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LSA Project
Task Report

JPL- 5101-58

Measurement of Solar and Simulator Ultraviolet Spectral Irradiance

March 15, 1978

Prepared for

Department of Energy

by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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ACKNOWLEDGEMENT

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SECTION I

INTRODUCTION

This report presents in summary form the intensity and spectral characteristics of the sun and various engineering sources of radiation relevant to the operation and testing of photovoltaic cell arrays and presents a description of the characteristics and operation of a spectroradiometer system developed to measure and document the radiation from the source of interest. Sun and other source measurements support durability studies of external surfaces exposed to sun and weather. These studies are a part of the LSSA program to develop low cost and long life solar cells.

This report discusses the characteristics of sun and sky radiation, the ultraviolet from the solar simulators, the details of the ultraviolet spectroradiometer system and field measurements.

In the selection of terminology and of units, this report follows the latest practice and uses System International (SI) units and the preferred choice of decimal multipliers (Ref. 1-1). For the purpose of this report we are primarily concerned with the radiant flux incident on a surface or passing through the location which such a surface represents. The flux density, i.e., flux/unit area, is termed *irradiance* with the symbol, E, and the units milliwatts centimeter^{-2}. When the *spectral irradiance* is measured, the wavelength unit, nanometer, and symbol, E (λ), are used. The spectral irradiance at wavelength, λ, is symbolized as E (λ) with the units (as customarily abbreviated), mW cm^{-2} nm^{-1}. The above choice of units and symbols conforms to the SI system and represents the best current practice.

SECTION II

SPECTRUM OF SUN AND SKY

The intensity and spectral distribution of solar flux at the earth's surface is represented by the solar flux generated in the sun and reaching the earth's atmosphere. These details will be discussed in turn.

A. SOLAR FLUX IN SPACE

The sun behaves much like a blackbody radiator with the flux outside the earth's atmosphere extending over the entire optical spectrum. The total radiation at the earth but outside of the atmosphere has been measured by different experimenters and by different techniques. The results, expressed as the *Solar Constant*, are best described in a recent paper (Ref. 2-1), wherein the best value is stated as 1.36 kW m^{-2} at one Astronomical Unit. Since the earth's orbit is elliptical, the value at earth varies seasonally over a range of ± 3.5 percent. If this variation is important one may use the critical values given in Table 2-1.

The region of interest with respect to this report extends from the onset of ozone absorption at 290 nm to the limit of solar cell response at about 1100 nm. The spectral distribution is similar to but not identical with that of a blackbody. The broad features of the solar spectrum are best described by a choice of blackbody temperatures as follows (Ref. 2-2, p. 7):

Region, nm	Color Temperature, K
300 - 400	5500
410 - 950	7140

Color temperature of a blackbody-like source is defined as the matching color of a true blackbody at the temperature named.

The extraterrestrial solar spectrum was first estimated from measurements through the atmosphere and subsequently measured directly from high altitude balloons and rockets. The principal sources of modern spectral data are Johnson,

Table 2-1. Factor correcting for ellipticity of
earth's orbit

Dates, Inclusive		S
Jan 1 - 13	Dec 23 - 21	0.965
Jan 14 - Feb 5	Dec 2 - 22	0.970
Feb 6 - 19	Nov 17 - Dec 1	0.975
Feb 20 - Mar 1	Nov 6 - 16	0.980
Mar 2 - 11	Oct 27 - Nov 5	0.985
Mar 12 - 20	Oct 18 - 26	0.990
Mar 21 - 29	Oct 9 - 17	0.995
Mar 30 - Apr 7	Oct 1 - 8	1.000
Apr 8 - 16	Sept 22 - 30	1.005
Apr 17 - 25	Sept 13 - 21	1.010
Apr 26 - May 4	Sept 4 - 12	1.015
May 5 - 15	Aug 23 - Sept 3	1.020
May 16 - 28	Aug 10 - 22	1.025
May 29 - June 18	July 20 - Aug 9	1.030
June 19 - July 19		1.035

Flux at mean distance = S x Flux at date

quoted in Ref. 2-2, p. 2, and Thekaekara, Ref. 2-3. The ultraviolet portion of
the Thekaekara data is shown in Table 2-2.

B.   SOLAR RADIATION AT THE EARTH'S SURFACE

At the earth's surface solar radiation is attenuated by absorbing and
scattering processes in the atmosphere. Rayleigh and Mie scattering and absorp-
tion by ozone control the character of the terrestrial ultraviolet solar spectrum.
These features will be discussed in turn. The attenuation due to these causes
is a function of air mass, a measure of the slant path through the atmosphere
from the sun to the observer. Neglecting refraction, the air mass, M, = sec Z,
where Z is the angular distance down from the zenith. Atmospheric refraction can
be neglected over most zenith angles. The effect of including a correction

Table 2-2. Solar irradiance at air mass one

Wavelength, nm	Irradiance, W m^{-2} nm^{-1}	Wavelength, nm	Irradiance, W m^{-2} nm^{-1}
290	0.0	350	480.5
295	0.0	355	498.0
300	4.1	360	513.7
305	11.4	365	561.3
310	30.5	370	603.5
315	79.4	375	609.4
320	202.6	380	608.0
325	269.5	385	609.8
330	331.6	390	623.9
335	383.4	395	691.2
340	431.3	400	849.9
345	449.2		

for refraction at large zenith angles has been computed by Bemporad, Ref. 2-2, p. 51, with the results given in Table 2-3. Table 2-3 demonstrates that the Bemporad corrections are unimportant at zenith angles less than 80 deg.

Table 2-3. Values of optical air mass

Zenith Angle	Secant Z	Bemporad Air Mass	Percent Secant Z Error
0	1.00	1.00	0.0
30	1.15	1.15	0.0
60	2.00	2.00	0.0
70	2.92	2.90	+ 0.7
80	5.76	5.60	+ 2.9
85	11.47	10.39	+10.4
86	14.34	12.44	+15.3
87	19.10	15.36	+24.3
88	28.65	19.79	+44.8

The zenith angle can be measured directly or can be computed from the equation:

$$\sec Z = \frac{1}{\sin \theta \sin \delta + \cos \theta \cos \delta \cos h}$$

where

θ = latitude of the place

δ = solar declination for the day

h = hour angle of the sun

The attenuation of solar ultraviolet radiation is caused by Rayleigh scattering (of small particles), Mie scattering (of large particles) and ozone absorption. The scattering is due to a variety of meterological conditions and varies slowly with wavelength, but at an unpredictable rate due to local conditions. It is similar to the gradual change in insolation due to the change in solar altitude with time. Thus, the effect of scattering due to local conditions covers a range of insolation attenuation similar to the gradual change in insolation due to the change in solar altitude.

While the attenuation due to scattering varies slowly with wavelength, the absorption curve of ozone is exceedingly steep. The general shape of the curve is shown in Figure 2-1, quoted from Ref. 2-4. The absorption of ozone varies over time and causes the observable limit of the solar spectrum to move back and forth over a narrow range of wavelengths between 290 and 300 nm.

The spectral irradiance of the sun measured through the atmosphere and at wavelengths longer than 300 nm is well represented by the measurements of Stair and Ellis, Ref. 2-4, and the related discussion of previous work. Note that in the vicinity of 300 nm the slope of the terrestrial solar spectrum is about 10 percent per 0.1 nm.

C.   SUN AND SKY RADIANCE

The solar radiation reaching a reference surface comprises the direct component from the sun and the indirect component from the sky. Sky radiation is derived entirely from scattering in the atmosphere which is due to air
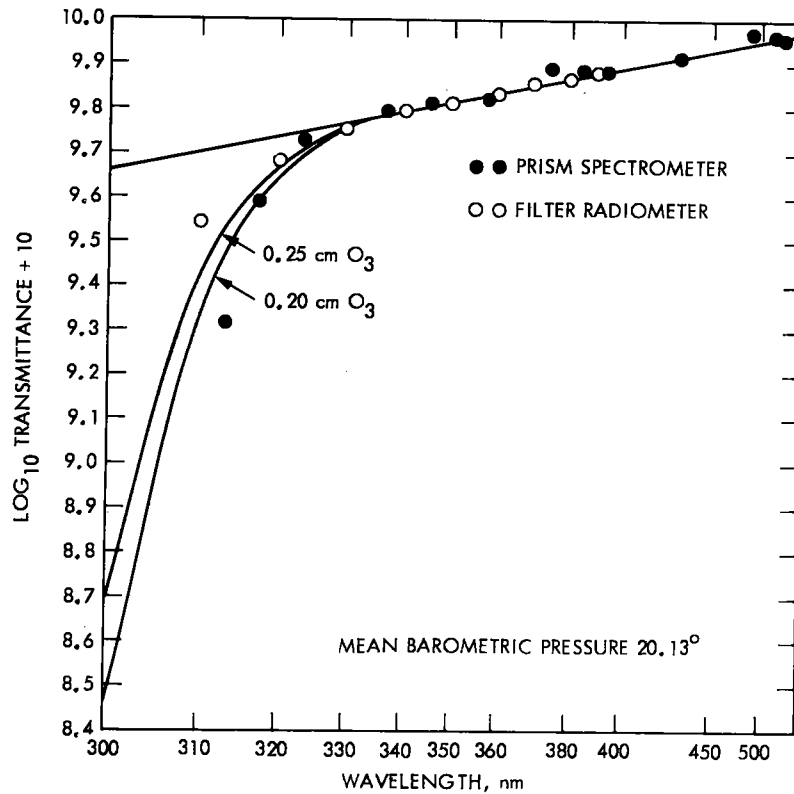
Figure 2-1. Transmission of ozone

molecules and larger particles including aerosols and the moisture particles present in the clouds. The total insolation of a horizontal or inclined surface varies in intensity and spectral distribution with the following principal variables:

(1) Time of day and time of year

(2) Latitude, longitude and elevation of the site

(3) Azimuth and altitude of the sun

(4) Azimuth and tilt of the receiving plane

(5) Atmospheric properties as effect of water vapor, turbidity and ozone

(6) Nature and extent of cloud cover

(7) Albedo of the ground

The literature on solar ultraviolet is limited in quantity and in breadth of treatment. The best theoretical and experimental treatment of this complex

subject known to me is found in Ref. 2-2, Chapters 3-5. In this reference the author deplores the lack of experimental data and is required to fall back on a theoretical treatment.

Only the direct solar radiation depends predictably on latitude, time of year and time of day. Taking 35° N. Lat. as typical, the solar noon zenith distance is plotted versus time of year in Figure 2-2, quoted from Ref. 2-5.

Sky radiation falls into two categories, blue sky and cloud cover. Examples of each will be discussed in terms of a model drawn from the illuminating engineering literature, which is more comprehensive than are treatments couched in radiometric rather than photometric concepts. This approach identifies luminance, symbol B, with radiance, symbol L, and defines either as the luminous (or radiant) intensity of a surface element in a specified direction. It identifies illumination, symbol E, with irradiance, also symbol E, and defines either as the luminous (or radiant) flux incident per unit area. The spatial distribution of either luminous or radiant flux over the sky can be described by a common model to a good approximation. However, the ratio between sun and sky luminance is, undoubtedly, far different than the ratio between sun and sky ultraviolet radiance.

Extreme conditions of cloudiness are shown by the clear sky graph, Figure 2-3, and the graph of densely overcast sky, Figure 2-4. Each graph depicts the hemisphere bounded by the meridian through the sun and shows contours of equal luminance scaled to unity at the zenith. The graphs are quoted from Ref. 2-5, pp. 42 and 44. These results illustrate the difficulty of generalizing the effect of cloud cover.

If it were possible to average the radiance zone by zone then we could estimate the irradiance on a horizontal surface due to the entire sky as follows:

$$E(\lambda) = \sum_{0}^{90°} L(\lambda, \theta) K(\theta) \cos \theta$$
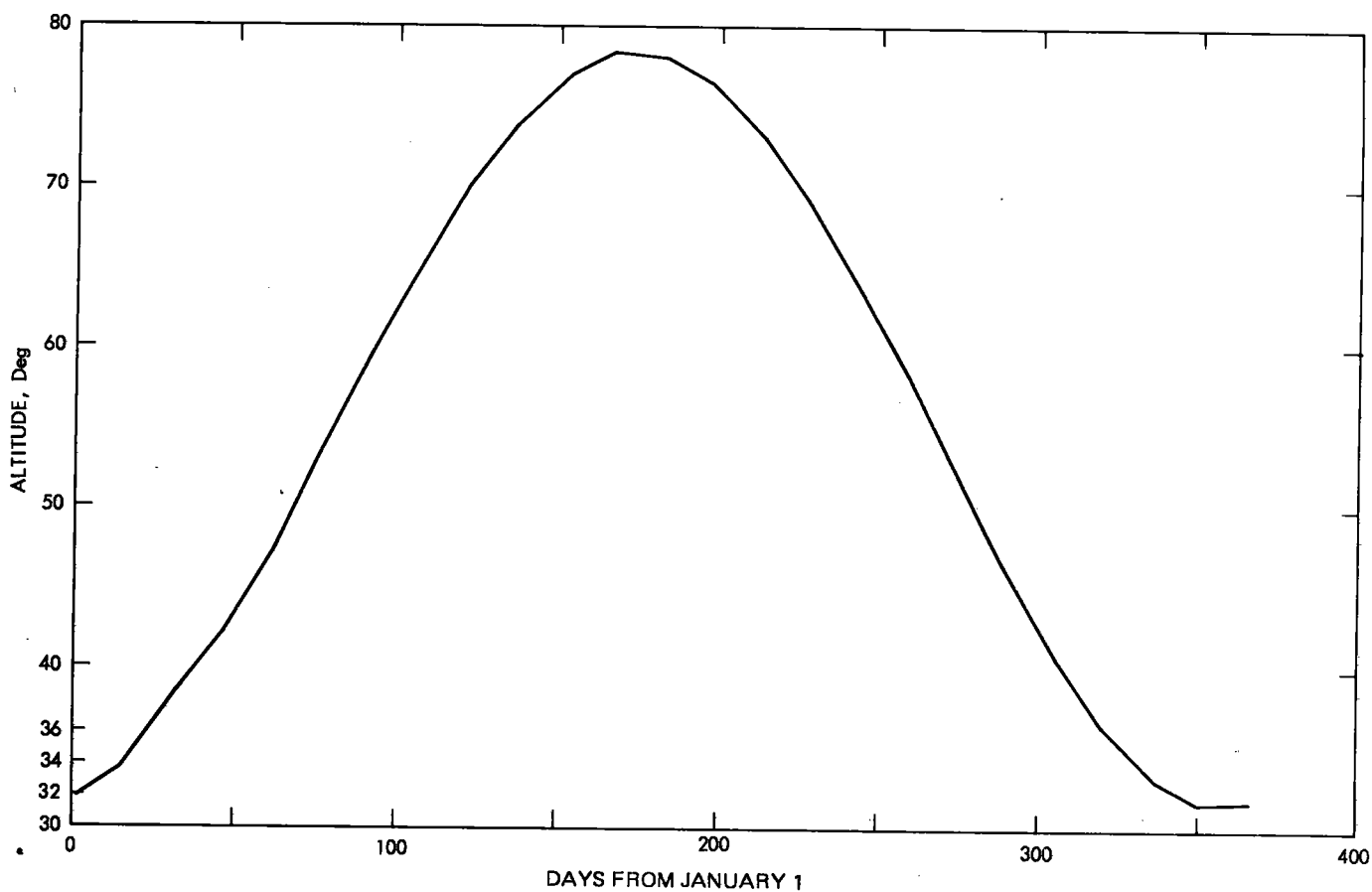
Figure 2-2. Noon altitude at 35° N. latitude

where

$E(\lambda)$ = spectral irradiance due to sky

$L(\lambda)$ = spectral radiance in zone

$K(\theta)$ = zonal factor

θ = zenith angle

Values of $K(\theta)$ and the product $K(\theta) \cos \theta$ are shown in Table 2-4.

