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SOLAR RADIATION MEASUREMENT:
TECHNIQUES AND INSTRUMENTATION

M. P. THEKAEKARA

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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SOLAR RADIATION MEASUREMENT: TECHNIQUES AND INSTRUMENTATION**

M. P. THEKAEKARA*

ABSTRACT

A general survey is presented of solar radiation measurement, the techniques and instrumentation. The importance of determining the total and spectral irradiance of the Sun is examined in the context of the energy crisis and utilization of solar energy. The survey includes the extraterrestrial solar fluxes, their possible variations, problems relating to energy received by collecting surfaces on the ground, major types of instrumentation and the radiation scales to which the measurements are referred. The type of insolation data available from the National Weather Service of NOAA and from other sources is reviewed. Alternate techniques of deriving insolation data with high space time resolution are discussed with reference to solar energy conversion requirements. Energy received on the ground can be computed from known values of the extraterrestrial solar spectrum and of the spectral absorption parameters of the atmosphere. Another technique is based on measurements made by meteorological satellites of the cloud-cover and of the solar energy reflected and scattered back to space by the Earth-atmosphere system.

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**"Special Lecture" delivered at the First Session of the 1975 International Solar Energy Society Congress, July 28-Aug. 1, 1975, University of California, Los Angeles, CA.

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SOLAR RADIATION MEASUREMENT: TECHNIQUES AND INSTRUMENTATION

INTRODUCTION

This Congress of the International Solar Energy Society has adopted a stirring theme: "Solar use now—a resource for people." During these days we will be considering varied ways of using the Sun's energy, of harnessing this bountiful resource for the benefit of mankind. A wide vista of problems, policies, programs, will claim our attention—a large variety of applications ranging from heating and cooling of homes to megawatt power stations, from drying crops and distilling water to gigantic solar furnaces, from tiny doped crystals and solar cell wafers to multi-billion dollar solar panels in space. It is but natural to inquire at the outset how much is this resource, this solar energy, how much of it is available to us at a given time and place, how do we measure it.

The size of this Congress is ample proof of a new-found enthusiasm, a great expectation. The attendance has increased, the scope has widened in each succeeding Congress of recent years, from Melbourne, through NASA, Goddard, UNESCO, Paris, CSU, Fort Collins, to the present one at UCLA. The membership of the Society has tripled in two years. Several new societies with titles strangely familiar and many new publications, new hardware, new instruments have come to public attention. This is not because there has been any major breakthrough in heliotechnology, any startling discovery, but because the need has been felt and felt deeply. The energy crisis loomed on the horizon rather suddenly. The rising cost of fossil fuels and their dwindling supply, the long lines at gasoline stations and the threat of power blackout in home and factory

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area and is highly variable. As the energy crisis becomes worse and conventional fuels more expensive, increased attention is paid to systems for direct solar energy utilization. But these systems are expensive to build and maintain; they have to be made economically competitive. If the systems are not built for the available supply of solar energy, they will either be unable to deliver the required energy or cost unnecessary outlay of capital. Insolation is therefore an essential design parameter. It is also necessary for evaluation of competing systems; input solar energy is one of the two factors in computing the efficiency of a system. Insolation data are needed for large scale conversion systems, for example, the megawatt power stations and the high temperature solar furnaces. Optimum sites have to be chosen for these, sites with high irradiance, small cloud cover, few days of continuous cloud duration. Since solar energy is widely distributed, distribution of conversion systems to where energy will be used presents many advantages. Hence aside from selecting optimum sites for large systems, data should be available on insolation for subregional to microclimate scales, for the many applications like heating and airconditioning, refrigeration and ice-making, desalination and crop-drying, solar cooking and domestic hot water, water pumps and rural radio receivers, and so on and so on.

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INSOLATION DATA FOR ENERGY CONVERSION

Measurement of solar irradiance has been made for many years at a large number of stations throughout the world. These measurements were coordinated through the WMO, the World Meteorological Organization. Various governmental agencies, like the NOAA in the United States, the Meteorological Office in the United Kingdom and many Commonwealth countries, were responsible for

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maintaining the stations and collecting and publishing the data. The principal objective in these measurements was weather prediction. Solar data were also used for other practical applications, in agriculture for forecasting harvest dates and issuing irrigation advisories, in hydrology for predicting snow-melt amounts and evaporation loss from reservoirs, in construction industry for the design of heating, air-conditioning and lighting. The data which are available are for the most part on the irradiance on a horizontal surface due to the Sun and sky, what is referred to as global irradiance. This should be distinguished from direct solar irradiance, the irradiance from the Sun received on a surface normal to the Sun's rays.

Solar energy conversion has not been hitherto a major application area for insolation data, and it is not surprising that data gathered for other purposes are not those most needed in heliotechnology. There are two major types of collectors, flat plate collectors and focussing collectors. The latter focusses the direct solar irradiance received on a large area to a relatively small focal area. The former collects the global irradiance; but on a sloping surface the direct solar and sky irradiances have different effects. The energy absorbed by the surface of the collector per unit area,

$$E_n = \alpha_s E_s \cos C + \alpha_a E_a \cos^2 \frac{B}{2} \quad (1)$$

where E_n is energy absorbed per unit area, (n for net energy).

E_s is direct irradiance from the Sun, on unit area exposed normally to the Sun's rays.

E_a is sky irradiance, energy received per unit horizontal area from the sky (a for atmosphere).

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α_s and α_a are the absorbance of the surface for E_s and E_a respectively.

B is the slope of the surface, the angle between the normal to the surface and the local vertical.

C is the angle between the normal to the surface and the Sun-Earth line.

There is a unique value for α_s and α_a only if the surface is black or 'grey', that is, if it has an absorbance equal to unity or a constant value less than unity for all wavelengths. Since a constant spectral absorbance independent of wavelength is a theoretical limit and is never realized in practice, the absorbance is dependent on the spectral distribution of E_s and E_a .

$$\alpha_s = \frac{\int_0^{\infty} E_{s\lambda} \alpha_{s\lambda} d\lambda}{\int_0^{\infty} E_{s\lambda} d\lambda} \quad (2)$$

(with a similar expression for α_a), where $E_{s\lambda}$ and $\alpha_{s\lambda}$ are respectively the solar spectral irradiance and the spectral absorbance per unit wavelength interval at a specific wavelength. The wavelength dependence of α becomes more important for focussing systems and for photovoltaic conversion systems.

The solar irradiance data usually measured at the weather stations are neither E_s or E_a , much less the spectral distribution of these quantities, but the global irradiance,

$$E_g = E_s \cos z + E_a \quad (3)$$

where z is the zenith angle of the Sun.

For a collector system which is directed towards the Sun and focusses the energy, the energy received per unit area is E_g , with an additional term which represents the energy from a small portion of the circumsolar sky.

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To obtain the solar irradiance data necessary for energy conversion the method is to use a combination of direct measurement on the ground and of numerical computations based on known parameters of extraterrestrial solar irradiance and atmospheric absorption and scattering. Since it is not possible to have a ground weather station at all locations, it will also be necessary to interpolate between available stations or to use alternate methods such as remote sensing.

THE SOLAR CONSTANT AND EXTRATERRESTRIAL SOLAR SPECTRUM

In a survey of solar radiation measurement a parameter that should be considered first is the energy received outside the Earth's atmosphere. Compared to that received on the ground it has a certain degree of constancy, and hence the term the solar constant. The solar constant is the energy received from the Sun on unit area exposed normally to the Sun's rays at the average Sun-Earth distance in the absence of the Earth's atmosphere. The solar constant and its spectral distribution are of primary importance to space-borne solar energy conversion systems. There are such systems on all satellites. A space station in geosynchronous orbit has been envisioned by P. Glaser. The power output of such a station can range from about 3000 to about 15,000 megawatts [1, 2]. Since solar cells are spectrally sensitive, the important parameter is not the solar constant itself but the distribution of that energy in the wavelength range 0.37 to 1.16 μm . Figure 2 is an average curve of the relative spectral response of a silicon solar cell; it is based on measurements made at GSFC on solar cells from eight manufacturers [3]. The response of individual cells varies by $\pm 5\%$ from the average shown here.

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The extraterrestrial values are also of importance for ground based systems of energy conversion. Precise measurement of the total and spectral irradiance of the Sun is a tedious and time consuming process. It entails expensive instrumentation and manpower and periodic recalibration of the instruments; nor can measurements be made at every location where data are needed. In many cases solar energy parameters of sufficient accuracy can be obtained by computing the fractional loss due to the atmosphere. Since these losses are highly dependent on the wavelength, the extraterrestrial solar spectrum is an essential input parameter for such computer programs.

The currently accepted value of the solar constant is 1353 Wm^{-2} . This value was first announced at the 1970 ISES Congress in Melbourne. It has since become the design value for the NASA space vehicles design criteria [4] and the Standard for the ASTM (American Society of Testing and Materials) [5]. The estimated error in the value of the solar constant is ± 1.5 percent. The value is the average of the results derived from nine long series of measurements, all made from high altitude platforms, Convair 990, balloons, X-15 aircraft and Mariner Mars probe, during the period 1967-1970, (Figure 3). Different types of instruments were used, cavity radiometers, normal incidence pyrhelimeters, Ångström pyrhelimeters, etc. The NASA/ASTM standard includes also the spectral distribution of the solar constant. It is shown graphically in Figure 4 and in tabular form in Table 1. These data are based mainly on the detailed measurements made from a Convair 990 jet aircraft at an altitude of 11.6 km [6]. In the wavelength range 0.3 to $2.6 \mu\text{m}$ which contains over 95% of the solar energy, four spectroradiometric instruments were used, a Perkin-Elmer monochromator with lithium fluoride prism, a Leiss quartz double prism monochromator, a

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filter radiometer and a polarization type interferometer. A Michelson type interferometer was used for the range 2.6 to 15 μ m. The spectral irradiance curve obtained from these measurements was modified slightly in the visible and near UV in the light of the extensive filter radiometer data obtained by the Eppley-JPL team under the direction of A. J. Drummond. References [7] and [8] should be consulted for a more detailed account of the derivation of the total and spectral extraterrestrial solar irradiance.

The solar constant and its spectrum are defined, as stated earlier, for the average Sun-Earth distance of one astronomical unit, equal to 1.496×10^{13} cm. As is well known from Kepler's law, the Earth like every other planet moves along an elliptical orbit, with the Sun at one of the foci of the ellipse. Hence the Sun-Earth distance varies with the seasons of the year. The seasonal variations are known with considerably higher precision than the absolute value of the solar constant. Typical values of total solar irradiance per unit area outside the atmosphere on the first day of the month, in units of Wm^{-2} , are: January, 1399; March, 1378; June, 1316; September, 1328. The maximum value is 1400 around January 4 and the minimum 1309 around July 5. The mean value 1353 occurs around April 4 and October 5. The spectral values vary in the same ratio as the total irradiance.

VARIATIONS OF SOLAR IRRADIANCE

In all applications of the NASA/ASTM standard values, a question which has often been raised is their intrinsic variability apart from that due to the Sun-Earth distance. The possible variations in the energy output of the Sun has been studied by many investigators. The most significant measurements are those

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made by C. G. Abbot and his co-workers of the Smithsonian Institution [9, 10]. They extended for over half a century and were made at many different locations. Abbott concluded that while the solar constant has a definite value, close to $1.94 \text{ cal cm}^{-2} \text{ min}^{-1}$ (1353 Wm^{-2}), there are many small variations with different periodicities. The cyclic variations are about 2 or 3%, and occasionally greater changes occur as when a large sunspot crosses the solar disc. Among other authors who have examined in detail the Smithsonian data and Abbot's analysis, there are some who firmly believe that significant variations do occur and others who say that the experimental errors are too large to draw any firm conclusions. C. W. Allen [11] concluded that the solar constant variations derived from the Smithsonian data are due either to data processing methods or to variations in atmospheric transparency and that intrinsic changes are less than 0.1%. On the other hand Kondratyev [12] and several others strongly support Abbot's findings. Based on his own measurements from balloons at high altitudes over a six year period, Kondratyev finds that the solar constant is a maximum for sunspot numbers between 80 and 100 and that it is lower by 2 to 2.5% at sunspot maxima and minima.

There are several intriguing meteorological phenomena which seem to follow the cyclic and sporadic changes in the Sun. Among these are the number of days in the year when Etesian winds, winds from the NE and NNE as opposed to sea-breeze, blow over Greece, the wintriness index of northern hemisphere pressure pattern, the annual march of temperature in different cities of Europe, annual frequency of west winds over the British Isles, changes in rainfall and frequency of thunderstorms in different parts of the world, growth rings of petrified and living trees, ozone density, geomagnetism, glacier movement, etc.

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While there is a great deal in published literature about changes in the solar constant and their effects on weather, a great deal which is conflicting and inconclusive, there is hardly any mention of the changes in spectral distribution in the visible and near infrared where the energy output is greatest. The reason is not that changes do not exist but that they are totally unknown and unexplored. If the solar constant is known to be changing, it is also important to know what spectral regions are causing this change. Nor is there any reason to assume that the changes in the Sun's energy output over limited wavelength bands are as small as in the solar constant itself. To establish on firm experimental basis the changes in the solar constant and the solar spectrum, measurements are needed with considerably greater accuracy and precision than have hitherto been possible. Measurements from the ground through the highly absorbing and highly variable atmosphere of the Earth are inadequate for this purpose. Measurements from spacecraft are needed for a long period of time and on a continuous basis.

In earlier years solar constant determinations from spacecraft were made only on two Mariner Mars Missions of 1969. The ERB experiment on NIMBUS-F has just started collecting data on the solar constant and the partition of this energy in several filter bands. Some highly valuable information is available. Several other spacecraft experiments are in the planning stage, in particular, the SEMIS (Solar Energy Monitor in Space) which is a combination of a small prism monochromator and a total radiation detector.

The problems of extraterrestrial solar irradiance and its possible variations are all quite relevant to the problem of more immediate interest, the irradiance, total and spectral, at ground level. The variability of the energy incident on a collector surface on the ground is considerably greater than that of the

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extraterrestrial solar energy. On days of clear sunshine the energy increases from zero at sunrise to a maximum at solar noon and decreases to zero at sunset. At any moment clouds may intercept the Sun and decrease the energy to a very low value, that of the diffuse sky radiation. Figures 5 and 6 based on measurements made on two consecutive days illustrate the wide variations that can be expected. The instrument was an Eppley pyranometer, model 2, mounted on a roof top at GSFC; readings were recorded every 4 seconds. May 13, 1971 was heavily overcast and May 14 was rather clear; the total irradiance on these two days were 732 and 2707 joules cm^{-2} (175 and 647 cal cm^{-2}) respectively. There is also the familiar variation of solar irradiance with seasons of the year, the variation which arises from the rotation axis of the Earth being inclined at 23.5° to the ecliptic, and hence the Sun being higher in the sky during summer than during winter. The absorbance of the atmosphere also changes with the seasons and from day to day, mainly due to the variations in the water vapor content and the atmospheric turbidity. Further, collecting surfaces for solar energy conversion systems are not usually horizontal, nor are they fixed to an equatorial mount so as to be always perpendicular to the Sun's rays. The slope of the receiving surface is another factor to be considered. Some of these factors are amenable to precise computations; others require direct measurements and statistical treatment of available data. The major questions to be considered are radiometric instrumentation, types of available insolation data, computational methods from extraterrestrial data, and remote sensing techniques as an alternate to ground measurements.

