

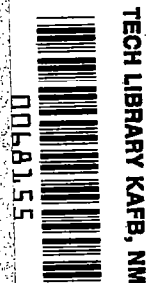
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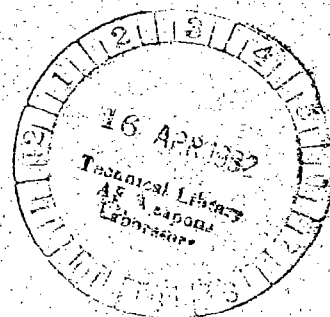
Laboratory Upwelled Radiance and Reflectance Spectra of Kerr Reservoir Sediment Waters

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Laboratory Upwelled Radiance and Reflectance Spectra of Kerr Reservoir Sediment Waters

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National Aeronautics
and Space Administration

**Scientific and Technical
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SUMMARY

Reflectance, chromaticity, and several other physical and chemical properties were measured for various water mixtures of bottom sediments taken from two sites at Kerr Reservoir, Virginia. Mixture concentrations ranged from 5 to 1000 ppm by weight of total suspended solids (TSS) in filtered deionized tap water. The two sets of radiance and reflectance spectra obtained were similar in shape and magnitude for comparable values of TSS. Upwelled reflectance was observed to be a nonlinear function of TSS with the degree of curvature a function of wavelength. Sediment from the downstream site contained a greater amount of particulate organic carbon than from the upstream site. No strong conclusions can be made regarding the effects of this difference on the radiance and reflectance spectra. The radiance and reflectance spectra of the two tests are consistent with previously published Lake Chicot data. Near-infrared wavelengths appear useful for measuring highly turbid water with concentrations up to 1000 ppm or more. Chromaticity characteristics do not appear useful for monitoring sediment loads above 150 ppm.

INTRODUCTION

The National Aeronautics and Space Administration (NASA), the United States Department of Agriculture (USDA), and three other federal agencies have entered into a 6-year joint program called AgRISTARS (Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing). This program addresses one of the serious problems presently facing agriculture - the excessive loss of topsoil caused by modern agricultural practices. Topsoil erosion not only degrades the land for growing food but accumulates in lakes and reservoirs thereby destroying them as storage places for valuable water supply. It is an aim of AgRISTARS to test remote-sensing methods and to develop the technology necessary to solve the current problem.

Remote-sensing methods are essential to measure and monitor soil sediment runoff; the data collected are necessary as remote-sensing inputs for pollution models and model validation. During fiscal year 1980, two sites were selected for USDA/NASA pilot experiments, and initial laboratory tests were conducted to determine the spectral characteristics and reflectivity of backscattered light for sediment waters from the two sites. One of the sites was Lake Chicot in Arkansas. Reference 1 presented laboratory radiance and reflectance spectra measured for several mixture concentrations of bottom sediment from Lake Chicot. Also, beam attenuation coefficients, diffuse attenuation coefficients, and several other physical and chemical parameters obtained from laboratory analyses were presented.

The other site of interest in the AgRISTARS program was Kerr Reservoir in Virginia (fig. 1). Samples of sediment were taken from two different locations in the reservoir, one in October 1980, downstream, and one in April 1981, upstream. The samples were sent to the marine upwelled spectral signature laboratory (MUSSL) at the Langley Research Center for immediate testing. The samples were taken from different locations in the reservoir in order to determine whether they would have different characteristics as a result of different origins, hence, different settling rates. The inset in figure 1 shows each location of the sampling sites and the direction of the streamflow in the reservoir. Heavier, coarser particles fall out of a streamflow faster than finer, lighter particles; in addition, the fallout of heavier, coarser

particles generally occurs farther upstream from a dam than for finer, lighter particles. This pattern can change during storms or after periods of heavier than usual rainfall when the flow of water is greater than usual. Yet, over long periods of time the accumulation of sediment reflects the usual sedimentation process. To take the samples, a clamshell-type grab sampler was used to dig deeply (several centimeters) into the sediment to obtain samples believed to be representative of the long-term sedimentation process. Reference 2 presents mineralogical and chemical properties of the two site samples obtained by X-ray diffraction and spectroscopy. The sediments are composed primarily of illite, kaolinite, and quartz. The October 1980 sample (identified as K-10-80 in ref. 2) has an overall greater kaolinite content and lower quartz content than the April 1981 (March) sample (identified as K-3-81 in ref. 2). Also the kaolinite of the October sample has a higher index of refraction than the April sample.

In the laboratory, remote-sensing radiances and reflectances and other physical and chemical properties were measured over a wide range of concentrations. Upwelled radiance and reflectance were obtained for wavelengths between 400 and 980 nm; in addition, chromaticity characteristics for the mixture concentrations were calculated. It is the purpose of this paper to present and discuss these data.

EXPERIMENTAL PROCEDURE

Laboratory tests were conducted with the laboratory setup shown in figure 2. Major parts of the system include a water tank, circulation system, filtration and deionization system, solar simulator, first-surface mirror, and rapid-scan spectrometer (RSS). The light source is a 2.5-kW xenon short-arc lamp which produces a spectrum similar to that of the Sun (ref. 3) with about 50 percent of its sea-level intensity. This system is the same as that used in similar tests reported in reference 1. Figure 3 shows standard sea-level solar irradiance spectra $E(\lambda)$ and the solar simulator data normalized to the irradiance at a wavelength of 600 nm, compared with the normalized irradiance curve for a solar elevation angle of 30°. A more complete description of the laboratory equipment and its limitations is given in reference 1.

Two samples of Kerr Reservoir bottom sediments were tested, one in October 1980, downstream, and the other in April 1981, upstream. To prepare for the experiment, the water tank was filled to within 0.3 m of the top with 11 600 liters of conditioned tap water (filtered and deionized). Just prior to testing, the sediment was placed in a large vat and stirred; this procedure assured homogeneity among subsequent samples or increments. Small amounts of sediment from the vat were placed into a graduated cylinder and then gradually added to the MUSSL water tank until the transmission of the mixture in the tank was approximately 65 percent, which corresponds to a beam attenuation coefficient of 5 m^{-1} . A modified Model 912S Hydro Products Transmissometer, with a 10-cm beam path length and a filter with a peak transmission of 560 nm and 80 nm half the maximum band-pass width, measured the transmission of the mixture. (Reflectance of the clear water was not measured because reflectance of light from the tank bottom might influence the upwelled signal.) The quantity of sediment added was noted and estimates were made of the increments needed to obtain a range of mixture concentrations in the water tank. These additional increments were similarly withdrawn and added to the tank to obtain concentrations covering the sediment range (5 to 1000 ppm) likely to be observed at Kerr Reservoir.

During testing, the circulation system was activated and the mixtures were circulated without filtration. At the start of the experiment, a radiance spectrum $L_u(\lambda)$ was obtained of light reflected from a white card, i.e., a plate painted with a 99-percent reflective paint placed near the surface of the water (a near-Lambertian 99-percent horizontal diffuse reflector). The same measurements were made halfway through and at the end of the experiment to check for instrument drift. These data were combined with the radiance spectra for the various mixture concentrations to obtain corresponding reflectance spectra using the equation:

$$\rho_u(\lambda) = \frac{|L_u(\lambda)|_{\text{Water mixture}}}{|L_u(\lambda)|_{\text{99-percent diffuse reflector}}}$$

where $\rho_u(\lambda)$ is the spectral reflectance.

After the white card measurements, an upwelled radiance spectrum for the first concentration was obtained. Then the next increment of Kerr Reservoir sediment was mixed with the water in the tank to achieve the second mixture concentration. The new mixture was allowed to circulate for approximately 15 minutes until the sediment was evenly distributed throughout the tank. An upwelled radiance spectrum was measured as before; the procedure was repeated to obtain upwelled spectra for the other concentrations as well.