As an application of this discussion of zonal analysis, consider the case of a simplistic model in which the sky radiance is uniform in all zones and use this model to estimate the importance of skyline obstructions at the horizon. For this purpose the values of $E(\lambda)$ versus angle have been normalized and plotted in Figure 2-5. Note that the zone extending 15 degrees up from the horizon
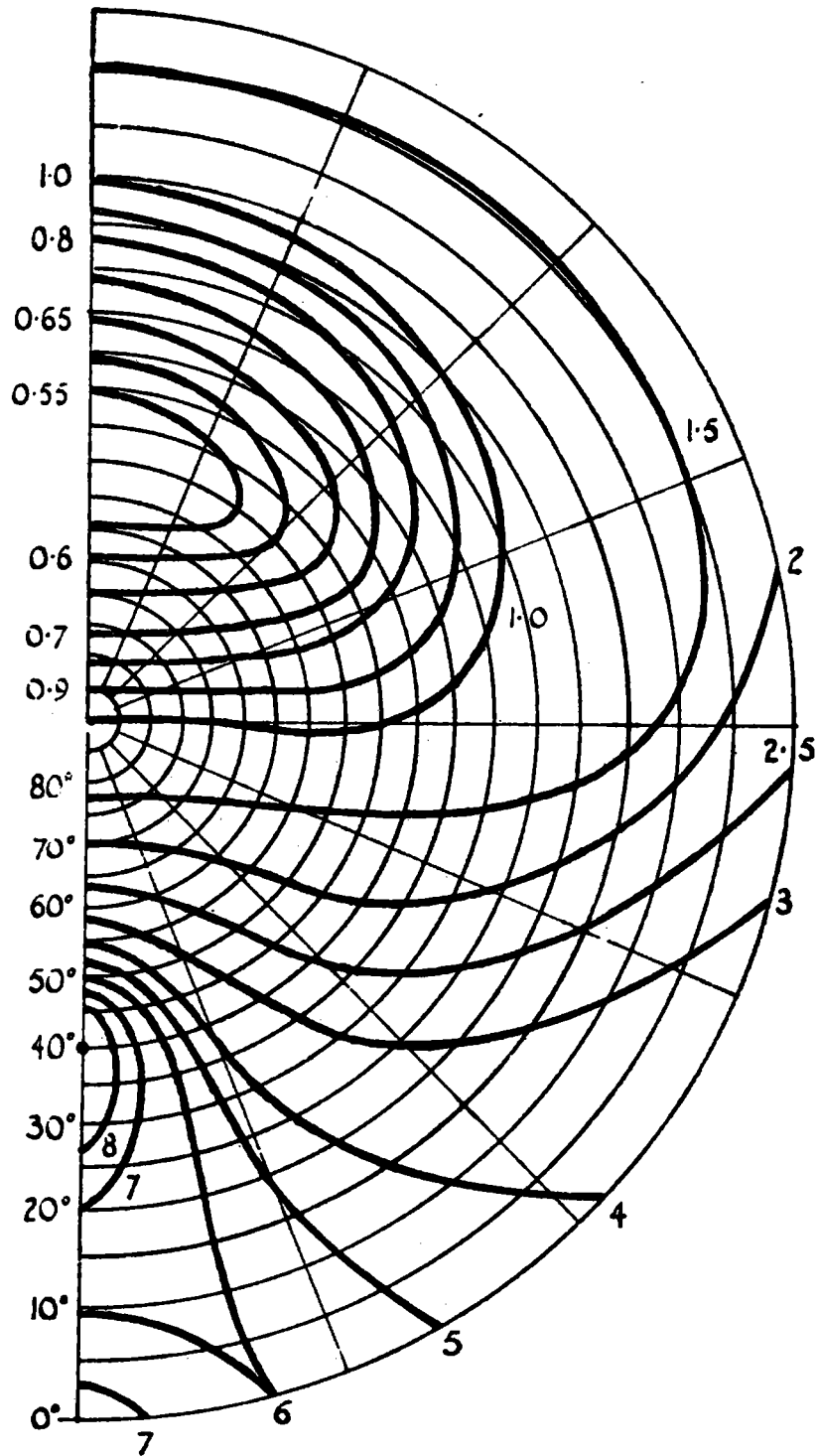
Figure 2-3. Luminance distribution in a clear sky
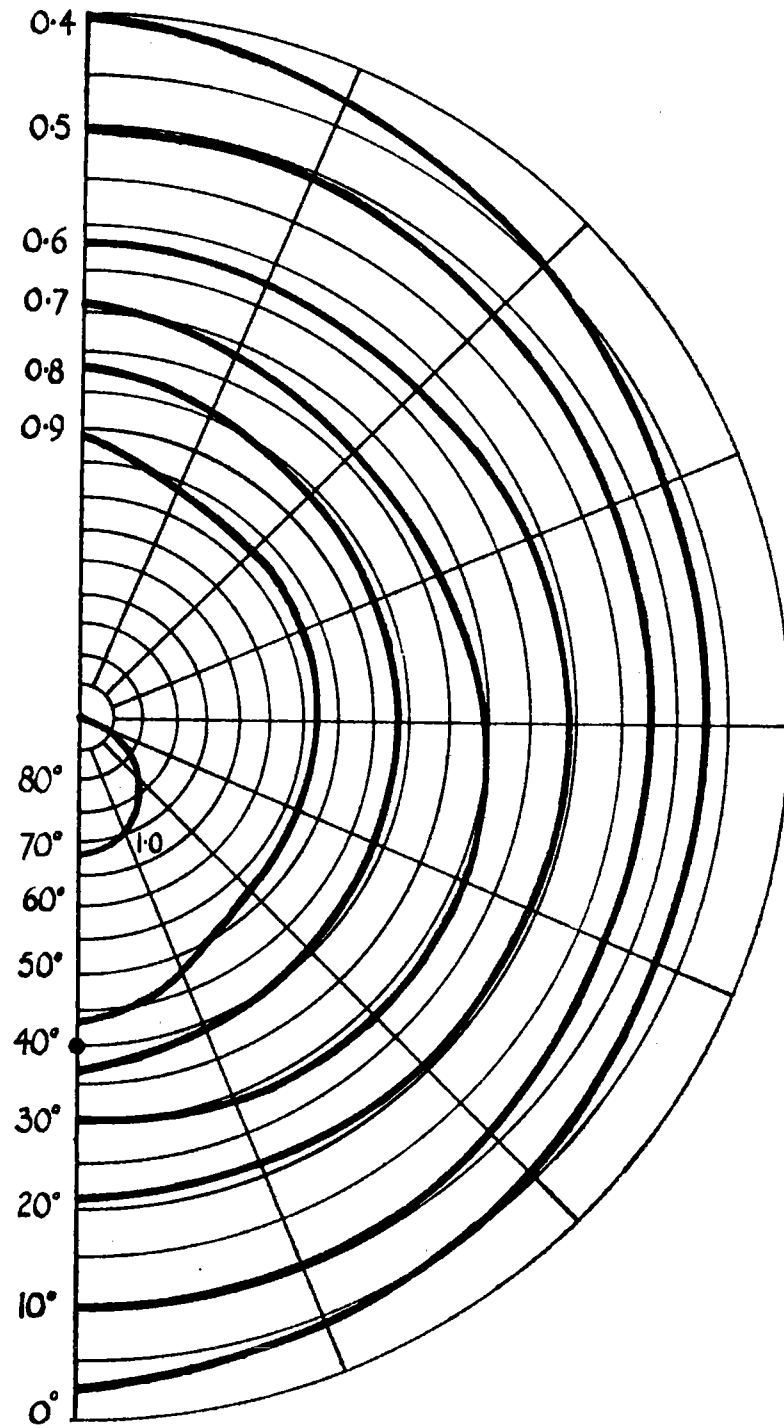
Figure 2-4. Luminance distribution in a densely covered sky

Table 2-4. Functions of zone angle

θ	K(θ)	K(θ) cos θ	θ	K(θ)	K(θ) cos θ
2.5	0.0239	0.0239	47.5	0.404	0.273
7.5	0.0715	0.0709	52.5	0.435	0.265
12.5	0.119	0.116	57.5	0.462	0.248
17.5	0.165	0.157	62.5	0.486	0.224
22.5	0.210	0.194	67.5	0.506	0.194
27.5	0.253	0.224	72.5	0.523	0.157
32.5	0.295	0.249	77.5	0.535	0.116
37.5	0.334	0.265	82.5	0.544	0.0710
42.5	0.370	0.273	87.5	0.548	0.0239
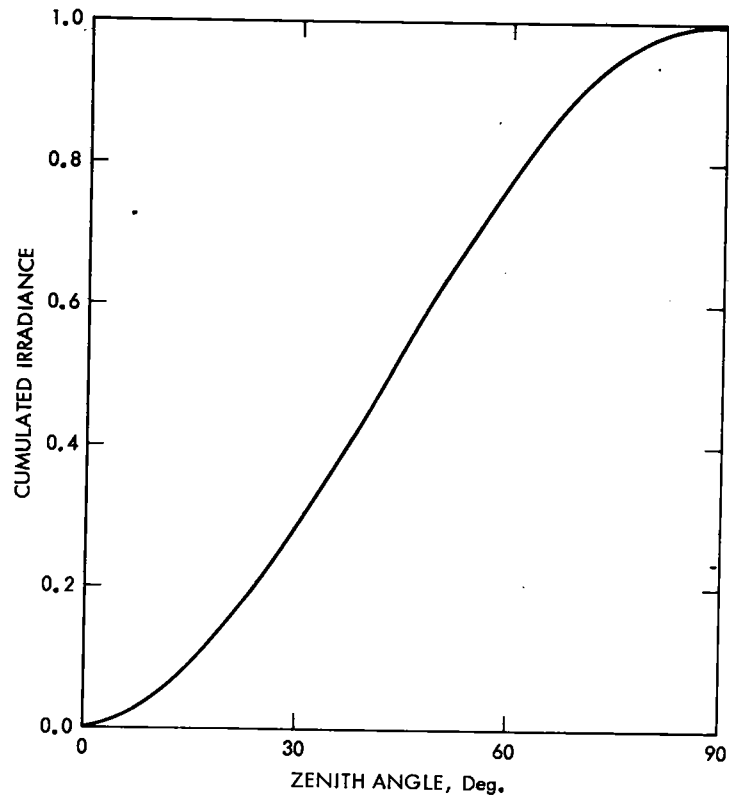
Figure 2-5. Cumulated irradiance of overcast sky versus zenith angle

contributes only five percent to the total flux incident on a horizontal surface. Using a more realistic model, the 15 degree zone would contribute even less.

A program is now under way in support of Task III, by which many ultraviolet spectra of sun and sky will be measured. From these measurements some of the variables listed above can be evaluated. The results most significant to Task III will be: (1) spectral fluence over an extended time period, (2) effect of cloud cover, and (3) effect of geographic location (including altitude). In these experiments a choice of instrument orientation must be made: whether to arrange the axis of the input optics vertically or in the direction parallel to the normal to such solar panels as may be in the vicinity. The first alternative considers the entire hemisphere of the sky and yields data appropriate to a meteorological survey. The second alternative considers a hemisphere tipped with respect to the horizon in such a manner that the northern sky is deemphasized and the radiation from the southern sky quadrant and some foreground terrain is accentuated. This latter condition more faithfully represents the ultraviolet radiation incident on solar panels and related test samples.

SECTION III

SOLAR SIMULATORS AND STANDARD SOURCES

The ultraviolet sources discussed in this section comprise very accurate standards of spectral radiation used to calibrate the spectroradiometer and commercial sources of ultraviolet used to irradiate samples and study photo-chemical degradation. The sources used to irradiate samples are called solar simulators, but it is by no means clear that the duplication of the solar spectrum is the most effective way to irradiate samples on a real time or accelerated basis. Consequently, each commercial source must be evaluated in terms of its spectral characteristics and intensity.

A.   STANDARD OF SPECTRAL IRRADIANCE

The General Electric 1000 W tungsten-halogen lamp, ANSI symbol FEL, has been investigated by the National Bureau of Standards and a group of these lamps has been calibrated against the NBS radiometric standards. The lamp, identified by G. E. as Q1000/4CL, has a coiled-coil filament rated at 120 V. The design current, color temperature and life are 8.3 A, 3200 K and 500 hours respectively. This lamp is pictured in Figure 3-1.

Copies of the NBS lamp standards are available commercially, Ref. 3-1. As supplied by the standardizing laboratories, the lamp base is converted to a medium bipost base. Before calibration the lamps are seasoned for 40 hours at 120 V and then monitored for drift rate. A lamp is rejected if its drift in radiant output at 650 nm exceeds 0.5 percent over 14 hours. The selected lamps are calibrated by the National Bureau of Standards and traceable to the spectral irradiance of a blackbody as defined by Planck's equation.

The spectral irradiance values are transferred with the aid of a large grating double monochromator. The quantity tabulated is spectral irradiance, $W cm^{-2} nm^{-1}$, measured in a plane precisely 50 cm from the near side of the base pins. The lamp must be operated at 8.00 A to meet the specification. In use at JPL, the lamp current is held at 8.000 $\pm$ 0.003 A. Thirty-two well spaced measurements are made and certified over the range of 250 to 2500 nm. Closer intervals are reported by interpolation. The uncertainty in the reported values comprises the NBS uncertainty plus that added by the transfer in the calibrating
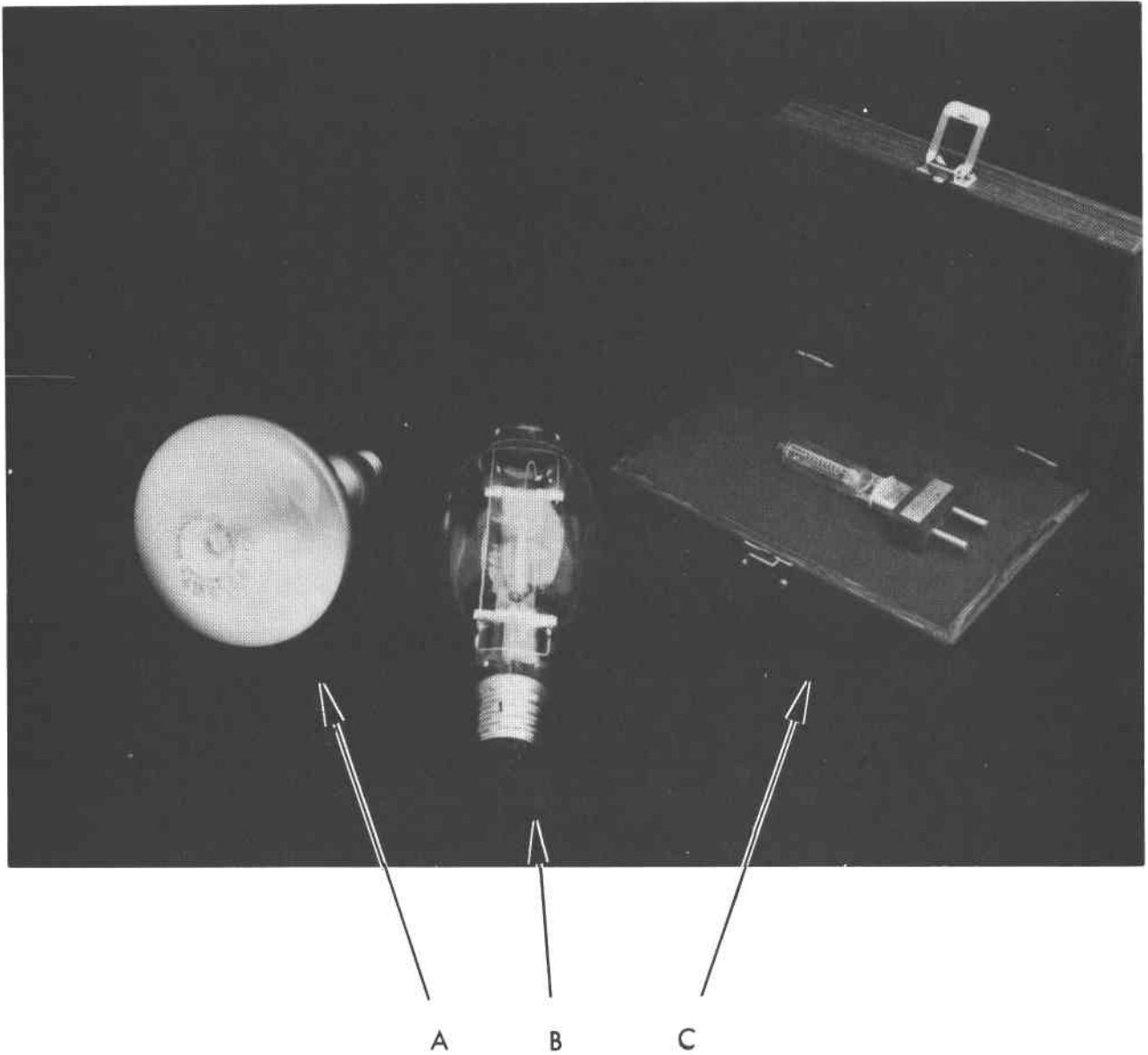
A. Type RS sunlamp
B. Mercury lamp, 175 W, medium pressure
C. Lamp standard of spectral irradiance

Figure 3-1. Group of ultraviolet lamps

laboratory. The estimated uncertainties are shown in Table 3-1. The calibration certificate for JPL lamp, S/N F011F, is shown in Figure 3-2. The estimated life of the calibration is 50-100 hours.

The 1000 W tungsten lamp with quartz envelope generates a continuous spectrum which can be made to approximate terrestrial solar ultraviolet by adding a filter having a sharp cutoff on the short wavelength side. Such filters are obtainable from Corning or Schott. The tungsten lamp and sun spectra are shown in Figure 3-3. Although sun irradiance is much greater than the lamp provides at 50 cm, the lamp irradiance can be increased by using a shorter distance, collective optics, or both.