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INSTRUMENTATION AND RADIATION SCALES

The instrument most widely used in solar radiation measurement is the pyranometer. It has a view angle of 2π steradian and measures the global (Sun and sky) irradiance received on a horizontal surface. There are many models and types as seen in Figure 7. These instruments from major meteorological institutions throughout the world were brought together at GSFC during the 1971 ISES Congress for the first international comparison of working standard pyranometers. All these instruments operate on the principle of the thermopile; an electrical voltage is generated which is recorded on a magnetic tape, on a strip chart or in some other manner. Major commercial suppliers are Eppley, Kahl and Spectrolab in the U.S., Kipp and Zonen in the Netherlands, Groiss in Australia, Mashpriborintorg in USSR and EKO in Japan. The response time is of the order of several seconds. Silicon solar cell pyranometers have response time less than a millisecond but have a limited spectral sensitivity. Yellow Springs Inst. Co. and Matrix, Inc., are major suppliers. Bimetallic strip pyranometers, as those supplied by Casella Co. in the U.K. and R. Feuss in W. Germany, are more rugged but less accurate.

An older model of the Eppley pyranometer (50 j) which is used in about three-fourths of the National Weather Service stations in the U.S. is shown in Fig. 8. The rest of the stations use the newer model 2 [13]. An Eppley Model 2 pyranometer mounted on a roof top at GSFC is shown in Figure 9. It is part of an evaluation program in support of the Greenbelt Community Project of solar heated homes. Other instruments in this program are the normal incidence pyrliometer (Figure 10), six thermopiles on sloping surfaces (Figure 11) facing different directions of the compass and a Groiss pyranometer mounted on the

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flat plate collectors (Fig. 12). Reference [13] as also other papers in the NSF/NOAA Solar Energy Data Workshop Report and Reference [14] which discusses the results of the GSFC intercomparison should be consulted for further information on pyranometers.

The normal incidence pyrhelometer (NIP) is used to measure the direct solar radiation. The sensor is a thermopile at the base of a cylindrical tube which limits the view angle to the Sun and about 5 degrees of the circumsolar sky. The instrument is mounted on a motor driven heliostat. The axis of the heliostat should be readjusted two or three times a week as the declination of the Sun changes.

The pyranometer and the NIP are not self-checking or absolute instruments; their sensitivity, output in millivolts per mW cm^{-2} of irradiance, should be determined by comparing them with some other "standard" instrument. Two standards commonly used in meteorology are the Ångström compensation pyrhelometer and the Abbot silver disc pyrhelometer, referred to for the sake of brevity as the Ångström and Abbott silver disc, respectively. The Ångström 6618 which was used in the GSFC determination of the solar constant is shown in Figure 13 along with its electrical control unit. In principle the Ångström is an absolute instrument. It consists of two blackened metal strips, one of which is exposed to the Sun and the other is shielded from the Sun but is heated by an electric current until both strips attain the same temperature. If the area and absorbance of the strips and the electrical input energy are known, the irradiance can be calculated. But there are several difficult correction factors and hence in practice the "standard" Ångströms of different countries are calibrated periodically with reference to a few "primary standards". In the Abbott silver

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U of Wisconsin, WRC Davos, IMB Brussels, and so on. They operate on the principle of electrical substitution and claim a high degree of absolute accuracy, less than $\pm 0.5\%$. Three of these used in the Davos intercomparison seem to show that the IPS 56 is in error by about -2% , and that SS 13 is nearer the accurate scale. But questions have been raised about a bias error common to these measurements. Considerably more work needs to be done. If the IPS 56 is in error, it is to be hoped that the replacement will not be another erroneous "gentlemen's agreement".

The distribution of the energy received from the Sun as a function of wavelength is also of considerable importance. The instrumentation is far more complex and of much greater variety than for total irradiance. The solar energy is received on a diffusing surface or an integrating sphere and dispersed by a monochromator. The wavelength range is usually from 0.29 to $3 \mu\text{m}$ which contains most of the energy of the Sun as received on the ground. For this range quartz prism instruments (Leiss, Perkin-Elmer, etc.) are the most convenient, but they have a non-uniform wavelength resolution. The Perkin Elmer monochromator used in the GSFC measurements of the solar spectrum is shown in Figure 14. Grating instruments (Cary 14, Jarrell-Ash, Ebert-Fastie, etc.) give greater and more uniform wavelength resolution, but have problems of multiple orders and scattered light. The detectors are photomultipliers, photodiodes, lead sulfide cells, thermopiles, etc. The instruments should be calibrated periodically for wavelength and spectral sensitivity. For wavelength calibration spectral lines of mercury, xenon, neon and other elements are available. Solar spectrum itself has an internal wavelength calibration in the Fraunhofer lines and the atmospheric absorption lines.

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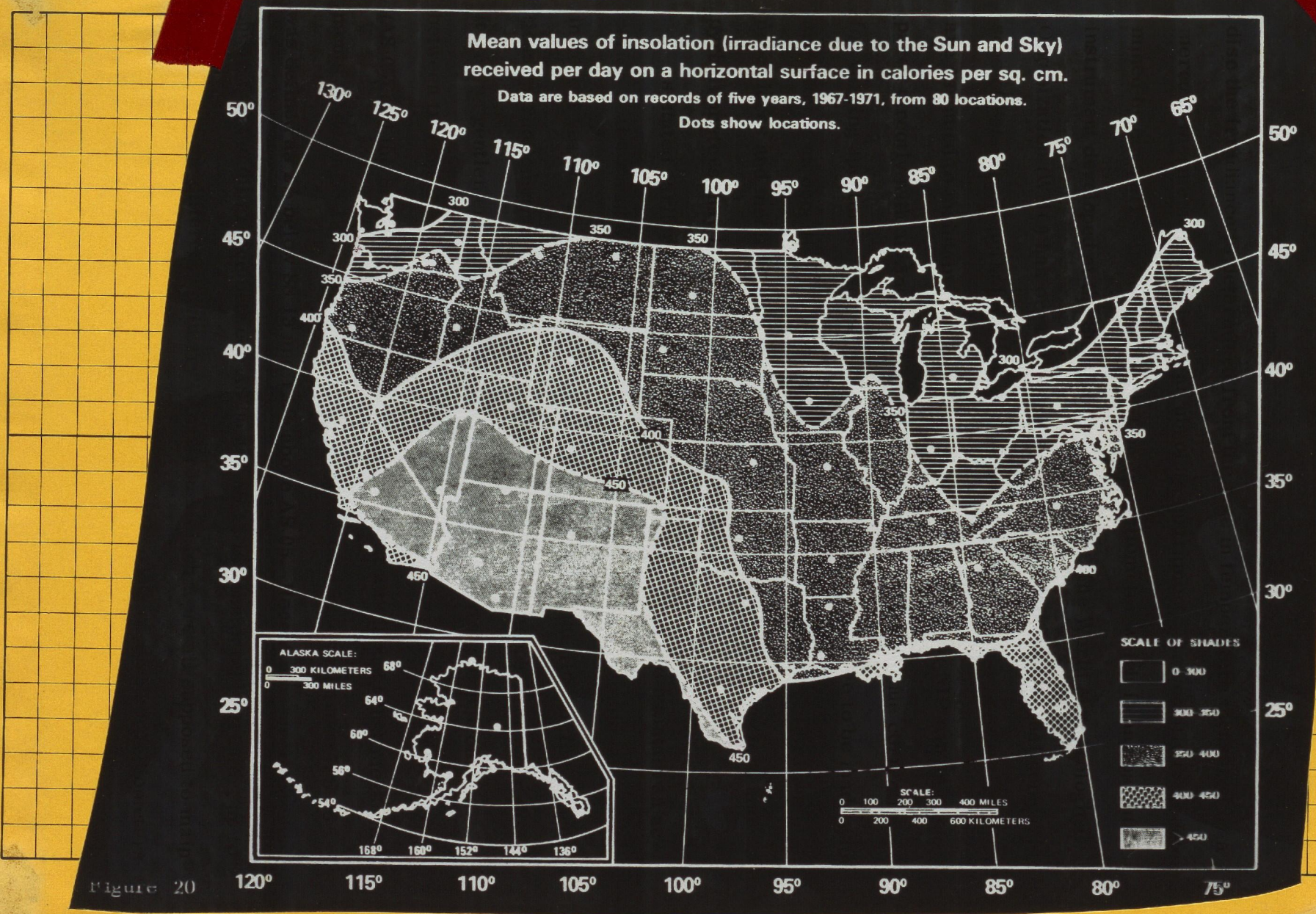
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disc the irradiance is determined from the rise in temperature measured by a mercury thermometer. It is not an absolute instrument. Its sensitivity is determined by comparison with the water-flow pyrhelimeter which is an absolute instrument developed at the Smithsonian by Abbot. The World Meteorological Organization (WMO) has organized several international and regional comparisons of "standard" pyrhelimeters with reference to "primary standards" which are assumed to maintain an accurate scale of radiometry. A NIP can be compared directly with an Ångström or an Abbot silver disc, with due corrections for varying apertures. For a pyranometer, measurements have to be made with and without an occulting disc and at different solar elevations. Calibration procedures and methods of using different WMO approved pyranometers and pyrhelimeters may be found in references [15] and [16].

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As stated earlier the "primary standards" are assumed to maintain an accurate scale of radiometry. This has been the topic of considerable discussion in recent years. The WMO approved scale at present is the IPS 56, the international pyrhelimetric scale adopted for the international geophysical year (IGY). It was a "gentlemen's agreement" among radiation experts, a compromise between two scales which had been in use earlier, the Ångström scale of 1905 (AS 05) and the Smithsonian scale of 1913 (SS 13). It was thought that measurements made on SS 13 were 3.5% higher than those on AS 05, and hence IPS 56 was defined as 2% below SS 13 and 1.5% above AS 05. Recent measurements have shown that the difference between AS 05 and SS 13 is considerably greater, up to 5%, and that the different "primary" Ångströms which were all supposed to maintain the IPS 56 differ by 2 or 3%. Many different models of absolute radiometers are now available, those developed at JPL, NBS Boulder, NBS Washington, GSFC,

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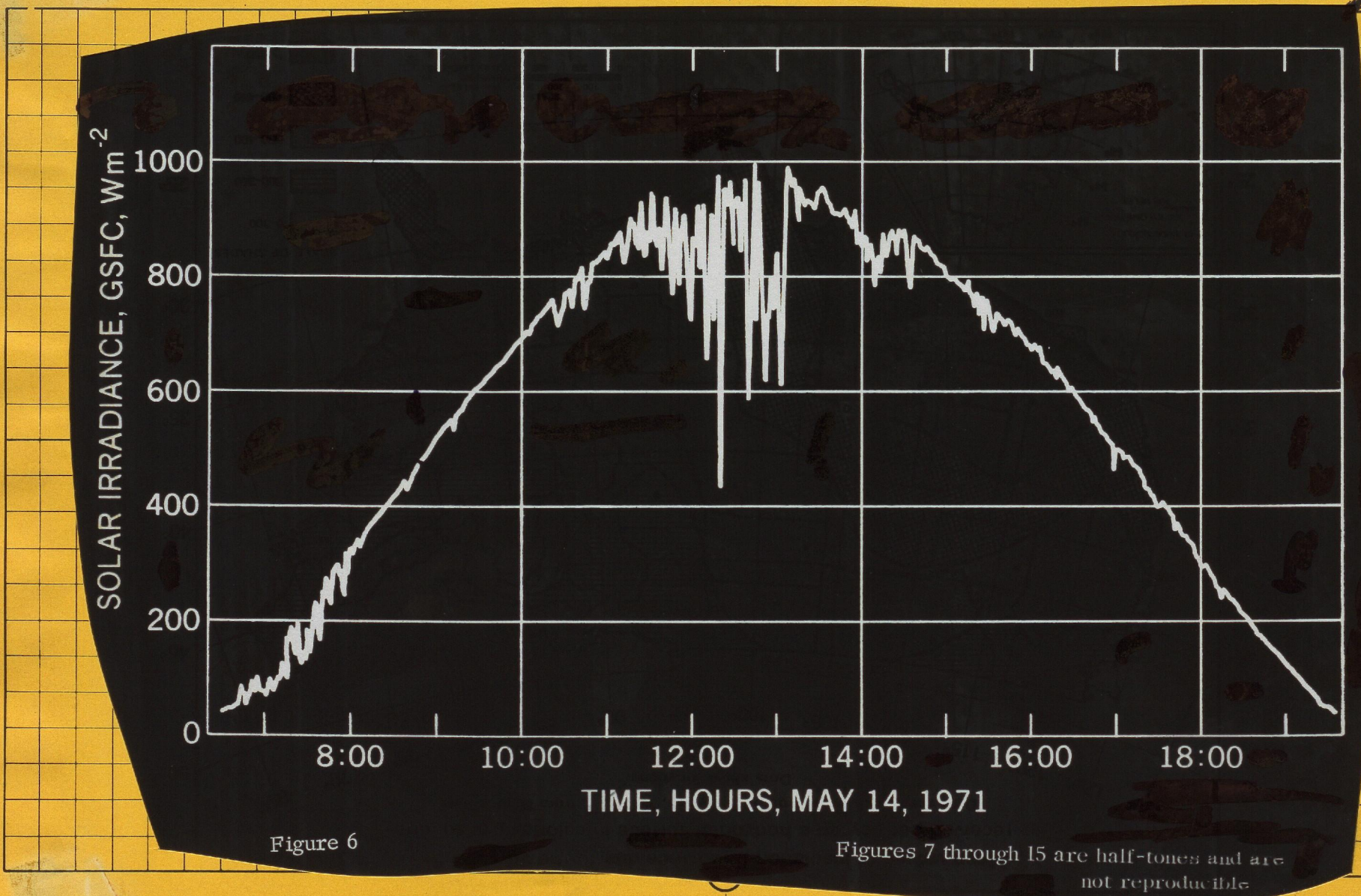


