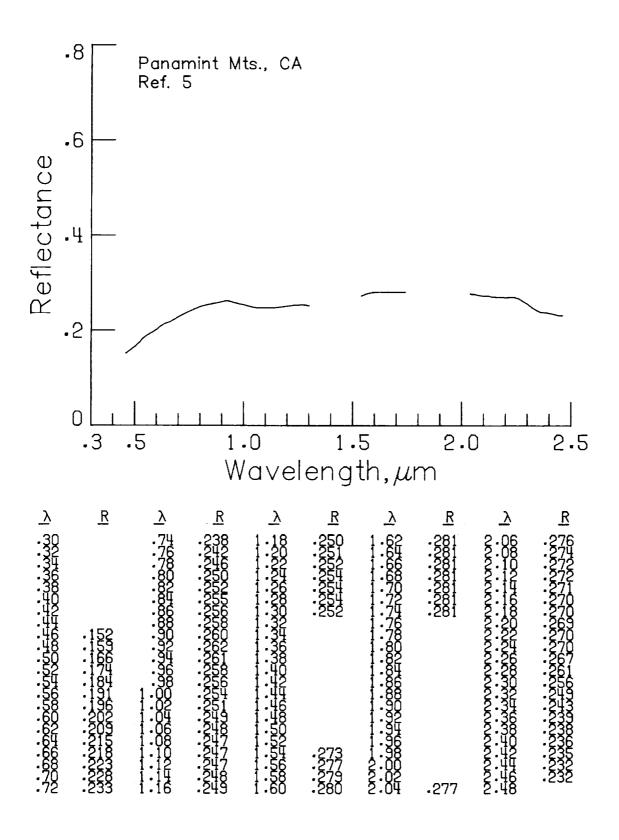
NO.100 - LIMESTONE



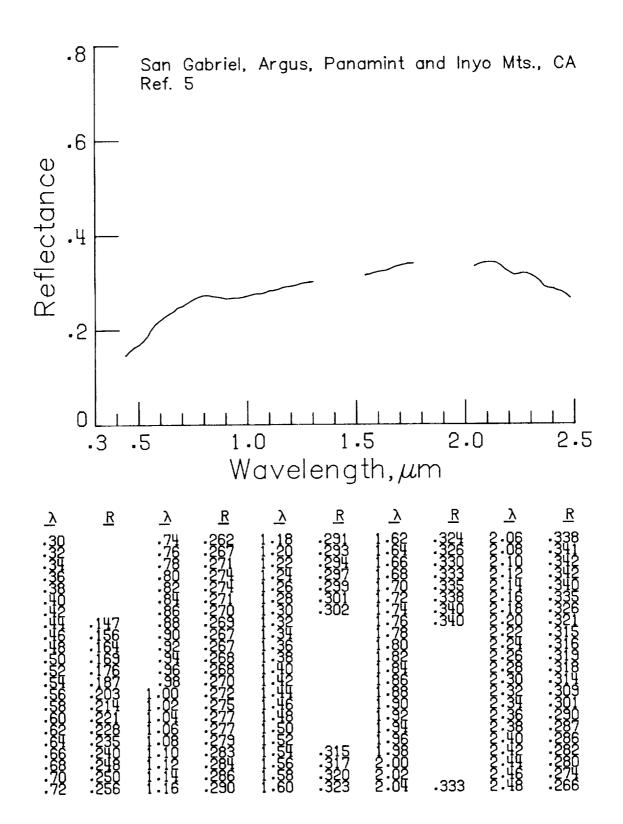
NO.101 - LIMESTONE SAMPLE



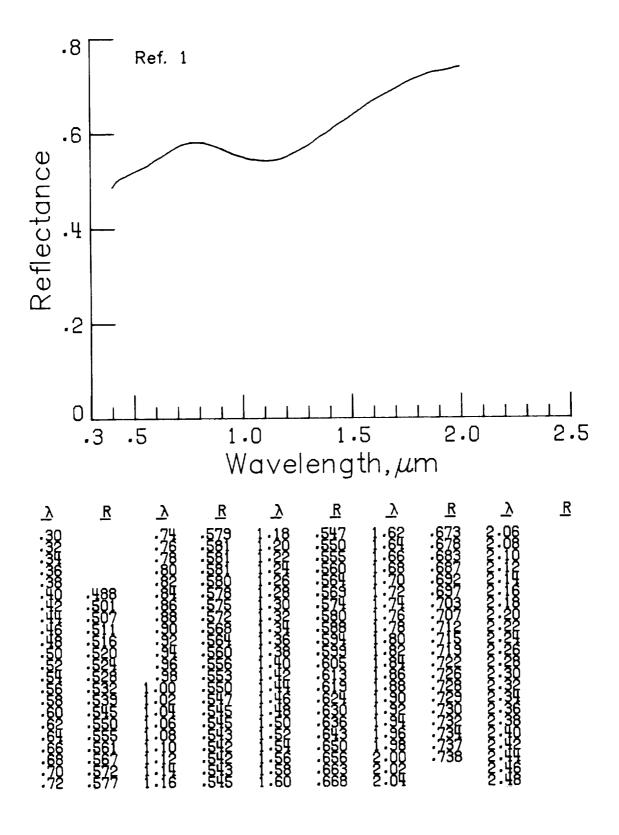
NO.102 - MONZONITE



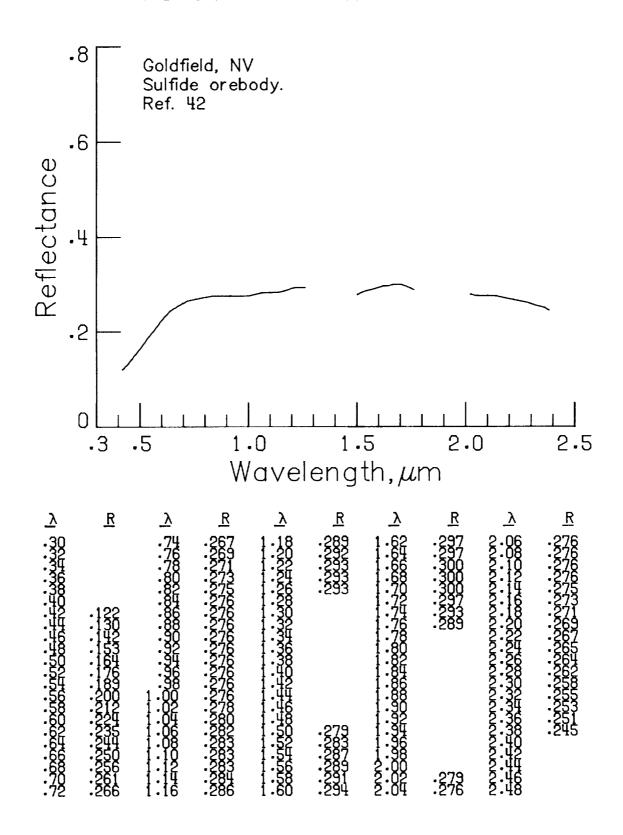
NO.103 - QUARTZ MONZONITE



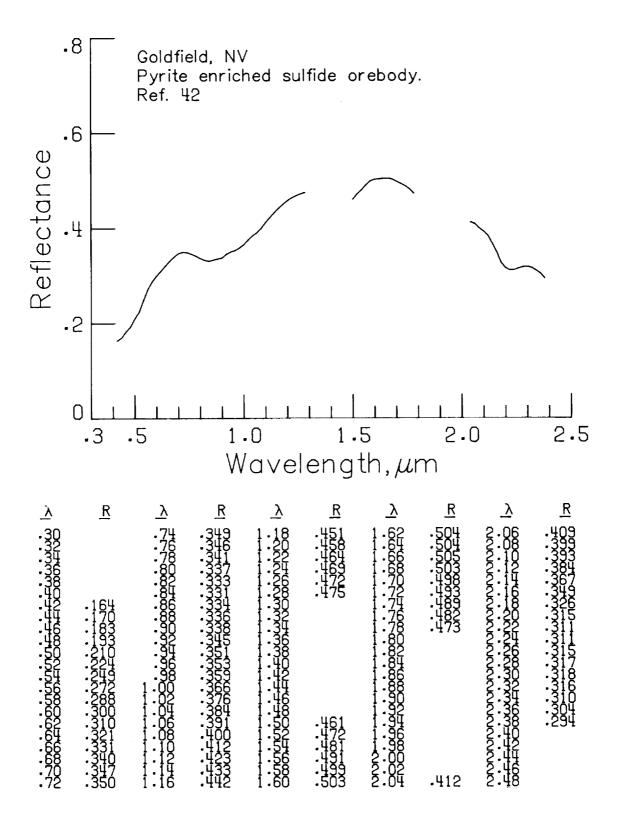
NO.104 - OBSIDIAN SAMPLE

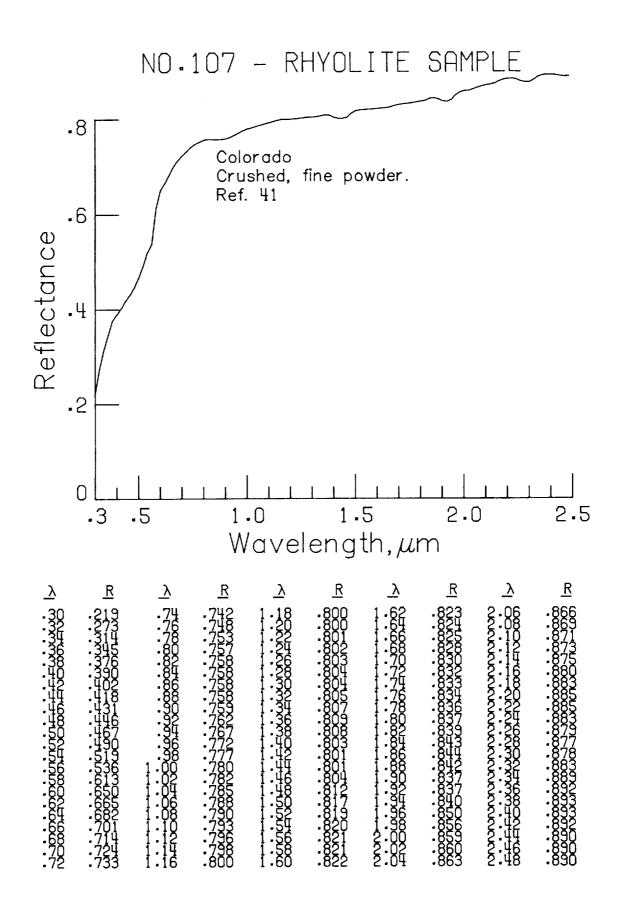


NO.105 - UNALTERED ROCKS

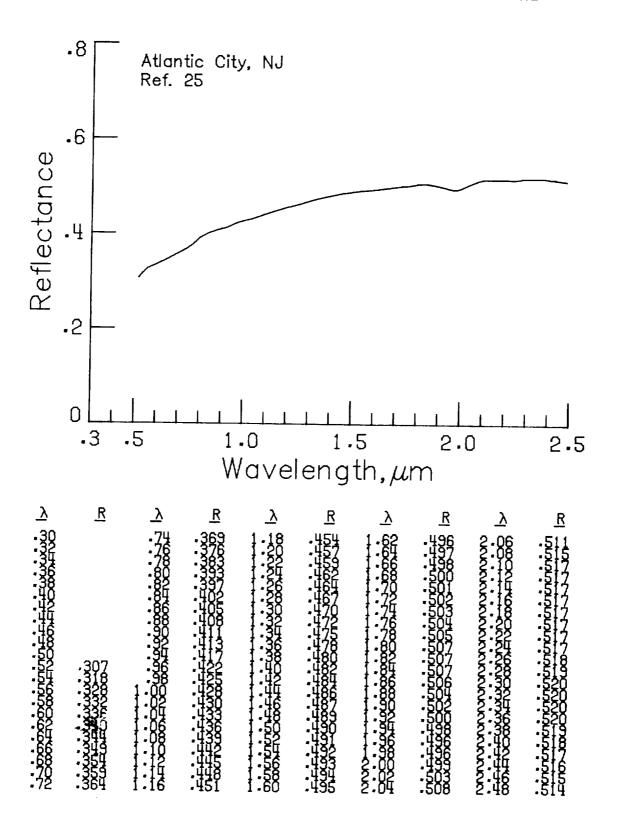


NO.106 - ALTERED ROCKS

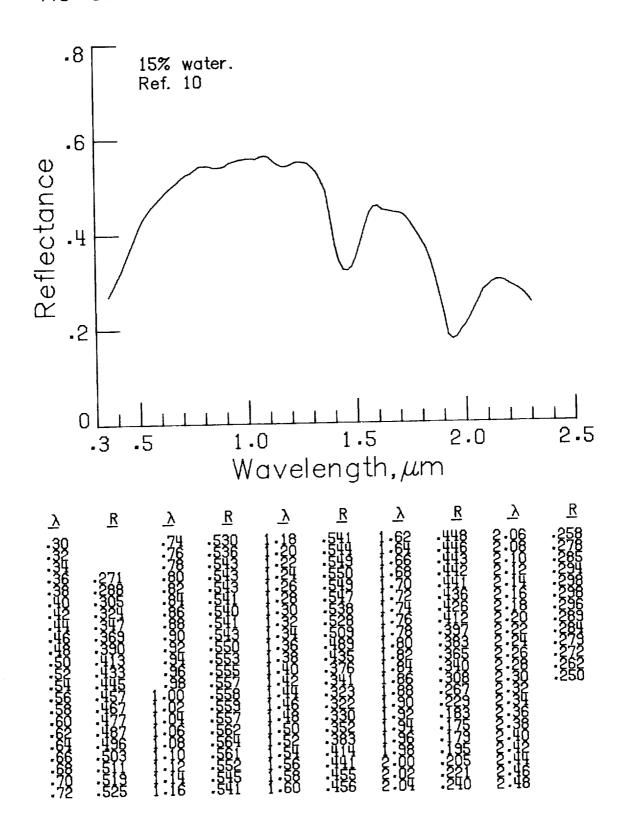




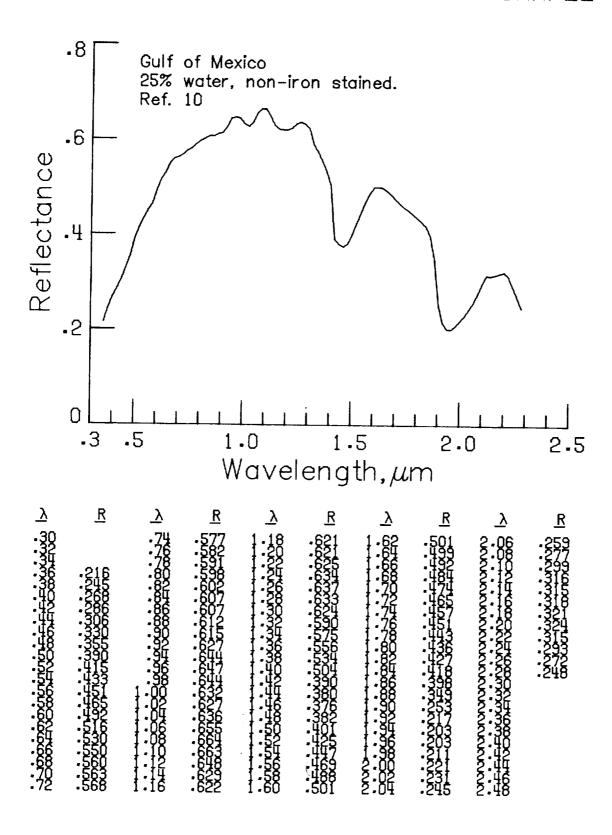
NO.108 - BEACH SAND SAMPLE



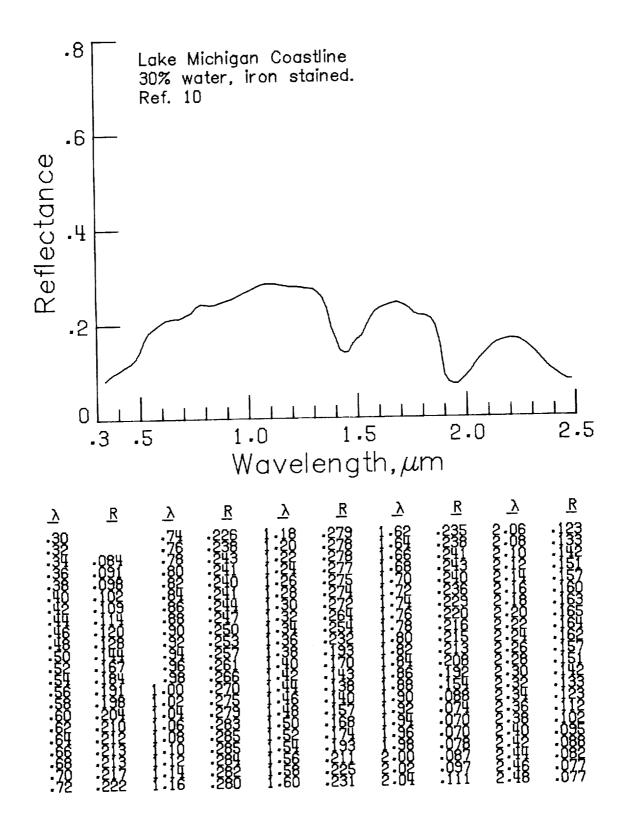