B.   BZ LAMP STANDARD

The National Bureau of Standards has announced, Ref. 3-2, a special fluorescent lamp calibrated for spectral irradiance. The lamps are 20 W, 24-in. in size and designated as type BZ. The output peaks at 313 nm with the

Table 3-1. Uncertainty in standard lamp irradiance

Wavelength, nm	Percent Uncertainty
250	2.5
350	1.7
450	1.6
555	1.5
654.6	1.5
800	1.5
1300	1.6
1600	1.6
1700	2.7
2000	3.3
2500	4.8

NOTES: 1. The uncertainty includes the estimate made by the National Bureau of Standards plus that added by transfer in the calibrating laboratory.

2. The values from 250 nm to 1600 nm are based on the 1973 radiometric scale, and those from 1700 nm to 2500 nm are based on the 1963 radiometric scale.

CERTIFICATE OF CALIBRATION

STANDARD OF SPECTRAL IRRADIANCE

TYPE: FEL, 1000 WATT TUNGSTEN HALOGEN
LAMP CURRENT: 8.00 AMPERES
CALIBRATION DISTANCE: 50 CENTIMETERS
NBS COMPARISON STANDARDS: QM198,QM199,F8
NBS TEST NOS.: 196160,211334
EG&G COMPARISON STANDARDS:AS265,AS266,FW011
EG&G TEST NOS.:508001,508002,512011,512012,512020,512021

DERIVED PHOTOMETRIC CALIBRATIONS

ILLUMINANCE AT 50 CM:7.103E-01 LUMENS/CM↑2(PHOT)
             6.598E+02 LUMENS/FT↑2(FOOTCANDLES)

LUMINOUS INTENSITY:1.776E+03 LUMENS/STERADIAN(CANDELA)

CHROMATICITY COORDINATES:X=.4356 Y=.4037

CORRELATED COLOR TEMPERTURE:3017 KELVIN

THIS STANDARD HAS BEEN PREPARED BY TRANSFER
MEASUREMENT FROM A GROUP OF LAMPS CALIBRATED
BY THE NATIONAL BUREAU OF STANDARDS. POINTS
OF COMPARISON ARE MARKED WITH AN ASTERISK (*)
IN THE TABULAR LISTING. THE INTERPOLATED POINTS
LIE ON THE BLACK BODY CURVE PASSING THROUGH THE
TWO NEAREST COMPARISON POINTS. THE DATA HAS
BEEN VERIFIED IN ACCORDANCE WITH CURRENT RADIO-
METRIC CALIBRATION LAB QA PROCEDURE.

CALIBRATED BY
    LEN BORDZOL
APPROVED BY
    ROBERT D. WATSON

CALIBRATION DATE

21 JUN 1976

TABULAR LISTING OF SPECTRAL IRRADIANCE VALUES

NM	W/CM↑2 NM	NM	W/CM↑2 NM	NM	W/CM↑2 NM
* 250	1.271E-08	650	1.493E-05	*1200	1.863E-05
255	1.717E-08	660	1.542E-05	1225	1.803E-05
* 260	2.288E-08	670	1.590E-05	1250	1.744E-05
265	3.009E-08	680	1.636E-05	1275	1.686E-05
* 270	3.910E-08	690	1.680E-05	*1300	1.629E-05
275	4.967E-08	* 700	1.722E-05	1325	1.588E-05
* 280	6.247E-08	710	1.761E-05	1350	1.548E-05
285	7.804E-08	720	1.799E-05	1375	1.507E-05
* 290	9.660E-08	730	1.834E-05	1400	1.466E-05
295	1.170E-07	740	1.868E-05	1425	1.426E-05
* 300	1.407E-07	750	1.899E-05	1450	1.386E-05
305	1.679E-07	760	1.929E-05	1475	1.346E-05
* 310	1.989E-07	770	1.956E-05	1500	1.307E-05
315	2.366E-07	780	1.982E-05	1525	1.268E-05
* 320	2.796E-07	790	2.005E-05	1550	1.231E-05
325	3.269E-07	* 800	2.027E-05	1575	1.193E-05
* 330	3.801E+07	810	2.047E-05	*1600	1.157E-05
335	4.377E-07	820	2.066E-05	1625	1.125E-05
* 340	5.014E-07	830	2.083E-05	1650	1.092E-05
345	5.679E-07	840	2.098E-05	1675	1.061E-05
* 350	6.402E-07	850	2.111E-05	*1700	1.030E-05
355	7.213E-07	860	2.123E-05	1725	9.978E-06
360	8.091E-07	870	2.133E-05	1750	9.663E-06
365	9.040E-07	880	2.142E-05	1775	9.357E-06
370	1.006E-06	890	2.149E-05	*1800	9.060E-06
375	1.115E-06	* 900	2.154E-05	1825	8.665E-06
380	1.232E-06	910	2.155E-05	1850	8.291E-06
385	1.357E-06	920	2.155E-05	1875	7.934E-06
390	1.489E-06	930	2.153E-05	*1900	7.595E-06
395	1.628E-06	940	2.150E-05	1925	7.332E-06
* 400	1.776E-06	950	2.146E-05	1950	7.079E-06
410	2.090E-06	960	2.141E-05	1975	6.834E-06
420	2.434E-06	970	2.134E-05	*2000	6.599E-06
430	2.807E-06	980	2.127E-05	2025	6.413E-06
440	3.207E-06	990	2.119E-05	2050	6.232E-06
* 450	3.634E-06	1000	2.110E-05	2075	6.056E-06
460	4.095E-06	1010	2.100E-05	*2100	5.884E-06
470	4.579E-06	1020	2.090E-05	2125	5.737E-06
480	5.086E-06	1030	2.079E-05	2150	5.592E-06
490	5.613E-06	1040	2.067E-05	2175	5.451E-06
* 500	6.157E-06	*1050	2.054E-05	*2200	5.313E-06
510	6.731E-06	1060	2.044E-05	2225	5.108E-06
520	7.318E-06	1070	2.033E-05	2250	4.912E-06
530	7.918E-06	1080	2.021E-05	2275	4.725E-06
540	8.527E-06	1090	2.009E-05	*2300	4.546E-06
550	9.143E-06	1100	1.996E-05	2325	4.432E-06
560	9.762E-06	1110	1.983E-05	2350	4.322E-06
570	1.038E-05	1120	1.970E-05	2375	4.214E-06
580	1.101E-05	1130	1.955E-05	*2400	4.108E-06
590	1.162E-05	1140	1.941E-05	2425	4.047E-06
* 600	1.224E-05	*1150	1.926E-05	2450	3.986E-06
610	1.280E-05	1160	1.914E-05	2475	3.924E-06
620	1.335E-05	1170	1.902E-05	*2500	3.863E-06
630	1.389E-05	1180	1.889E-05	* 555	9.420E-06
640	1.442E-05	1190	1.876E-05	*1540	1.246E-05
				* 654.6	1.505E-05

Figure 3-2. Lamp S/N F011F calibration certificate
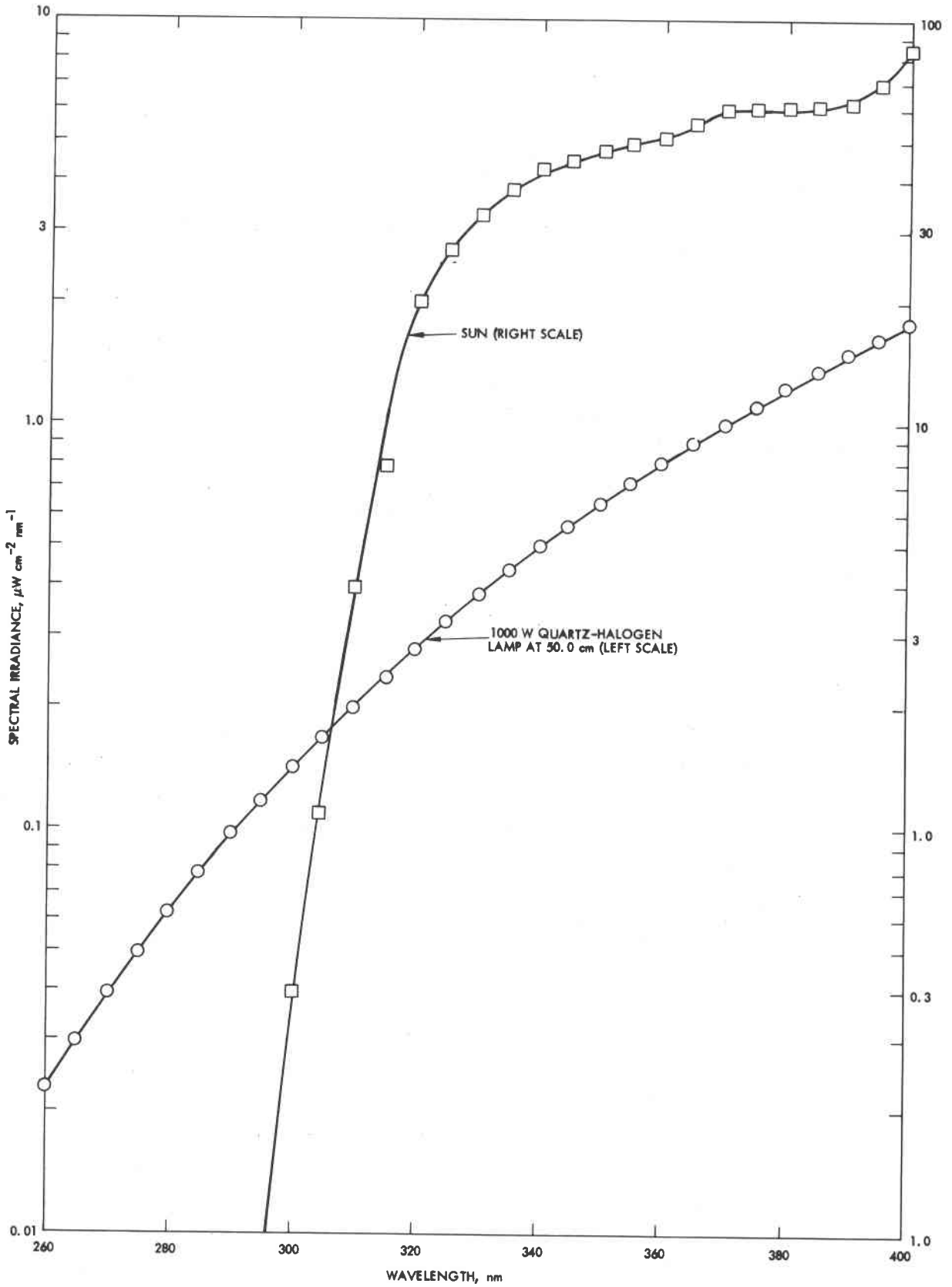
Figure 3-3.   Tungsten lamp and sun spectra

value 1.1 μW cm^{-2} nm^{-1} at 50 cm. Note that the corresponding irradiance of the quartz-halogen lamp standard is about 0.22 μW cm^{-2} nm^{-1}. The relative and absolute uncertainties are pegged at 2-3 percent and 5-6 percent respectively. These lamps have been under recent development but should be available now. JPL has no plan to use this lamp standard at present.

C.   TYPE RS SUNLAMP

The type RS sunlamp is a G.E. product having a low pressure mercury arc and a tungsten filament ballast in a 5-in. diameter reflector bulb. This lamp is shown in Figure 3-1. The unit draws 275 W at 120 V and requires no external ballast. The bulb is made of ultraviolet transmitting glass which minimizes the emission of short wave ultraviolet. The manufacturer's estimate of the ultraviolet radiated is given in Ref. 3-3 and Table 3-2.

Notice that the shape of the reflector constrains the flux to a limited solid angle, not defined, within which the radiant power is as stated.

Table 3-2. Vendor's appraisal of RS sunlamp

Wavelength Band, nm	Radiant Power, W
260 - 280	0.004
280 - 290	0.050
290 - 300	0.130
300 - 310	0.340
310 - 320	0.880
320 - 340	0.230
340 - 360	0.140
360 - 380	2.570
380 - 400	0.130

Information from General Electric suggests that the RS sunlamp may be redesigned in the near future. This may affect the ultraviolet cutoff, the spectral distribution and the total flux. Until such a design change occurs, the best information available on the RS sunlamp will be found in Section VI.

D. MEDIUM PRESSURE MERCURY LAMP

The standard mercury lamp, so called, is available in sizes ranging from 40 to 1000 W. A 175 W lamp is shown in Figure 3-1. This type of lamp comprises a quartz arc tube housed in a glass bulb. The arc is maintained by means of a special reactive ballast. The outer bulb cuts off radiation shorter than 300 nm. The shorter wavelength radiations can be obtained if the outer bulb is removed. The lamp operation is not adversely affected.

E. CARBON ARC

A carbon arc is used in some test equipment to simulate degradation due to the actinic rays of sunlight. As an example of this type of source the Weather-Ometer made by Atlas, Ref. 3-4, will be discussed in appropriate detail.

The carbon arc source uses a trim of "Sunshine" carbons, 22 mm upper and 13 mm lower. The arc draws 60 A at 50 V, and burns in a free flow of air which removes the products of combustion. The carbons are obtained from Union Carbide through its subsidiary formerly identified as National Carbon Company. The following details are extracted from Ref. 3-5. The core of the "Sunshine" carbon contains metals of the cerium group which generate a line spectrum practically as continuous as sunlight. The bulk of the radiation extends to 280 nm with scattered lines extending to shorter wavelengths.

Samples are exposed in the Atlas unit in a drum surrounding the arc. The projection distance is 18.8 in. at the center line and 21.3 in. at the upper and lower extremities of the sample holders where the irradiance is diminished by 22 percent. Typically the samples are covered with Corex D glass filters.

Note that Atlas describes these filters as cutting at 255 nm and reducing the energy up to 355 nm by 10 to 50 percent, beyond which the transmission is 92 percent. Corning has changed filter identification over the years and Corex D is not identified in recent catalogs or technical literature. Note further that these filters deteriorate in transmission with ultraviolet exposure. Atlas claims a useful filter life of 2000 hours.

Atlas also makes a Weather-Ometer which uses an arc enclosed in a glass globe. This "violet arc", so called, has been measured and the results reported in Section VI.

F. XENON ARC

Xenon sources are available in two varieties: the high pressure short arc which radiates from a small hot spot on the cathode, and the long arc which radiates over the entire length of the burner which is several inches long.

The typical xenon spectrum is characterized by a continuous spectrum on which clusters of lines at 450 and 850 nm are superimposed. The ultraviolet portion does not cut off as sharply as does solar radiation and this difference is often corrected by filters which cut sharply on the short wavelength side.

In the evaluation of these sources used as simulators of solar ultraviolet, it must be noted that the intensity of the arcs deteriorates with age and that the filter transmission decreases with exposure to the ultraviolet due to a photochemical effect.

G. ULTRAVIOLET CUTOFF FILTERS

Since the solar spectrum cuts off near 290 nm and sources used as simulators may not, filters are used in some cases to eliminate actinic radiation of shorter wavelengths than those in solar radiation. Filters which cut on the short wavelength side are described in Ref. 3-6, pp. 332 et seq. As said before, the user must appreciate that filters deteriorate and lose transmission due to the accumulation of dirt and to the solarization effect of exposure to intense ultraviolet radiation.

SECTION IV

INSTRUMENTATION

The instrumentation described below comprises a spectroradiometer and accessories designed to measure the ultraviolet irradiance produced by the sun, sky, or artificial sources. Measurements are made over the range 250-398 nm with 2 nm resolution. The equipment design which emphasizes high sensitivity near 290 nm and freedom from stray radiation has many similarities with the system developed by Karl Norris of the Instrumentation Research Laboratory, USDA, Ref. 4-1.

This section will describe the spectroradiometer in considerable detail, including the nature and characteristics of the major subsystems and accessories. The system can be operated manually or automatically from a programmable calculator. Since the system will be used primarily in the automatic mode, the programs and related software are of such importance that they will be discussed in depth in the following section.