Samples of the conditioned tap water and of each mixture were analyzed for selected physical and chemical properties and the results are presented in table I for the October 1980 test and in table II for the April 1981 test. Total suspended solids (TSS) were obtained by both the standard crucible method and the membrane filter method. Fiberglass filters with a variable pore size of 1.2 to 1.6 μm were used for the crucible method and enabled volatile and nonvolatile solids, in addition to TSS, to be measured from the same sample. The membrane filters have a pore size of 0.4 μm ; therefore, TSS obtained by this method were usually higher than those obtained by the crucible method. The TSS obtained by the crucible method are presented in the figures and discussed in the text of this report.

RESULTS AND DISCUSSION

Reflectance

Spectral radiance curves are shown in figure 4 for the 99-percent near-Lambertian white card and in figures 5(a) and 5(b) for the water mixtures of the October and April tests, respectively. Spectral reflectance curves, as a ratio of the water mixture radiance to white card radiance, are shown in figures 6(a) and 6(b) for the two tests. Both radiance and reflectance generally increase at all wavelengths with increasing concentration of suspended solids; peak reflectance gradually shifts to longer wavelengths with increasing concentration. Sediment increases, however, had less and less effect on reflectance, except for the two highest concentration mixtures (13 and 14) of the downstream sediment for the October test. The reflectance curves for these two mixtures do not follow the usual trend because their TSS were higher than expected.

The October test was not completed in 1 day; rather, the test was interrupted after the measurement of mixture 12 and was resumed the next morning with mixtures 13 and 14. Mixture 12 was circulated through the pumping system overnight to prevent sediment from settling to the bottom of the tank. The prolonged churning action of the pump impellers on mixture 12 could have altered the sediment in some way (e.g., by breaking down the sediment into finer particles) so that the backscattering properties of the mixture were changed. As a result, the spectra for mixtures 13 and 14 (the two highest concentrations) did not follow the trend for the rest of the data; instead they were apparently too high. This anomaly may have resulted from a deviation from the usual laboratory procedure.

The reflectance curves for comparable total suspended solids are higher for the October test than for the April test. Overall, the shapes and magnitudes of the reflectance curves are similar for both tests and similar to the curves for Lake Chicot presented in reference 1.

Values of particulate organic carbon and total organic carbon are higher for the October test than for the April test. (See tables I and II.) These differences in physical and chemical composition of the sediments may be random or may be associated with the sampling sites.

Linearity

Figure 7 shows graphically the decreasing effect on reflectance of increasing sediment concentration at certain wavelengths.

For the October test, at low concentrations the upwelled reflectance $\rho_u(\lambda)$ increases sharply for all wavelengths presented; but at concentrations of roughly 100 and 200 ppm, the curves for $\rho_u(\lambda)$ at 450 and 550 nm, respectively, become nearly asymptotic (or saturated). At the red wavelength of 650 nm and at near-infrared wavelengths of 750, 840, and 900 nm, the curves have a smaller slope at TSS concentrations greater than 200 ppm than at lower sediment concentrations but continue to show positive increases in upwelled reflectance for TSS values as high as 650 ppm. Again, the values of $\rho_u(\lambda)$ for the two highest TSS concentrations (mixtures 13 and 14) appear to be too high for the reasons stated previously.

Similarly for the April test, at concentrations of roughly 50, 150, 400, and 700 ppm, the $\rho_u(\lambda)$ curves at the blue, green, red, and near-infrared wavelengths (450, 550, 650, and 750 nm), respectively, become nearly asymptotic. However, at near-infrared wavelengths of 840 and 900 nm, the curves have a smaller slope at TSS concentrations greater than 400 ppm than at lower concentrations but continue to show positive increases in upwelled reflectance for TSS values as high as 1000 ppm.

These results are consistent with the simplified model calculations of reference 4, satellite field data in references 5 and 6, and results reported from Lake Chicot water in reference 1. Upwelled reflectance from the water column is not a linear function of total suspended solids except over limited concentration ranges. The degree of nonlinearity is a function of wavelength and sediment composition.

Chromaticity

Optical chromaticity characteristics of upwelled radiance spectra have received attention as one property which may be useful for remote monitoring of suspended

sediments (ref. 7). For this reason, chromaticity characteristics were calculated for each of the reflectance spectra shown in figure 6 using the International Commission on Illumination (ICI) standard functions. (See ref. 8.) Results of these calculations are shown in figure 8. Point C represents the coordinates of ICI Illuminant C (white light) upon which most color observations are based. A straight line from point C through a water mixture point extended to the locus line of color gives the dominant wavelength of that water mixture. Applying this process to each water mixture point indicates that the dominant mixture color ranged from 514 nm for low sediment concentrations to 585 nm for the highest turbidities in the October test and from 552 nm to 582 nm in the April test. Large changes in chromaticity coordinates x and y occurred when concentration varied from 5 to 150 ppm, but only small changes were evident from 150 ppm $<$ TSS $<$ 650 ppm (October test) and 150 ppm $<$ TSS $<$ 1000 ppm (April test). These controlled-experiment data confirm similar observations from a simplified theoretical model (ref. 7) and from field measurements with multiconstituent waters (ref. 9). Similar results from all these sources indicate that chromaticity characteristics may not be useful for quantifying concentration values in water with large amounts of sediment.

CONCLUSIONS

Radiance and reflectance spectra were measured for several mixture concentrations of bottom sediment from two sites (one upstream and one downstream near the dam) at Kerr Reservoir, Virginia. Also, several other physical and chemical parameters obtained from laboratory analyses were presented.

Based on the analyses of these data, the following conclusions were drawn:

1. The two sets of radiance and reflectance spectra obtained for the several mixture concentrations of sediment were overall similar in shape and magnitude, although the spectra for the downstream sediment were somewhat higher than for the upstream sediment. The two highest concentration mixtures of the downstream sediment did not follow the trend for the rest of the spectra data; instead they were apparently too high. This anomaly may have resulted from a deviation from the usual laboratory procedure.

2. The sediments from the two sites had different physical and chemical characteristics. The sediment from the downstream site contained more particulate organic carbon than that from the upstream site. This difference may be random or may be associated with the different locations of the sampling sites. No strong conclusion can be made regarding the effects of the difference on the radiance and reflectance spectra.

3. Upwelled reflectance from the water column is not a linear function of total suspended solids except over limited concentration ranges. The degree of nonlinearity is a function of wavelength with reflectance becoming asymptotic (or saturated) first at blue, second at green, and finally at red wavelengths with increasing total suspended solids. The upwelled reflectance in the near-infrared wavelength range continued to respond to changes in concentration over the sediment ranges of the tests.

4. The radiance and reflectance spectra and reflectance nonlinearity are similar not only for the two samples from Kerr Reservoir, but they are similar to previously reported Lake Chicot data. This suggests that the measurements are consistent and that remote-sensing methods may be useful for measuring soil sediment runoff for

total suspended solids over the range of 5 to 1000 ppm; also, the useful measurement range may be extended to concentrations greater than 1000 ppm by utilizing upwelled reflectance in the near-infrared wavelength range.

5. Controlled-experiment laboratory results agree with theoretical and field data trends, which indicate that chromaticity characteristics may not be useful for quantifying concentration values in water with large amounts of sediment.