NO.109 - CARBONATE BEACH SAND SAMPLE



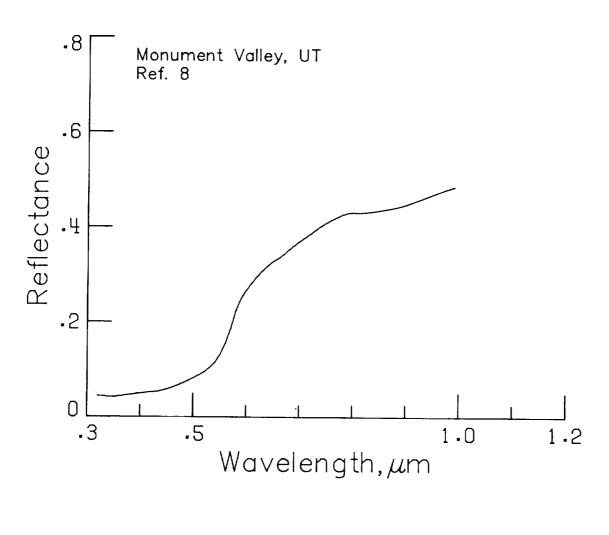
NO.110 - QUARTZ BEACH SAND SAMPLE

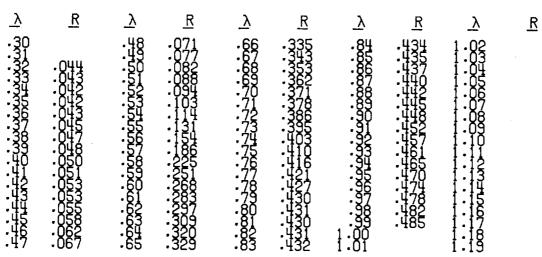


NO.111 - QUARTZ BEACH SAND SAMPLE

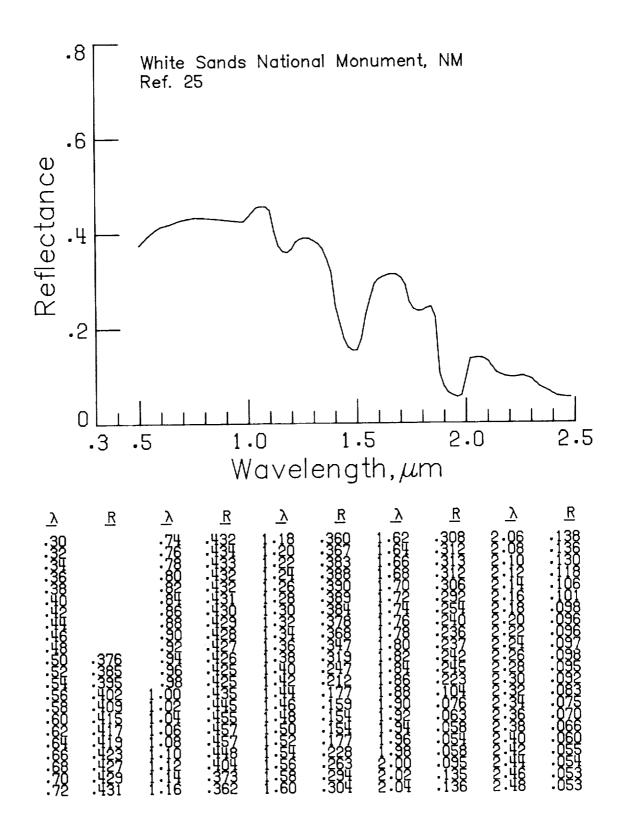


NO.112 - DRY SAND

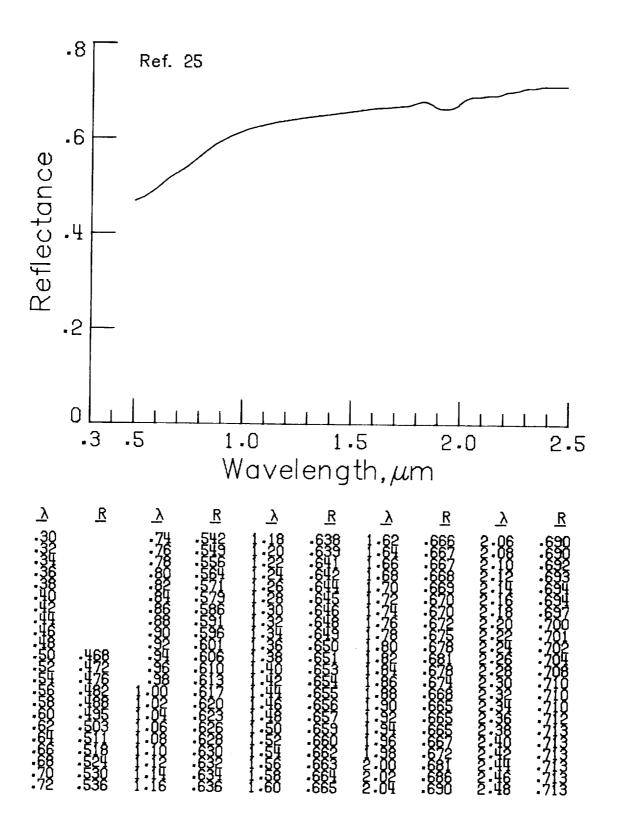




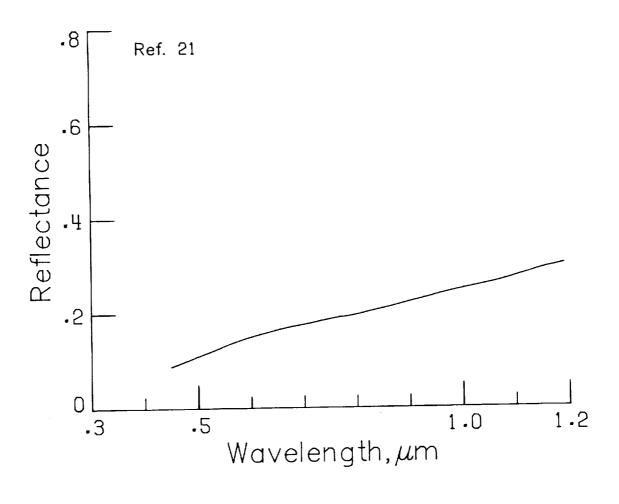
NO.113 - GYPSUM SAND SAMPLE



NO.114 - SILICA SAND SAMPLE

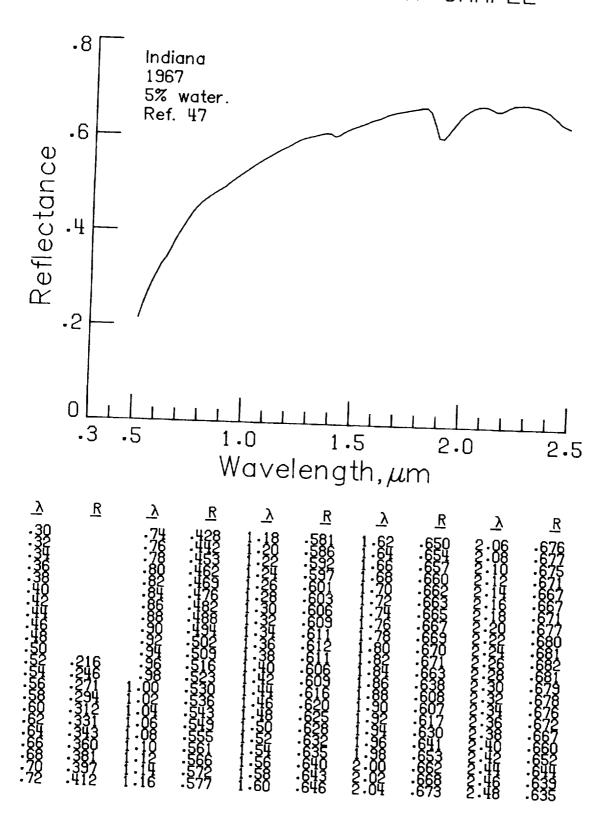


NO.115 - SHALE

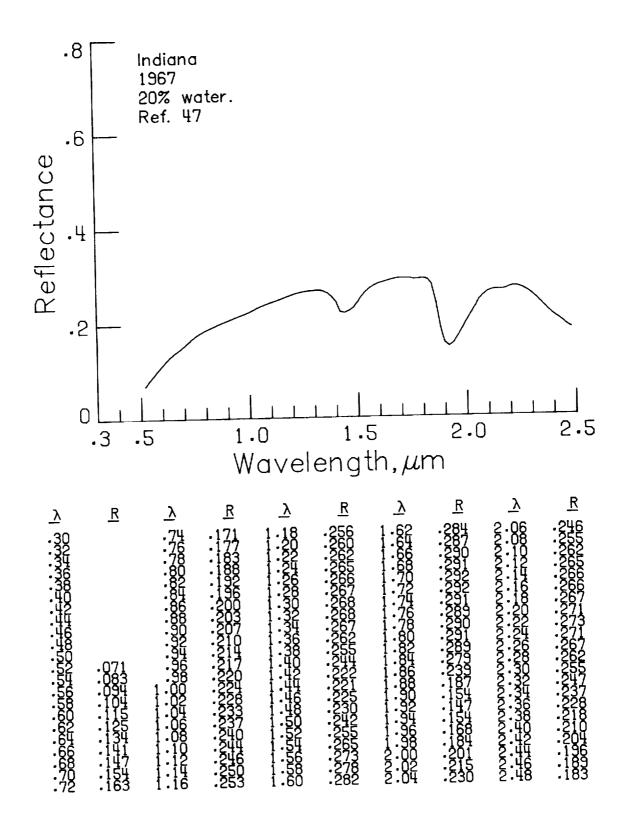


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.47	.097	-65	165	. 83	•204	1.01	.251	1.15	•301