A.   GENERAL DESCRIPTION

The ultraviolet spectroradiometer system is shown in Figure 4-1. With the exception of the Hewlett-Packard calculator the components form a system built up by Gamma Scientific. The double monochromator, model NM-9, and attached photomultiplier tube receives the incoming radiation and generates an intensity signal. This signal is processed by the digital radiometer, model DR-1, and transmitted through Gamma and HP interfaces to the calculator. A wavelength drive and wavelength sensor in NM-9 cooperate with the wavelength controller, model NM-3, to advance the wavelength control to selected values and to display the wavelength information and transmit same to the calculator. The calculator performs the dual function of system command and data processing. For a better understanding of the following description refer to the block diagram, Figure 4-2, and the optical diagram, Figure 4-3.
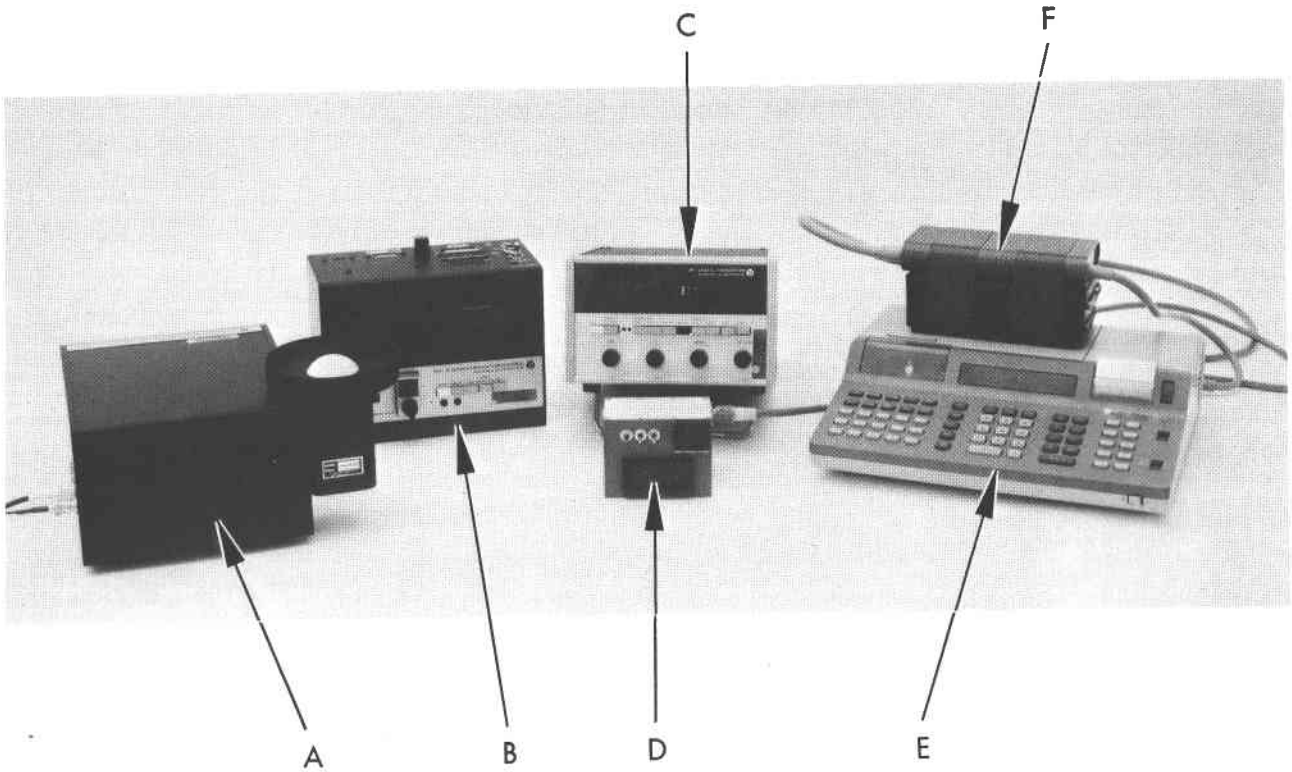
A. NM-9 double monochromator with cosine-corrected receptor

B. NM-3 wavelength controller

C. DR-1 digital radiometer

D. Interval timer

E. 9815A calculator

F. Calculator-to-system interface

Figure 4-1. Ultraviolet spectroradiometer components
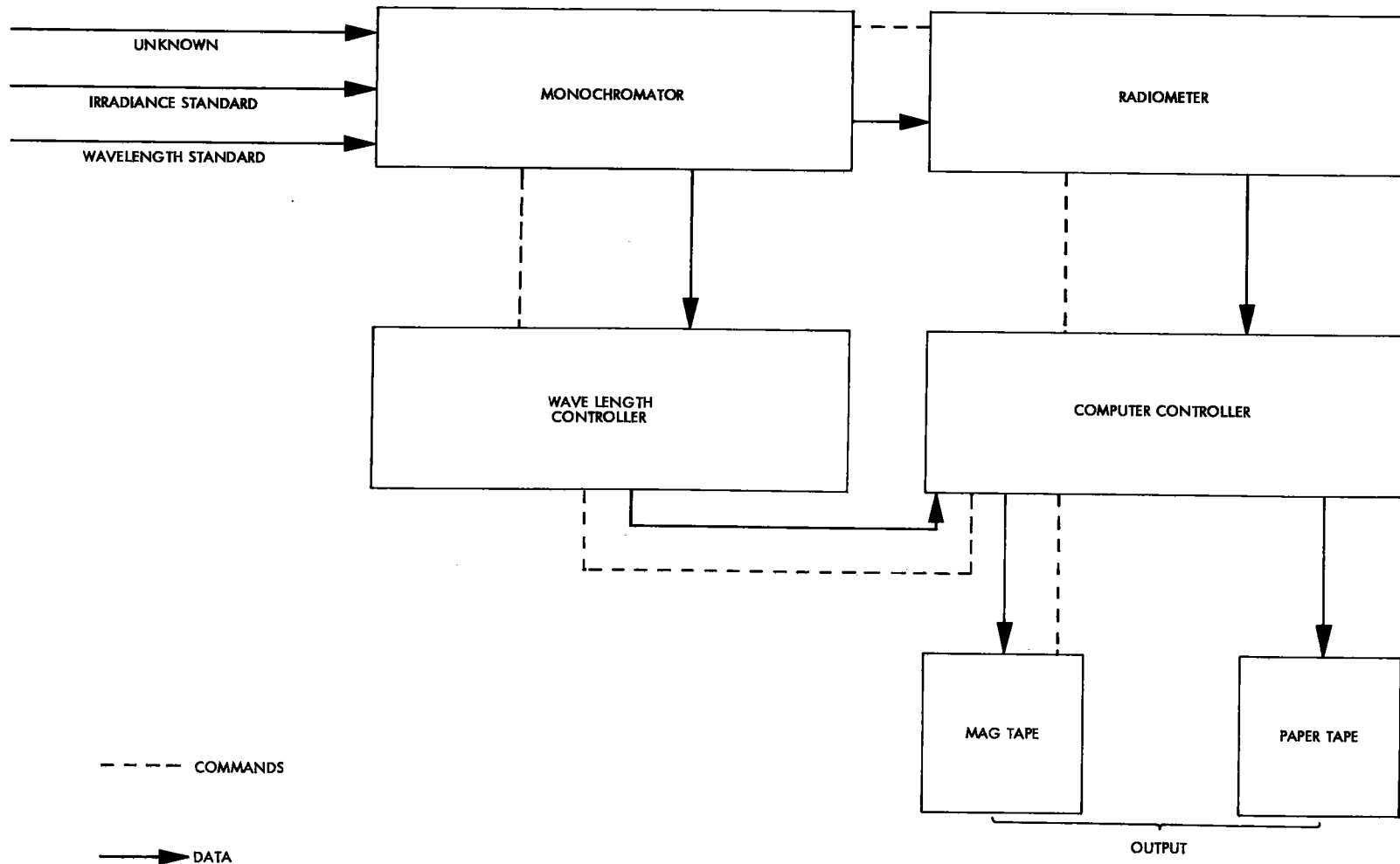
Figure 4-2. Ultraviolet spectroradiometer system block diagram

CONCAVE HOLOGRAPHIC
GRATING 27.5 x 27.5 mm
1200 g/mm

INTERMEDIATE SLIT 0.5 mm

R106UH PMT

ELECTRIC SHUTTER

EXIT SLIT 0.5 mm

REFERENCE CALI-
BRATOR WITH 47B
FILTER

93.9 mm

100 mm

100 mm

93.9 mm

ENTRANCE SLIT 0.5 mm

ND FILTER

CONCAVE HOLOGRAPHIC GRATING
27.5 x 27.5 mm
1200g/mm

INCIDENT RAYS

Hg LAMP PORT

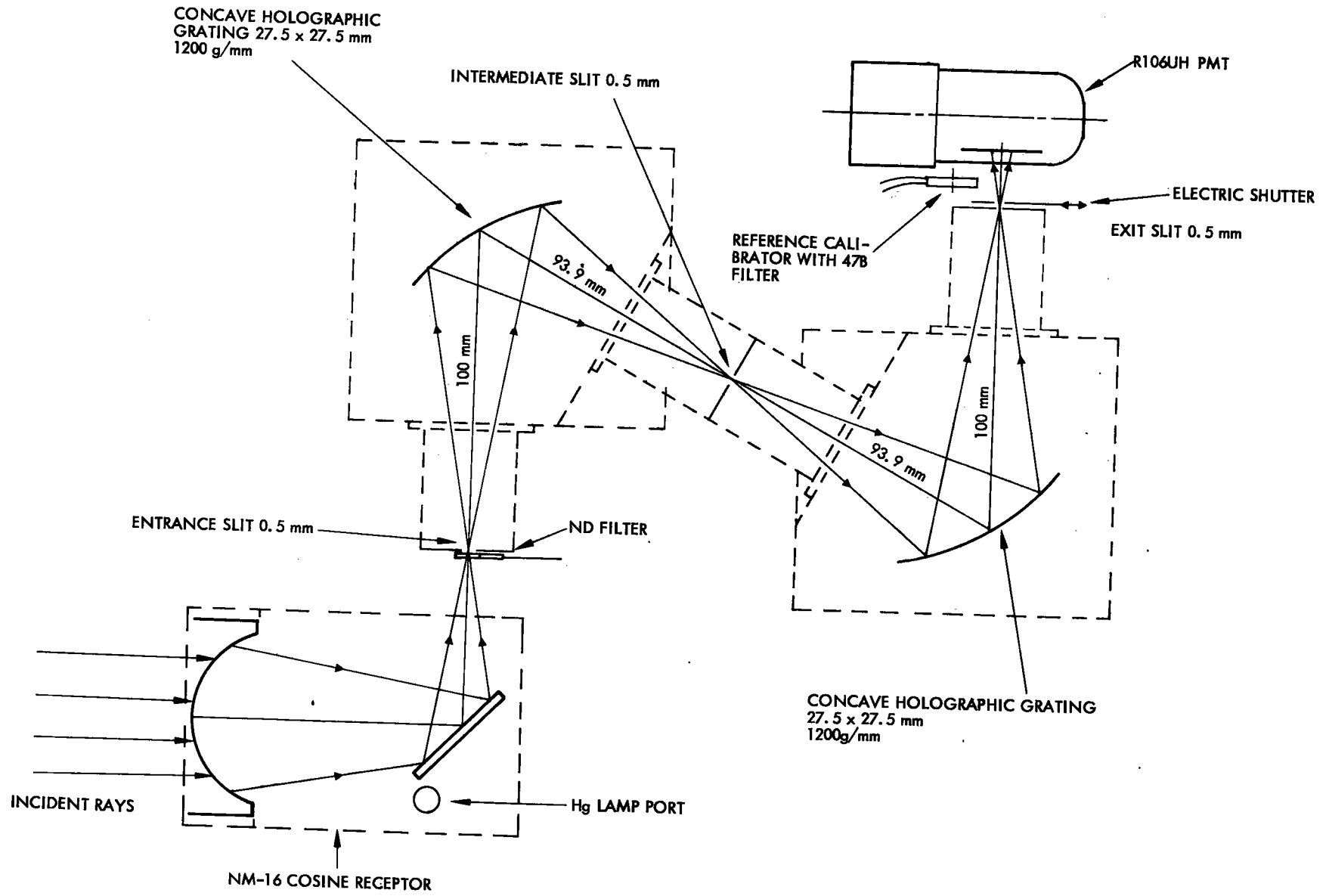NM-16 COSINE RECEPTOR

Figure 4-3. Ultraviolet radiometer optical diagram

B.   SPECIFICATIONS

Gratings: Two holographic-recorded, aberration-corrected.

1200 grooves/mm   4 nm/mm reciprocal dispersion
100 mm radius of curvature   Stray light $<10^{-7}$
F/3.5 aperture   Ghosts $<10^{-10}$
2.1 nm half power bandwidth

Wavelength Specifications:

Calibration: 5 mercury lines 254-436 nm
$\pm$0.15 nm accuracy
$\pm$0.1 nm readout and least count
Scan range 250-398 nm in 2 nm steps

Electrical Specifications:

PMT high voltage 350-1650 volts

Signal current 1 x 10^{-9} to 1 x 10^{-6} A full scale with
extension to 1 x 10^{-3} A (equivalent) by
neutral density filter

Dark current suppression >11 na

Electric shutter and internal calibration lamp
PMT Cs-Sb cathode, Hamamatsu type R10GUH

Programs:

Make a working tape
Store standard irradiance values
Perform wavelength calibration
Calculate throughput factors
Measure unknown source

C.   INPUT OPTICS

The input optics is a device identified with the label "NM-16 Cosine
Receptor" in Figure 4-3. This device receives the incoming flux on the dome-
shaped reference surface and delivers the flux to the entrance slit in a manner
to fill the F/3.5 entrance cone of the monochromator. Because the source may
cover either large or small field angles, it is important that the input optics
be cosine-corrected, that is, a ray bundle at any angle to the axis and measured
from the reference plane must deliver flux to the entrance slit in an amount
proportional to the cosine of the angle between the ray bundle and the optical
axis.

Two input devices are supplied. The larger is a Teflon dome-shaped diffusing element and an equatorial diaphragm in a mount which attaches directly to the input port of the monochromator. The smaller cosine head, not shown on the diagram, is mounted in the end of a quartz optical fiber bundle which also attaches to the input port. The cosine error of the larger unit has been measured by the vendor and the results are shown in Table 4-1.

It should be noted that only at 85 deg does the error have an unreasonable value. The error reduction in the zone between 80 and 90 deg would be exceedingly difficult in anything less than a research-type device.

Table 4-1. Errors in model NM-16 Cosine Head

Ray Angle, Deg	Flux	Percent Error	Ray Angle, Deg	Flux	Percent Error
0	100.5	0.00	45	69.8	-1.78
5	100.2	+0.08	50	63.4	-1.86
10	99.0	+0.03	55	56.6	-1.81
15	97.0	-0.08	60	49.8	-0.90
20	94.2	-0.25	65	43.2	+1.71
25	90.5	-0.64	70	35.2	+2.41
30	86.0	-1.19	75	27.0	+3.80
35	81.5	-1.00	80	17.2	-1.44
40	76.0	-1.28	85	6.8	-22.37

D.   DOUBLE MONOCHROMATOR

The double monochromator, model NM-9, is represented in Figure 4-3 by the assembly of two gratings and three slits. The gratings, produced by J-Y Optical Systems, are of the concave reflecting type with holographically produced grooves. The design features unusual stray light reduction, elimination of aberration, particularly astigmatism, and maximization of throughput at 250 nm. The grating and slits are so disposed that the entrance and exit axes subtend a fixed angle of 61° 36" identified as 2ϕ. For this case of constant ϕ the grating equation is

$$\lambda = (2d \cos \phi) \sin \theta \text{ (Ref. 4-2)}$$

where

    d = grating space

    2ϕ = included angle subtended by the slits at the grating

    θ = angle rotated by the grating

    λ = wavelength passed by the grating

Each grating is rotated and the scale linearized by a lead screw and sine bar linkage. The two lead screws are connected to each other and motor driven through anti-backlash gearing. An attached ten-turn precision potentiometer serves as an angle-to-voltage transducer.

The photomultiplier, identified as model R106UH PMT, is mounted in the monochromator case. Adjoining the PMT cathode is a very small calibration lamp mounted behind a blue filter. With the adjoining shutter closed and the lamp on, the PMT can be calibrated under the anode voltage and other conditions prevalent at the time.

A neutral density filter is mounted in the case and located in front of the entrance slit. In this position it can be inserted in the beam when required to extend the intensity scale by three decades.

E.   WAVELENGTH CONTROLLER

The wavelength controller, model NM-3, supplies power and direction to the wavelength drive motor and filter actuators. The front panel contains fast-slow and forward-reverse wavelength controls. The 3½-digit digital panel meter converts the analog wavelength signal to a digital, but not direct reading, display. The conversion equation is

$$\text{True wavelength, nm,} = 250 + \frac{\text{Scale}}{10}$$

F.   DIGITAL RADIOMETER

The digital radiometer, model DR-1, comprises all of the circuitry needed to process and display the intensity signal.

Power supplies are provided to produce the high voltage for the PMT, adjustable from 350 to 1650 V. The voltage selected is read on the panel meter. A low-voltage supply provides dark current suppression and power for the calibration lamp. Either the lamp current or the generated lamp flux value can be controlled from the panel and read on the meter.

The intensity signal information is available as a BCD output at a 25-pin connector located on the back panel.