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February 24, 1982

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TABLE I.- TEST WATER CONDITIONS FOR OCTOBER 1980

	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5	Mixture 6	Mixture 7	Mixture 8	Mixture 9	Mixture 10	Mixture 11	Mixture 12	Mixture 13	Mixture 14
Total suspended solids - crucible (av. ^a), ppm		4.0	8.6	12.8	18.3	22.0	36.1	72.6	154.0	224.0	270.0	356.0	472.0	653.0
Total suspended solids - membrane (av. ^a), ppm	1.3	5.7	10.4	16.3	22.4	28.6	44.3	88.5	166.1	243.1	364.8	461.7	605.3	783.0
Volatile suspended solids (av. ^a), ppm		2.0	2.6	3.2	3.4	5.1	6.8	13.3	20.5	32.5	51.0	54.0	68.0	96.0
Nonvolatile suspended solids (av. ^a), ppm		2.1	6.1	9.6	14.8	16.9	29.3	59.3	133.0	192.0	219.0	302.0	403.0	557.0
Iron, ppm	0.05	0.10	0.21	0.30	0.36	0.54	0.49	1.4	2.6	4.6	8.9	6.6	1.6	4.3
Copper, ppm	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	0.05	<0.05	0.33	0.11
Total organic carbon, ppm	1.3	0.8	<0.4	<0.4	<0.4	<0.4	<0.4	1.2	3.3	6.8	8.5	7.7	13.8	17.1
Particulate organic carbon, ppm	0.1	0.1	0.3	0.2	0.4	0.4	0.7	1.4	3.3	6.0	5.4	5.6	9.5	9.8
Dissolved organic carbon, ppm	1.3	0.9	<0.4	<0.4	<0.4	<0.4	<0.4	0.4	<0.4	0.8	3.8	<0.5	2.3	3.1
Inherent ICI chromaticity:														
Color, nm	514	570	574	576	577	578	579	581	584	584	584	585	585	585
Purity	0.019	0.143	0.194	0.240	0.292	0.330	0.388	0.477	0.588	0.569	0.569	0.570	0.581	0.592

^aAverage of three measurements.

TABLE II.- TEST WATER CONDITIONS FOR APRIL 1981

	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5	Mixture 6	Mixture 7	Mixture 8	Mixture 9	Mixture 10	Mixture 11	Mixture 12
Total suspended solids - crucible (av. ^a), ppm	7.4	12.9	18.0	25.7	35.1	48.2	158.2		389.8	530.2	685.7	1013.7
Total suspended solids - membrane (av. ^a), ppm	5.4	11.9	18.0	24.2	33.0	48.7	112.2		431.6	604.3	716.3	1005.9
Volatile suspended solids (av. ^a), ppm	5.4	4.7	3.5	5.8	8.8	8.1	19.3		62.2	78.2	95.7	127.8
Nonvolatile suspended solids (av. ^a), ppm	2.0	8.2	14.5	19.9	26.3	40.1	138.9		327.6	452.0	590.0	885.9
Iron, ppm	0.1	0.45	0.1	1.0	0.7	1.9	4.4		2.85	3.2	1.95	1.9
Copper, ppm	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05		<0.05	<0.05	<0.05	<0.05
Total organic carbon, ppm	0.42	0.5	0.7	1.03	1.3	2.2	3.13		7.3	11.6	13.9	17.4
Particulate organic carbon, ppm	0.23	0.32	0.41	0.55	0.47	1.05	1.79		4.8	6.0	6.4	7.7
Dissolved organic carbon, ppm	0.7	0.21	0.08	0.14	0.17	0.92	0.39		0.9	1.0	0.51	0.8
Inherent ICI chromaticity:												
Color, nm	552	573	573	574	576	578	580	582	582	582	583	582
Purity	0.026	0.117	0.161	0.222	0.266	0.339	0.441	0.506	0.489	0.518	0.513	0.515

^aAverage of three measurements.

John H. Kerr Reservoir, Virginia

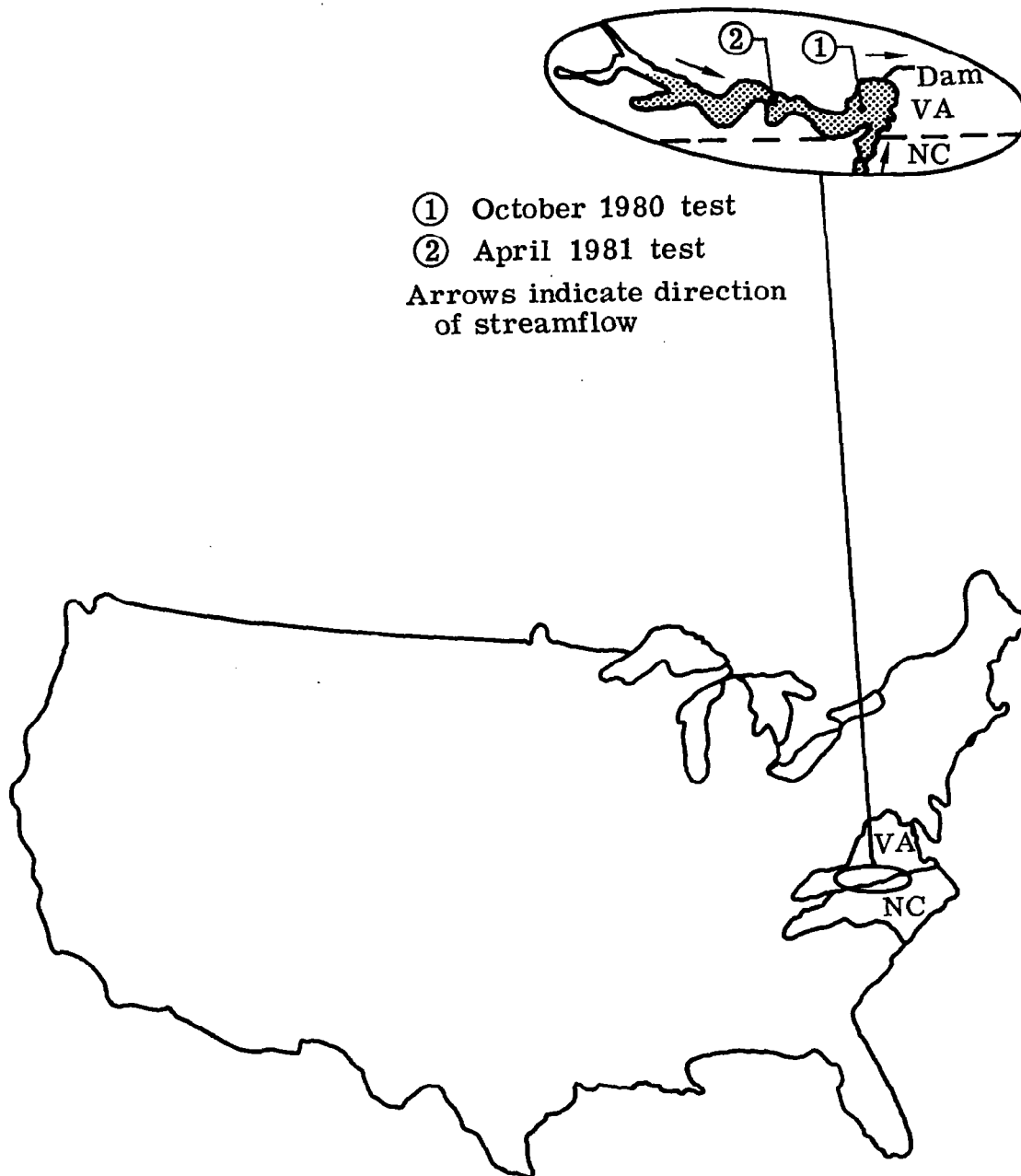


Figure 1.- Kerr Reservoir test site for AgRISTARS Conservation Assessment Task.

