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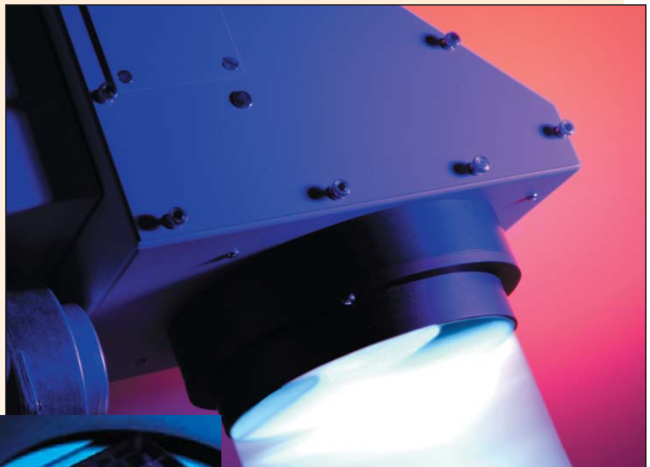

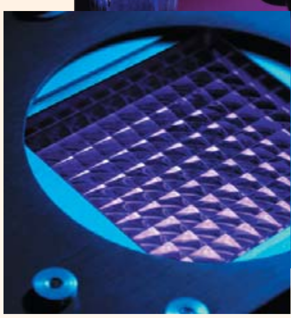

Solar Simulation

SECTION FEATURES

- Glossary of Terms and Units
- Introduction to Solar Radiation
- Solar UV and Ozone Layer
- Energy Conversion
- Weathering
- Sample Calulations
- Spectral Irradiance Data
- Curve Normalization

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These two pages briefly define the terms and units most frequently used in the following Technical Discussion. These definitions are limited to the context in which the terms are used in this catalog.

Actinic dose: Quantity obtained by weighing spectrally the radiation dose using the action spectrum.

Actinic (radiation): The radiation that produces a specified effect.

Action spectrum (actinic): Efficiency of monochromatic radiations for producing a specified actinic phenomenon in a specified system.

Air mass (relative optical): Ratio of the slant optical thickness, to the vertical optical thickness of the standard atmosphere.

Albedo: (Definition limited to solar radiation) Reflectance of solar radiation by the surroundings. This applies to the full integrated spectrum; the reflectance may depend strongly on the spectral region.

Blackbody: A body that absorbs all radiant energy incident on it.

Collimation and angle of terrestrial solar irradiation: The terrestrial irradiance from the sun is composed of a direct beam with a collimation angle of approximately 0.5° and a diffuse component. The spectra and magnitude of each component changes through the day. Measurement of direct radiation requires limiting the field of view (FOV). (The recommended aperturing system limits the input to a slope half angle of 0.5°, an opening half angle of 2.65°, and a limit half angle of 4.65°. Measuring the total radiation requires an instrument with a 180° FOV.)

Daylight: Visible part of global solar radiation.

Diffuse sky radiation: The part of solar radiation which reaches the earth as a result of being scattered by the air molecules, aerosol particles, cloud particles, or other particles.

Direct solar radiation: The part of extraterrestrial solar radiation which, as a collimated beam, reaches the earth's surface after selective attenuation by the atmosphere.

Dobson unit (D.U.): Measure of columnar density of ozone. 1 D.U. is one milliatmosphere centimeter of ozone at STP. Typical values range from 200 - 600 D.U. with values of 110 in the Antarctic "ozone hole."

Dose: (Of optical radiation of a specified spectral distribution) Term used in photochemistry, phototherapy, and photobiology for the quantity radiant exposure. Unit, J m^{-2}.

Dose Rate: Term used in photochemistry, phototherapy, and photobiology for the quantity irradiance. Unit, W m^{-2}.

Effective dose: That part of the dose that actually produces the actinic effect considered.

Effective exposure rate: The integrated product of the spectral irradiance and action spectra.

Erythema (actinic): Reddening of the skin, with or without inflammation, caused by the actinic effect of solar radiation or artificial optical radiation.

Erythemal radiation: Optical radiation effective in causing actinic erythema.

Extraterrestrial solar radiation: Solar radiation incident on the outer limit of the earth's atmosphere.

Global illuminance (Eg): Illuminance produced by daylight on a horizontal surface of the earth.

Global solar radiation: Combined direct solar radiation and diffuse sky radiation.

Infrared radiation: Optical radiation for which the wavelengths are longer than those for visible radiation, 700 nm to 1000 µm.

Irradiance: Describes the flux, radiative power density, and incidence on a surface. Units, W m^{-2} or W cm^{-2}. The surface must be specified for the irradiance to have meaning. (Laboratory surfaces are not usually as large as a square meter; this happens to be the appropriate SI unit of area).