Figure 6

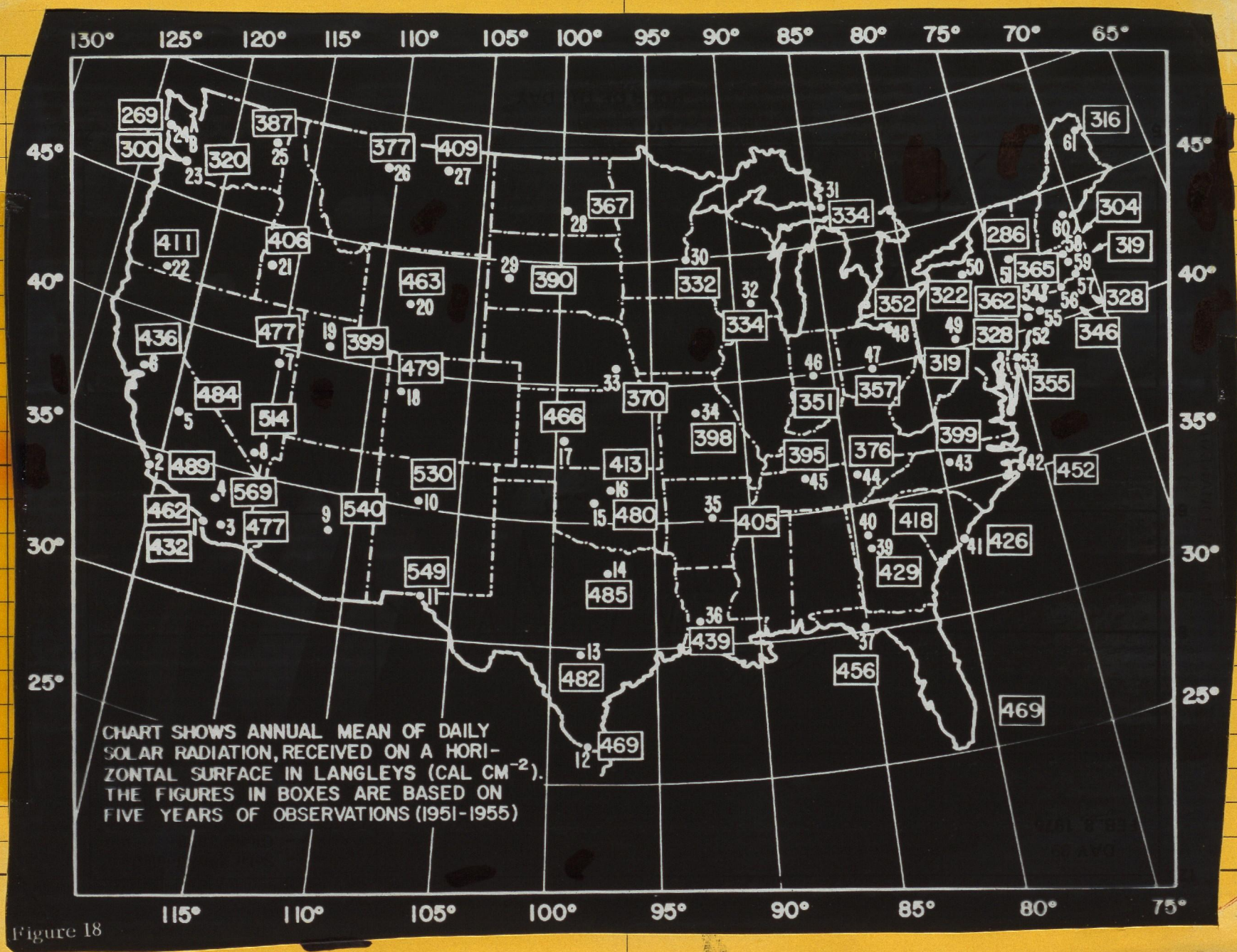
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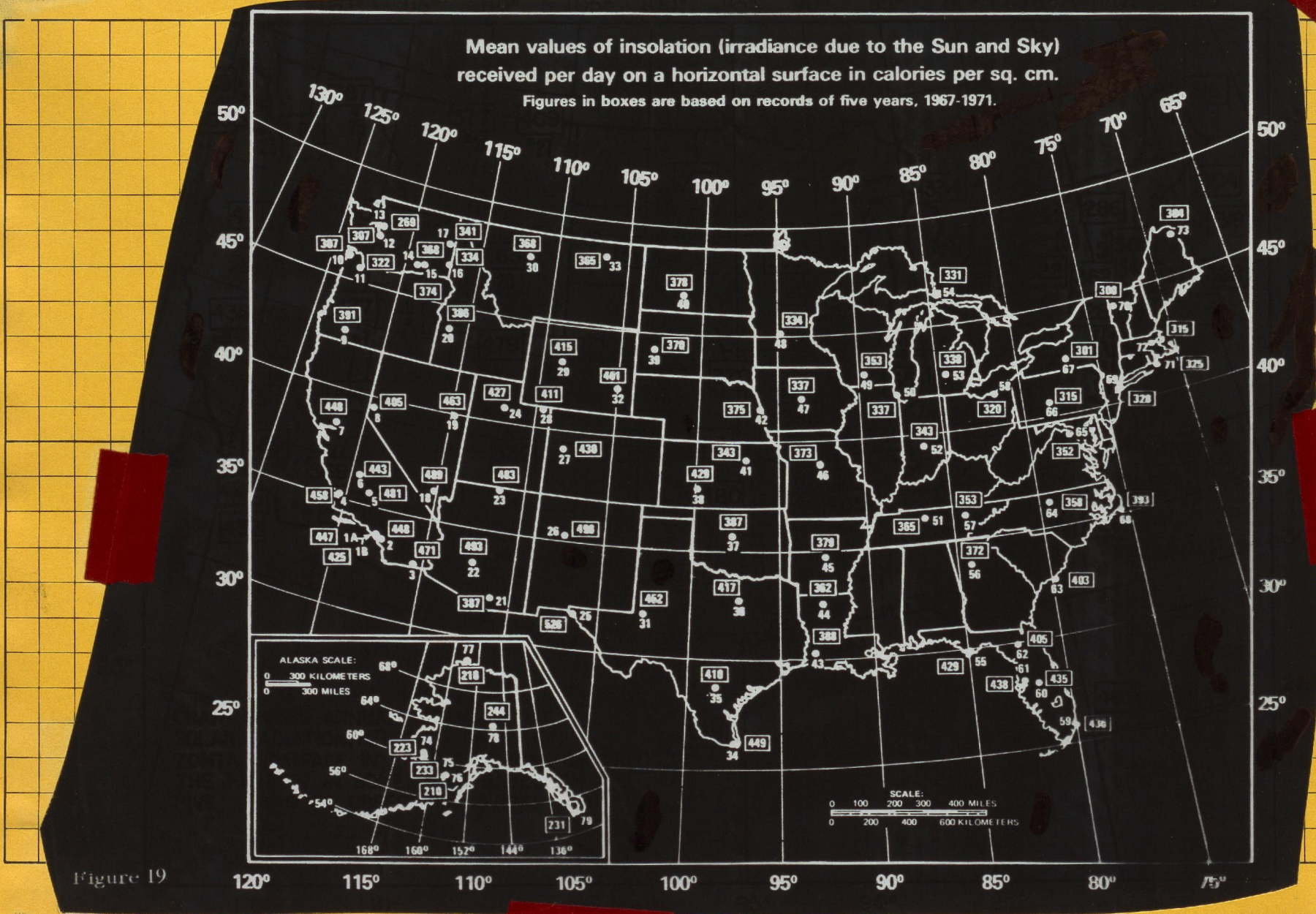


Figure 19

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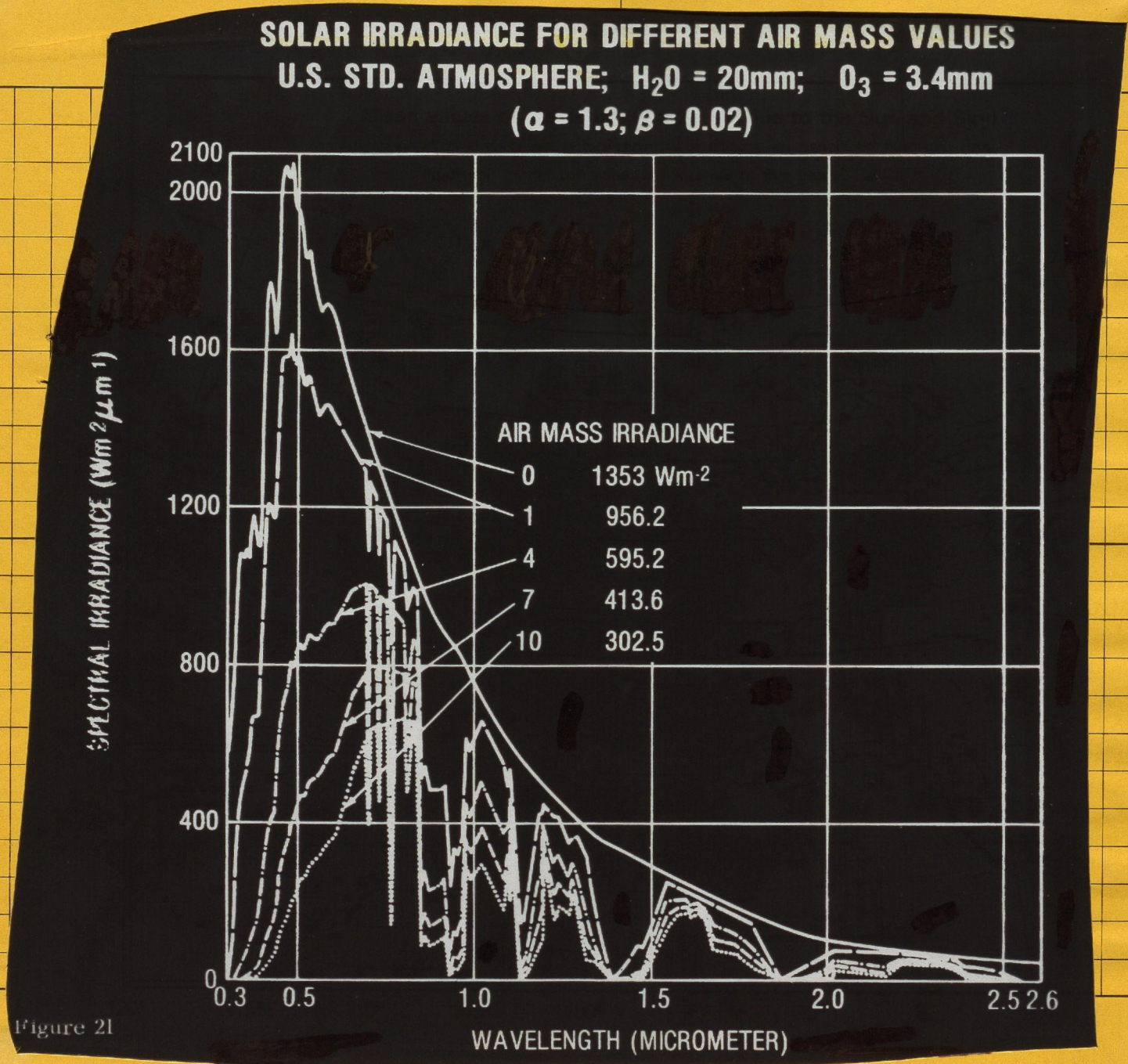


Figure 21

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TABLE 2
MEAN DAILY INSOLATION AVERAGED OVER FIVE YEAR PERIODS
AT TEN SELECTED STATIONS
in calories per cm²

STATION	1951-55 E _{g1}	1967-71 E _{g2}	RATIO R ₁₂
MEDFORD, OR	411	391	1.051
LAS VEGAS, NV	514	489	1.051
EL PASO, TX	549	526	1.044
DODGE CITY, KS	466	429	1.086
LITTLE ROCK, AR	405	379	1.069
OAK RIDGE, TN	376	353	1.065
INYOKERN, CA	569	481	1.183
SEATTLE, WA	269	269	1.000
SALT LAKE CITY, UT	399	427	0.934
MADISON, WI	334	353	0.946

AVERAGE FOR 47 STATIONS RATIO IS 1.066 WITH STANDARD DEVIATION 0.069

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TABLE 3
DIRECT SOLAR IRRADIANCE AS A FUNCTION OF AIR MASS
FOR VARYING ATMOSPHERIC PARAMETERS (Wm⁻²)

ATMOSPHERIC PARAMETERS				SOLAR IRRADIANCE				
				FOR AIR MASS				
H ₂ O _{cm}	O ₃ _{cm}	β	α	1	1.5	2	3	5
				FOR SOLAR ZENITH ANGLES				
				0	48.2°	60°	70.5°	78.5°
2.0	0.20	0.02	1.3	961	876	805	693	534
2.0	0.20	0.17	0.66	804	672	568	414	232
2.0	0.34	0.02	1.3	956	870	798	684	523
2.0	0.34	0.17	0.66	800	668	563	409	228
2.0	0.55	0.02	1.3	949	861	788	672	508
2.0	0.55	0.17	0.66	795	661	556	402	222
0.5	0.34	0.02	1.3	1024	943	875	767	612
0.5	0.34	0.17	0.66	859	727	622	464	273
1.0	0.34	0.02	1.3	992	909	840	729	571
1.0	0.34	0.17	0.66	832	700	595	439	252
5.0	0.34	0.02	1.3	898	807	732	615	454
5.0	0.34	0.17	0.66	750	616	513	363	193