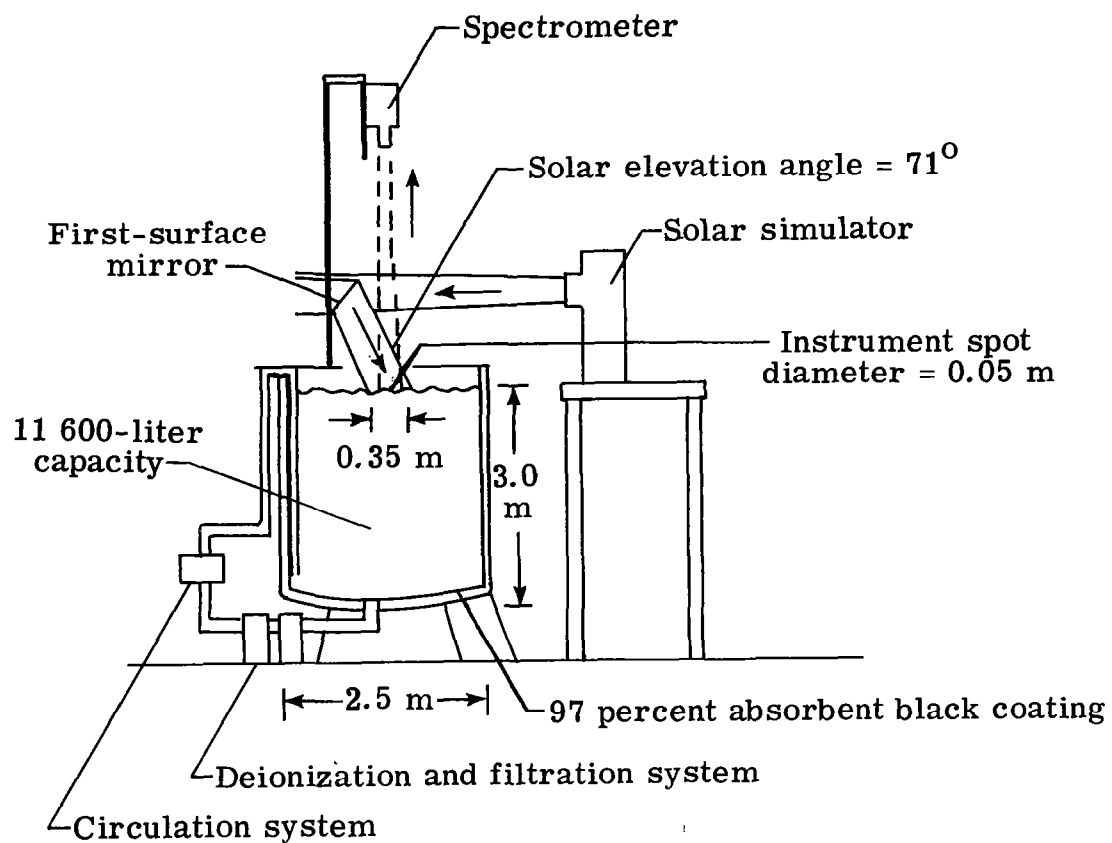
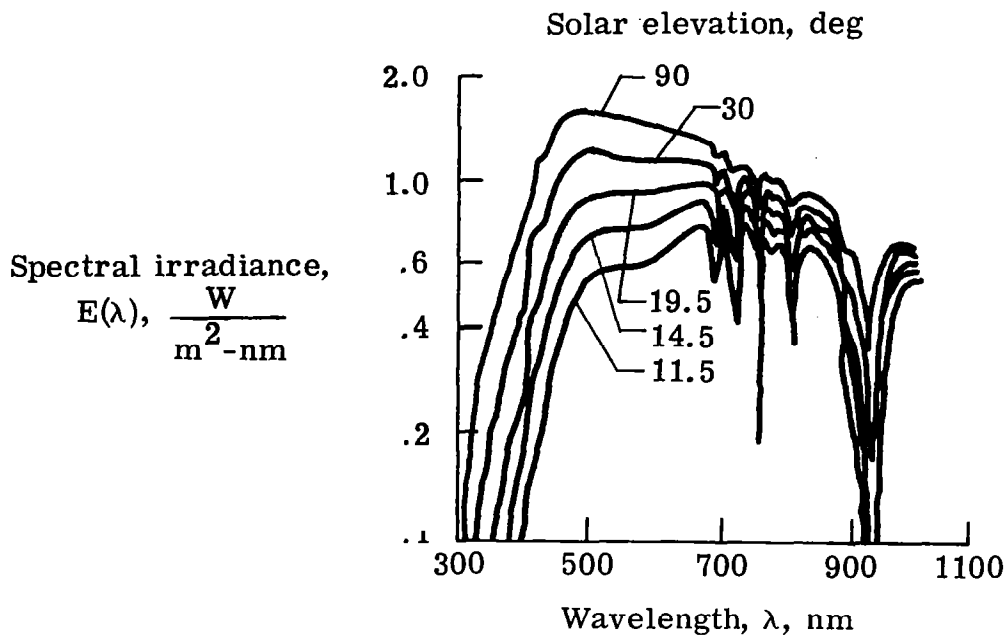
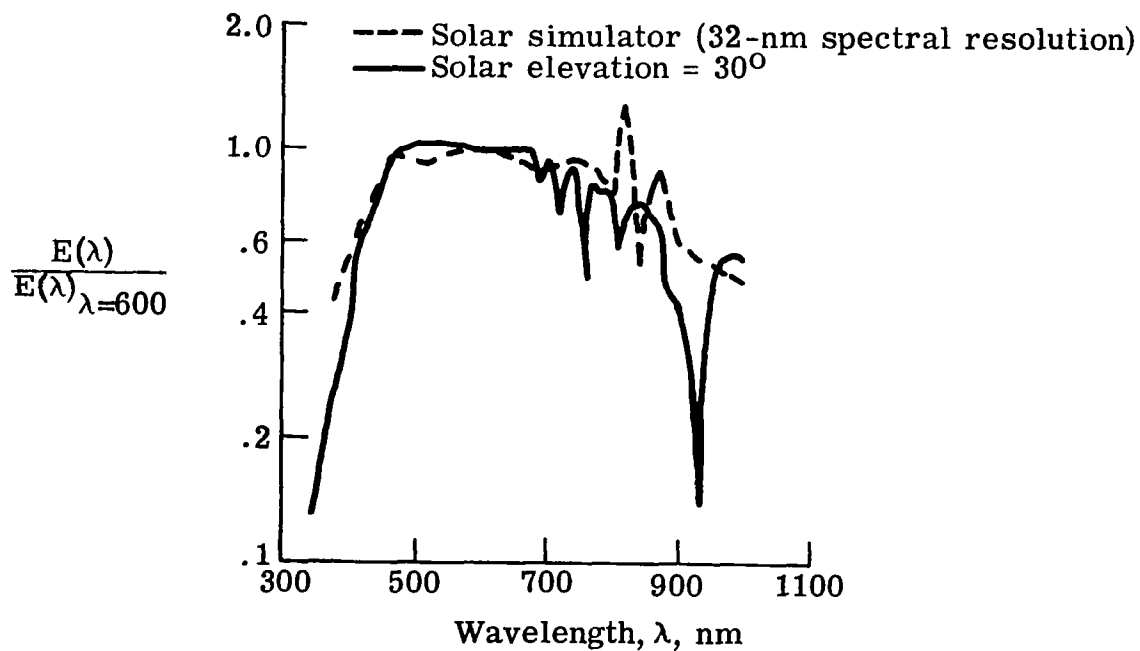


Figure 2.- Sketch of laboratory setup.



(a) Standard sea-level solar irradiance spectra (ref. 1).



(b) Solar simulator and standard sea-level spectra.

Figure 3.- Standard sea-level solar irradiance spectra and comparison with solar simulator data.