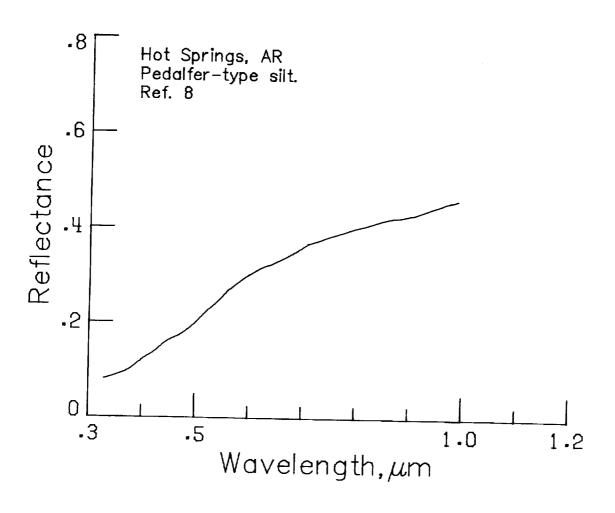
NO.116 - DRY SILT SAMPLE

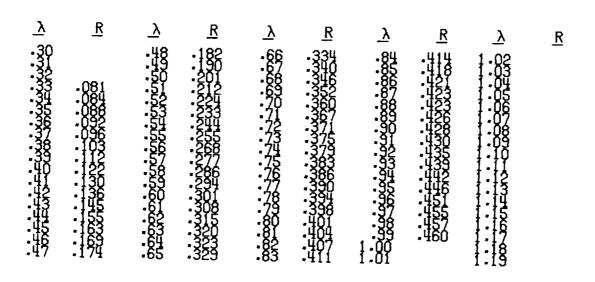


NO.117 - WET SILT SAMPLE

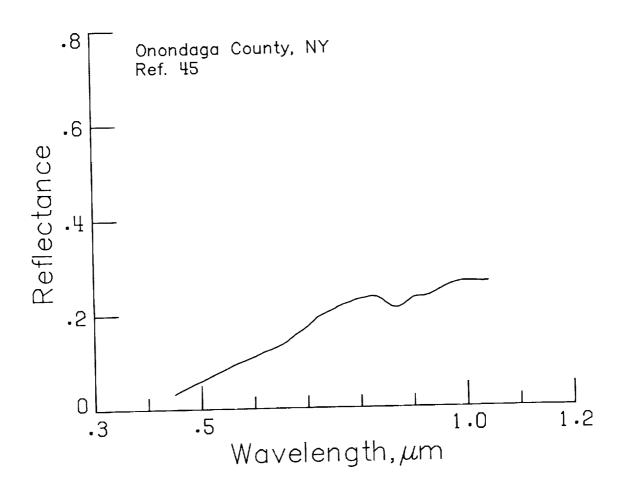


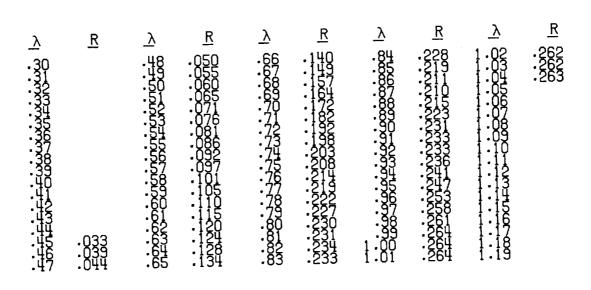
NO.118 - DRY SILT



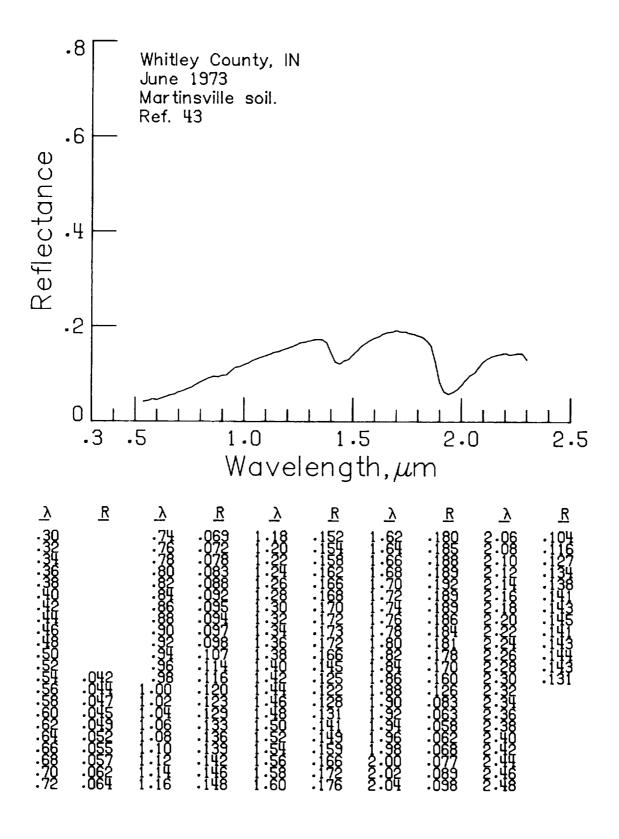


NO.119 - DRY LACUSTRINE SILT AND CLAY

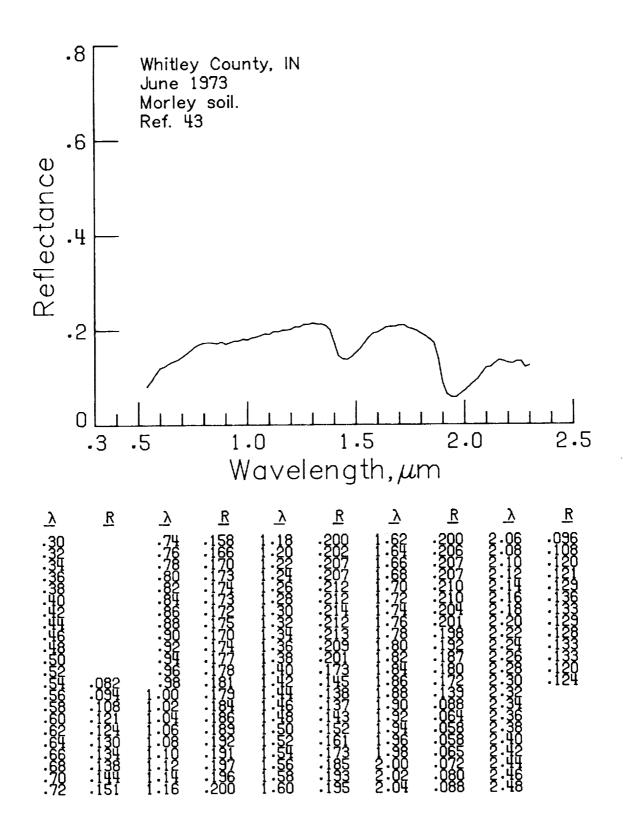




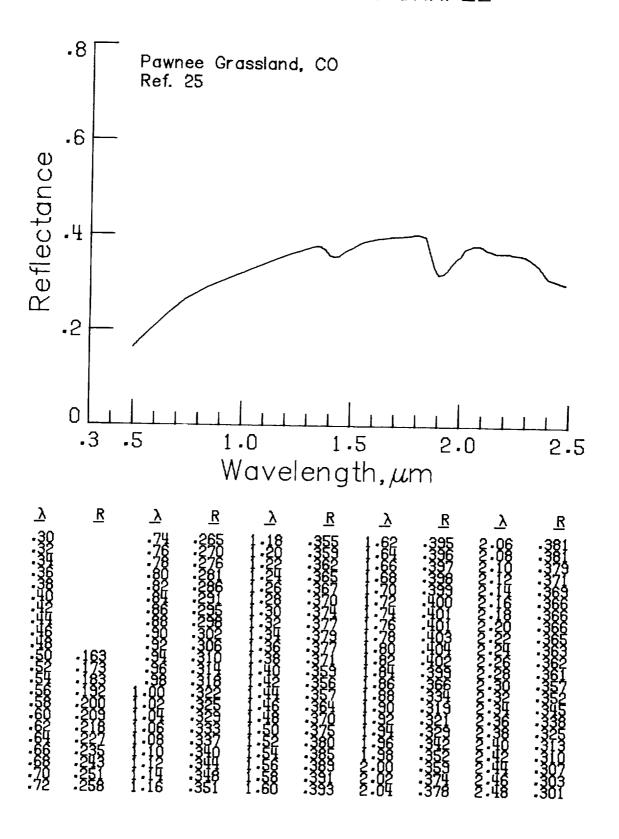
NO.120 - SOIL SAMPLE



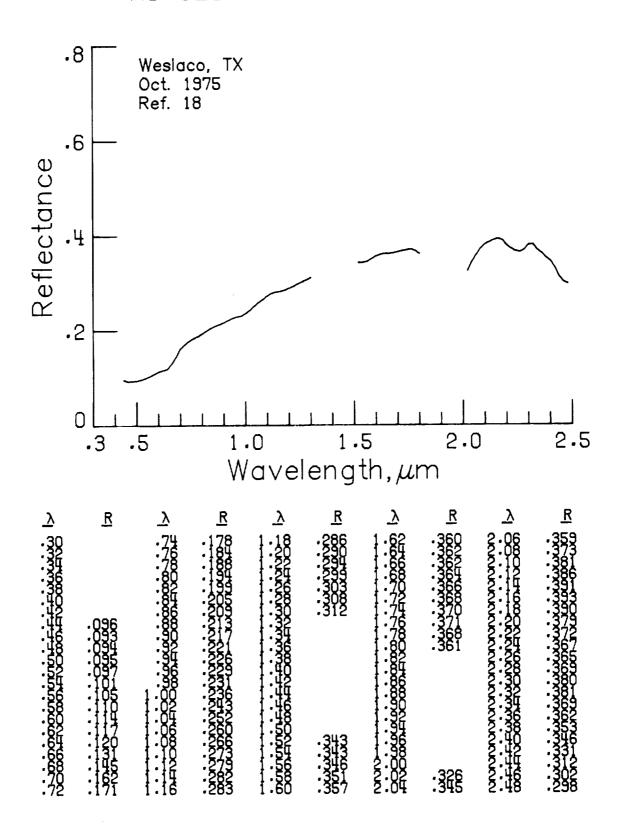