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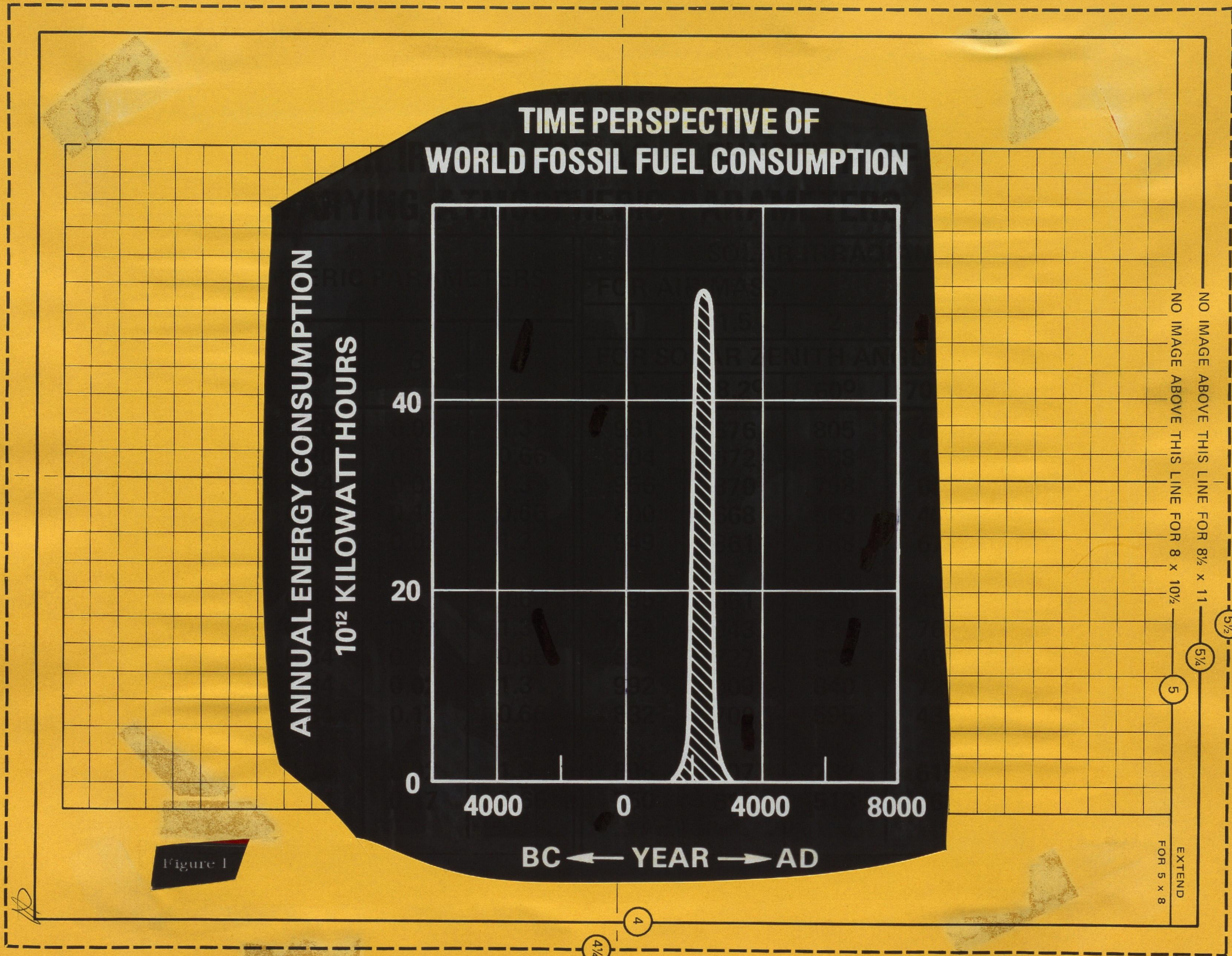


Figure 1

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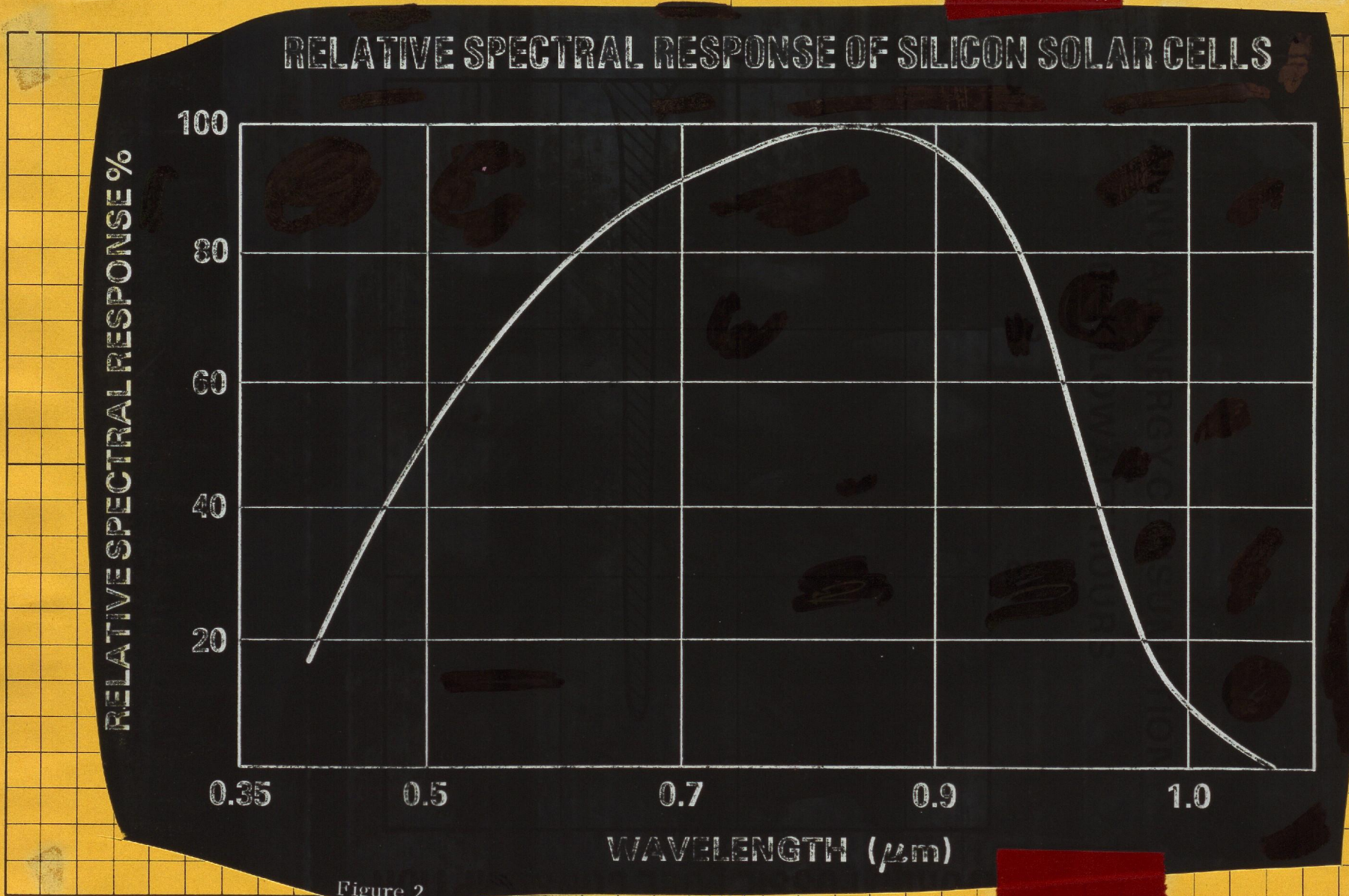


Figure 2

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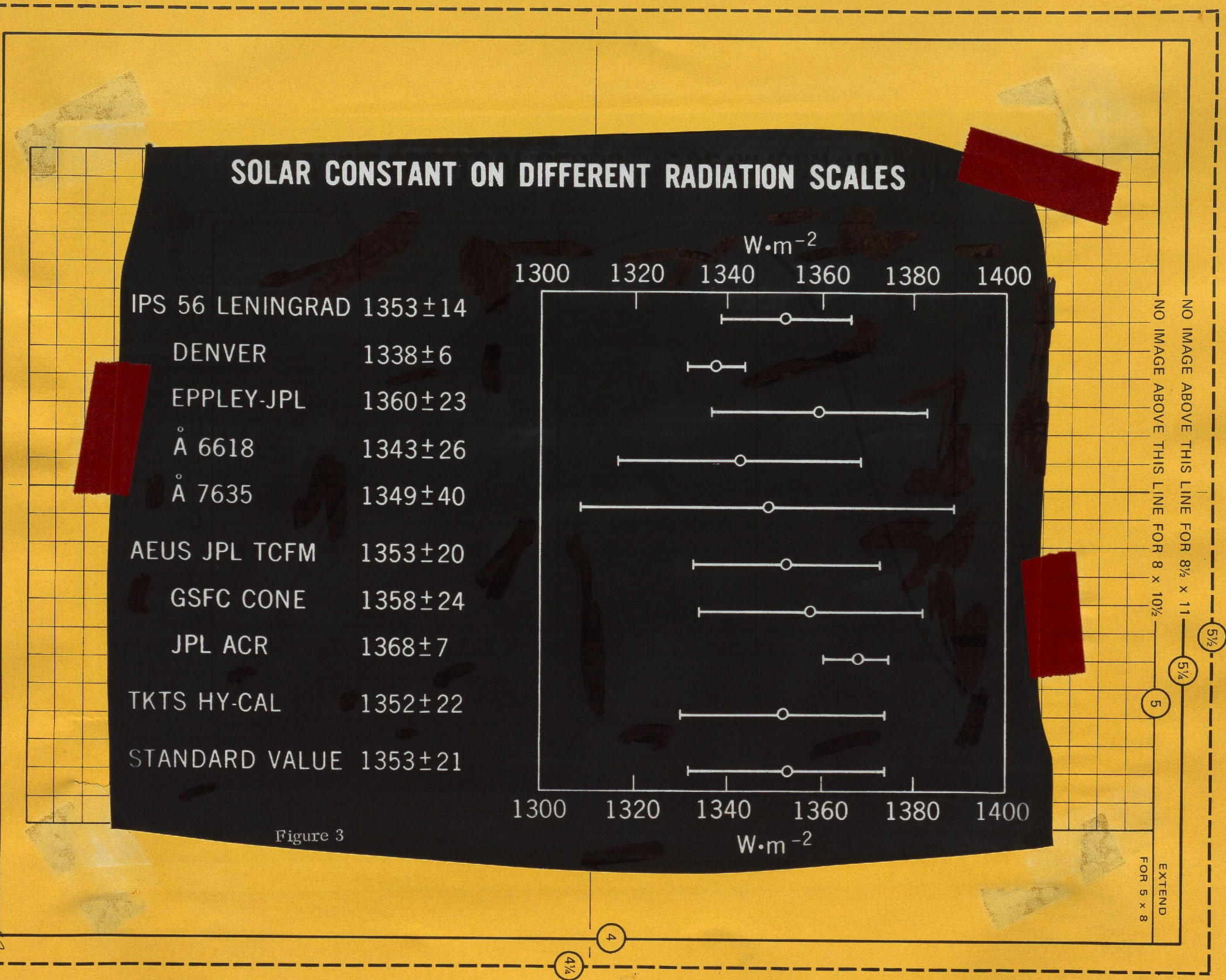
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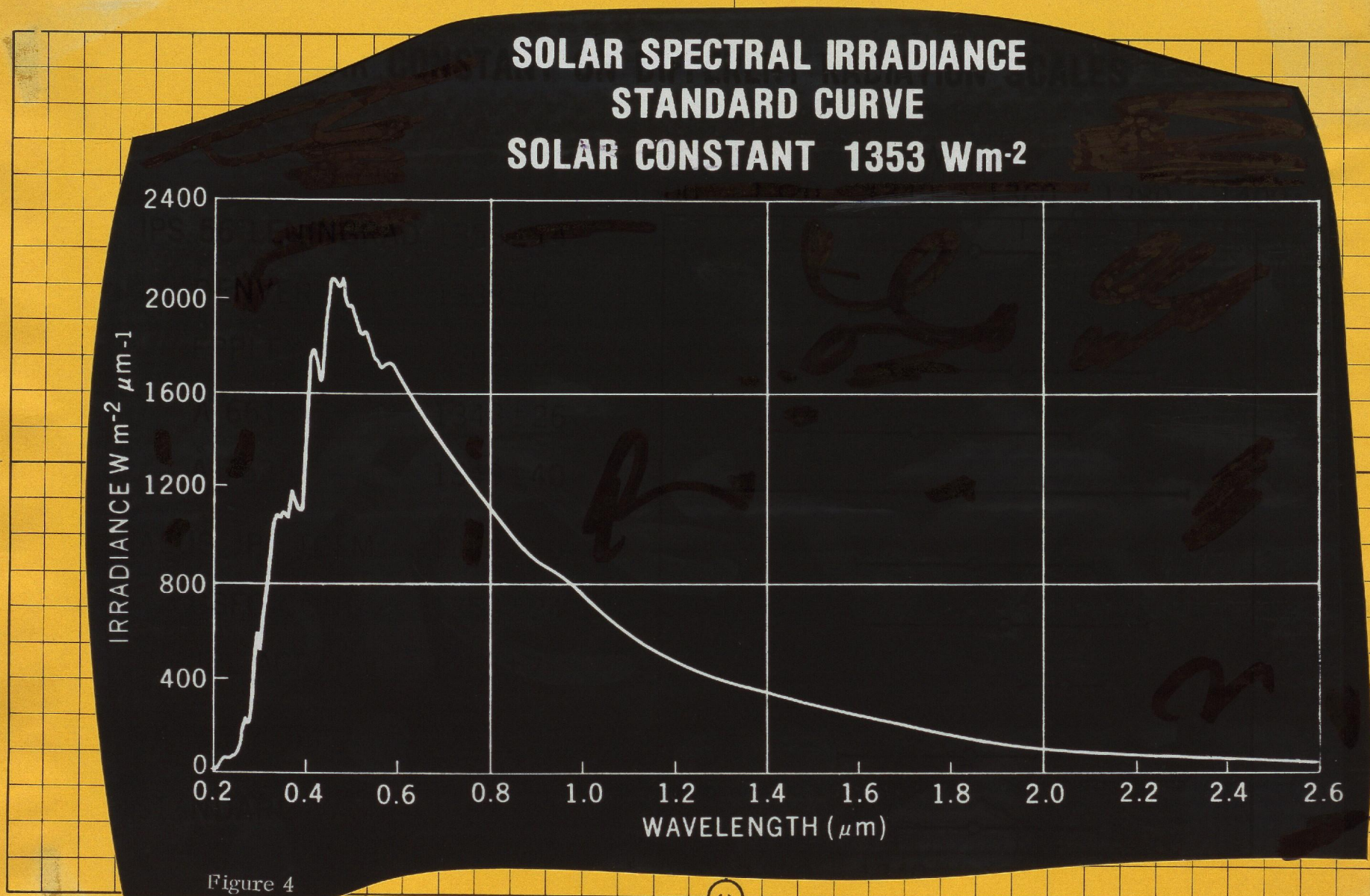


Figure 4

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Calibration for spectral sensitivity raises another and a more difficult problem of radiation scales. For total irradiance there are standard detectors; for spectral irradiance there are standard sources. The standard detectors are traceable to the absolute electrical units scale (AEUS) through the so-called absolute radiometers; the sources of spectral irradiance are traceable to the thermodynamic Kelvin temperature scale (TKTS) through the gold point blackbody and Planck's equation for blackbody radiation. The AEUS and the TKTS are the two primary radiation scales of absolute validity since they can be related through basic physical laws to the fundamental units of length, mass and time. The most widely used standards of spectral irradiance are the 1000 W tungsten lamps issued by NBS, Washington, but the steps in the transfer of the TKTS to the tungsten lamps are more involved than in the transfer from the AEUS to the Ångströms. There is international agreement on the temperature of the gold point – the currently accepted value is the third revision – but there has been no serious effort at an international comparison of lamp standards of irradiance or radiance. Even more disturbing is the disagreement which has recently been observed between two NBS spectral irradiance scales, those of 1964 and of 1973. But happily in the visible and near IR up to 1 μm which contains most of the Sun's energy at ground level and which is important to silicon solar cells, the disagreement between the two NBS scales is small. The spectral sensitivity of the monochromator is determined by illuminating the diffusing screen or integrating sphere with the standard lamp. The spectral irradiance of the standard lamp is known in units of $\text{Wm}^{-2} \mu\text{m}^{-1}$ or its equivalent on a surface at a known distance (usually 50 cm) from the lamp. It is important that the same optical arrangement be used for the spectral scans of the Sun and of the standard lamp.