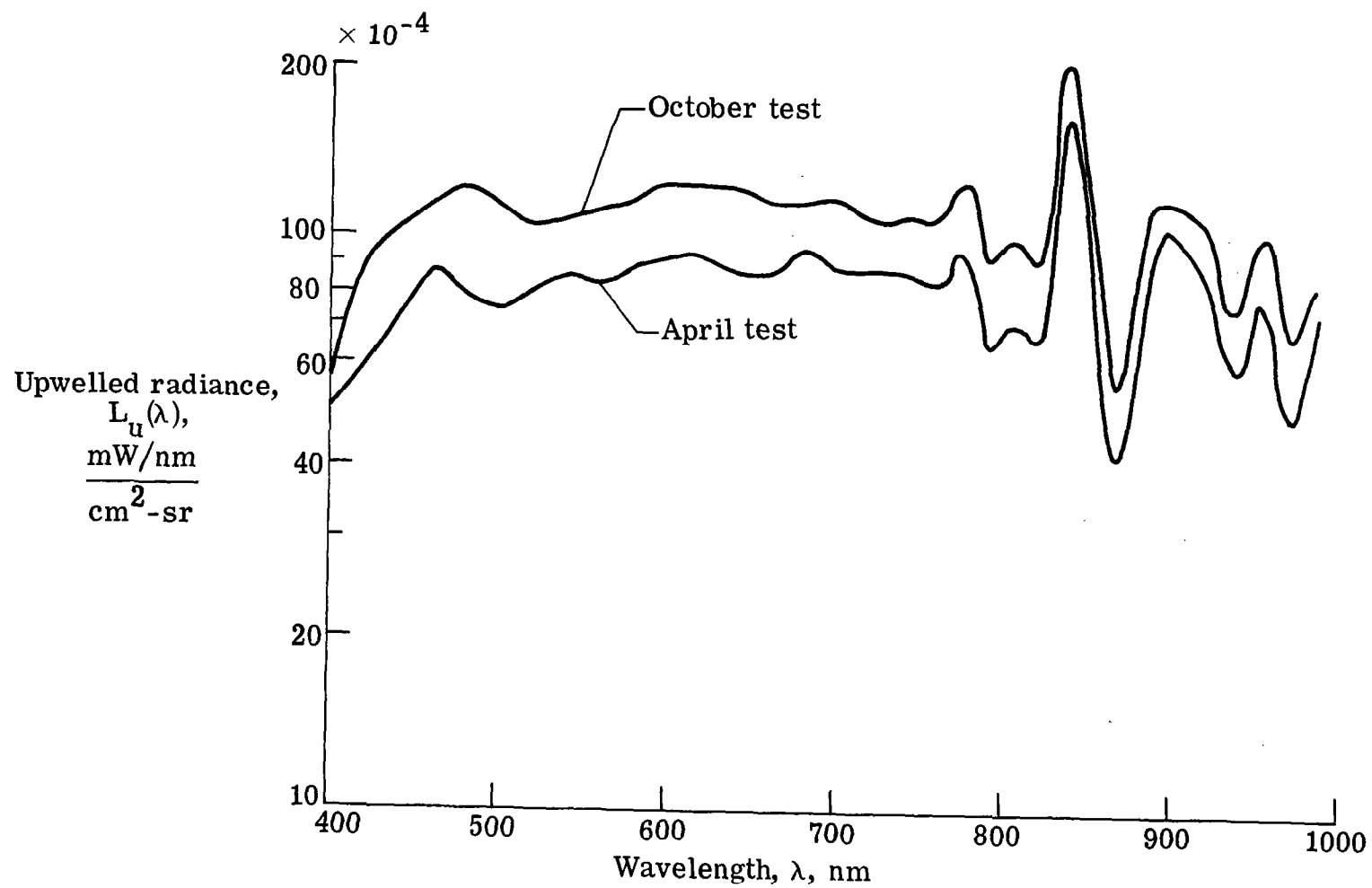
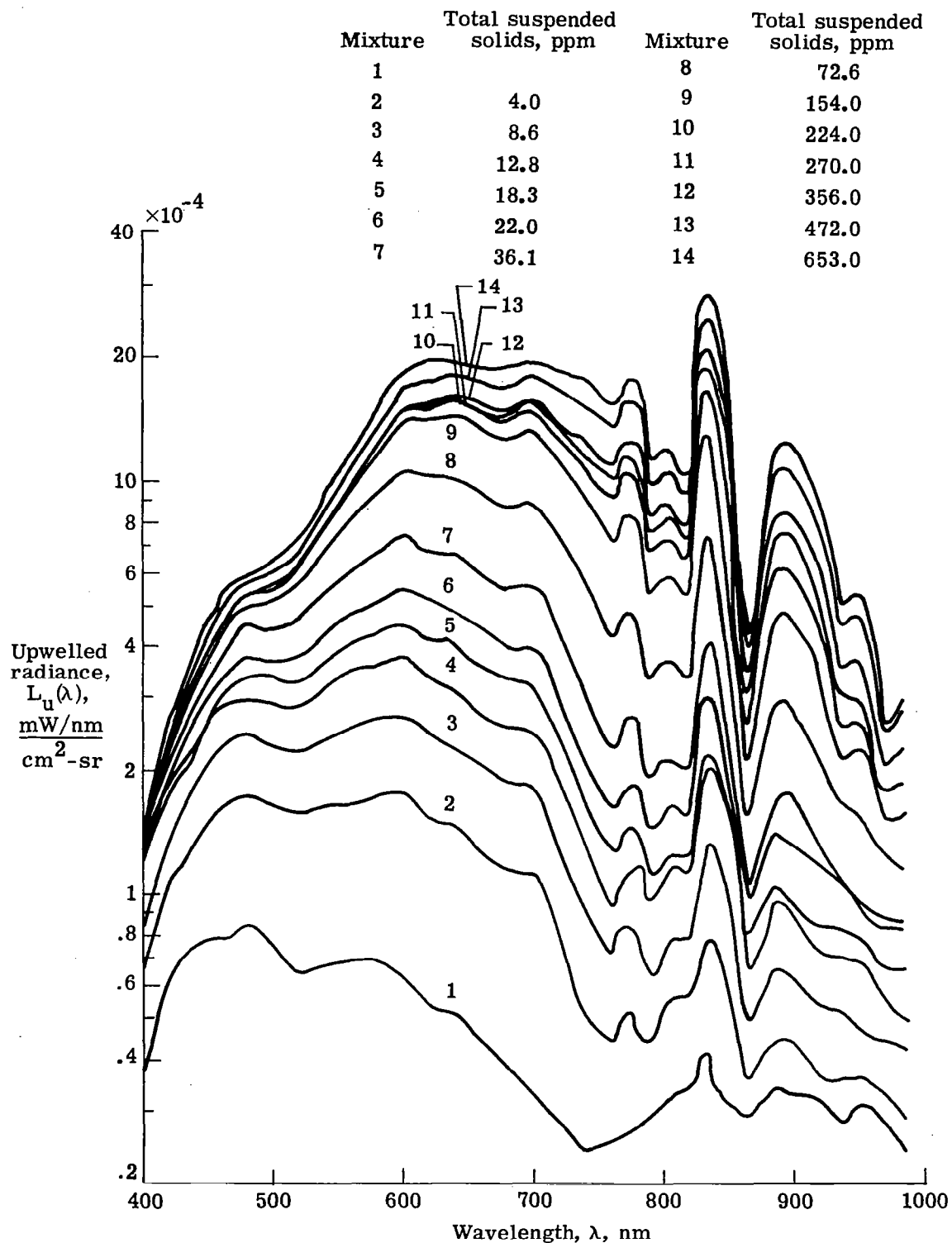
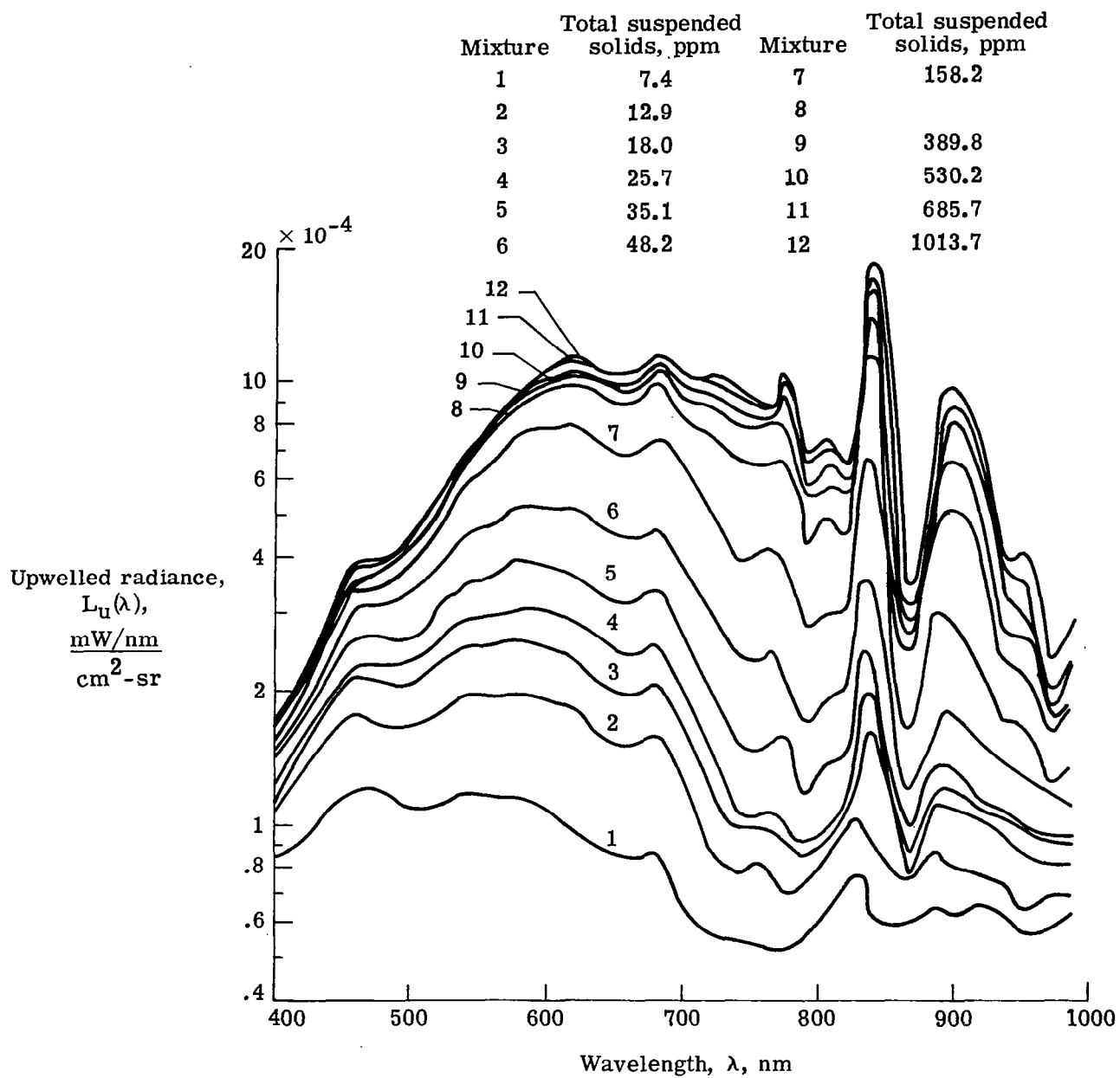