NO.121 - SOIL SAMPLE



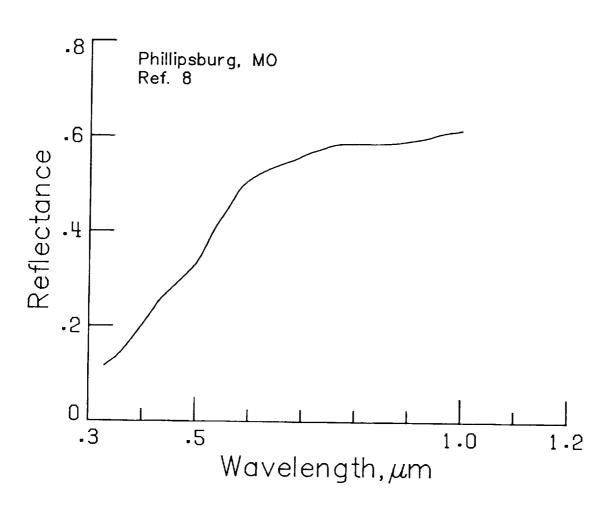
NO.122 - SOIL SAMPLE

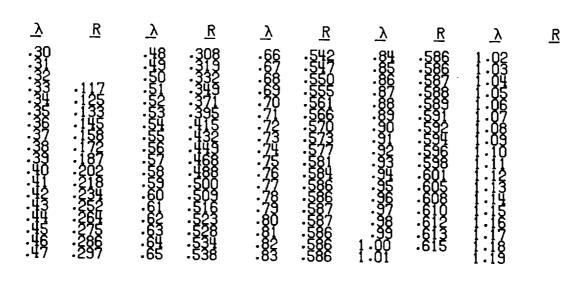


NO.123 - DISKED BARE SOIL

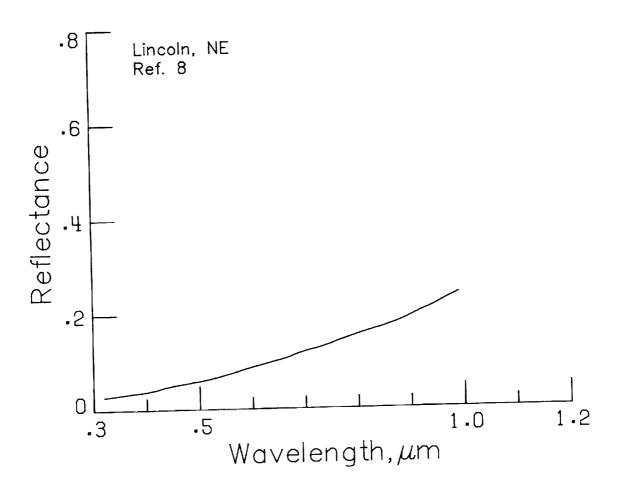


NO.124 - DRY PEDOCAL-TYPE SOIL



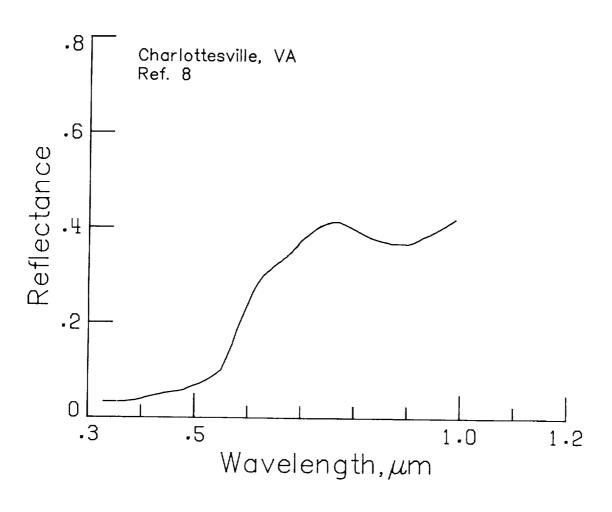


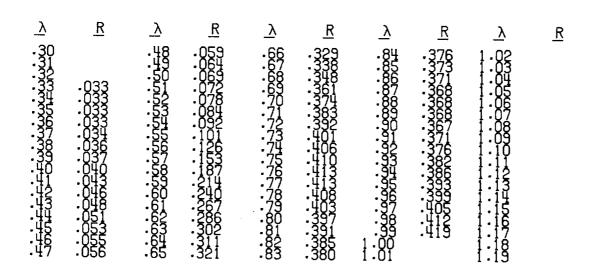
NO.125 - DRY CHERNOZEM-TYPE SOIL



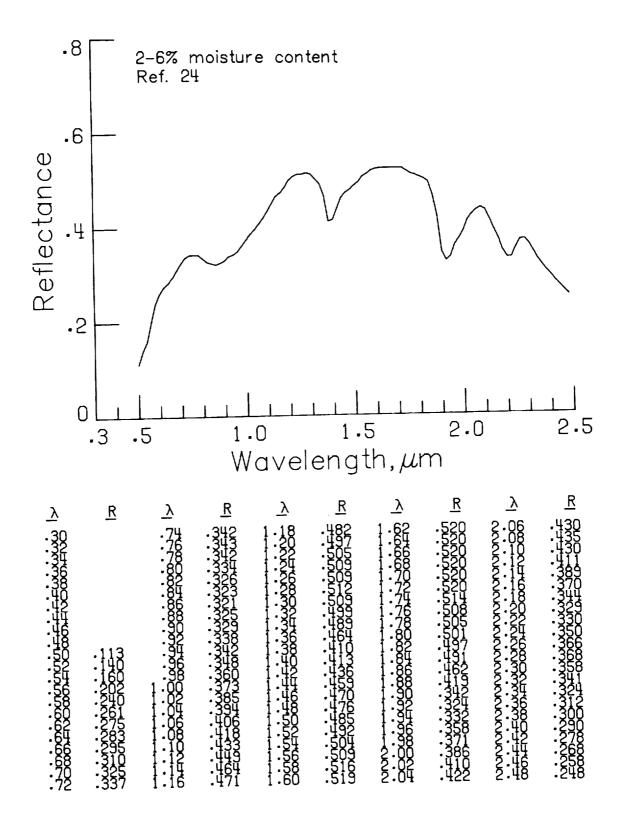
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46	.055	.65	:103	.83 .83	165	1.01		1.19	