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An alternate method preferred by meteorologists is filter radiometry. Interference filters which transmit the energy over a known spectral band or glass cut-off filters which transmit all wavelengths beyond a known limit are used in combination with a total irradiance detector. The wavelength resolution is 10 to 100 times less than for a monochromator. A more serious difficulty is that the spectral irradiance which one is trying to determine is an essential input parameter for the data analysis, since the transmittance of the filter is a convolution of the spectral irradiance of the source and the spectral transmittance of the filter.

$$T_{\lambda_1-\lambda_2} = \int_{\lambda_1}^{\lambda_2} E_{\lambda} T_{\lambda} d\lambda \quad (4)$$

where $T_{\lambda_1-\lambda_2}$ is the total energy transmitted by the filter, λ_1 and λ_2 are the two extreme wavelengths where the filter transmittance becomes zero, and E_{λ} and T_{λ} are the solar spectral irradiance and filter transmittance respectively over a narrow band $d\lambda$ centered at λ . The T_{λ} curve has a bell shape or a more irregular shape; the filter pass band, $(\lambda_2 - \lambda_1)$, is often quite wide, up to 1000 Å; and more importantly the E_{λ} curve varies rapidly with solar zenith angle and atmospheric parameters. Hence the evaluation of $T_{\lambda_1-\lambda_2}$ is often an approximation. Computerized iteration techniques can reduce the uncertainty. One advantage is that the primary reference scale in filter radiometry is the AEUS and not the TKTS, and hence the method is independent of systematic errors, if any, in spectral irradiance standards. Reference [17] which discusses filter radiometry for solar simulation sources and Chapter 5 of reference [8] which gives a detailed description of the NIMBUS ERB experiment may be consulted for further details on filter radiometry.

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INSOLATION DATA FROM NOAA/NWS

A discussion of the instrumentation leads naturally to the type of solar data available from these instruments. An example of the solar spectrum obtained by Abbot and Freeman using a triple prism instrument is shown in Figure 15. This is a reproduction of the trace made on the photographic plate by the bolometer with no corrections for wavelength or irradiance. Three successive traces of September 4, 1928 in the range 0.85 to 1.0 μm are shown. These curves were made for the study of H_2O bands. The main objective of the Smithsonian solar spectral curves, made over a period of several years, was extrapolation to zero air mass and the evaluation of the solar constant. Figures 16 and 17 give examples of the data obtained from the pyranometer and NIP of the GSFC installation. The x-axis is time in hour of the day and the y-axis is irradiance in mW cm^{-2} . The data points are 10 minute averages. The continuous curve gives the NIP (direct solar) readings and the dashed curve gives the pyranometer (global) readings. The totals for the day are given to the top right of the figures.

Daily totals and monthly averages of global (Sun and sky) irradiance are available from pyranometers of many weather stations around the world. An excellent survey of irradiance over the whole Earth was made by Löff, Duffie and Smith in 1966. [18, 19]. They prepared 12 monthly world maps of daily average global irradiance received on a horizontal surface. The authors used radiation data from 668 stations; for 233 other stations where only data for sunshine hours were available approximation methods were used to estimate the global irradiance. An earlier world survey of insolation which is often referred to in meteorology had been made by Budyko [20].

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In the United States there are 90 stations where solar irradiance data are being recorded. Sixty of these are NOAA stations and 30 are cooperating stations maintained by universities and other organizations. They constitute the Sun and sky irradiance network of the U.S. Fig. 18 is a map based on the NOAA data of the years 1951 through 1955. The dots show the locations of the 61 stations with complete records for the period and the figures in boxes show the mean values of irradiance due to the Sun and sky received per day determined from the data of the five year period. The units are calories cm⁻². This is a map which has been reproduced in many handbooks and reference works. An updated version which was prepared at GSFC is shown in Figure 19. It was based on the data supplied by the National Climatic Center, Asheville, N.C., on monthly averages of the five year period 1967-71. There were 80 stations for which the data were more or less complete, and they are shown in Figure 19. In these 345 monthly means (7.3% of the total) were randomly missing from the records and they were supplied by record of the same place, same month, adjacent year. A more graphic presentation of the numerical data of Figure 19 is given in Figure 20 where different shades are used to show increase in insolation in steps of 50 cal. cm⁻². The NOAA/NWS insolation records cover a long period of time, from 1909. In the early years there were only a few stations, and not all stations were in continual operation during the whole period. In addition to the pyranometer network there are 160 stations with sunshine recorder, an instrument which shows the number of hours per day when the Sun shines sufficiently to cast a shadow. Forty of these sunshine recorder stations have also a pyranometer. There are also 5 stations with NIP's which record direct solar radiation. At present a program is under way to upgrade many of the stations replacing the old bulb type pyranometer with newer models

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with the double dome. Detailed descriptions of the history, present status and data distribution format of the NOAA solar measurement program are available in Reference [13].

The National Climatic Center used to publish monthly and yearly records of solar irradiance data collected at each of the stations. However, in recent years doubts were raised about the accuracy of the earlier data, and in September 1972 the NWS of NOAA requested the NCC to stop publishing the data. Estimated errors ranged from $\pm 5\%$ to $\pm 30\%$, though perhaps very few stations have the 30% error [13]. Currently the insolation data are archived, but they are not included in the routine publications of meteorological data from the NCC. In this connection we may mention the results of a comparison made between the data presented in Figures 18 and 19. There are 47 stations which have mean daily values for both the five-year periods. The ratio, R_{12} , of the old value, E_{g_1} , (1951-55) to the new value, E_{g_2} , (1967-71) is in most cases more than one. The average of R_{12} is 1.066 with a standard deviation of 0.069. Thus the older values are higher by 6.6%. Of this 2% can readily be explained. A change in scale from SS 13 to IPS 56 was introduced before the IGY. The remaining 4.6% and the large standard deviation raise several interesting questions. Table 2 gives the values of E_{g_1} , E_{g_2} and R_{12} at 10 selected stations; six of these were selected because the ratio values are rather close to the mean value, and four others because the ratios show a wide scatter.

The NOAA/NWS records provide a very valuable source of data for a long period of time; but for solar energy conversion considerably more information is needed with greater resolution for time and location, wavelength distribution and radiation components. Over continental United States there is one NWS station on an average for about 10^5 sq km; for the land area of the Earth as a

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whole the 901 stations surveyed by Löf, Duffie and Smith provide on an average one station for 1.5×10^5 sq. km.

INSOLATION DATA COMPUTED FROM EXTRATERRESTRIAL SPECTRUM

Direct solar spectral irradiance for any time of the day and any location can be computed from the extraterrestrial values of the solar spectrum, using atmospheric parameters of scattering and absorption and the air mass. The air mass is the secant of the solar zenith angle. The atmospheric parameters are known to a fair degree of accuracy.

The solar zenith angle is given by

$$\cos z = \sin \theta \sin \delta + \cos \theta \cos \delta \cos h \quad (5)$$

where z is the zenith angle of the Sun, θ is the latitude of the place, δ is the solar declination and h is the hour angle. The hour angle is an angle in the plane of the apparent motion of the Sun, between two lines from the observer to the actual position and to the position at local noon of the Sun.

The spectral irradiance is given by

$$E_\lambda = E_\lambda^0 e^{-(c_1 + c_2 + c_3)m} T_{\lambda i} \quad (6)$$

where E_λ and E_λ^0 are irradiance on the ground and outside the atmosphere respectively at wavelength λ , c_1 and c_2 are Rayleigh and ozone optical depth, c_3 is optical depth due to turbidity, m is the air mass, $T_{\lambda i}$ is a transmittance factor valid for the molecular bands and can have one of three forms:

$$T_{\lambda 1} = e^{-c_4 \sqrt{wm}}; T_{\lambda 2} = e^{-c_5 wm}; \text{ or } T_{\lambda 3} = (1 - c_6 \sqrt{m}). \quad (7)$$

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w is the amount of precipitable water vapor, c_4 , c_5 and c_6 are empirical constants. c_1 and c_2 are available in reference [21]; c_4 , c_5 and c_6 in ref. [22] and [23]; c_3 is expressed in terms of the two Ångström turbidity parameters, α and β

$$c_3 = \frac{\beta}{\lambda^\alpha} \quad (8)$$

A sample of the spectral irradiance curves obtained from these computations is shown in Figure 21. Integrating the area under curve the total irradiance is obtained. Values of total and spectral irradiance at ground level have been computed for 32 sets of atmospheric parameters, in each case for 10 values of air mass. The results are too detailed to be reproduced here. Punched card decks are available for most of these spectral distribution curves as also for the standard spectrum of Table 1. User organizations may obtain them from the National Space Science Data Center, Code 601, NASA/GSFC. An empirical equation has also been developed which gives the irradiance at ground level as a function of the atmospheric parameters. Further information about these computational techniques and their results may be found in Chapter 2 of ref. [2] and in ref. [24]. A highly abridged version of the results, giving the total irradiance at ground level is shown in Table 3. Twelve sets of parameters (first four columns) are considered. The solar irradiance values in Wm^{-2} for a surface exposed normally to the Sun's rays for five values of air mass are given in columns 5 through 9.

Attention should also be drawn to tables of solar irradiance published in the ASHRAE Handbook of Fundamentals [25]. The units are $\text{Btu ft}^{-2} \text{hr}^{-1}$. These tables are in a form more convenient for engineering use and do not require computation of the air mass. Solar irradiance on a surface normal to the Sun's

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rays and global irradiance on a horizontal surface are given for the 21st day of each month and for different values of latitude. Typical values of the water vapor in the atmosphere for each date have been assumed and variations in Sun-Earth distance have been taken into account, but not variations in ozone and turbidity. Another approximation which has been assumed is that the logarithm of solar irradiance varies linearly with air mass; this is strictly true only for monochromatic radiation outside the molecular bands. The ASHRAE Handbook cites the NASA/ASTM value of the solar constant, 1353 Wm^{-2} , but the tables of irradiance on the ground are based on the work done many years earlier by different authors. Though it is highly desirable that the ASHRAE data be updated in the light of more recent measurements and computations, the microclimate variations of the atmosphere and the complexity of ground insolation are such that the handy form of the ASHRAE tables makes them highly valuable for engineering design. The ASHRAE Handbook as also Chapter 2 of reference [2] discuss in some detail the related problem of irradiance on a sloping surface.

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REMOTE SENSING TECHNIQUES

Theoretical computations from extraterrestrial solar fluxes provide one alternate method for adequate space time coverage of insolation data. Another alternate method now being developed is to make use of the abundant data gathered by meteorological satellites of the energy scattered and reflected into space by the Earth-atmosphere system. From these it should be possible to survey insolation as a function of location, seasons of the year and time of day, to select optimum sites for large scale energy conversion systems and to make insolation maps of high spatial resolution of selected areas. Key factors in this method are that global irradiance is primarily determined by cloud cover and

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is the excess of solar input over what is scattered or reflected into space and what is absorbed in the atmosphere. Insolation data from the same instrument as one carried by a satellite offer certain advantages over those of many instruments from a network of stations. Measurements of the outgoing solar fluxes have been made from many satellites of the TIROS and NIMBUS series and others; more detailed information with spatial resolution up to a quarter of a mile is available from the Synchronous Meteorological Satellites, SMS 1 and 2. The SMS are located over the equator at longitudes 70° and 135° W and give complete pictures of the western hemisphere at intervals of half an hour. A program has recently been initiated by NASA for making effective use of SMS for ground insolation data. There are three parallel approaches in this program located at U. of Miami, Colorado State U. and GSFC.

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Equations of correlation will be developed between total insolation per day as given by ground stations and cloud cover duration as given by SMS. The dependence of the equation parameters on location, time of the year and cloud opacity will be studied. Thus it will be possible to make a complete survey of an 8 km x 8 km grid over all of continental U.S. and coastal waters, and provide a ranking of best locations for large scale power generation according to maximum annual insolation, smallest difference between seasons of high and low insolation and least number of consecutive cloudy days. Attempts will also be made to develop insolation data on a microclimate scale for selected regions which are indicated by engineering priorities. The detailed daily data collected by the pyranometer and pyrliometer at the GSFC ground station (Figures 16 and 17) provide a means of relating cloud cover of varying degrees of opacity and duration with global and solar irradiance and also the relation between

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cloud cover as measured from the ground and the same as measured from the SMS. This discussion of the use of the data from satellites for energy-related problems has necessarily been very brief. For further details references [24], [25] and [26] may be consulted.

CONCLUSION

A conclusion that emerges strongly from this survey of solar radiation measurement, its techniques and instrumentation, is that no single method can supply the type of information needed for the large variety of solar energy applications. Measurements of ground insolation and extra-terrestrial solar fluxes, total and spectral, numerical modelling and remote sensing techniques, all complement each other. Radiometry is a science and an art. While the fundamental units of length, mass and time and the derived units of energy, volt, ampere, etc., have been defined very precisely, the unit of radiance or irradiance is hard to measure. Most physical constants like the electron charge, Planck's constant, etc., have been measured to an accuracy of a few parts in a million, but the accuracy claimed for the solar constant is only one part in 67. The uncertainty in measurement of energy received on the ground is considerably greater. Great progress has been made during the last two decades, thanks to the IGY and the space age. Many new disciplines, new research groups are now interested in measuring solar energy; new techniques, new instruments are being developed. Solar energy is a resource for people. When one considers the prospects of vanishing fossil fuels and the annual cost of energy production, one finds in the harnessing of solar energy a challenge greater than the conquest of space. Knowing how much is that energy is part of meeting that challenge.