Figure 4.- Upwelled radiance of white card.



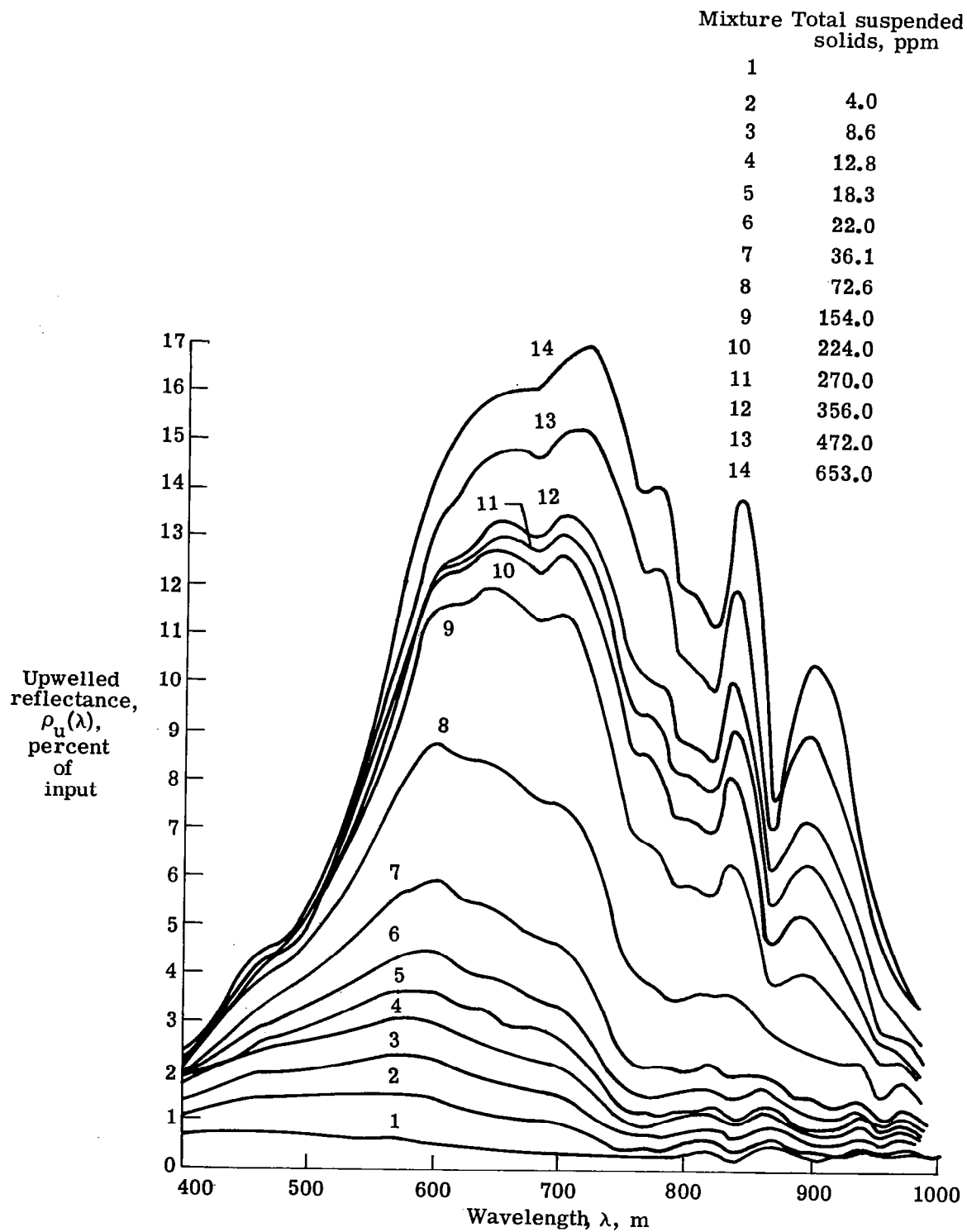
(a) October 1980 test.

Figure 5.- Upwelled radiance of mixtures.