Langley: 1 calorie cm^{-2} = 2.39 x 10^5 J m^{-2}

Minimum Erythema Dose (MED): The actinic dose that produces a just noticeable erythema on normal, non-exposed, "white" skin. This quantity corresponds to a radiant exposure of monochromatic radiation at the maximum spectral efficiency (λ = 295 nm) of roughly 100 J m^{-2}.

Ozone (O_3): What is produced when molecular oxygen in the stratosphere absorbs shortwave (up to 242.2 nm) ultraviolet, and photodissociates. Ozone can be a health hazard in concentrated amounts. (Our solar simulators use ozone free lamps.)

Solar constant (I_{SC}): Irradiance produced by the extraterrestrial solar radiation on a surface perpendicular to the sun's rays at a mean sun-earth distance (I_{SC} = (1367 ±7 W m^{-2}).

Spectral irradiance E(λ): The irradiance per unit wavelength interval at a specified wavelength.

Spectral irradiance units, W m^{-2} nm^{-1}
To convert into W m^{-2} μm^{-1}, multiply by 1000 (1000 E)
To convert into W cm^{-2} nm^{-1}, multiply by 10^{-4} (10^{-4} E)
To convert into W cm^{-2} μm^{-1}, multiply by 0.1 (0.1 E)

Standard solar radiation: Spectra that have been developed to provide a basis for theoretical evaluation of the effects of solar radiation, and as a basis for simulator design. In this catalog, we refer to the ASTM E490, E891 and E892 standards, which define AM 0, AM 1.5 D and 1.5 G, respectively. We also refer to the CIE Pub. 85 and 904-3 standards which define AM 1 and AM 1.5 G, respectively.

Sunlight: Visible part of direct solar radiation.

Sunshine duration: Sum of time intervals within a given time period during which the irradiance from direct solar radiation on a plane normal to the sun direction is equal to or greater than 200 W m^{-2}.

Terrestrial spectra: The spectrum of the solar radiation at the earth's surface.

Ultraviolet radiation: Optical radiation for which the wavelengths are shorter than those for visible radiation, <400 nm.

Note: For ultraviolet radiation, the range below 400 nm is commonly suddivided into:

UVA 320 - 400 nm
UVB 280 - 320 nm
UVC <280 nm

Uniformity: A measure of how the irradiance varies over a selected (or defined) area. Usually expressed as non-uniformity, the maximum and minimum % differences from the mean irradiance.

$$\pm 100\left(\frac{E_{max} - E_{min}}{E_{max} + E_{min}}\right)$$

Visible radiation: Any optical radiation capable of causing a visual sensation directly, 400 - 700 nm.

Newport's involvement with light sources to accurately simulate the sun has involved us in different scientific and technical areas. In this section we attempt to help the beginner with the basics of solar radiation and to explain the relevance of our products. We have structured this section to present basic material, and then deal with each main application area separately. The major areas of interest we deal with are:

BASICS OF SOLAR RADIATION

Radiation from the sun sustains life on earth and determines climate. The energy flow within the sun results in a surface temperature of around 5800 K, so the spectrum of the radiation from the sun is similar to that of a 5800 K blackbody with fine structure due to absorption in the cool peripheral solar gas (Fraunhofer lines).

EXTRATERRESTRIAL AND TERRESTRIAL SPECTRA

Extraterrestrial Spectra

Fig. 1 shows the spectrum of the solar radiation outside the earth's atmosphere. The range shown, 200 - 2500 nm, includes 96.3% of the total irradiance with most of the remaining 3.7% at longer wavelengths.