G.   CLOCK

In order to take full advantage of the system's automatic features, a clock is provided which, at thirty minute intervals, restarts the program to measure an unknown source. The clock program spans the twelve daylight hours and can be readily set to the local time of a test site or the applicable standard time. Note that the sunlight duration over the continental U.S. varies from 10.5 hours at latitude 25 deg in December to 17 hours at latitude 50 deg in June. The clock can be adjusted to extend the taking of data to an interval greater than twelve hours if desired.

H.   CALCULATOR

The control center of the Gamma spectroradiometer system is the Hewlett-Packard model 9815A calculator and related components. Commands are managed and signal processing is controlled by programs prerecorded on cassette tape. Data and constant values can be printed out on command. The passage of commands and data signals between the spectroradiometer and the calculator is facilitated by the HP and Gamma interfaces. These details are shown in the block diagram, Figure 4-2.

The calculator, per se, is operated by seven special purpose keys to initiate the various program segments. All program details are derived from a master tape. The calculator, including its core memory, is used to prepare a working tape which issues commands and stores constants and data.

I.   SYSTEM

The entire system is assembled into two subsystems, the monochromator subsystem and the control and readout subsystem. This situation is demonstrated in Figure 4-4. The monochromator can be mounted outdoors or close to a laboratory source as required. Sixty-five feet of cable is available to connect with the other subsystem which is assembled on a roll cart.
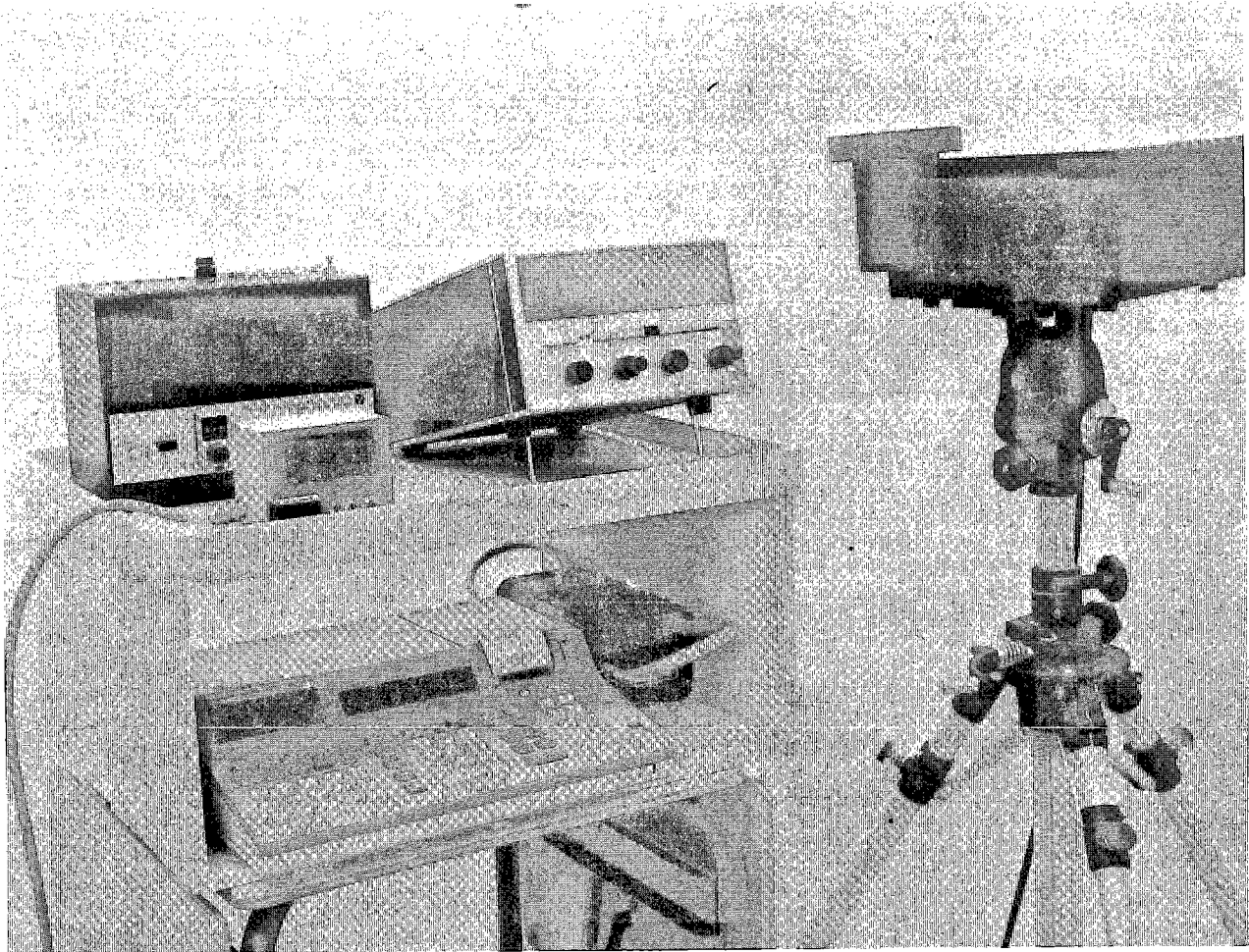

Figure 4-4. Ultraviolet spectroradiometer system

SECTION V

PROGRAMS/SOFTWARE

The calculator controls the spectroradiometer through programs prerecorded on digital magnetic tape cartridges and loaded into the working memory of the calculator. All of the programs, constant values, data and computed results are contained in two tape cartridges.

The master tape contains all of the program details plus a tabulation of the spectral irradiance values associated with the standard lamp used in system calibration. The working tape is made from the master and has transferred to it all of the program details. In addition, the working tape contains the wavelength correction, the instrumental calibration factors relating to throughput, and values of the internal calibrator lamp flux obtained with the instrument calibration.

The flow diagram, Figure 5-1, shows in a functional way the technique by which the working program performs the essential functions of self-calibration and data processing.

Special function keys on the calculator keyboard call up the various programs on the master or working tape as required. The details of these sub-programs are discussed below with the aid of the operating manual, Ref. 5-1. Once the program is completely understood, changes to increase its usefullness or other modifications can be made at will.

A.   MASTER TAPE

The function keys give access to the following subprograms:

1.   Key A: Make a New Tape

This program will copy the necessary routines to create a working program on a new digital tape. In so doing, a large number of files will be marked for the subsequent accomodation of data runs.
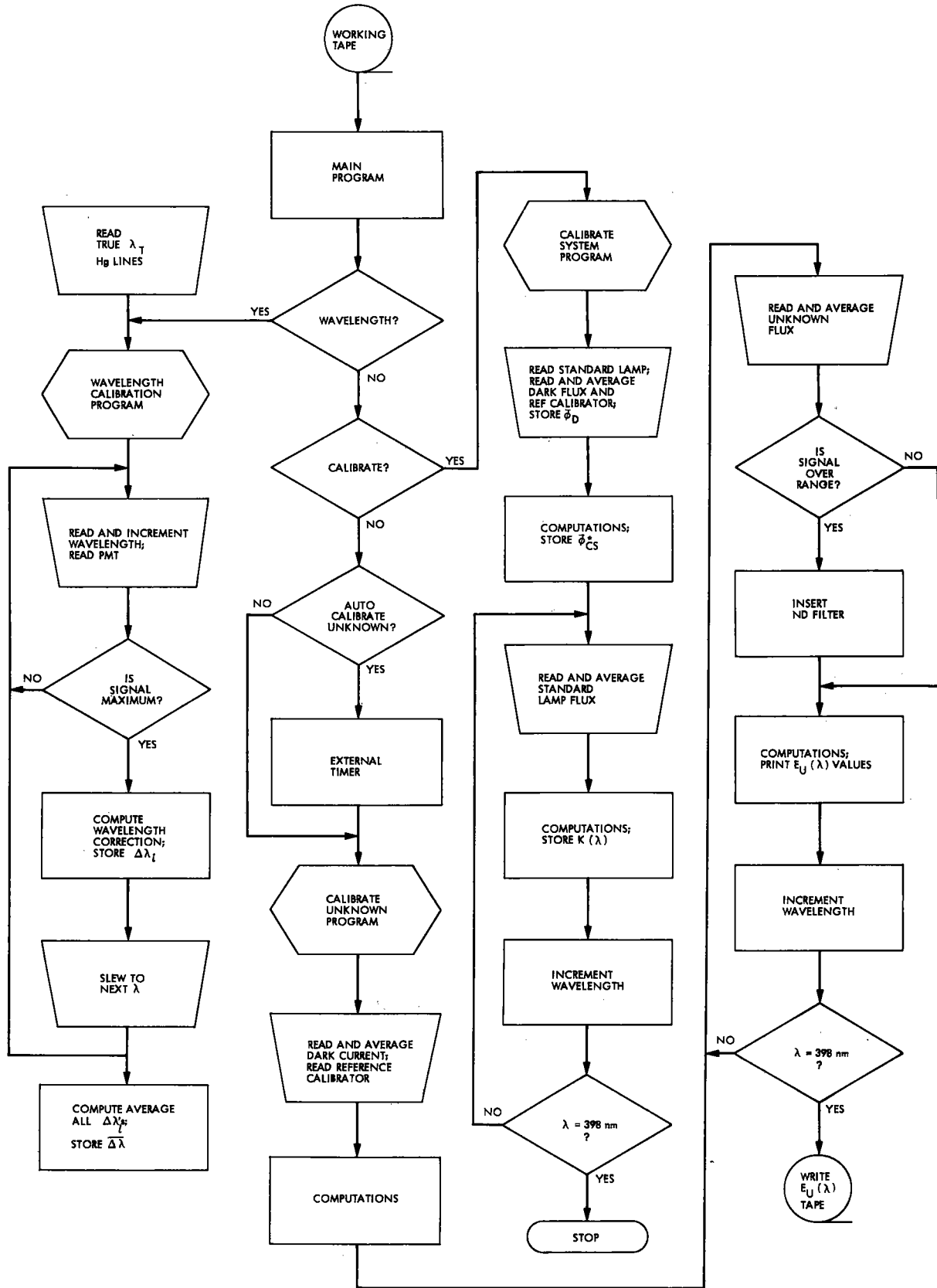
Figure 5-1. UV spectroradiometer system
flow diagram

2.   Key F: Input Standard Values

This routine allows the user to enter new spectral irradiance values defined in μW cm^{-2} nm^{-1} and representing certificate values of a suitable lamp standard. When seventy-five consecutive values have been entered in the working memory, the program will automatically transfer the irradiance and wavelength values in the correct format to the master tape file 3.

3.   Key K: Read Data Off Tape

By proper procedures this program can be used to list the standard values on the master tape, the calibration values or unknown run data from the working tape.

4.   Key O: Transfer Standard Values

This program is used to revise the standard values previously loaded on the tape through the use of Key F.

B.   WORKING TAPE

Using Key A with the master tape in the machine the working tape is generated. With the working tape in the machine the same special function keys call forth entirely different routines.

1.   Key A: Wavelength Correction

In setting up the instrument with the working tape the first step is to calibrate the wavelength scale against the line spectrum of a small low-pressure mercury lamp inserted in the cosine receptor as shown in Figure 4-3. Using key A (working), the system is programmed to seek out in turn the spectral lines at 253.6, 296.7, 313.2, 365.9, and 435.8 nm. The maximum signal is observed and the wavelength scale reading noted. The offset correction is computed for each line and the five offset values averaged and stored on the working tape where it remains until replaced by a subsequent wavelength calibration.

2.   Key F: Recalibrate

This program determines the instrument calibration coefficients to be applied in the "Unknown Run" program. The calibration factors, identified as $K(\lambda)$, are associated with throughput (including the effect of the input optics employed) and with photomultiplier gain. The gain is identified with the flux from the internal calibrator lamp measured during the execution of this program.

3.   Key K: Unknown Run

This program controls the instrument and computes the absolute spectral irradiance of an unknown source measured at 2 nm intervals from 250 through 398 nm. The program can be run from the calculator keyboard or can be rerun at intervals from an external signal. The program begins by loading the following from the working tape into the calculator:

Calibration coefficients $K(\lambda)$

Neutral density equation

Wavelength offset

Calibration lamp flux from program F

Following the assembly of the above constants, the measuring process starts by measuring the dark current and the calibration lamp flux. The monochromator is then set to 250 nm and advanced in 2 nm intervals. The raw signal is processed and the result printed out in absolute units. If the signal at any wavelength reads more than 1800 on the panel meter, the neutral filter drops in and decreases the panel meter reading by about 1000, thus extending the range by three decades. Since the netural density is slightly wavelength dependent, the program computes each proper filter value. The filter drops out of the beam when the panel meter reads less than 15. After the unknown run is completed and the absolute spectral irradiances printed out, the results are transferred from the calculator to an assigned file on the working tape.

C.   INTERFACE WITH COMPUTER TERMINAL

The working tape has about 150 files each large enough to contain an unknown run. In order to convert this information to a form acceptable to a

large computer, such as the 1108, it is necessary to read the data from the cassette through the calculator and a RS-232-C serial interface into a terminal such as HP Model 2645A Display Station. Alternatively the data can be key punched on cards and transferred to large tape reels.

SECTION VI

EXPERIMENTAL MEASUREMENTS

The preceeding sections discuss radiation sources, both natural and man-made, and also discuss the instrumentation by which ultraviolet spectral measurements are obtained. The use of the ultraviolet spectroradiometer is a program which will continue beyond the publication date of this report. Consequently, this section will contain current rather than long-term measurements of solar and artificial ultraviolet radiation.

A. MEASUREMENT ACCURACY

The accuracy of the various source measurements described in this section is limited by four major factors: lamp standard, calibration current, projection distance instrument-to-source, and line voltage at the source.

The lamp standard, as stated in Section III, has an uncertainty of about 2 percent and this figure is beyond our control. Uncertainty in the location and orientation of the lamp standard with respect to the cosine-corrected receptor also introduces small errors which are difficult to evaluate. At the standard distance, 50 cm (19.7 in.), the longitudinal error is about 10 percent per in. The measured spectral irradiance is somewhat less sensitive to small transverse displacements. The lamp current can be easily maintained to ±0.005 A and this degree of current control is sufficient. Measurements with the lamp standard require particular care because they represent a calibration which is transferred to the working tape and will affect all subsequent measurements made therewith.

A calibration lamp located just in front of the photomultiplier tube generates a standard value of flux controlled by the selected lamp current. The flux during calibration is stored on the working tape and is used by the calculator to account for choices in high voltage settings as they occur. In each test of an unknown source the calibrator lamp current must be set to the exact value used in the working tape calibration, otherwise the computed irradiance values will be in error. In a typical case the calibrator current can be read to 0.15 percent on the digital panel meter. The power supply controlling the calibrator is regulated to better than ±0.01 percent with temperature regulation better than ±0.01 percent per °C. With 400 V on the photomultiplier and the calibrator current near 0.95 mA the flux sensitivity is about 0.5 percent per μA.

Since the equipment will be used for solar measurements primarily, two points germane to that task should be noted. When the monochromator is exposed to direct sunlight for any length of time the resulting temperature rise alters the dark current and the anode sensitivity of the PMT. These changes are monitored by reading the PMT signal from the calibration lamp flux and by reading the dark current. These values are obtained automatically at the start of each run and are used to correct the calculated spectral irradiance values for temperature drift. The second point relates to the error caused by the exceedingly steep curve of solar spectral irradiance in the vicinity of 300 nm. For example, over the 2 nm half-power band-width at 300 nm the signal changes by 191 percent. Consequently, to avoid results which are much too high, one must determine the slit function of the monochromator and the spectral responsivity of the detector and convolve these factors. For the system described in this report the experimental data are not available and published values must be relied upon. For these reasons NBS Optical Radiation News, April 1977, is quoting uncertainties of about 6 percent laboratory or 25 percent field for first class solar measurements at 300 nm.

Many unknown sources do not have a well-defined point from which to measure the projection distance accurately. For example, reflecting surfaces may have an influence or the source may have a radiant volume of appreciable size.

The variation of irradiance with line voltage depends on the type of source involved. Furthermore, in the field it is not always feasible to measure the voltage at the source. In the following reports on typical sources this parameter will be reported when available.

B.   STANDARD OF SPECTRAL IRRADIANCE

The standard of spectral irradiance is a tungsten-halogen lamp with calibration traceable to NBS. The spectral irradiance values recorded on the certificate are loaded onto the master tape. The corresponding signal values are measured by locating the cosine receptor exactly 50 cm from the reference surface on the base of the standard lamp.

The lamp, under the specified conditions, has been measured as an unknown and the two sets of irradiance values compared. This has been done and the percent error computed. In a single such experiment, thirty wavelength readings

were compared and produced a mean error of 3.7 percent with 1.5 standard deviation. If necessary this error can be reduced by more careful monitoring of the internal calibrator setting.