NO.126 - DRY LATERITE-TYPE SOIL

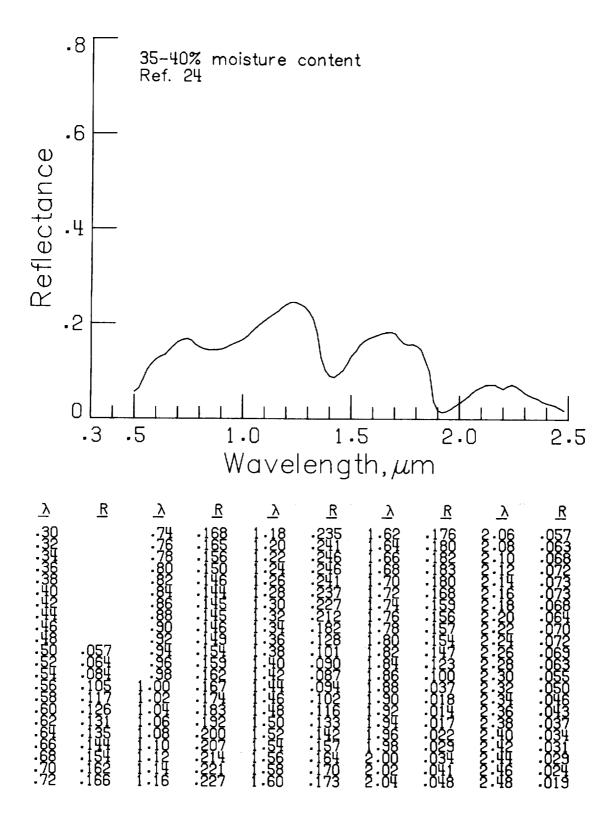




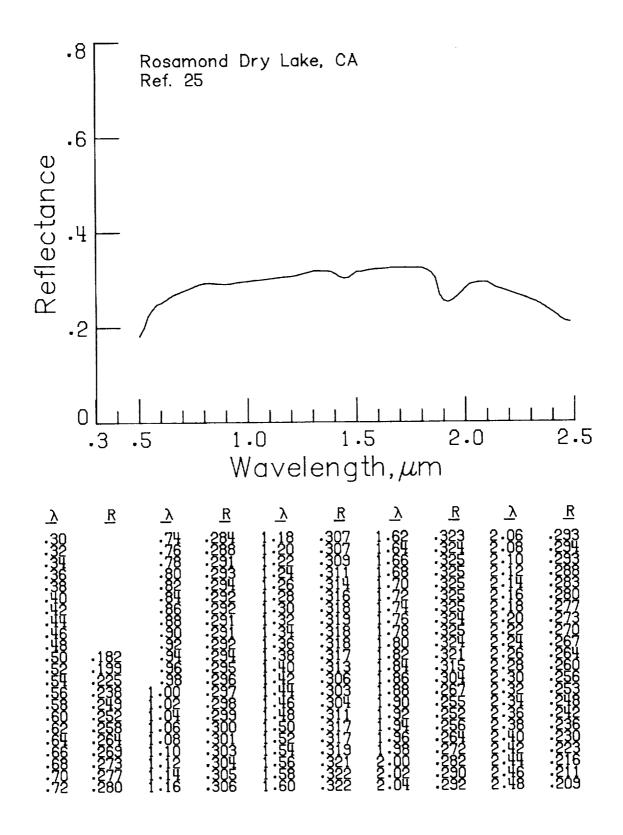
NO.127 - DRY CLAY SOIL SAMPLE



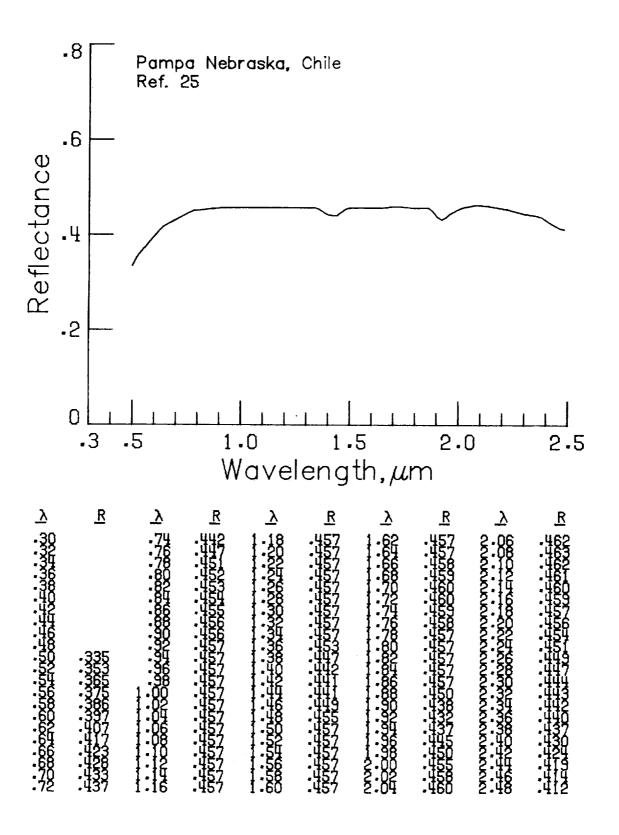
NO.128 - WET CLAY SOIL SAMPLE



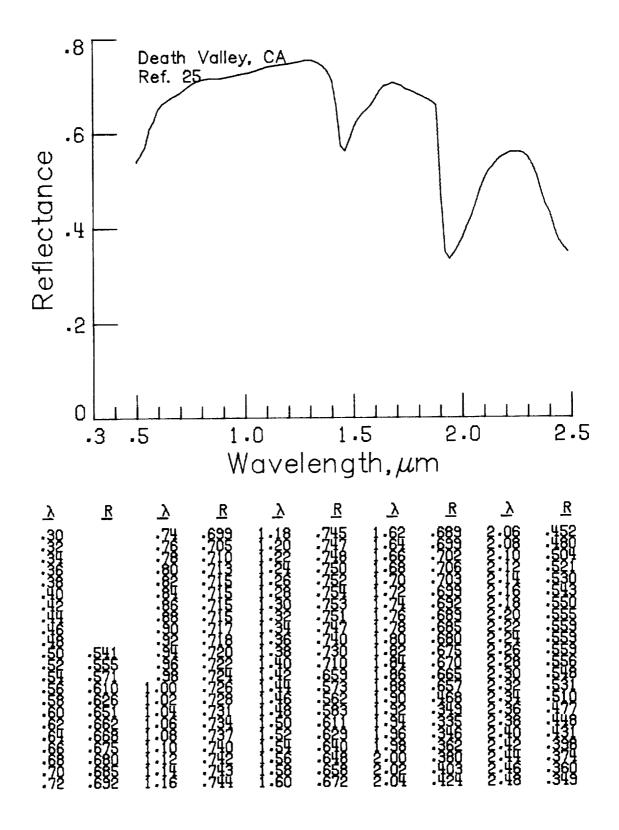
NO.129 - DRY LAKE SOIL SAMPLE



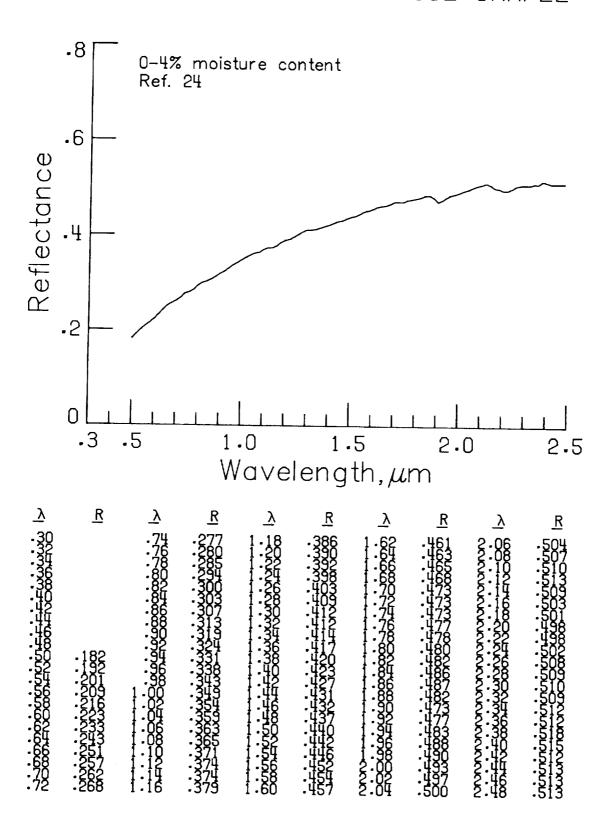
NO.130 - CHILEAN NITRATE SOIL SAMPLE



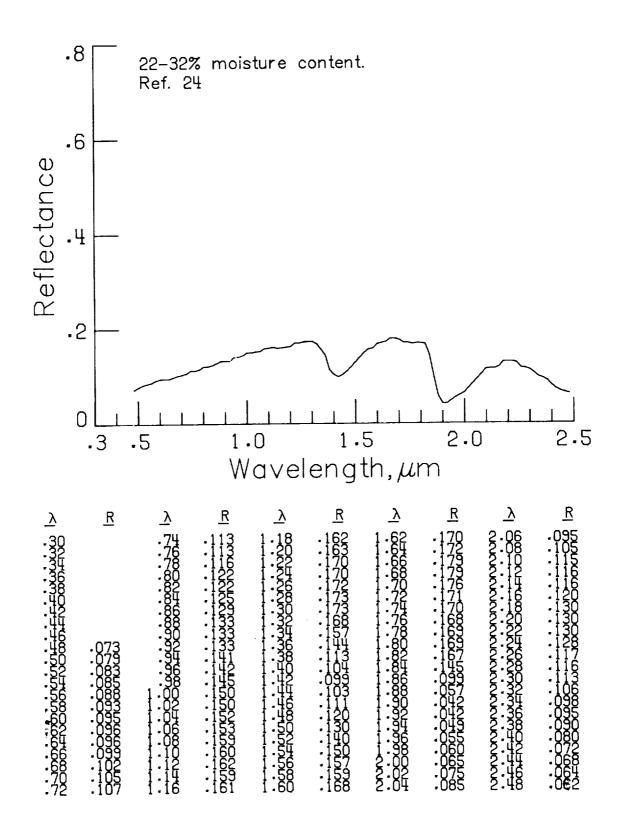
NO.131 - SALT POOL SOIL SAMPLE



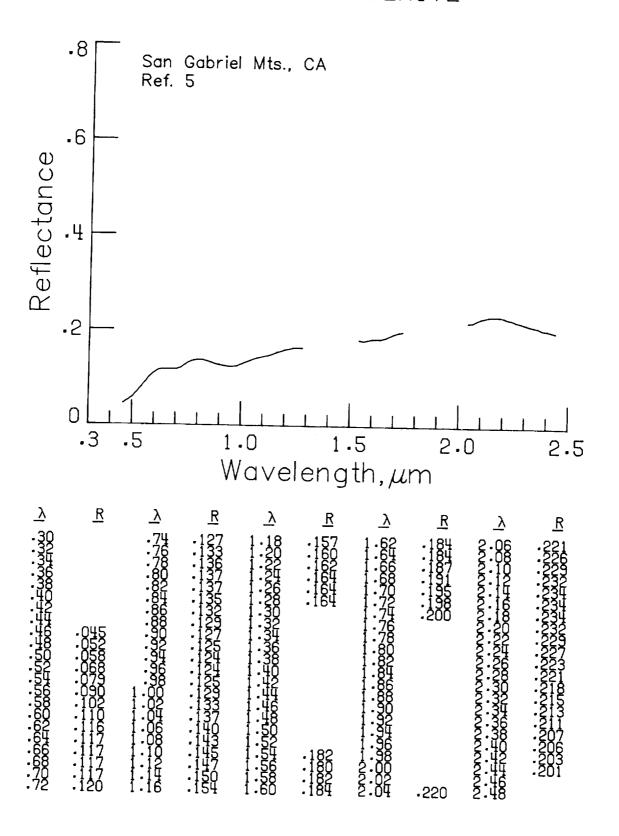
NO.132 - DRY SANDY SOIL SAMPLE



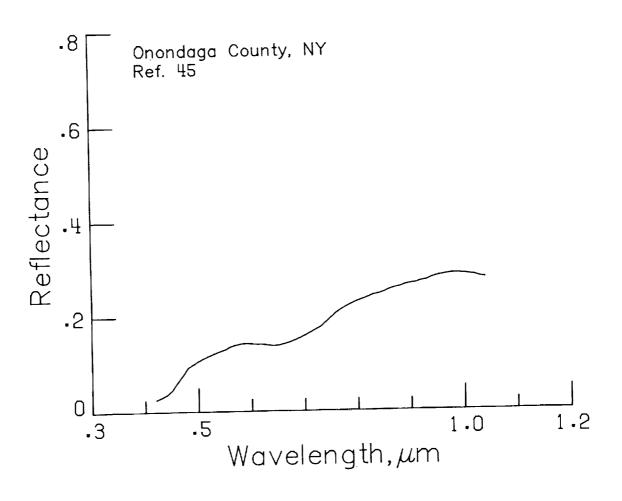
NO.133 - WET SANDY SOIL SAMPLE



NO.134 - SYENITE

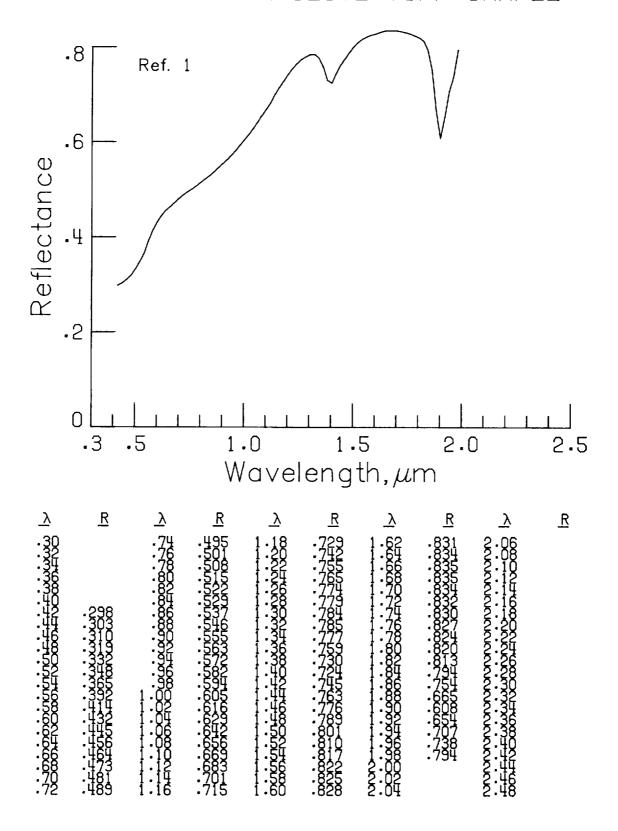


NO.135 - DRY GLACIAL TILL

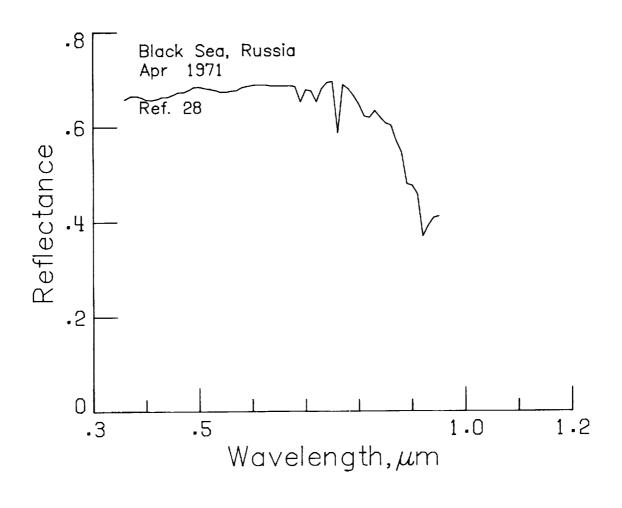


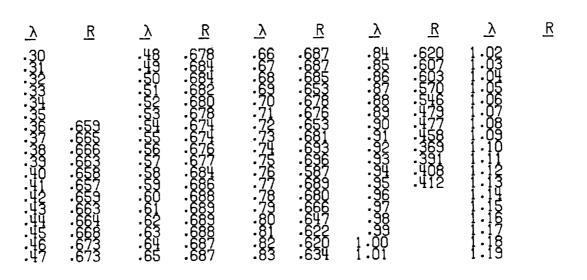
	R 0261 02337 0467	אן אביטיטיטיטיטיטיטיטיסיסיסיסיסיסיסיסיסיסיסי	RI 407383717134211099	A 667890-234567890-23 A 66667777777777778888888888888888888888	R 259495177764061499	\(\lambda\) \(\text{a}\) \(\tex	R 5974804778044677764 2000000000000000000000000000000000000	入 2m4567890-2m456789	R 283 2879 2278