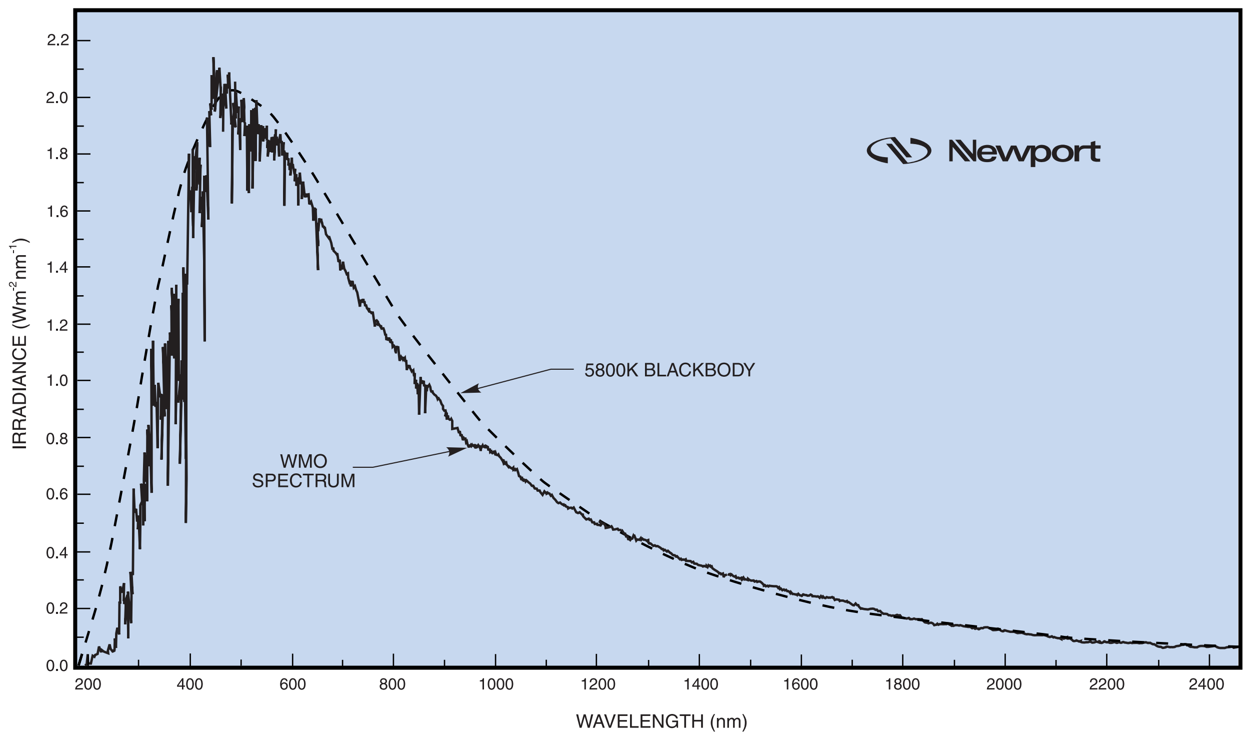


Fig. 1 Spectrum of the radiation outside the earth's atmosphere compared to spectrum of a 5800 K blackbody.

Solar Constant and "Sun Value"

The irradiance of the sun on the outer atmosphere when the sun and earth are spaced at 1 AU (the mean earth/sun distance of 149,597,890 km), is called the solar constant. Currently accepted values are about 1360 W m^{-2}. (The NASA value given in ASTM E 490-73a is 1353 (±21 W m^{-2}.) The World Metrological Organization (WMO) promotes a more recent value of 1367 W m^{-2}.) The solar constant is the total integrated irradiance over all of the spectrum; the area under the curve in Fig. 1 plus the 3.7% at shorter and longer wavelengths.

The irradiance falling on the earth's atmosphere changes over a year by about 6.6% due to the variation in the earth sun distance. Solar activity variations cause irradiance changes of up to 1%.

For a solar simulator, such as those described in detail on pages 7-36 to 7-47 in the Oriel Light Resource Catalog, it is convenient to describe the irradiance of the simulator in "suns." One "sun" is equivalent to irradiance of one solar constant.

Many applications involve only a selected region of the entire spectrum. In such a case, a "3 sun unit" has three times the actual solar irradiance in the spectral range of interest and a reasonable spectral match in this range.

EXAMPLE

The model 91160 Solar Simulator has a similar spectrum to the extraterrestrial spectrum and has an output of 2680 W m^{-2}. This is equivalent to 1.96 times 1367 W m^{-2} so the simulator is a 1.96 sun unit.

Terrestrial Spectra

The spectrum of the solar radiation at the earth's surface has several components (Fig. 2). Direct radiation comes straight from the sun, diffuse radiation is scattered from the sky and from the surroundings. Additional radiation reflected from the surroundings (ground or sea) depends on the local "albedo." The total ground radiation is called the global radiation. The direction of the target surface must be defined for global irradiance. For direct radiation the target surface faces the incoming beam.