C. SOLAR MEASUREMENTS

The ultraviolet radiation from the hemisphere of sun and sky was measured under completely clear sky conditions on February 22 and 23, 1978. The instrument was located on the roof of building 125, Jet Propulsion Laboratory, in latitude 34°12' N. At the measurement site buildings obstruct the horizon to the west and an up-sloping hillside lies to the north. The highest obstruction (ridge to the north) projects 12 degrees above the horizon. The measurements were made with the input axis of the monochromator mounted vertically. This choice of instrumentation gives the best general representation of the sun and sky radiation.

Two typical solar spectra are shown in Figure 6-1. The spectrum labeled "1200 hrs" was obtained with sun at its maximum altitude of 45 deg. The other spectrum represents the late afternoon sun with 20 deg altitude. From the photochemical point of view the total energy in each waveband received over time is of prime importance. The energies per day have been computed and are shown in Table 6-1. Ten nm pass bands have been reported but two nm data are available.

The effect of radiation reaching a particular or representative group of solar panels or other exposed samples is more accurately characterized by measurements with the input axis of the monochromator oriented in a direction parallel to the direction normal to the related samples. Since the instrument has true hemispherical coverage, this slanted orientation causes the measurements to include all of the direct solar radiation, only part of the sky and a certain amount of solar radiation reflected from the terrain south of the instrument.

The data were recorded on the hour and half hour from 0911 hours to 1700 hours on the 22nd and from 0600 hours to 1600 hours on the 23rd. Readings at comparable times were averaged if available. Note that the Laboratory is at 118°10' W. longitude. Consequently, the local civil time is 7.3 minutes later than Pacific Standard Time. The present report uses PST and ignores this small
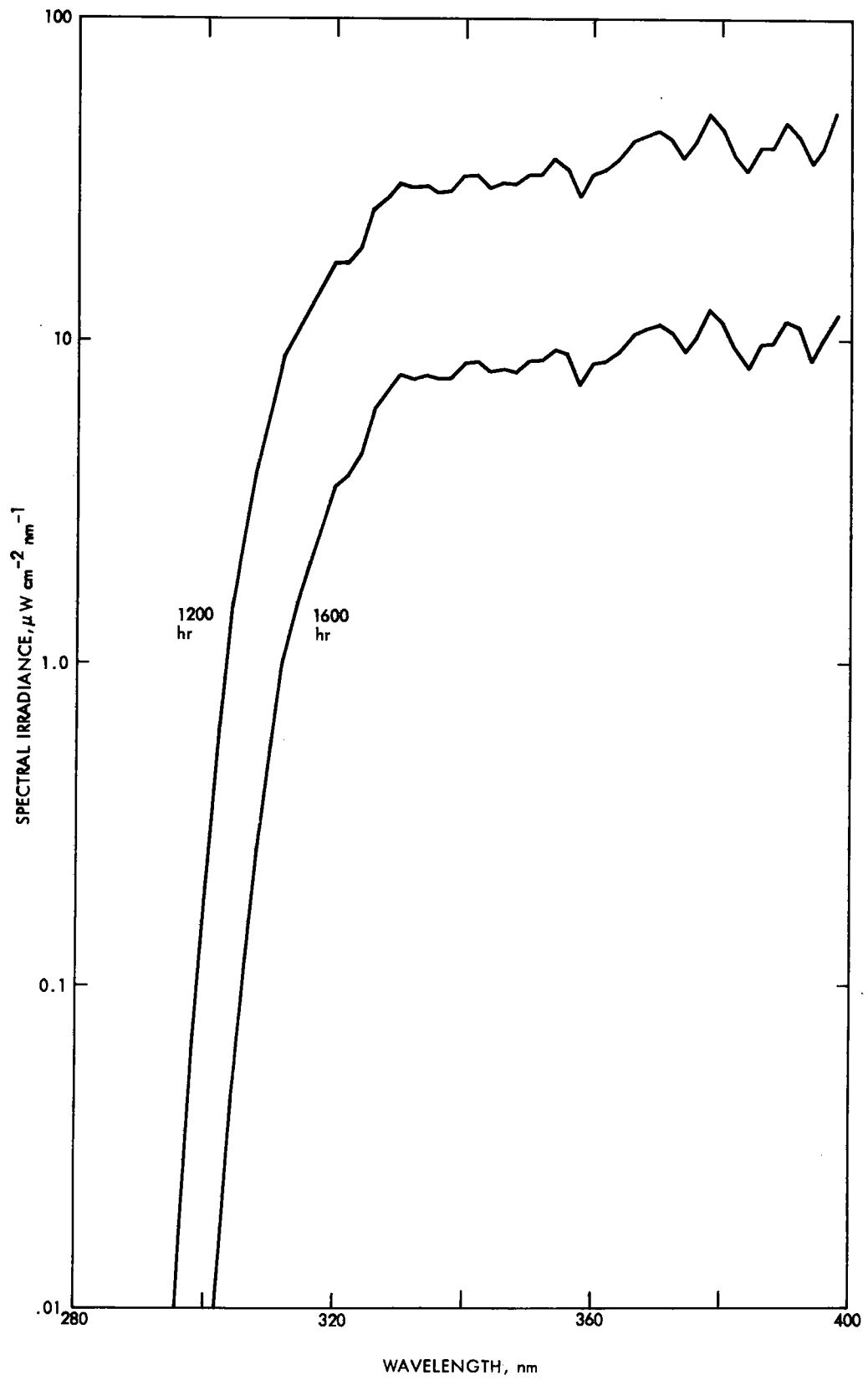
Figure 6-1. Representative solar spectra

Table 6-1.   Solar Energy Per Day Versus Wavelength

Wavelength, nm	Energy per Day, mW hr cm^{-2}
300-308	9.02
310-318	64.1
320-328	146.8
330-338	211.5
340-348	225.4
350-358	237.4
360-368	272.1
370-378	310.8
380-388	283.8
390-398	312.1

difference. Note that the irradiance values reflect the altitude of the sun observed over the course of the day. A plot of solar altitude versus time is shown in Figure 6-2. Note further that sunrise and sunset occurred at 0630 and 1745 hours respectively.
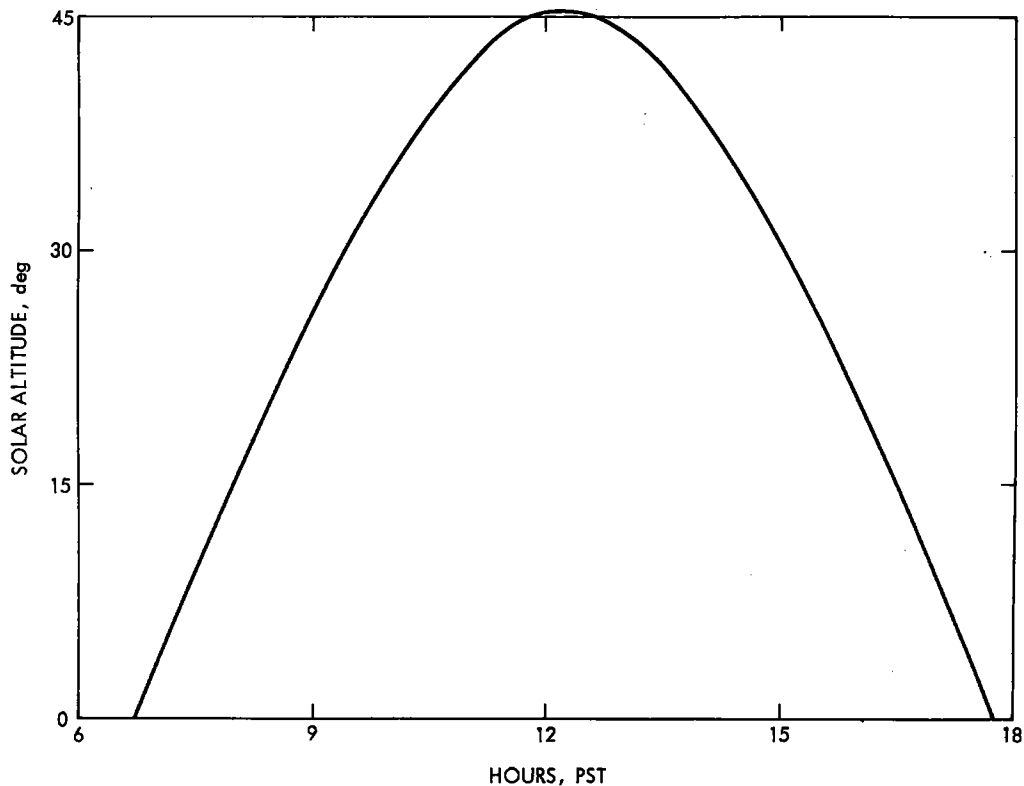
Figure 6-2. Altitude of the sun, February 22, 1978 at JPL

D. TYPE RS SUNLAMP

The design characteristics of this source are discussed in Section III. Tests on a single sample are presented below. The RS sunlamp is a mercury burner with a tungsten filament ballast, both components contained in a ultraviolet-transmitting glass bulb. The radiation is directed forward by an aluminum reflector integral with the inside wall of the bulb. Because of the directional properties of the reflector and its large diameter (5 in.) both spectral and spatial measurements are needed to characterize the source.

The spectral irradiance was measured at 17.5 in. from the front edge of the reflector (approximately center of the source) and the results are shown on the semilog plot, Figure 6-3. The shape of the curve clearly shows the short wavelength attenuation of the bulb glass.

The spectral irradiance at various distances along the axis was measured. The peak irradiance at 366 nm was normalized to the value at 17.5 in. and the flux versus lamp distance was plotted and is shown in Figure 6-4. The inverse square law is not obeyed in this region.

The transverse beam spread is symmetrical about the optical axis. Measurements have been made in a plane perpendicular to the lamp axis and 15 in. from the edge of the reflector which is on the inside of the bulb. The transverse measurements referred to the on-axis value are shown in Figure 6-5.

The lamp output is conditioned by line voltage. This effect has been measured and the percent change referred to the catalog value, 120 V, is shown in Figure 6-6.
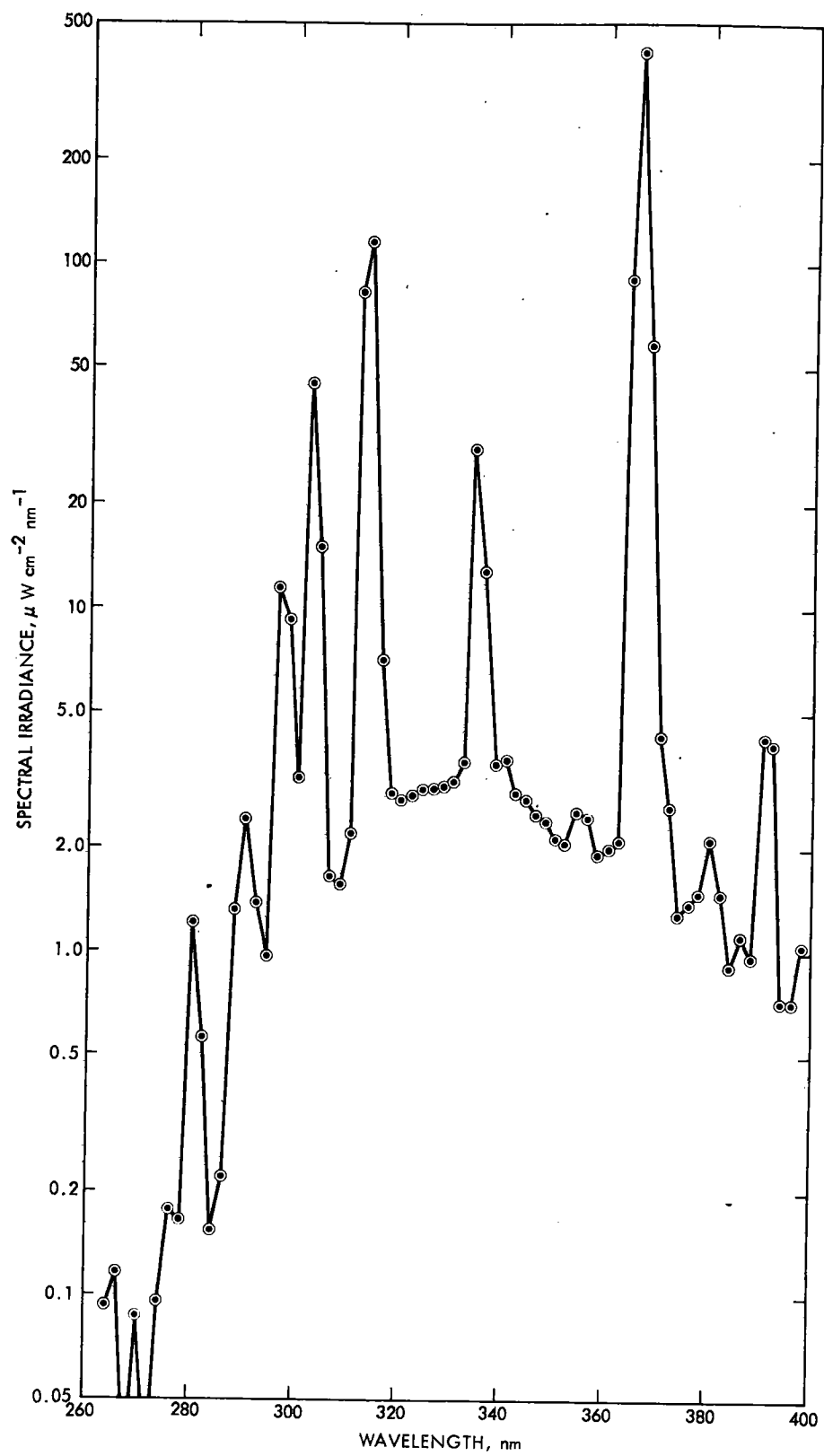
Figure 6-3.   Spectral irradiance of type RS sunlamp
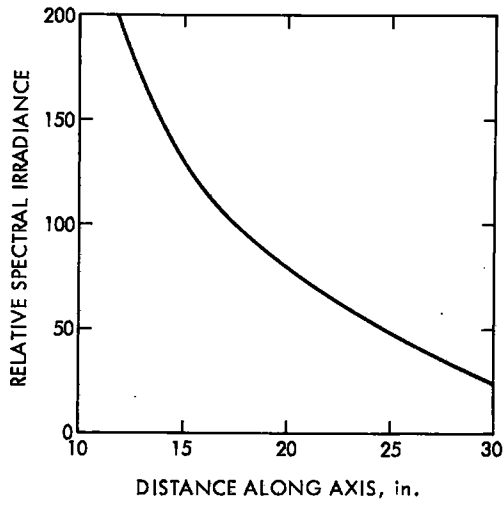measured at 17.5 in.

Figure 6-4. Irradiance on axis
vs. lamp distance

Figure 6-5. Transverse
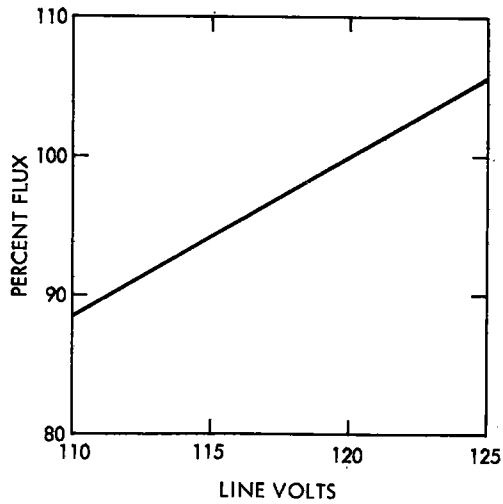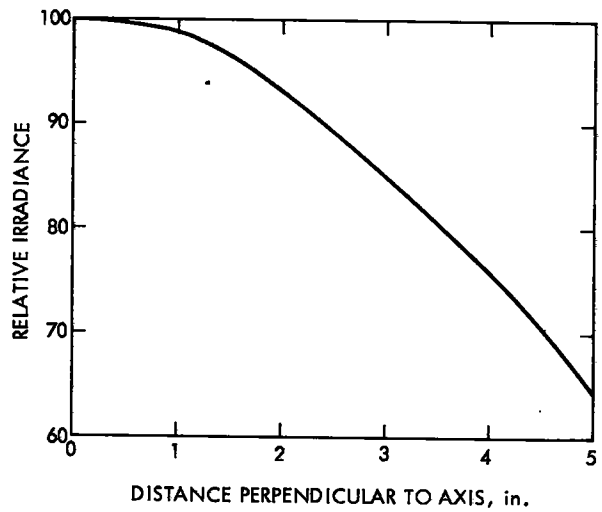irradiance of RS lamp
measured at 15 in

Figure 6-6. Output of RS lamp
vs. line voltage

E.   TYPE G15T8 GERMICIDAL LAMP

As measured, the lamp comprises two fluorescent tubes each 18 in. long and rated at 15 W mounted side by side in an enameled trough reflector. The reflector aperture is 4-1/4 by 18 in. The lamp unit was centered on the axis of the cosine-corrected head attached to the monochromator. The axis of the lamps and reflector was perpendicular to the optical axis.