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ACKNOWLEDGMENTS

This work would not have been possible but for the considerable help received from many co-workers at GSFC and fellow scientists in other institutions. Special mention should be made of R. Kruger, C. H. Duncan and other members of the GSFC CV 990 team for the high altitude solar measurements, A. E. McNutt and A. R. Winker for insolation studies related to the Greenbelt solar heating project, R. S. Mitchell and A. J. Villasenor for computer programming and B. M. Burda for data analysis. Among scientists at other institutions who were extremely helpful are the late A. J. Drummond of Eppley for developing the NASA/ASTM standard and for many helpful discussions on instrumentation, D. Hoyt of NOAA, Boulder, for computer generated ground insolation, and T. H. Von der Haar of Colorado State U. and H. W. Hiser of the U. of Miami for remote sensing techniques. The author gratefully acknowledges his indebtedness to all these persons.

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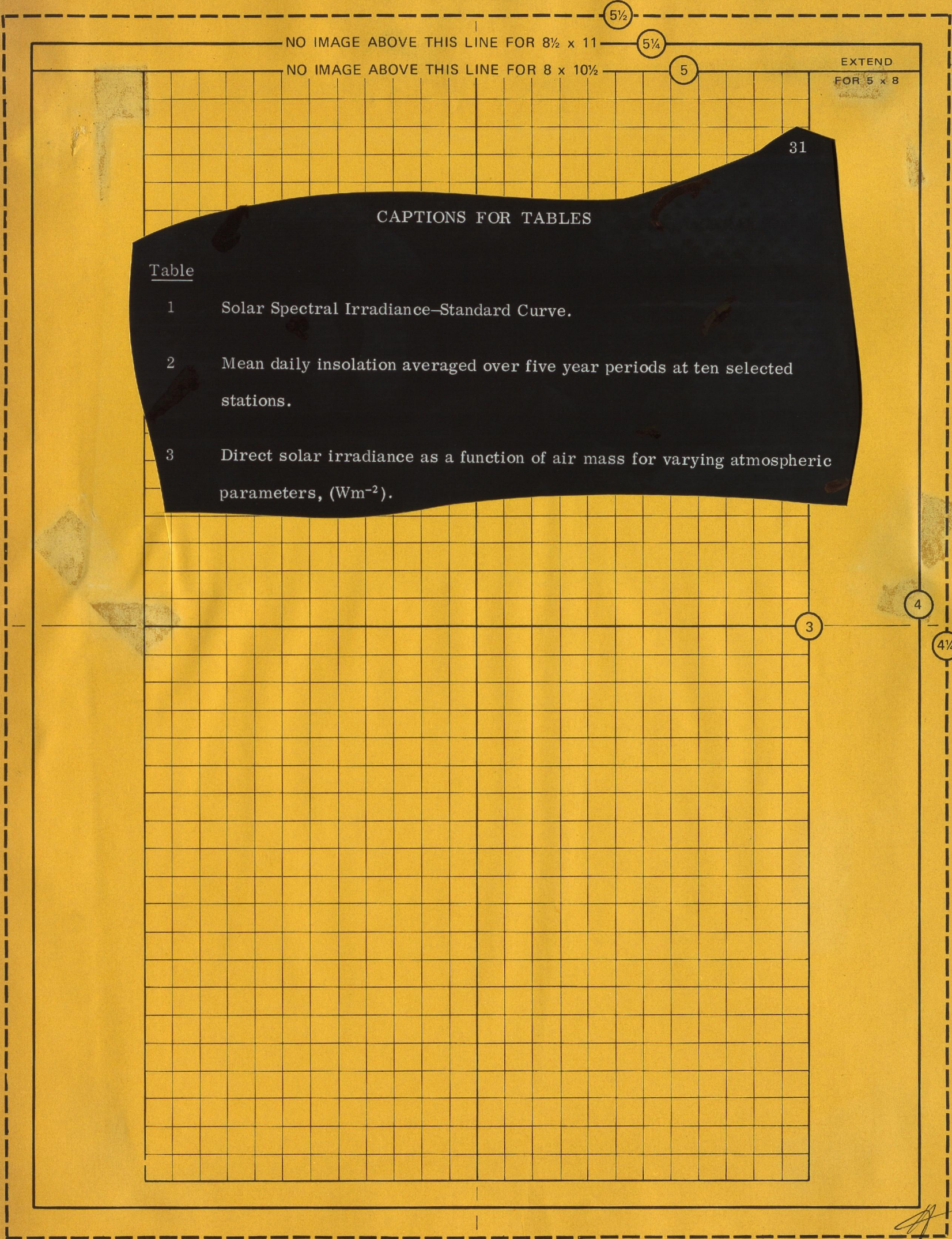
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CAPTIONS FOR TABLES

Table

- 1 Solar Spectral Irradiance—Standard Curve.
- 2 Mean daily insolation averaged over five year periods at ten selected stations.
- 3 Direct solar irradiance as a function of air mass for varying atmospheric parameters, (Wm^{-2}).

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CAPTIONS FOR FIGURES

Figure

- 1 Time perspective of world fossil fuel consumption.
- 2 Relative spectral response of silicon solar cells.
- 3 Values of the solar constant derived from high altitude measurements.
- 4 Solar spectral irradiance, standard curve, solar constant 1353 Wm^{-2} .
- 5 Global irradiance due to the Sun and sky on a horizontal surface, measured at GSFC, on May 13, 1971. Total energy received during the day, $732 \text{ joules cm}^{-2}$ (175 cal cm^{-2}).
- 6 Global irradiance due to the Sun and sky on a horizontal surface, measured at GSFC, on May 14, 1971. Total energy received during the day, $2707 \text{ joules cm}^{-2}$ (647 cal cm^{-2}).
- 7 Working standard pyranometers of different models from major meteorological institutions throughout the world set up on roof top for intercomparison.
- 8 Pyranometer, bulb type, Eppley Model 50 j.
- 9 Pyranometer, double dome type, Eppley Model 2.
- 10 Normal incidence pyrhelimeter, NIP, (Eppley) mounted on heliostat.
- 11 Thermopiles (Sensors Inc. Model C 1) mounted on sloping surfaces facing six directions.

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SECTION

10" x 15" LAYOUT FLAT

NO IMAGE ABOVE THIS LINE FOR 8½ x 11

NO IMAGE ABOVE THIS LINE FOR 8 x 10½

EXTEND
FOR 5 x 8

Figure

- 12 Pyranometer (Groiss, Trickett-Norris Model) mounted on flat plate solar collector.
- 13 Ångström electrical compensation pyrhelimeter (Eppley, No. 6618) with its electrical control unit.
- 14 Perkin Elmer monochromator used on CV 990 for solar spectral irradiance measurements.
- 15 Bolographs of the infrared prismatic solar spectrum, the $\rho\sigma\tau$ region, wavelengths 8500 to 10000 Ångströms, three successive traces made on Sept. 4, 1928.
- 16 Ten minute averages of direct solar and global irradiance at GSFC on Feb. 7, 1975.
- 17 Ten minute averages of direct solar and global irradiance at GSFC on Feb. 8, 1975.
- 18 Mean daily irradiance on a horizontal surface (in cal cm^{-2}) based on NWS (USA) records of 5 years, 1951-1955.
- 19 Mean daily irradiance on a horizontal surface (in cal cm^{-2}) based on NWS (USA) records of 5 years, 1967-1971.
- 20 Mean daily irradiance on a horizontal surface over the U.S., with different shades showing increase in insolation in steps of 50 cal cm^{-2} , based on NWS records of 5 years, 1967-1971.

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10" x 15" LAYOUT FLAT

**PYRANOMETERS MOUNTED ON BENCH ON
ROOFTOP OF BUILDING 7, GSFC**



Figure 7

NO IMAGE ABOVE THIS LINE FOR 8 1/2 x 11
NO IMAGE ABOVE THIS LINE FOR 8 x 10 1/2

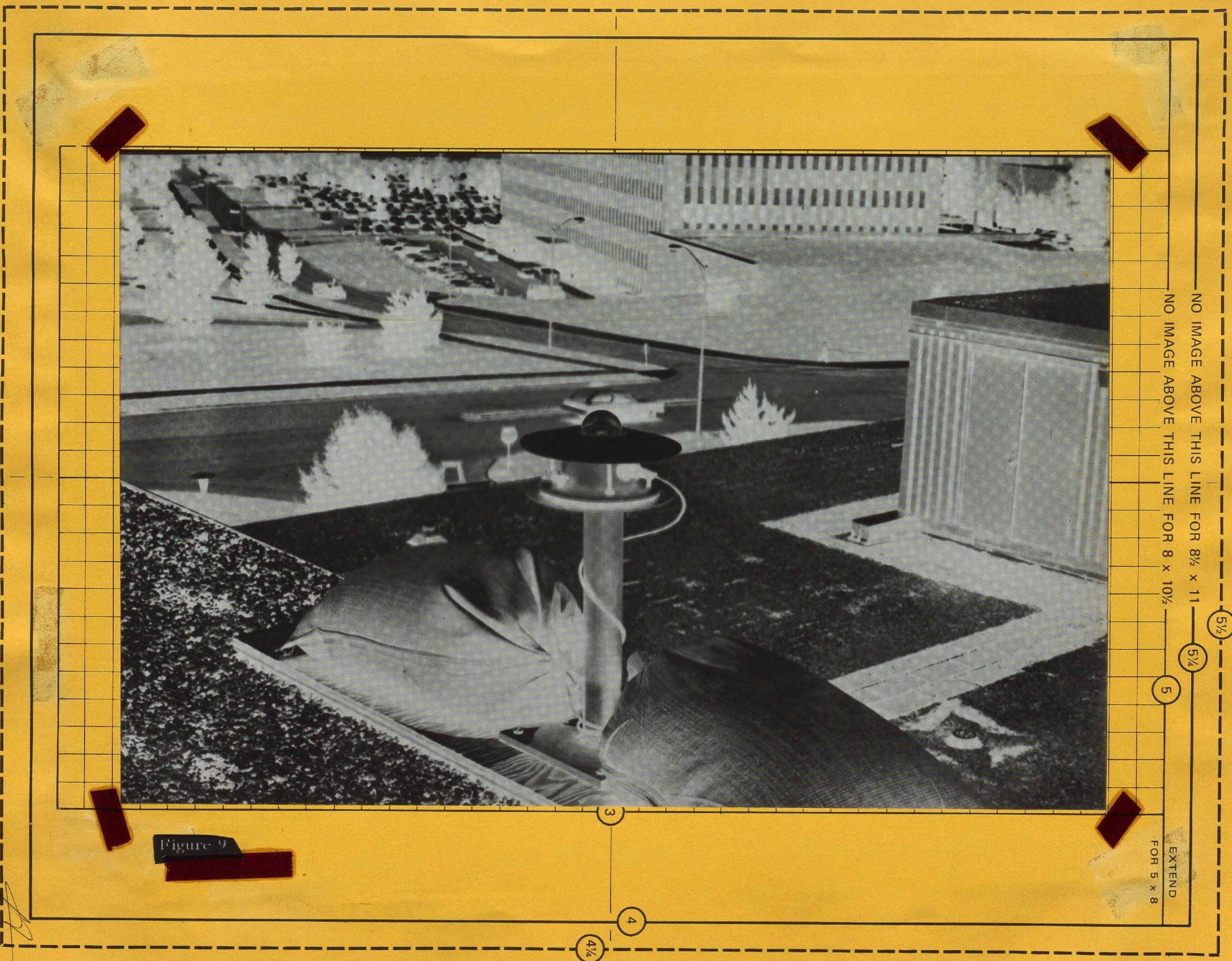
5 1/2 5 1/2 5

EXTEND
FOR 5 x 8

3 4 4 1/2

**PRINTING AND DUPLICATING
SECTION**

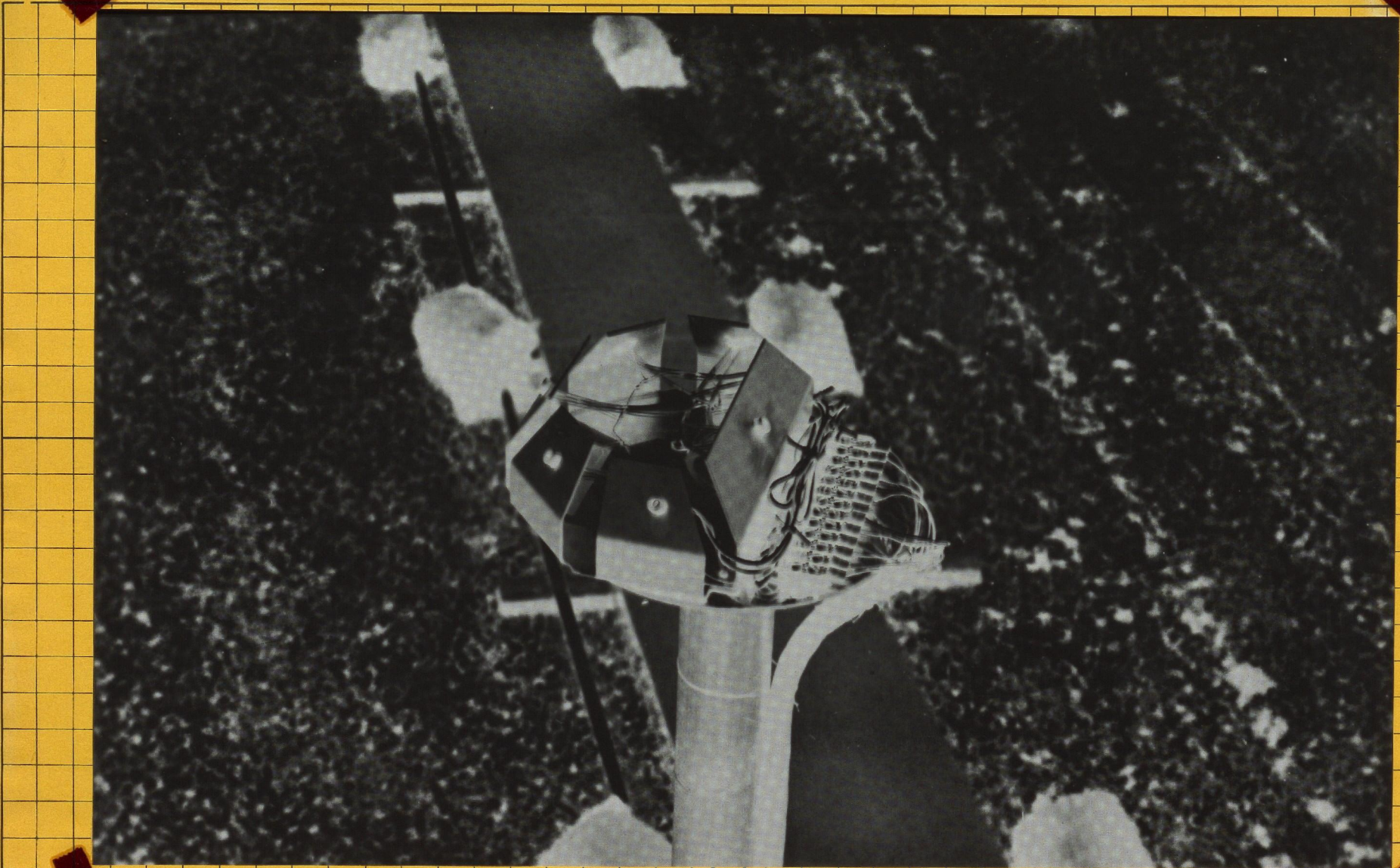
10" x 15" LAYOUT FLAT



PRINTING AND DUPLICATING
SECTION

10" x 15" LAYOUT FLAT

NO IMAGE ABOVE THIS LINE FOR 8 1/2" x 11"
NO IMAGE ABOVE THIS LINE FOR 8" x 10"