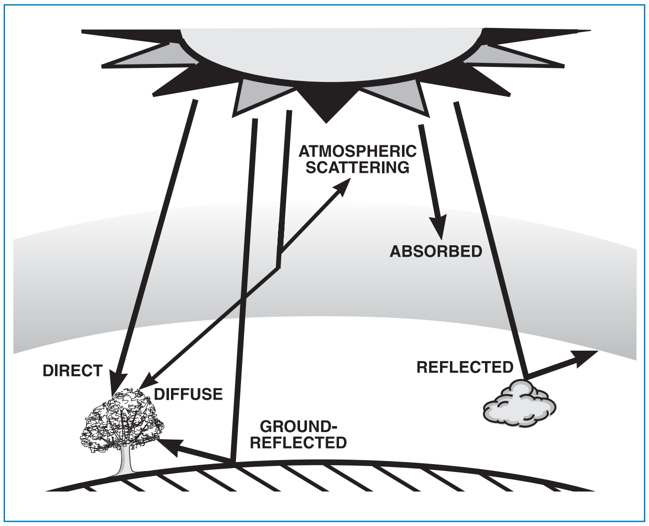


Fig. 2 The total global radiation on the ground has direct, scattered and reflective components.

All the radiation that reaches the ground passes through the atmosphere which modifies the spectrum by absorption and scattering. Atomic and molecular oxygen and nitrogen absorb very short wave radiation effectively blocking radiation with wavelengths <190 nm. When molecular oxygen in the atmosphere absorbs short wave ultraviolet radiation, it photodissociates. This leads to the production of ozone. Ozone strongly absorbs longer wavelength ultraviolet in the Hartley band from 200 - 300 nm and weakly absorbs visible radiation. The widely distributed stratospheric ozone produced by the sun's radiation corresponds to approximately a 3 mm layer of ozone at STP. The "thin ozone layer" absorbs UV up to 280 nm and (with atmospheric scattering) shapes the UV edge of the terrestrial solar spectrum.

Water vapor, carbon dioxide, and to a lesser extent, oxygen, selectively absorb in the near infrared, as indicated in Fig. 3. Wavelength dependent Rayleigh scattering and scattering from aerosols (particulates including water droplets) also change the spectrum of the radiation that reaches the ground (and make the sky blue). For a typical cloudless atmosphere in summer and for zero zenith angle, the 1367 W m^{-2} reaching the outer atmosphere is reduced to ca. 1050 W m^{-2} direct beam radiation, and ca. 1120 W m^{-2} global radiation on a horizontal surface at ground level.