When measuring the spectrum the lamps were located 16 in. from the diffuser and were operated at 119.7 V, 60 Hz. The data, expressed in $\mu W\ cm^{-2}\ nm^{-1}$, are presented on the semilog graph, Figure 6-7. This graph demonstrates in a spectacular way the extreme intensity of the 254 nm line relative to the rest of the spectrum.

The variation of irradiance with line voltage was measured and the results are presented in Figure 6-8.

The variation of irradiance with target distance was measured and the results are presented in Figure 6-9. Note that the lamps are tubular and present a long line source perpendicular to the optical axis. This configuration makes impossible the application of the inverse square law at any useful distance. .
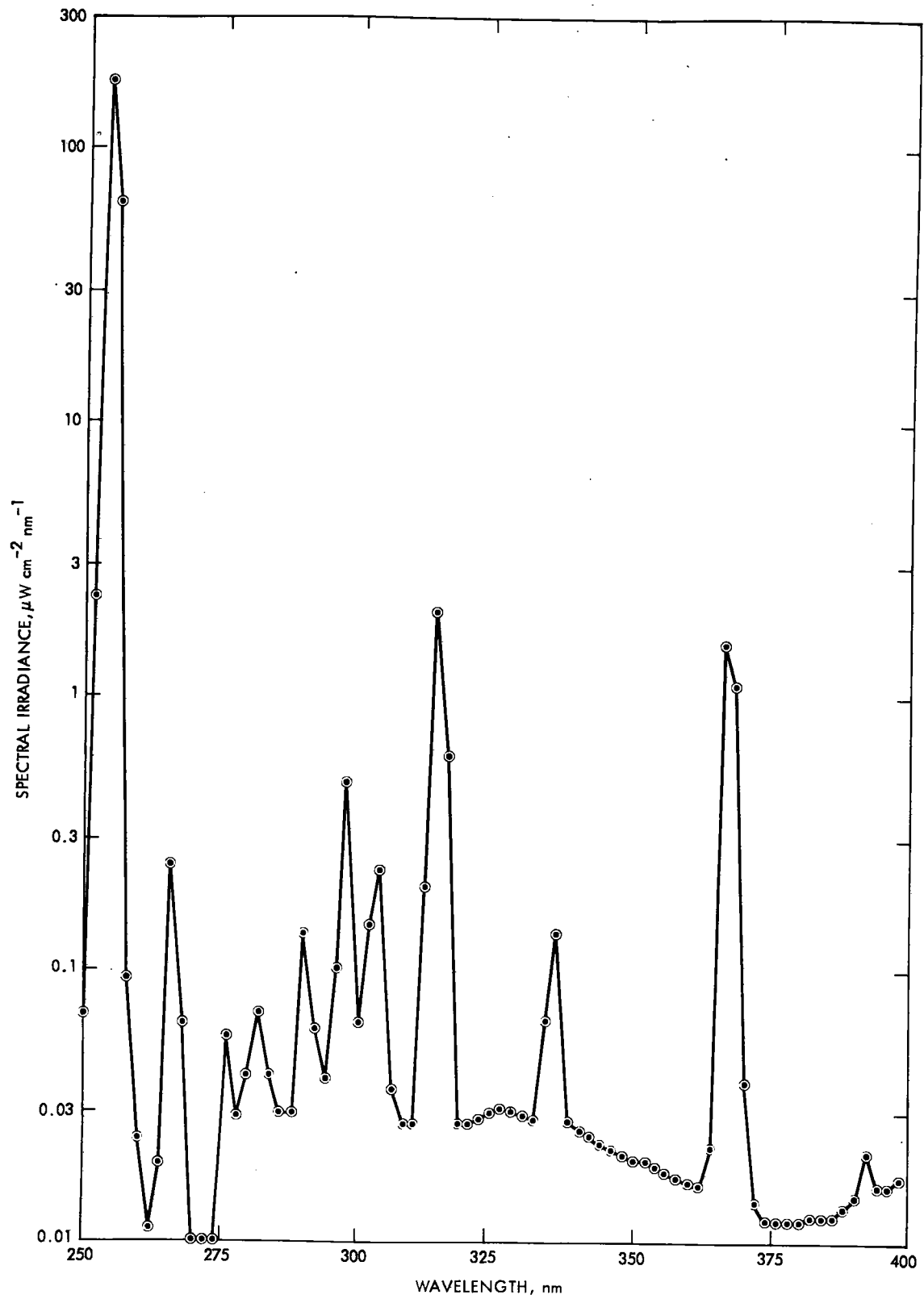
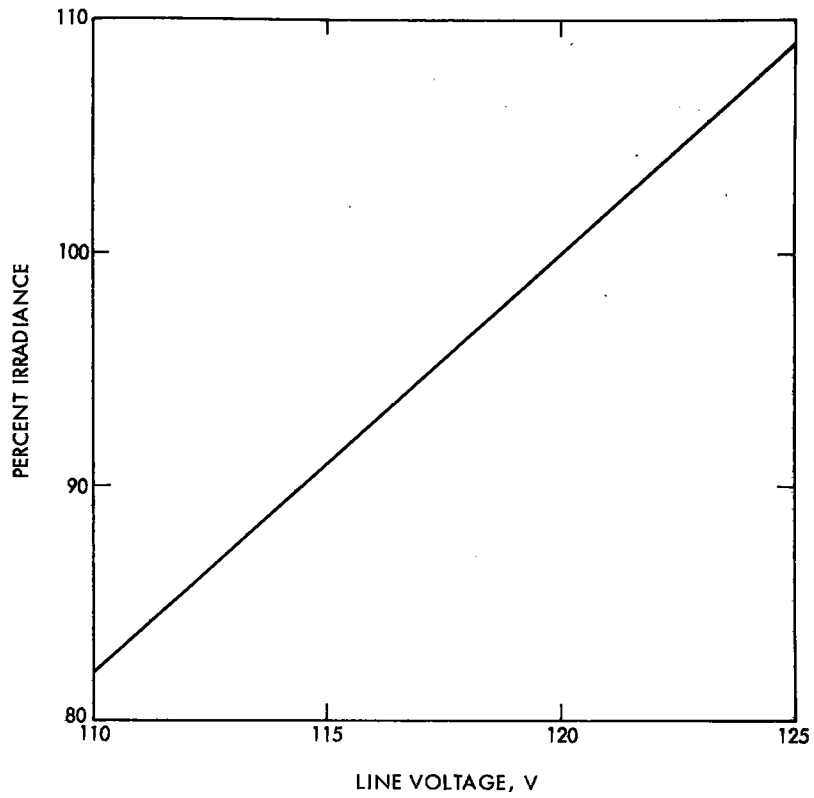Figure 6-7. Spectral irradiance of germicidal lamp at 16 in.

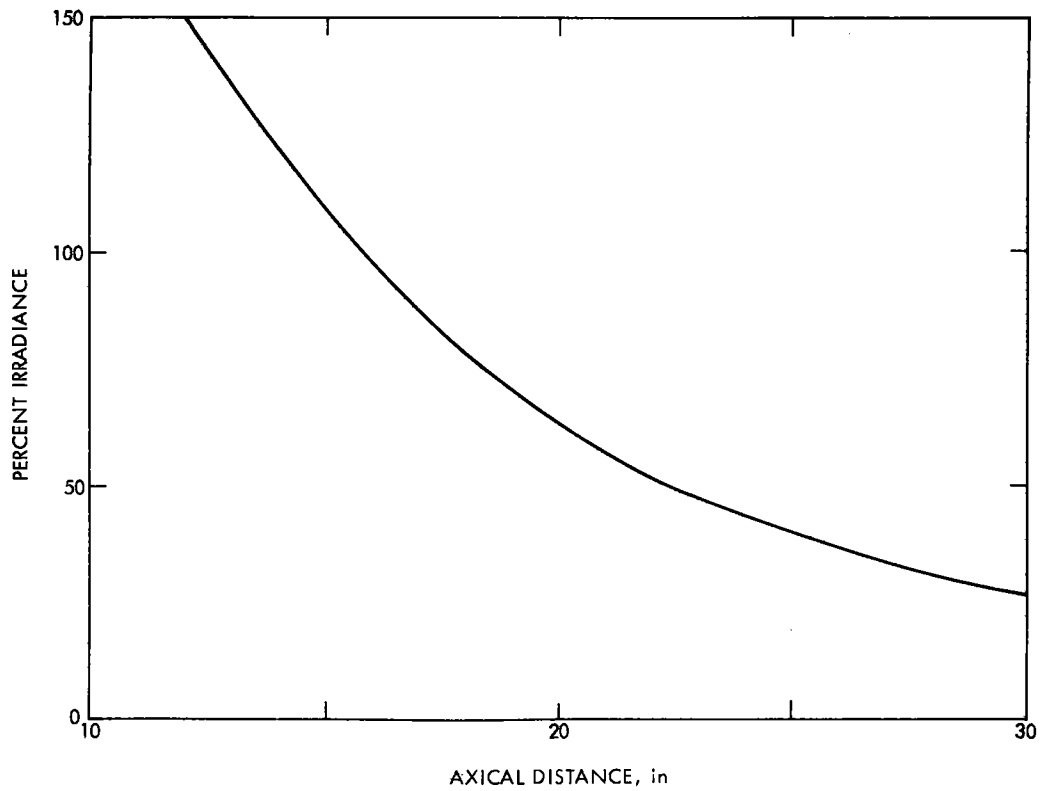Figure 6-8. Effect of line voltage, germicidal lamp

Figure 6-9. Effect of distance, germicidal lamp

F.   TYPE H39KB0175 MEDIUM PRESSURE MERCURY LAMP

This lamp comprises a short tubular quartz chamber mounted in a hard glass outer envelope. The lamp is operated at 120 V, 60 Hz in conjunction with a suitable ballast. The power rating, 175 W, refers to the lamp alone. Tests on a single sample are listed below.

The spectral irradiance was measured at various distances and at several line voltages. The spectrum at 15 in. from the source is shown in Figure 6-10. The effect of projection distance is shown in Figure 6-11 and the variation with line voltage is shown in Figure 6-12. In spite of the elongated configuration of the burner and the considerable effect of multiple reflections in the outer bulb, the source follows the inverse square law over the distances measured, as shown in Figure 6-11. Note that no appreciable radiation at wavelengths shorter than 290 nm gets through the hard glass outer bulb.

G.   BEMCO SIMULATOR (XENON SOURCE)

The Bemco simulator comprises a 5 kW G.E. xenon concentrated arc lamp in a stainless steel-lined cubical enclosure. The lamp is centered in the cube and the sample distance is about 18 in. Because of limitations imposed on the experiment by the lamp hazard and other circumstances, the data obtained in this study was somewhat limited. Measurements were made at one electrical setting, namely 115 A, 28 V, and at two distances, 37.5 and 76 in. The spectrum at 37.5 in. is shown in Figure 6-13. The significant portion of the solar spectrum, copied from Figure 6-1, is also shown.

Using measurements at 76 in., the conformance to the inverse square law was investigated. Note that true point source conditions do not obtain because of the flux contributed by multiple reflections from the chamber walls. Nevertheless, using the 76 in. measurements as reference and the measured flux at 37.5 in., we can estimate the irradiance at the sample distance to be 4 times the values shown in Figure 6-13 with about 10 percent uncertainty. Realizing that better data may be needed, the Bemco simulator will be remeasured soon.
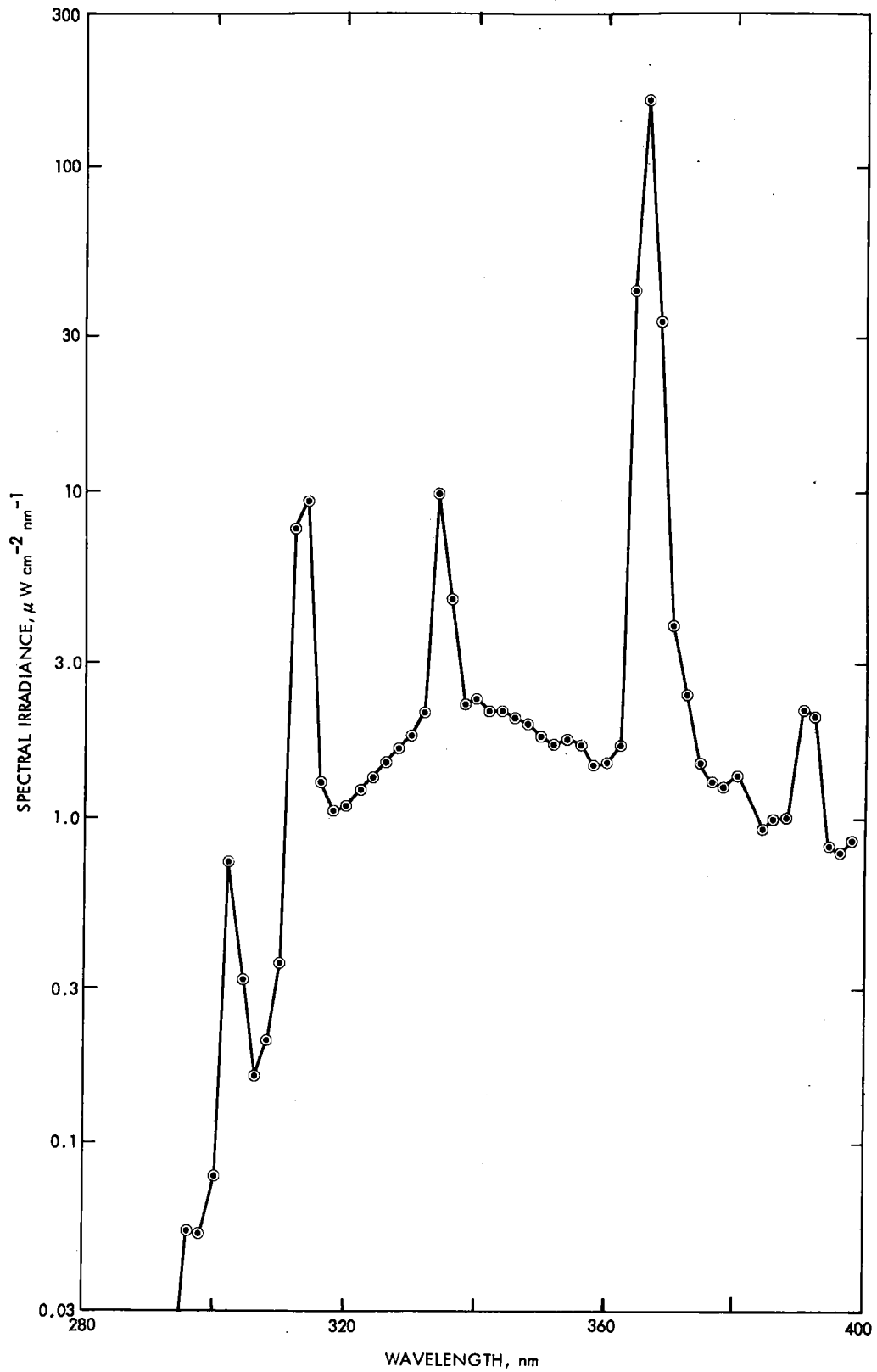
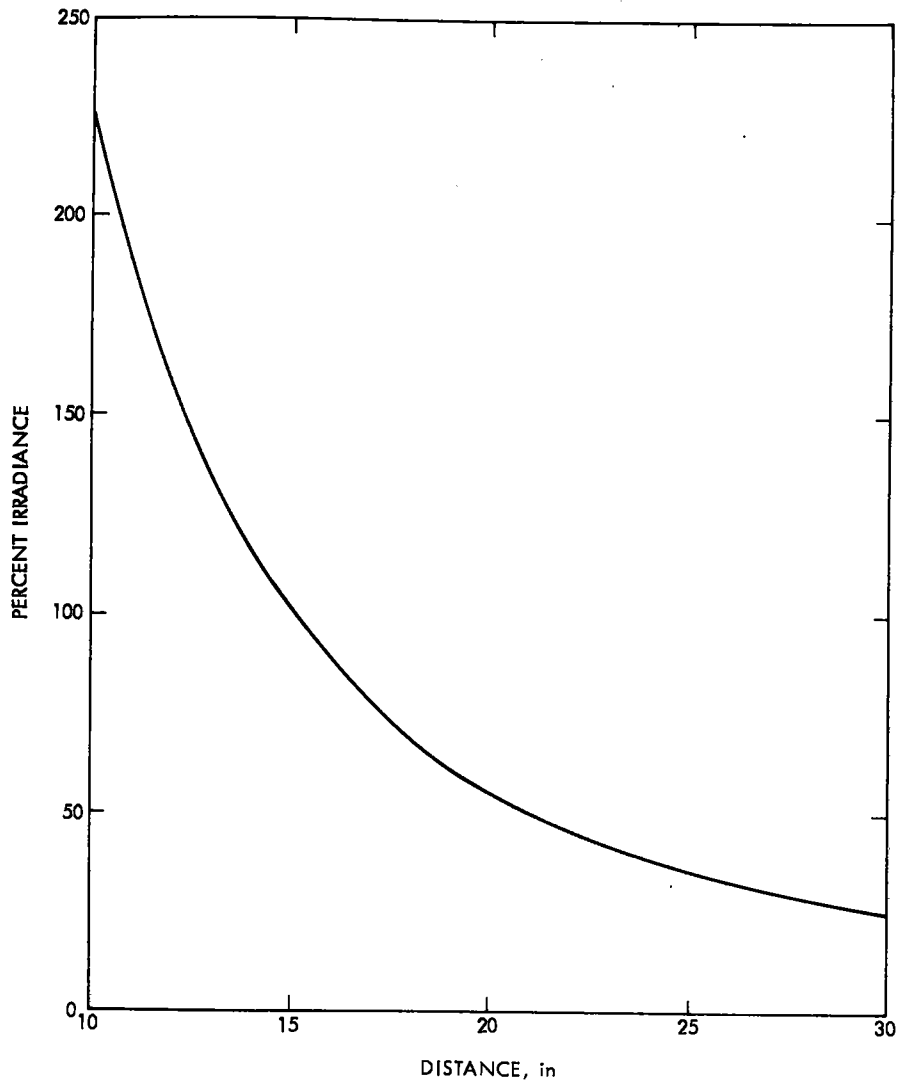Figure 6-10.   Spectral irradiance of medium pressure mercury lamp