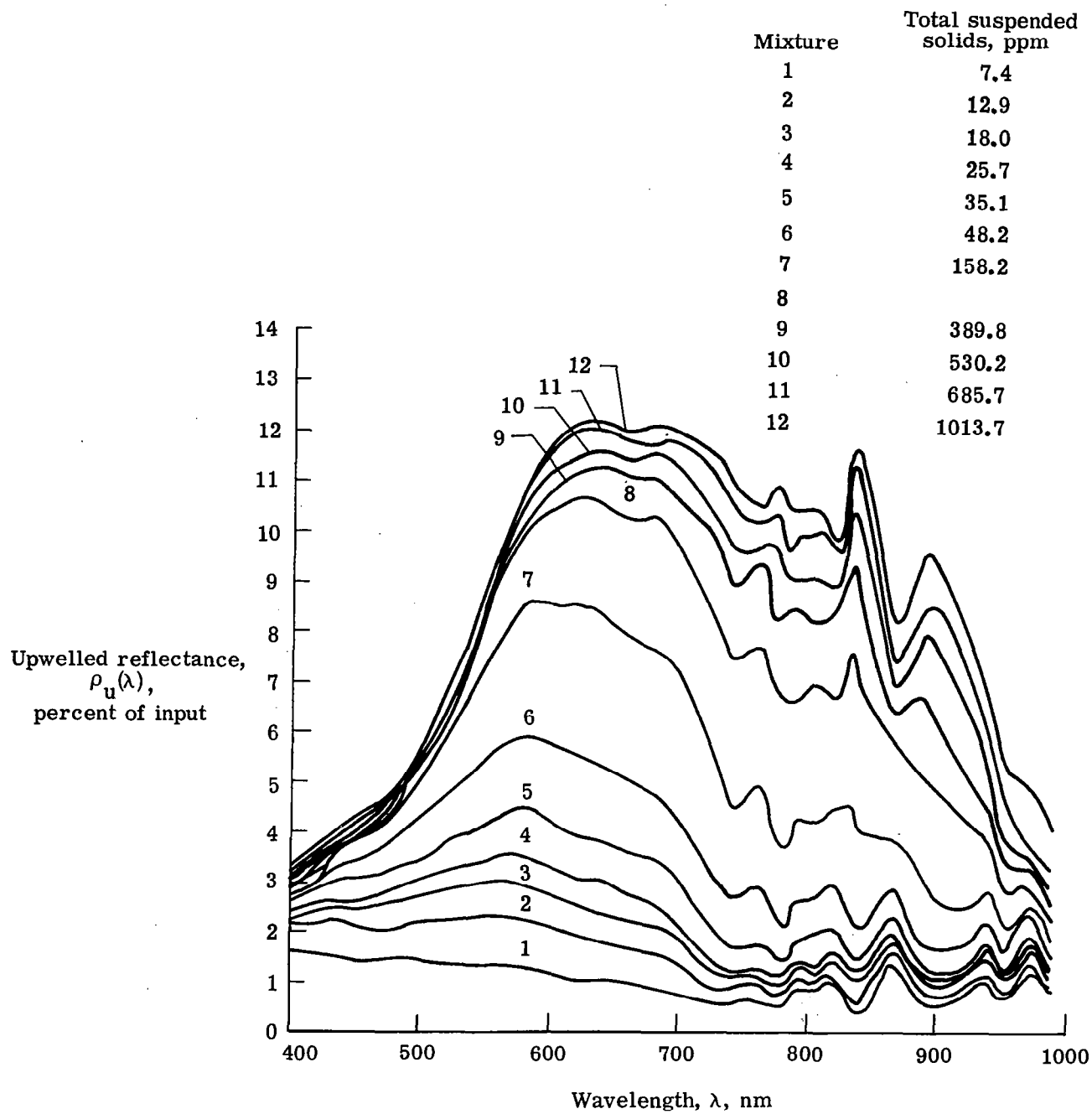
(b) April 1981 test.

Figure 5.- Concluded.



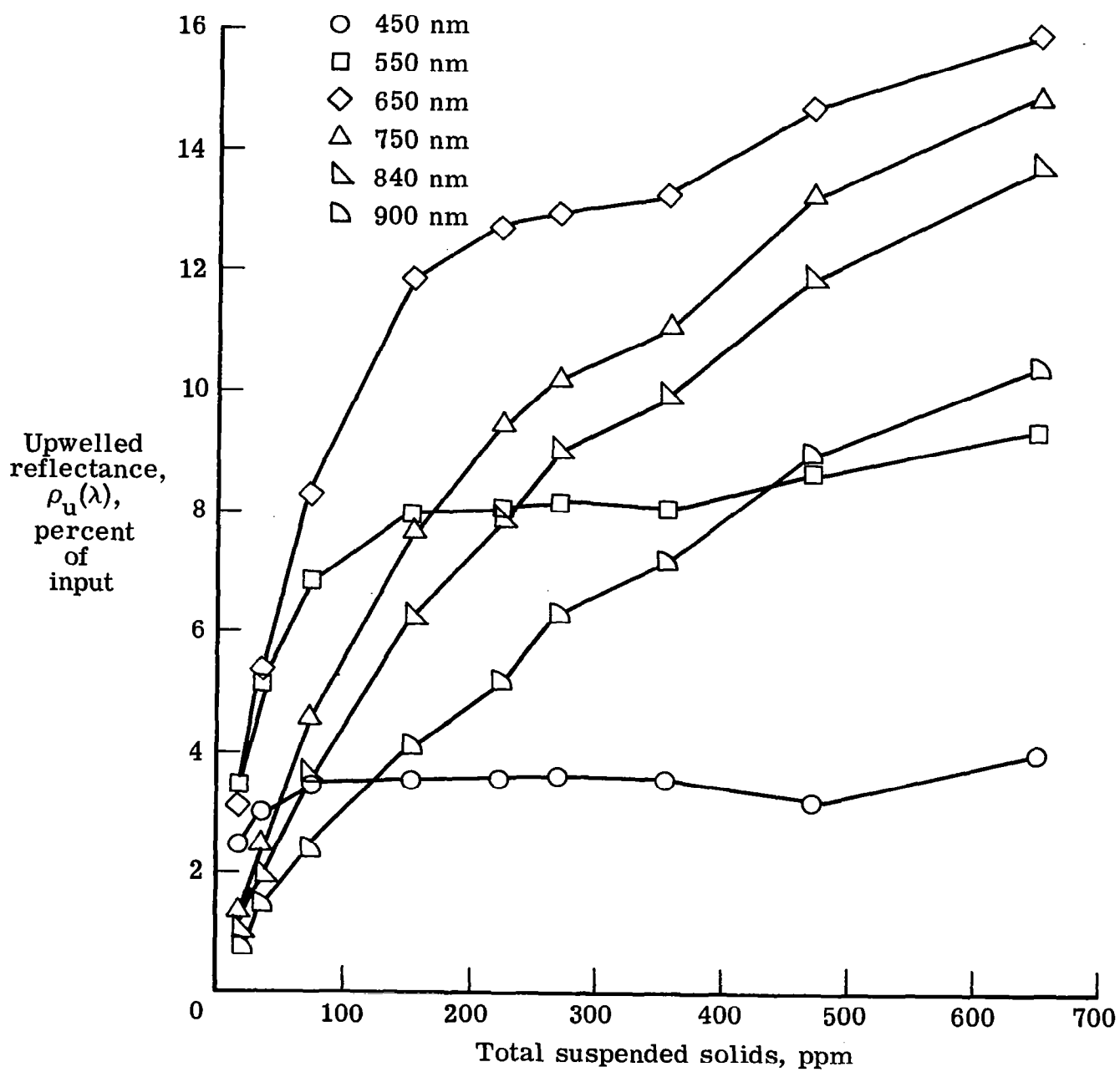
(a) October 1980 test.

Figure 6.- Upwelled reflectance of mixtures.