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NO.136 - RHYOLITE TUFF SAMPLE

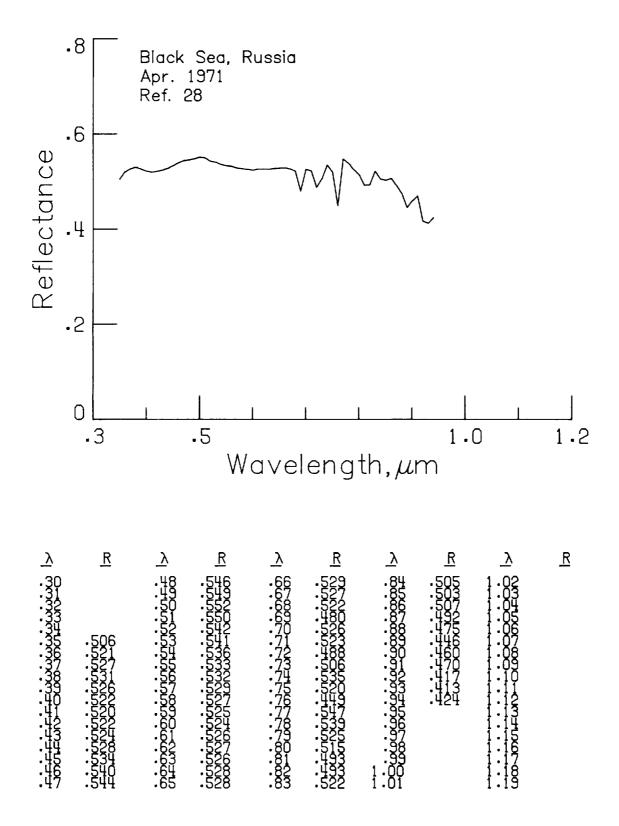


NO.137 - ALTOCUMULUS CLOUDS

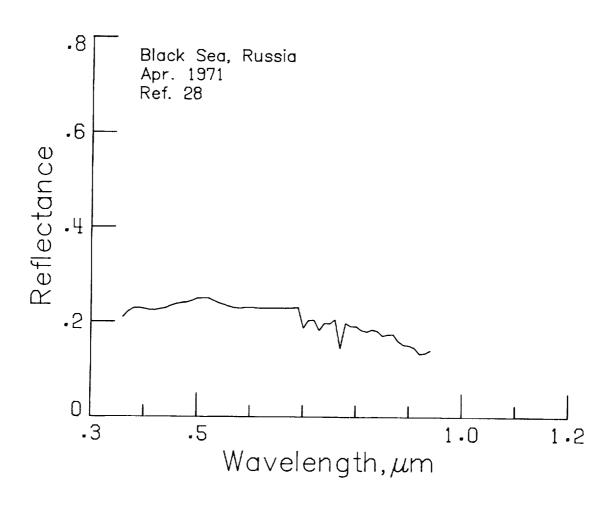




NO.138 - STRATUS CLOUDS

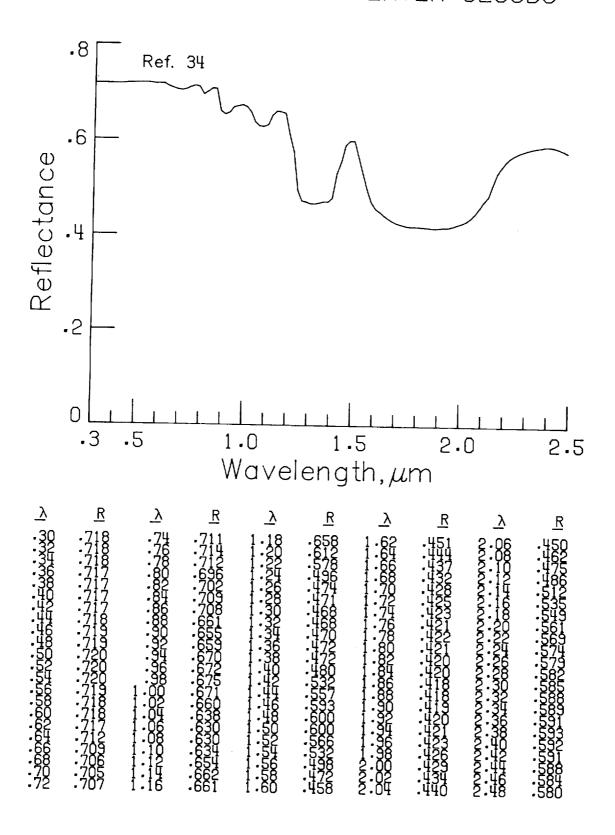


NO.139 - CIRROSTRATUS CLOUDS

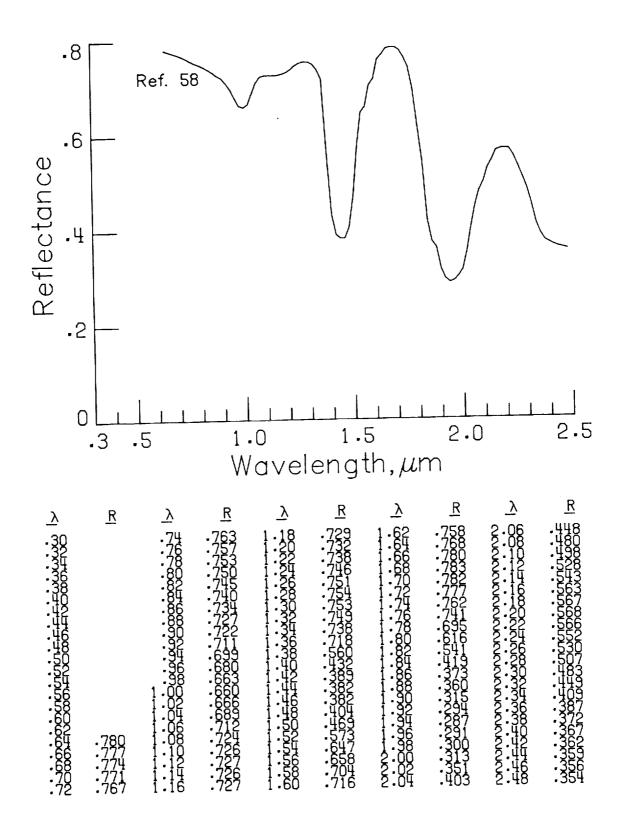


<u>\lambda</u>	<u>R</u>	<u>\lambda</u>	<u>R</u>	<u>\lambda</u>	<u>R</u>	<u>, λ</u>	<u>R</u>	<u>\lambda</u>	<u>R</u>
		##15555 8950		.667 .669 .77	2990 2223388 2223388 2001	.845.667 .888.888	-181 -174 -175 -158	1.02 1.03 1.05 1.06	
.36 .37 .38 .40	200000) 1565 1567 1567 1567 1567 1567 1567 1567	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	72 73 74 75	20837 1997 1995		0546356 054356	1.08 1.09 1.10	
4200415	2555795	550	222222	.77 .78 .79 .80 .82 .83	.197 .199 .199 .183	156789	-140	1.1567	
:45	.238 .240	.6⊈ .65	.229 .229	.82 .83	·180 ·184	1 .00 1 .01			