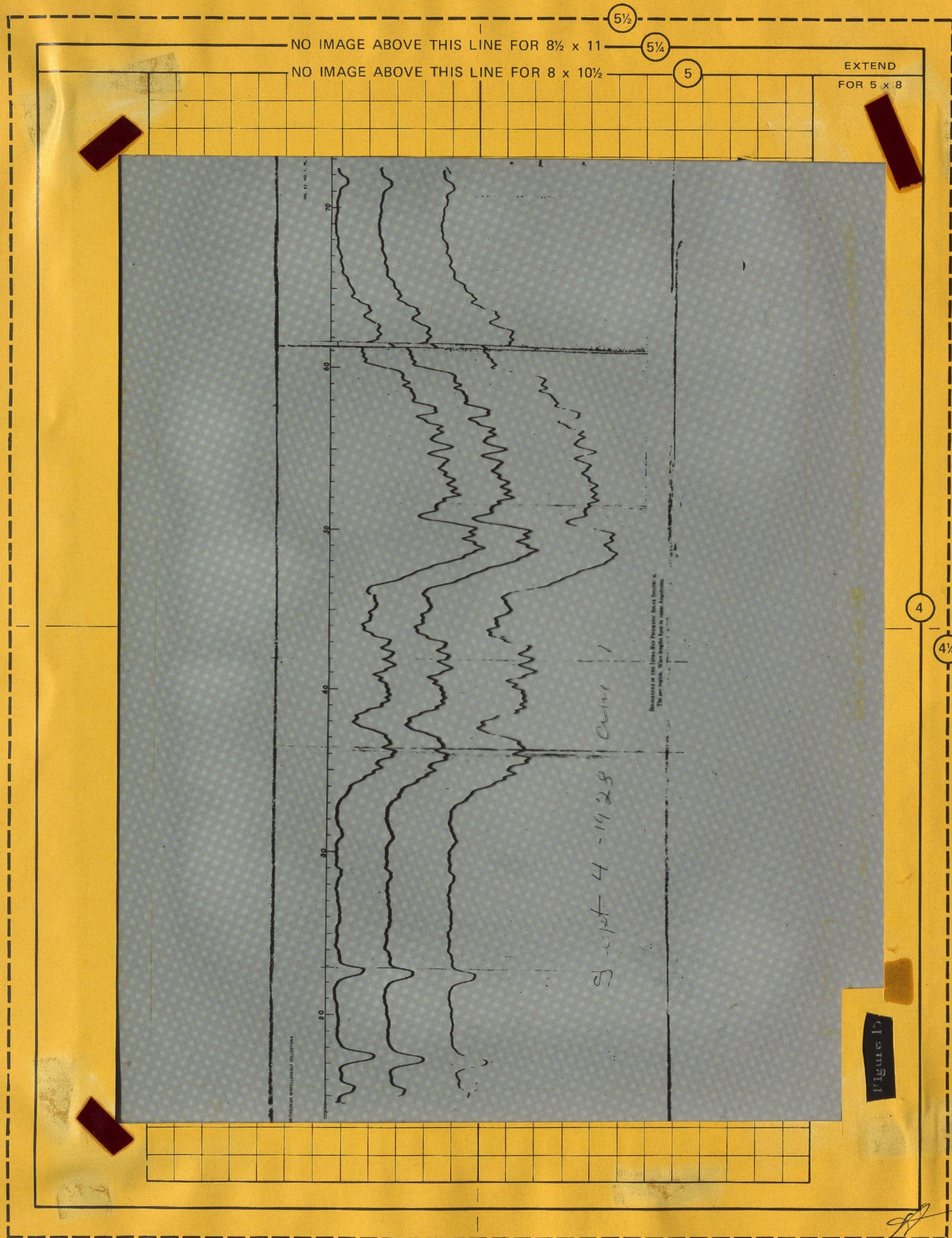
EXTEND
FOR 5" x 8"

Figure 11

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SECTION

10" x 15" LAYOUT FLAT



PRINTING AND DUPLICATING
SECTION

10" x 15" LAYOUT FLAT

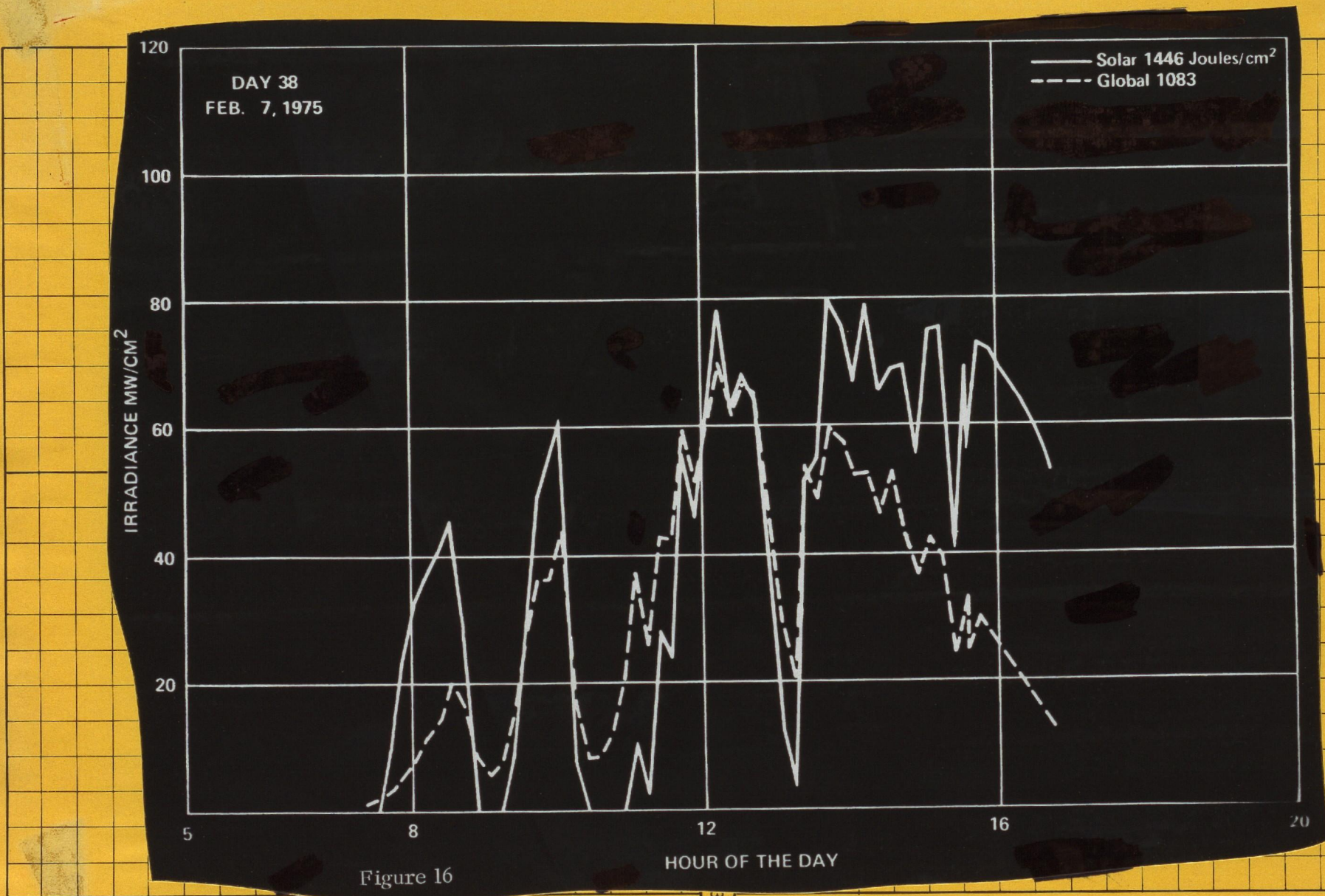


Figure 16

NO IMAGE ABOVE THIS LINE FOR 8 1/2 x 11
NO IMAGE ABOVE THIS LINE FOR 8 x 10 1/2

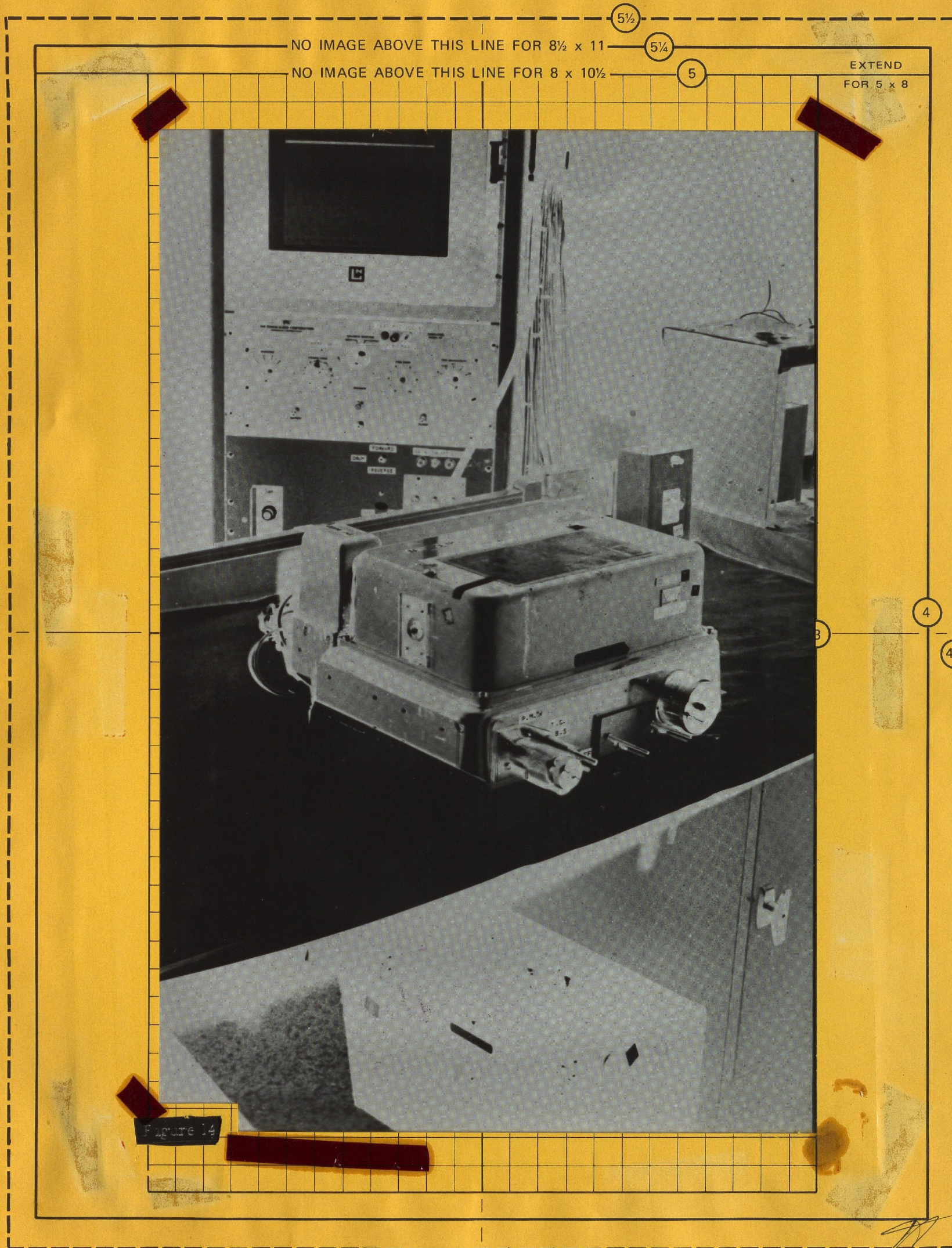
EXTEND
FOR 5 x 8

5 5 5 5

4 4 4

PRINTING AND DUPLICATING
SECTION

10" x 15" LAYOUT FLAT



PRINTING AND DUPLICATING
SECTION

10" x 15" LAYOUT FLAT

NO IMAGE ABOVE THIS LINE FOR 8 1/2" x 11"
NO IMAGE ABOVE THIS LINE FOR 8 x 10 1/2"