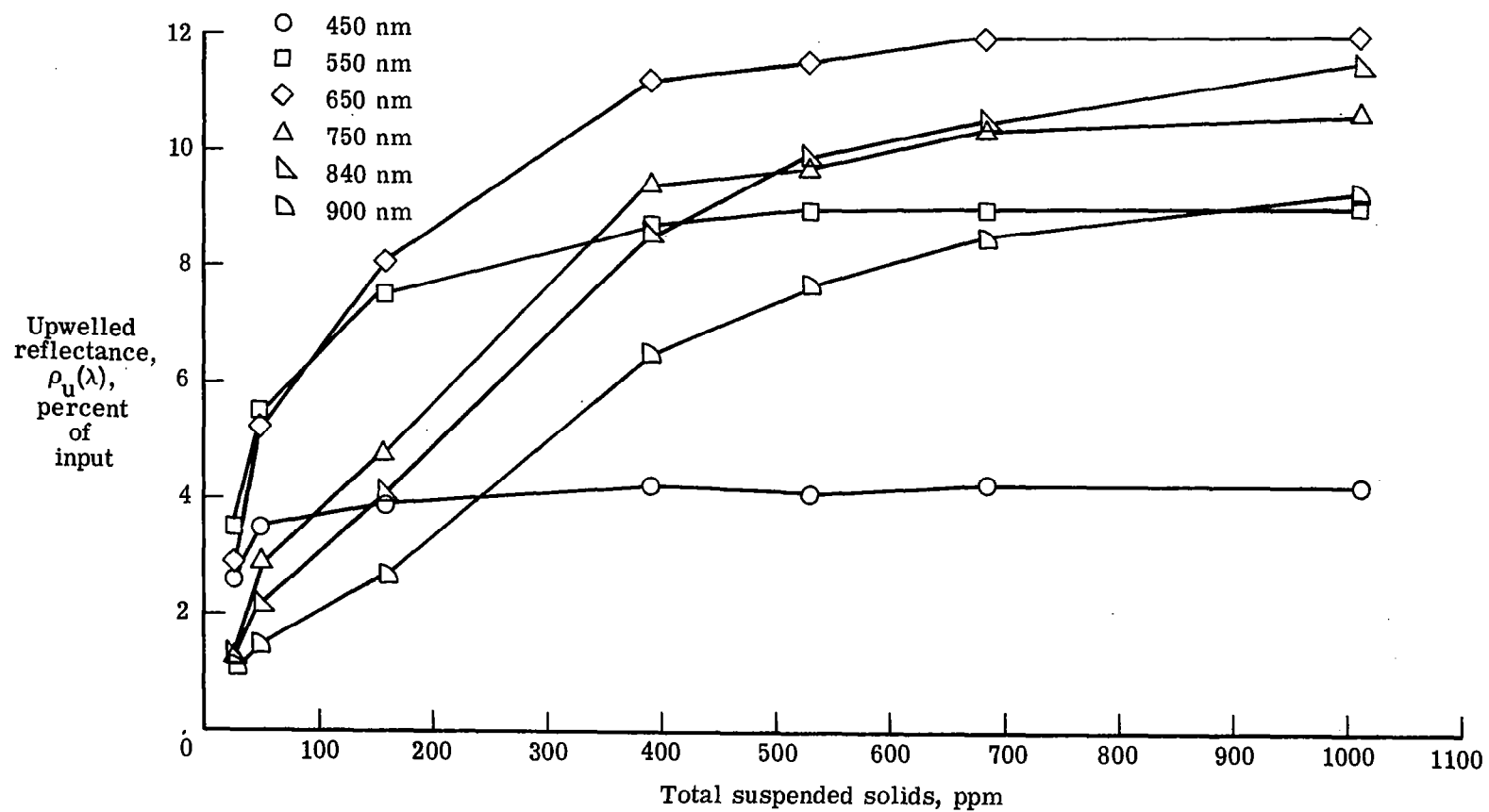
(b) April 1981 test.

Figure 6.- Concluded.



(a) October 1980 test.

Figure 7.- Upwelled reflectance as function of total suspended solids.



(b) April 1981 test.

Figure 7.- Concluded.

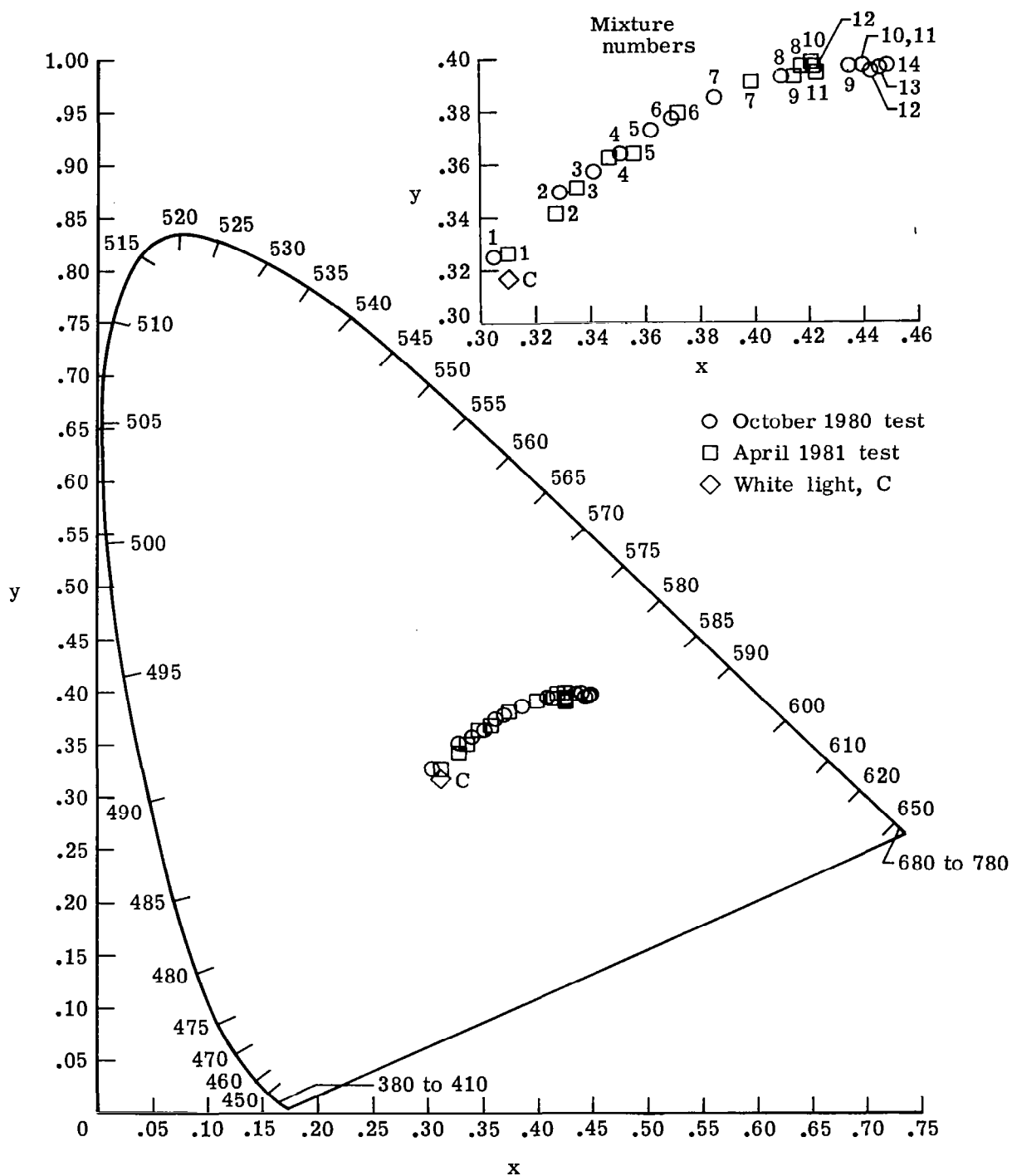


Figure 8.- ICI chromaticity.

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