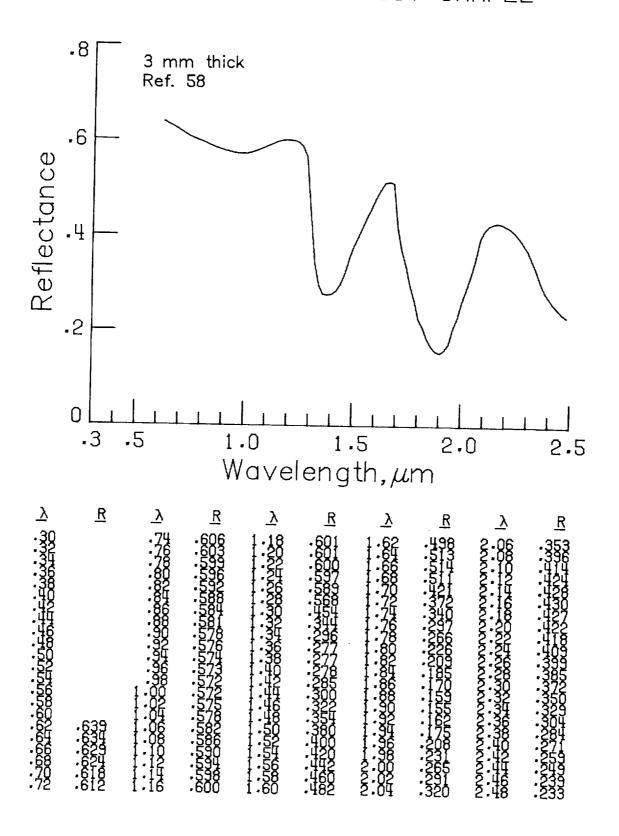
NO.140 - MIDDLE LAYER CLOUDS



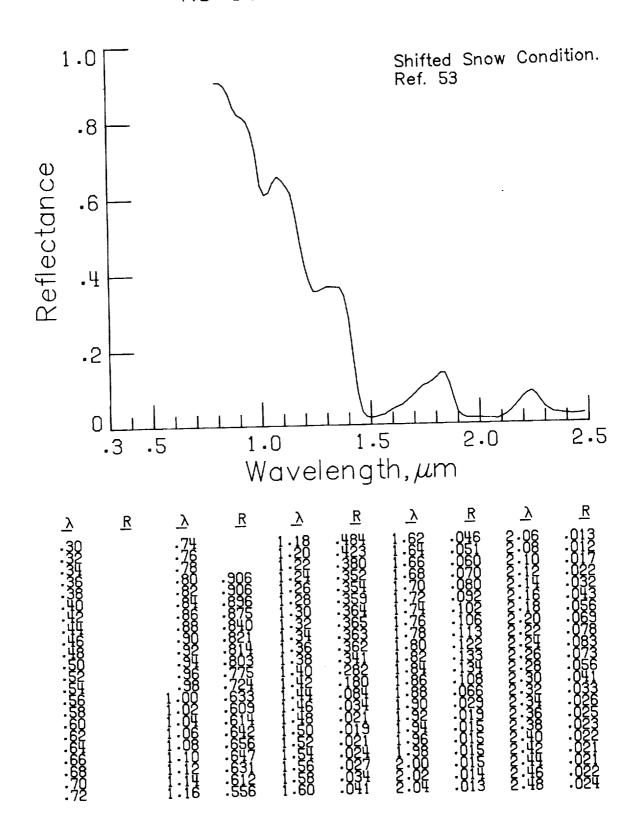
NO.141 - DENSE ICE CLOUD SAMPLE



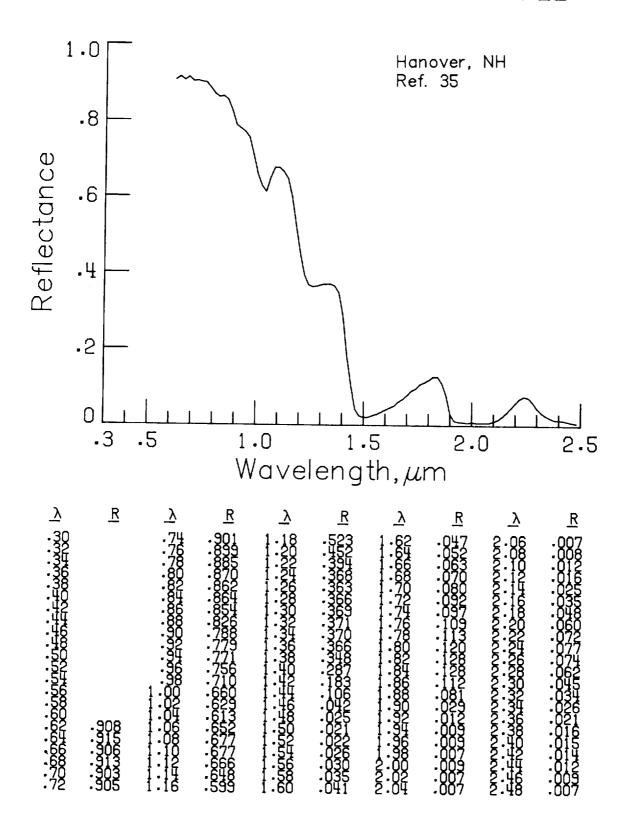
NO.142 - HOARFROST SAMPLE



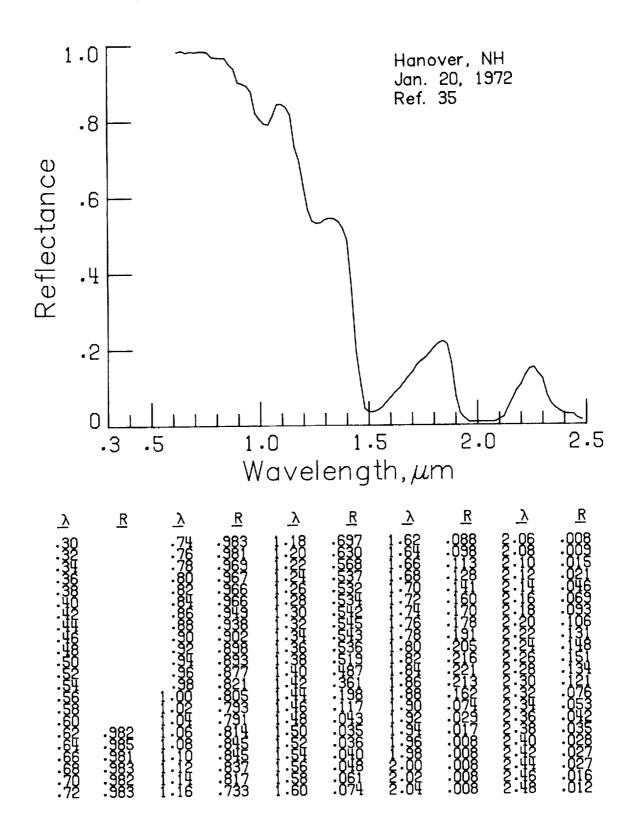
NO.143 - SNOW SAMPLE



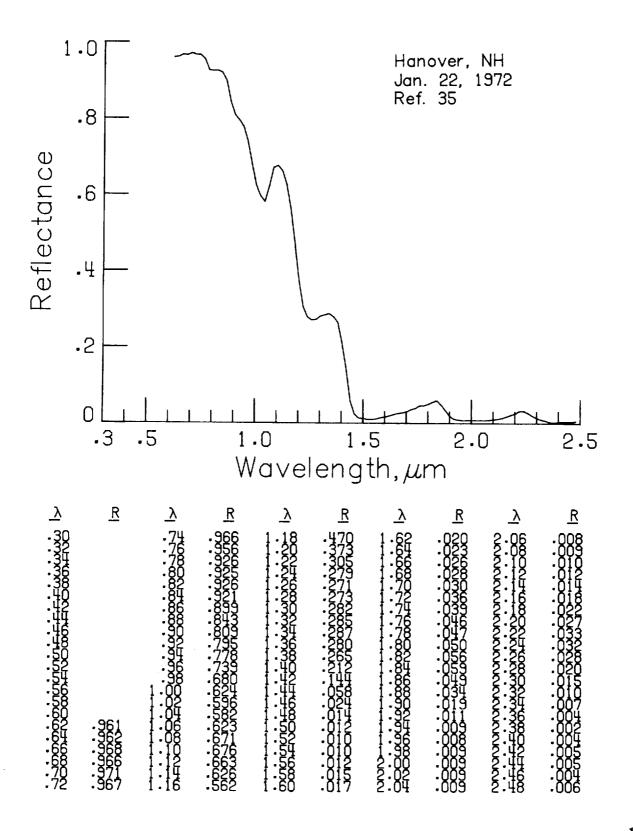
NO.144 - TYPICAL SNOW SAMPLE



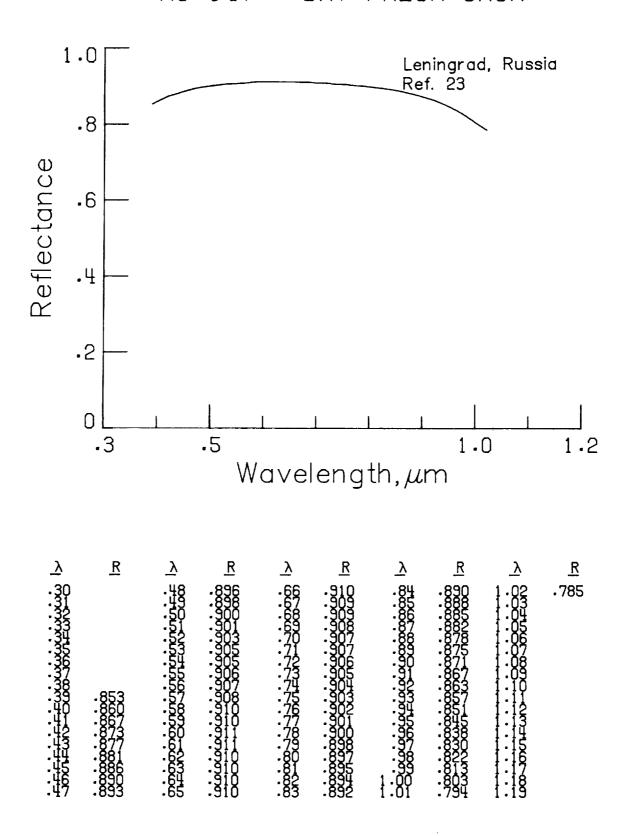
NO.145 - FRESH SNOW SAMPLE



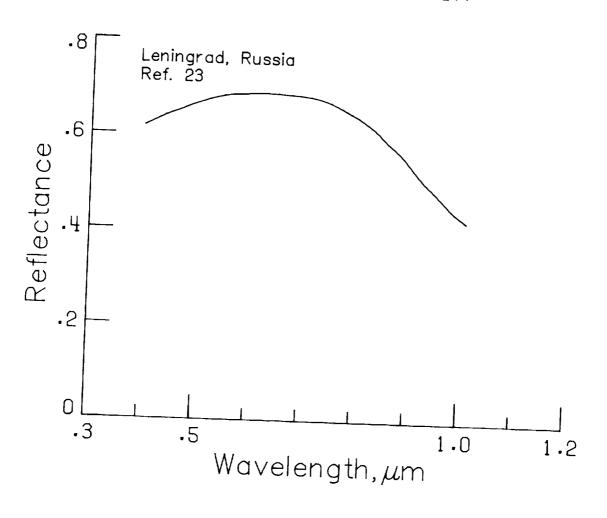
NO.146 - TWO DAY OLD SNOW SAMPLE

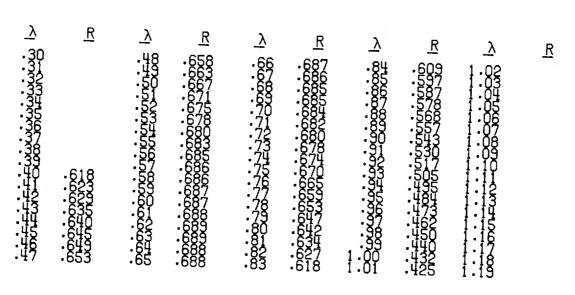


NO.147 - DRY FRESH SNOW

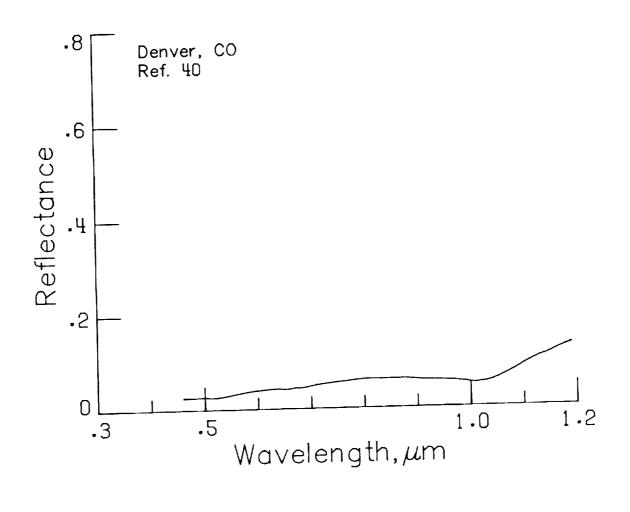


NO.148 - WET SNOW



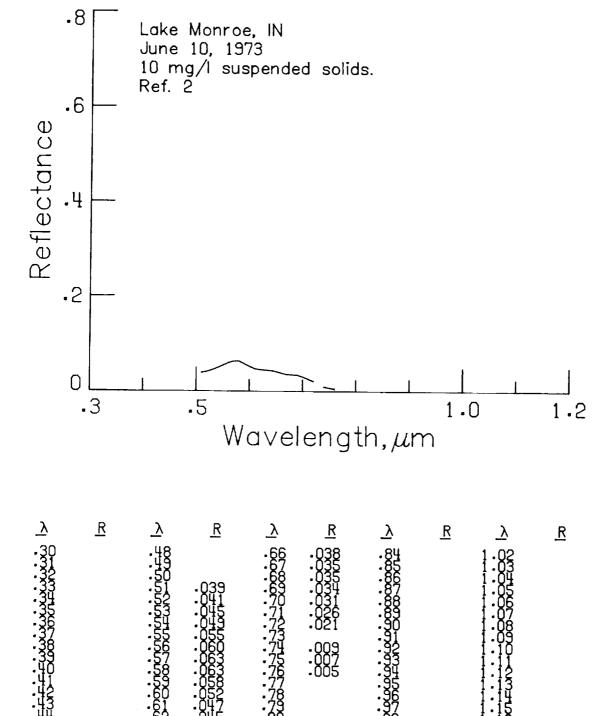


NO.149 - WATER

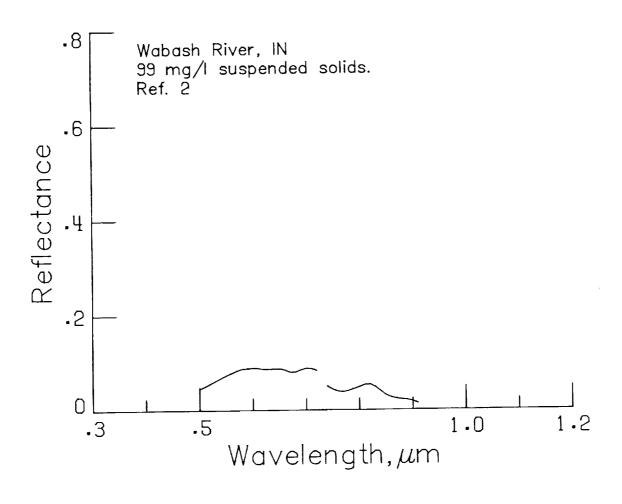


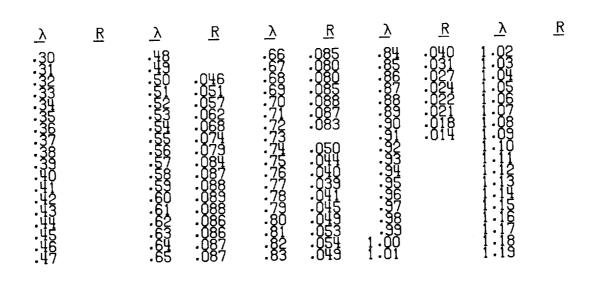