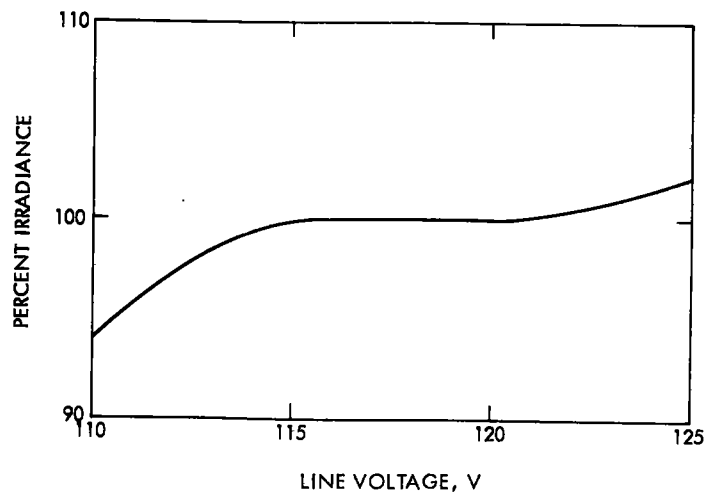Figure 6-11. Effect of distance, mercury lamp

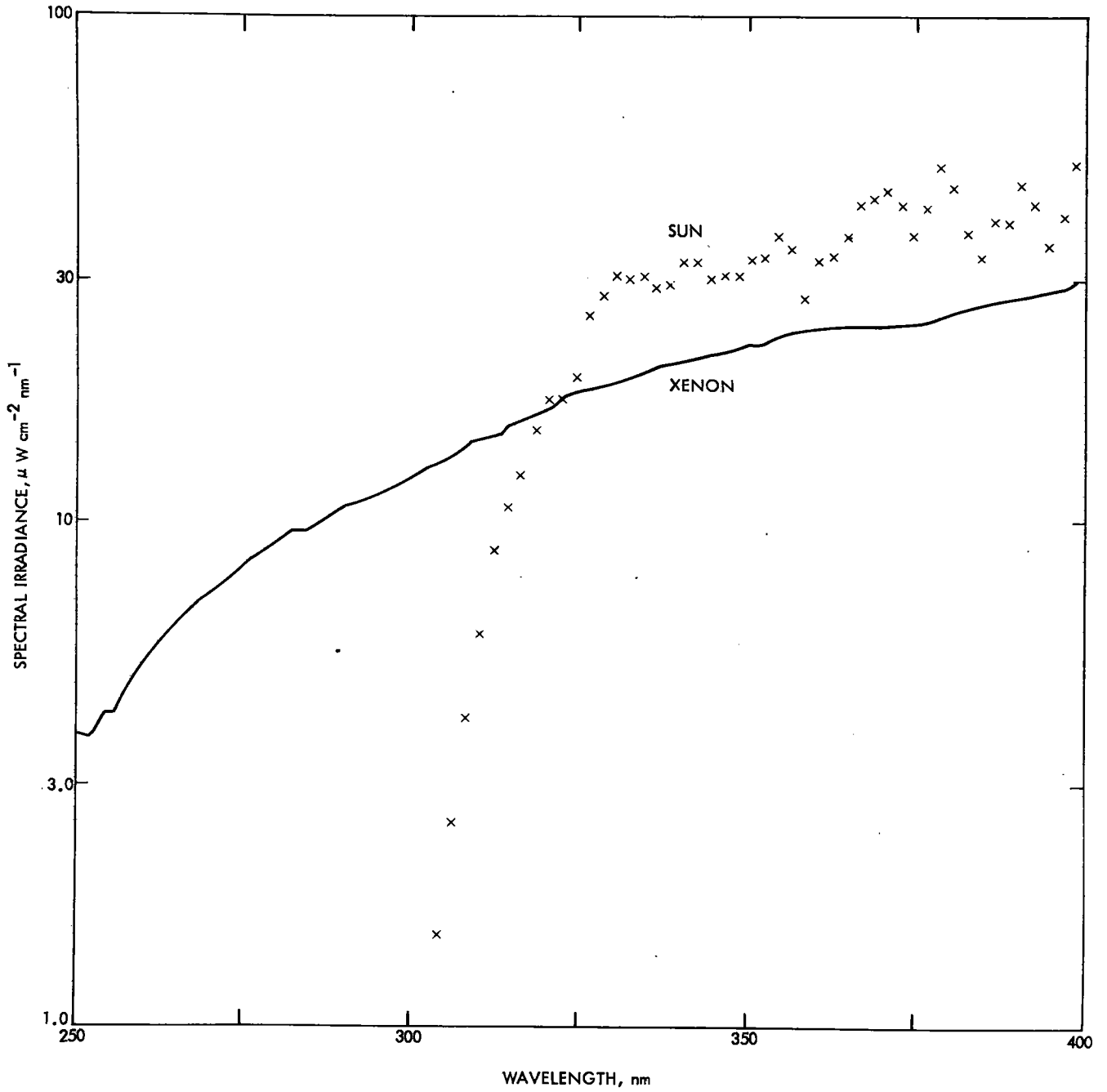Figure 6-12. Effect of line voltage, mercury lamp

Figure 6-13. Spectral irradiance of Bemco simulator

H. WEATHER-OMETER UNIT (ENCLOSED CARBON ARC)

Two carbon arc sources generating ultraviolet are in common use for testing materials. These are a flame arc using specifically impregnated carbons to enhance various ultraviolet passbands and an arc enclosed in a borosilicate glass globe. This enclosed arc burns carbons which are neutral in composition. The freedom from impregnation and the glass enclosure produce a source with a cutoff approximating sunlight. The following discussion relates to the enclosed type of arc source.

The following measurements were made on a Weather-Ometer made by Atlas Electric Devices. Two enclosed arcs mount side by side in a 30-in. diameter rotatable drum which holds the samples. The lamps are mounted 10 in. apart with 4 in. vertical separation. Each carbon set comprises one upper and two lowers. The arc contact with the upper carbon is steady but the arc plays at random onto the two lowers, thus producing some unsteadiness in the output radiation. The globe surrounding the arc flame gradually becomes coated with a film of ash particles which obstructs some radiation and must be cleaned off daily.

The spectral irradiance at 14.5 in. from each of the two arcs measured with clean globes is shown in Figure 6-14. The spectrum of noontime sun, copied from Figure 6-1, is also shown. The angular distribution of irradiance normalized to the average value is shown in Figure 6-15.

Analysis of the data obtained indicated that the twin arcs fluctuated in output to such a degree that the attenuation of dirt on the globe was too small to measure in a single comparison. Multiple measurements treated statistically would be necessary in order to obtain a meaningful value of attenuation due to dirt.

During the measurements the voltage across one arc plus ballast varied from 225 to 235 V. The current through one arc varied from 15 to 18 A.
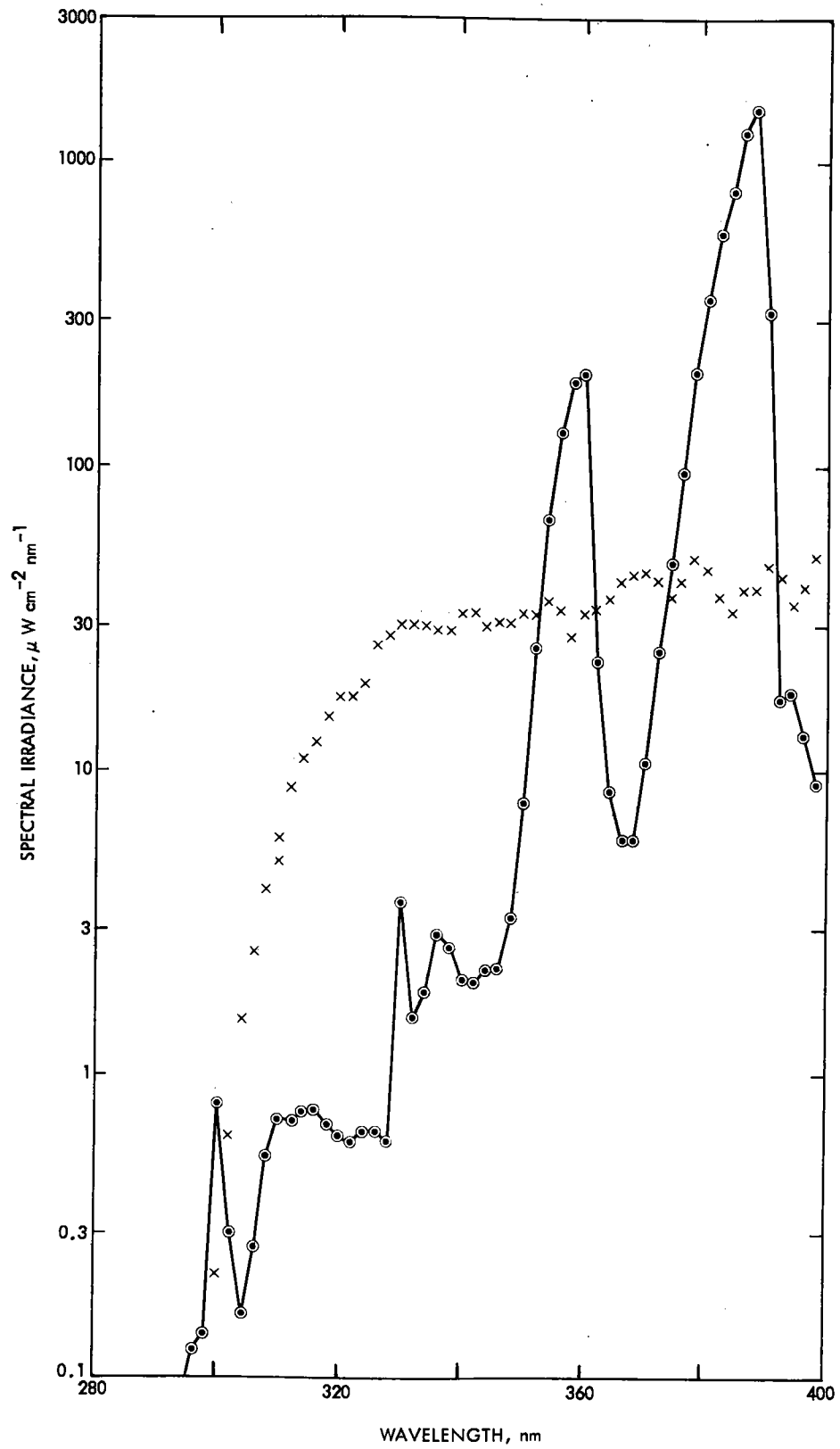
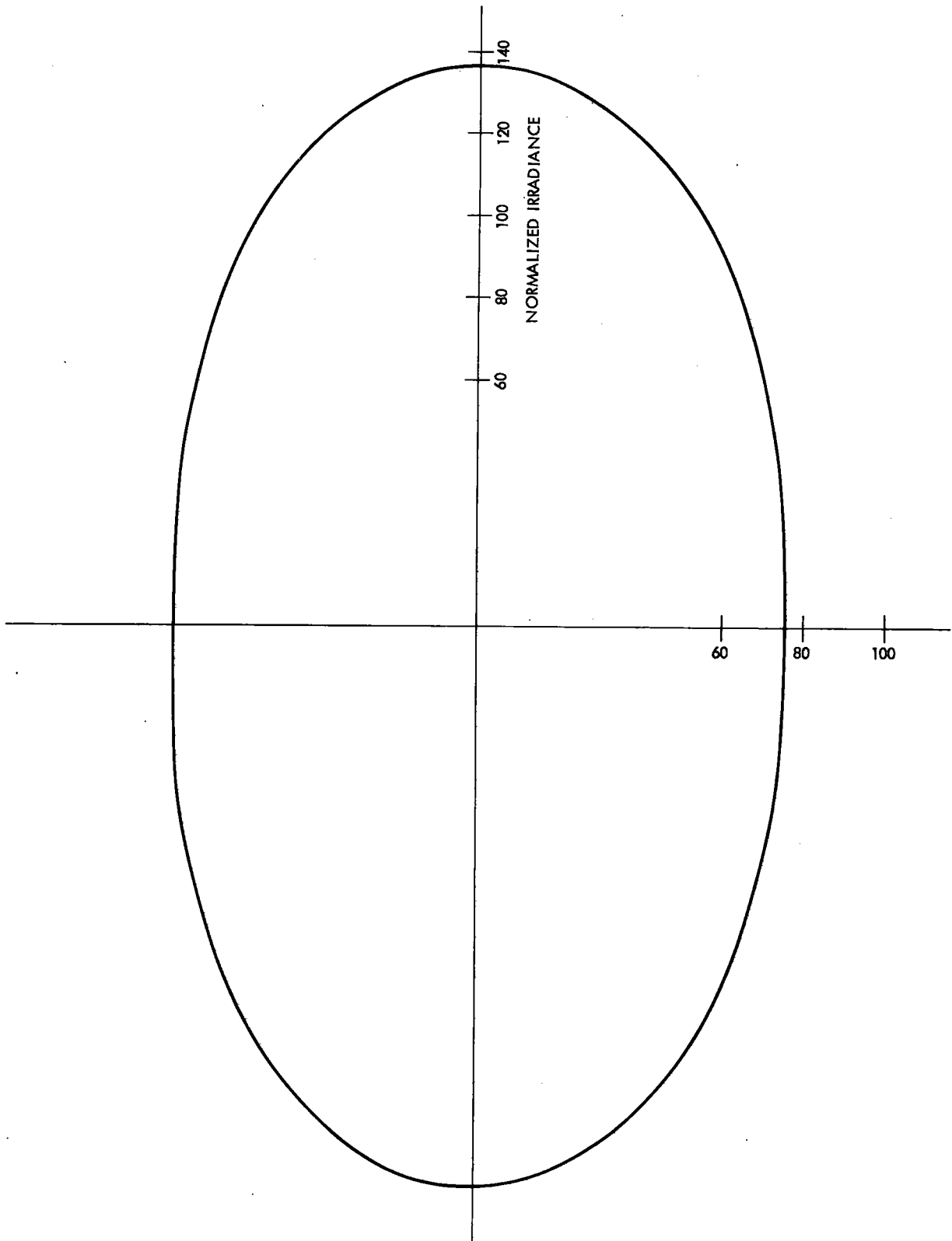Figure 6-14. Spectral irradiance of enclosed carbon arc

Figure 6-15. Profile of irradiance in the horizontal plane

SECTION VII

CONCLUSION

This report has described significant ultraviolet characteristics of solar radiation and that from artificial sources. The data gathering instrumentation has also been described.

Over the long term, solar ultraviolet deteriorates the surface of solar modules to a degree dependent of the long term accumulation of ultraviolet energy. Solar spectral measurements extending over periods of several months and recorded at several appropriate sites will be obtained with the UV spectroradiometer described in Sections IV and V. The results will be analyzed to predict the life expectancy of solar panels under field conditions.

Short term solar data will be used to evaluate the spectral response of the various photodegradation processes.

In the laboratory we have two types of solar simulators, those designed to simulate solar radiation in spectral quality and intensity and those designed to provide high intensity of solar flux at those ultraviolet wavelengths which are useful in various accelerated photodegradation studies. The UV spectroradiometer provides highly accurate data for each of these requirements.

The information contained in this report provides background fundamentals and a compilation of interim data. There is an on-going program which will obtain additional laboratory data as required and extensive field measurements of solar ultraviolet.

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