EXTEND
FOR 5 x 8

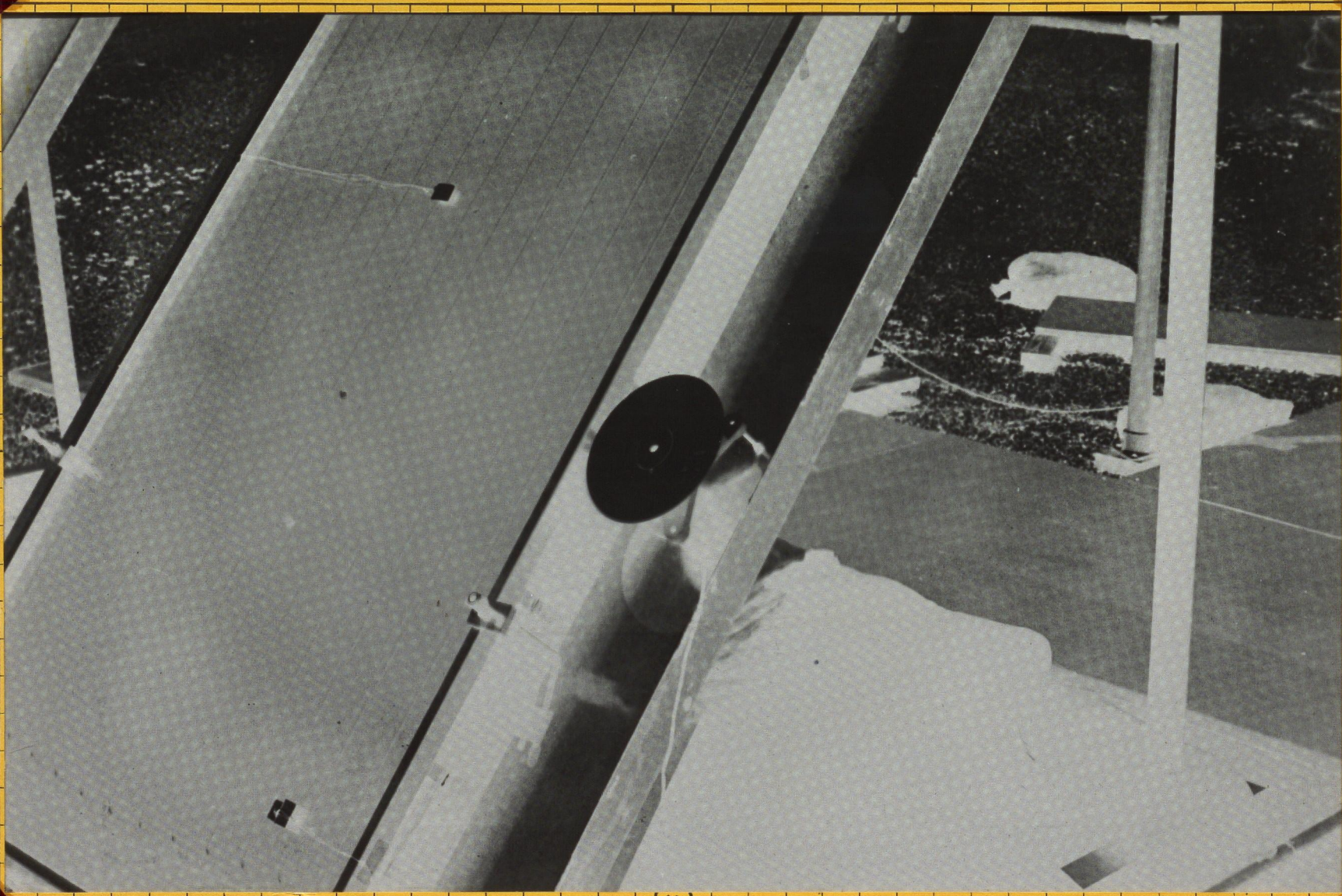


Figure 12

Handwritten initials or mark.

PRINTING AND DUPLICATING
SECTION

10" x 15" LAYOUT FLAT

NO IMAGE ABOVE THIS LINE FOR 8 1/2 x 11
NO IMAGE ABOVE THIS LINE FOR 8 x 10 1/2

EXTEND
FOR 5 x 8

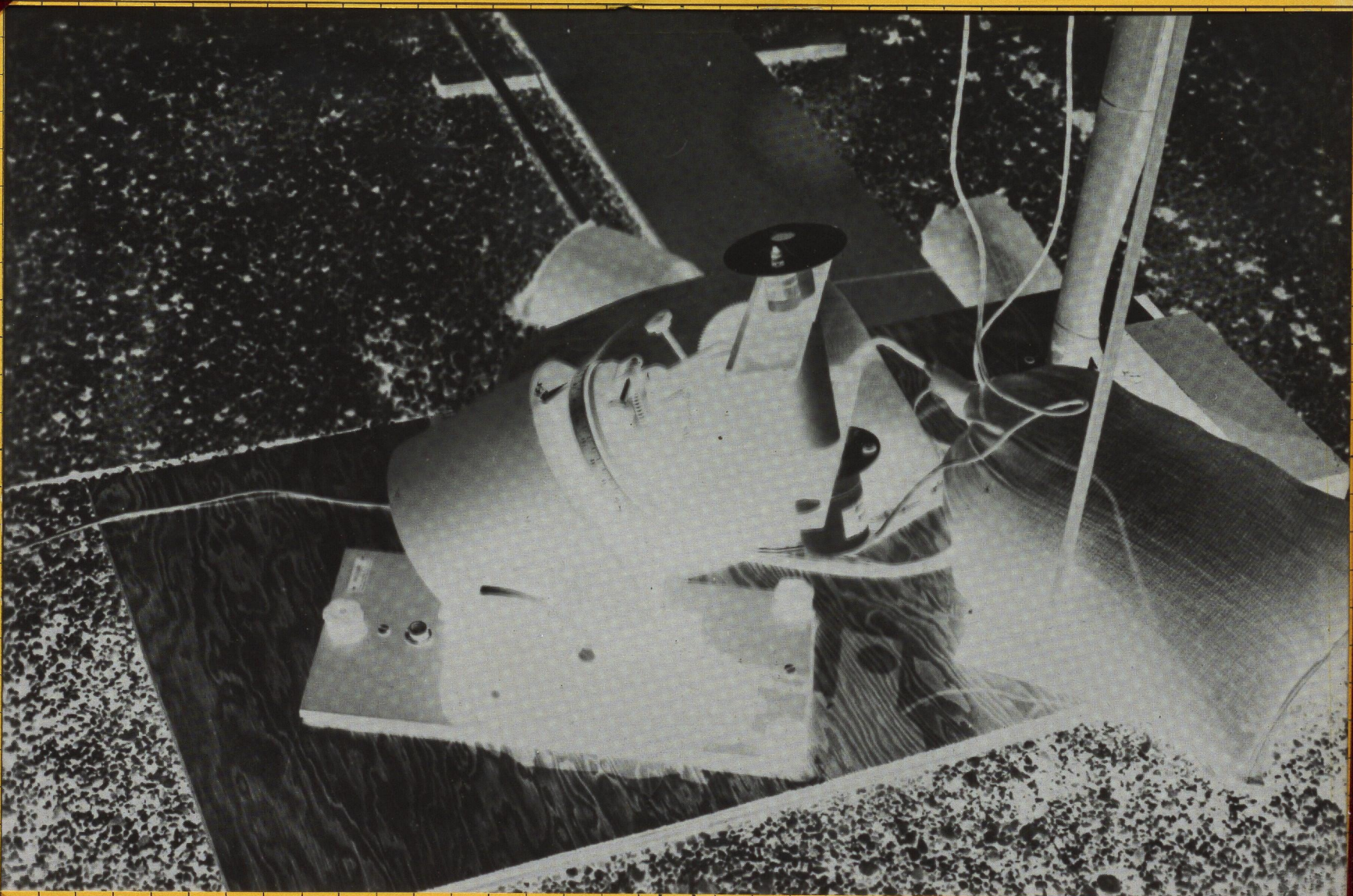


Figure 10



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PRINTING AND DUPLICATING
SECTION

10" x 15" LAYOUT FLAT

NO IMAGE ABOVE THIS LINE FOR 8 1/2 x 11
NO IMAGE ABOVE THIS LINE FOR 8 x 10 1/2

EXTEND
FOR 5 x 8

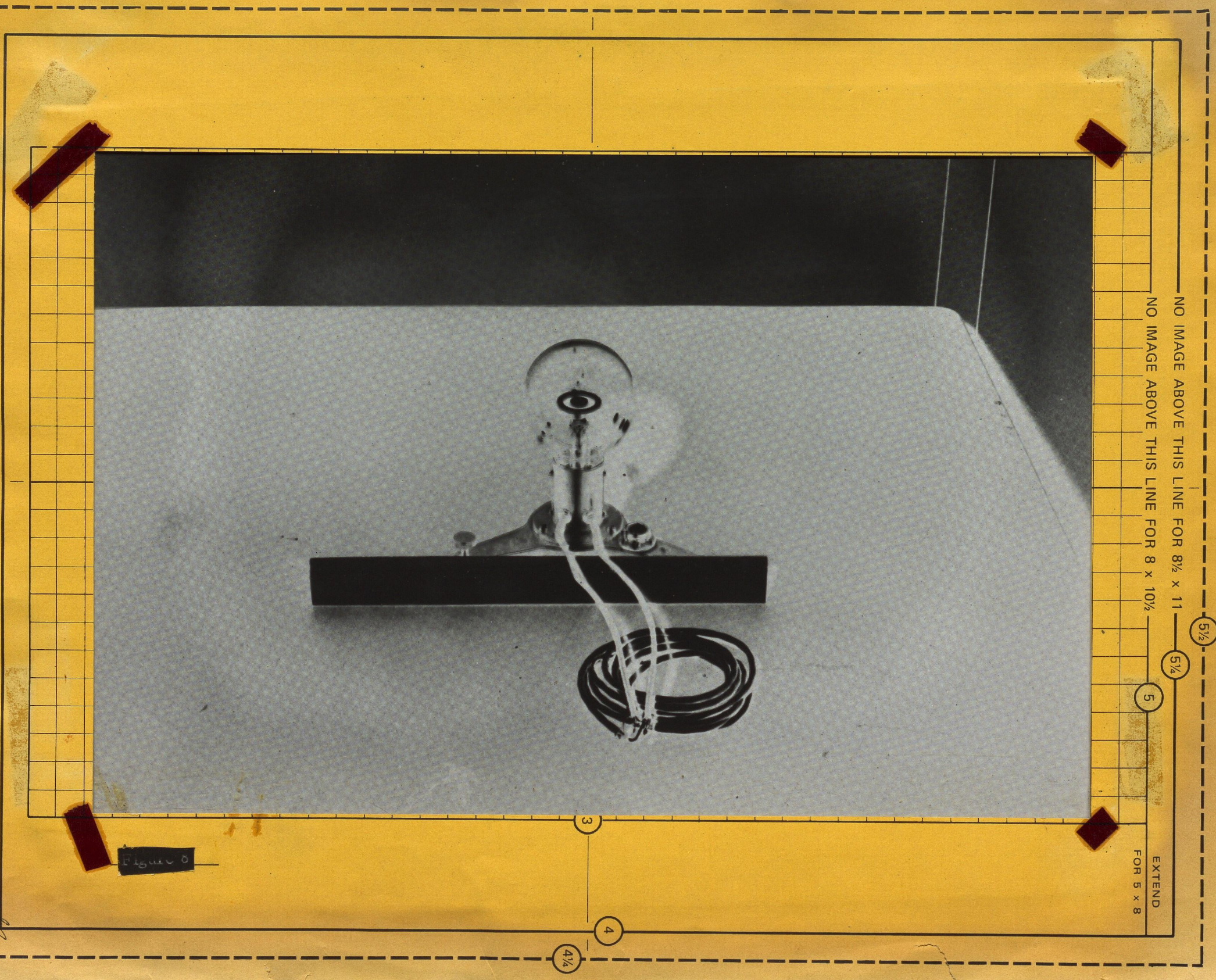
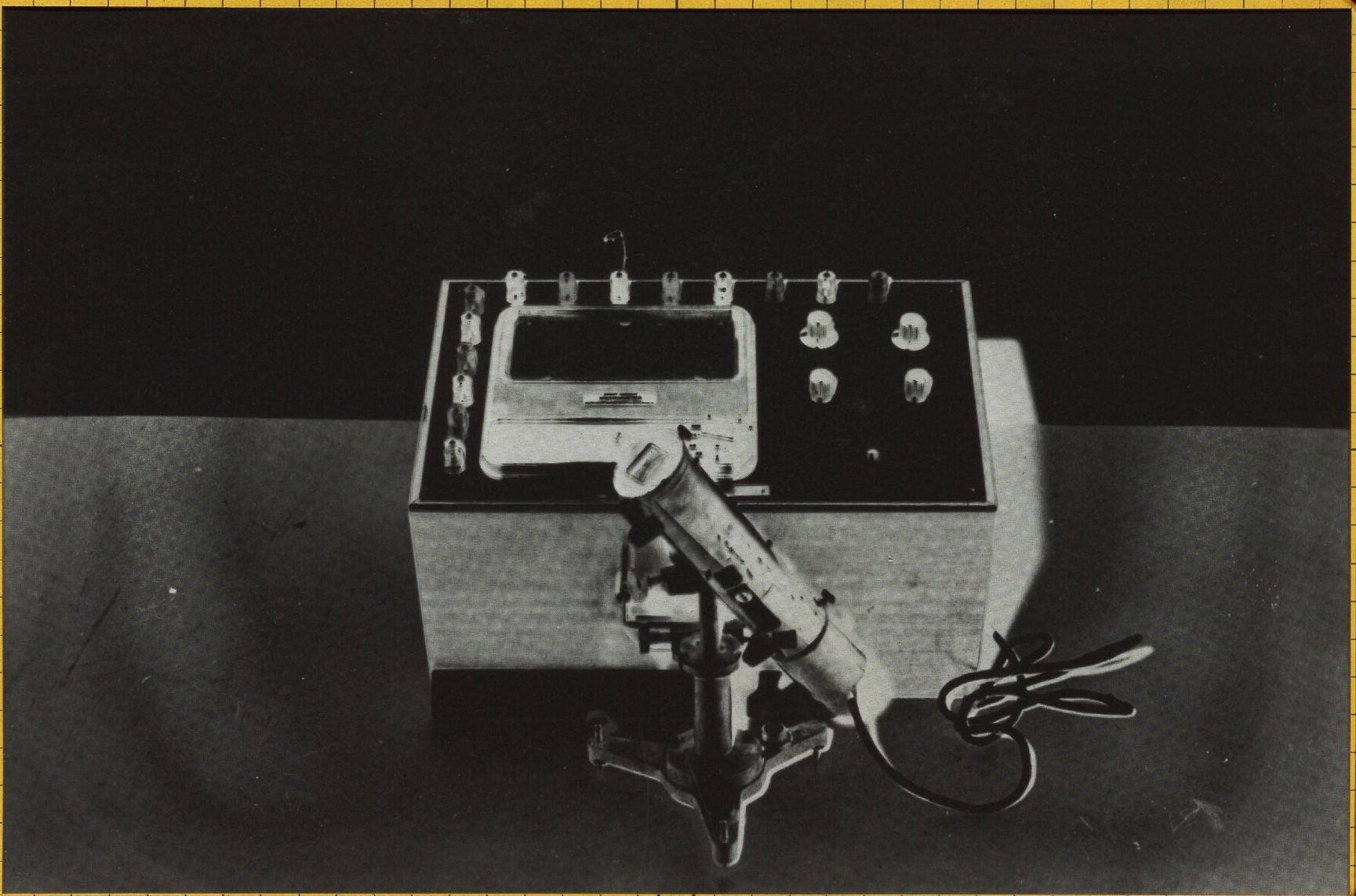


Figure 0

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PRINTING AND DUPLICATING
SECTION

10" x 15" LAYOUT FLAT



NO IMAGE ABOVE THIS LINE FOR 8 1/2 x 11
NO IMAGE ABOVE THIS LINE FOR 8 x 10 1/2

5 1/2

5 1/2

5

EXTEND
FOR 5 x 8

3

4

4 1/2

Figure 13