7 3000000000000000000000000000000000000	<u>R</u>	ا المال الما	RI 677666791-357901-2538	入 678901234567890123 88888 87777777777788888 878901234567890123	R) 44444680237467890011111	10678900-1097979799001 11 11 11 11 11 11 11	R 111121098887766554300	入 2の4567890-2m456789	RI 13505060x8494828271
:46	.026 .026	.65	:042	.83	.06i	1.01	.050	1.19	-151

NO.150 - CLEAR LAKE WATER

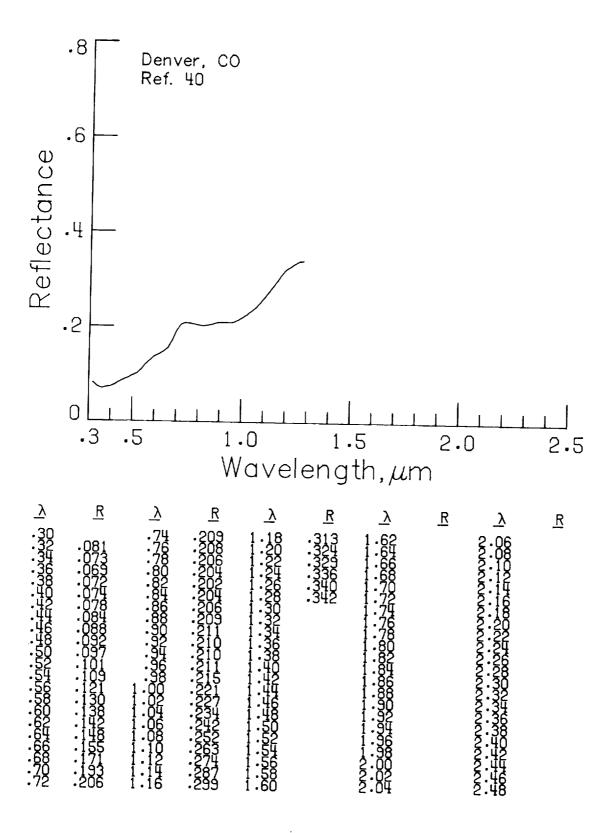


NO.151 - TURBID RIVER WATER

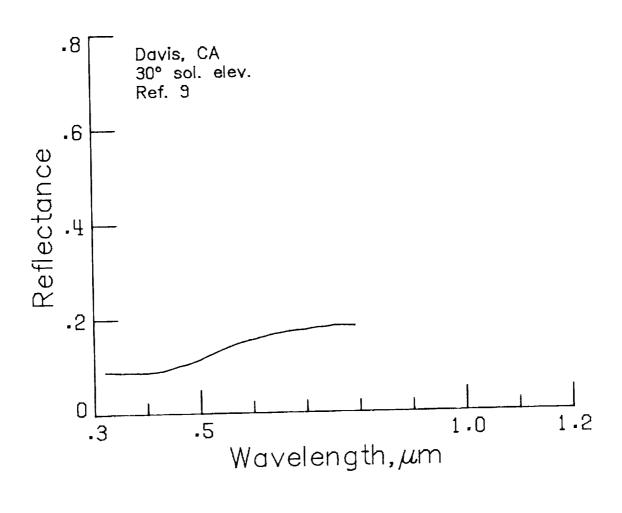


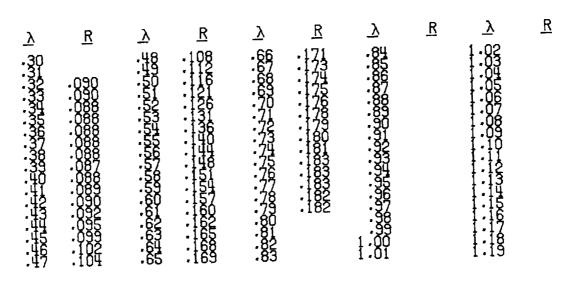


NO.152 - ASPHALT

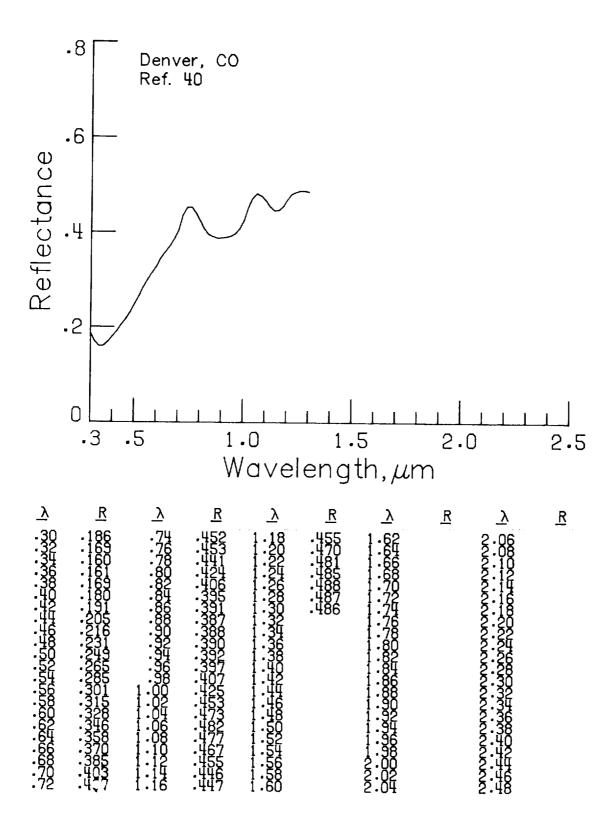


NO.153 - BLACKTOP

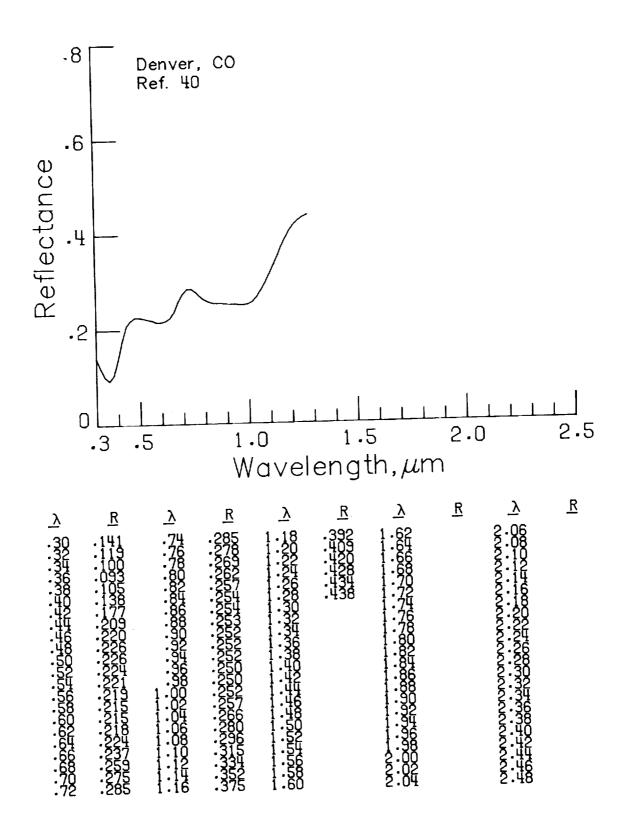




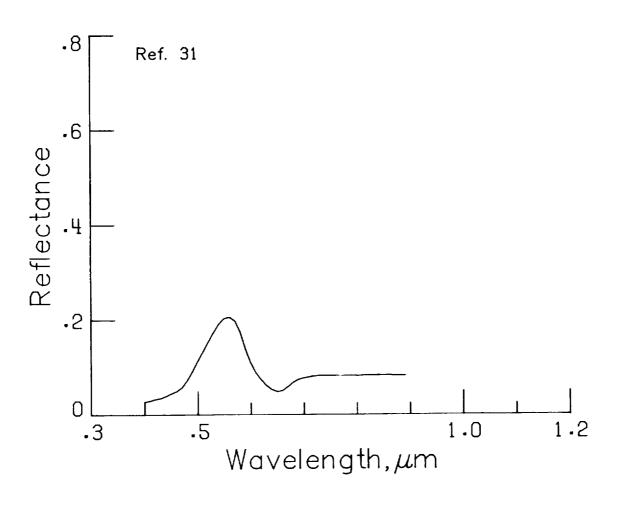
NO.154 - CONCRETE

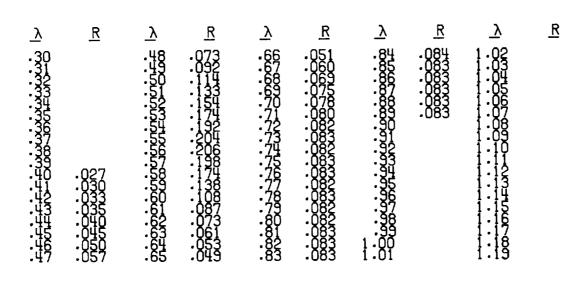


NO.155 - SHINGLES



NO.156 - ARTIFICIAL TURF





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