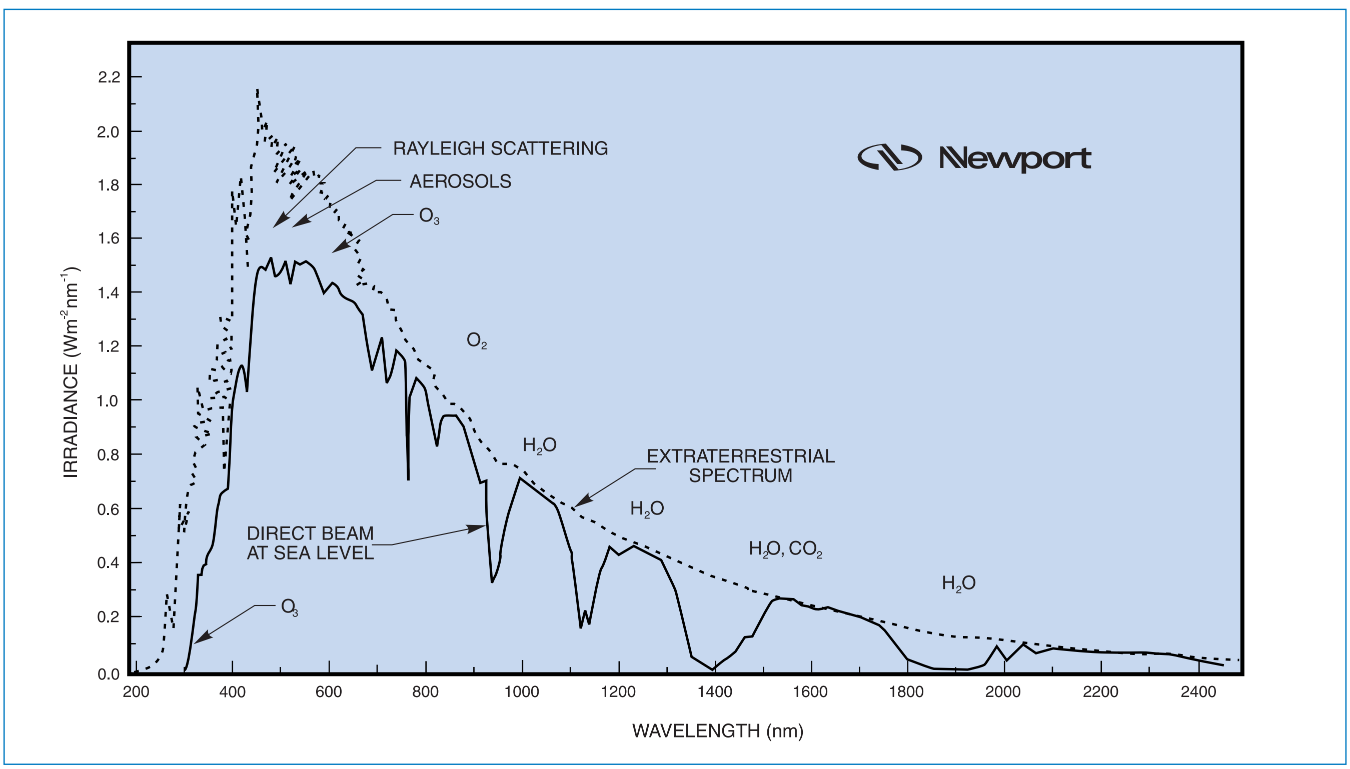


Fig. 3 Normally incident solar spectrum at sea level on a clear day. The dotted curve shows the extrarrestrial spectrum.

The Changing Terrestrial Solar Spectrum

Absorption and scattering levels change as the constituents of the atmosphere change. Clouds are the most familiar example of change; clouds can block most of the direct radiation. Seasonal variations and trends in ozone layer thickness have an important effect on terrestrial ultraviolet level.

The ground level spectrum also depends on how far the sun's radiation must pass through the atmosphere. Elevation is one factor. Denver has a mile (1.6 km) less atmosphere above it than does Washington, and the impact of time of year on solar angle is important, but the most significant changes are due to the earth's rotation (Fig. 4). At any location, the length of the path the radiation must take to reach ground level changes as the day progresses. So not only are there the obvious intensity changes in ground solar radiation level during the day, going to zero at night, but the spectrum of the radiation changes through each day because of the changing absorption and scattering path length.

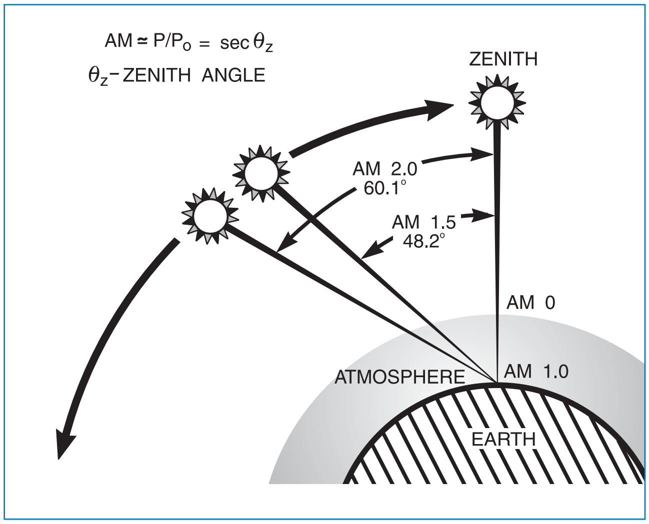


Fig. 4 The path length in units of Air Mass, changes with the zenith angle.

With the sun overhead, direct radiation that reaches the ground passes straight through all of the atmosphere, all of the air mass, overhead. We call this radiation "Air Mass 1 Direct" (AM 1D) radiation and for standardization purposes use a sea level reference site. The global radiation with the sun overhead is similarly called "Air Mass 1 Global" (AM 1G) radiation. Because it passes through no air mass, the extraterrestrial spectrum is called the "Air Mass 0" spectrum.

The atmospheric path for any zenith angle is simply described relative to the overhead air mass (Fig. 4). The actual path length can correspond to air masses of less than 1 (high altitude sites) to very high air mass values just before sunset. Our Oriel Solar Simulators use filters to duplicate spectra corresponding to air masses of 0, 1, 1.5 and 2, the values on which most comparative test work is based.

Standard Spectra

Solar radiation reaching the earth's surface varies significantly with location, atmospheric conditions (including cloud cover, aerosol content, and ozone layer condition), time of day, earth/sun distance, and solar rotation and activity. Since the solar spectra depend on so many variables, standard spectra have been developed to provide a basis for theoretical evaluation of the effects of solar radiation and as a basis for simulator design. These standard spectra start from a simplified (i.e. lower resolution) version of the measured extraterrestrial spectra, and use sophisticated models for the effects of the atmosphere to calculate terrestrial spectra.

The most widely used standard spectra are those published by The Committee Internationale d'Eclaraige (CIE), the world authority on radiometeric and photometric nomenclature and standards. The American Society for Testing and Materials (ASTM) publish three spectra, AM 0 AM 1.5 Direct and AM 1.5 Global for a 37° tilted surface. The conditions for the AM 1.5 spectra were chosen by ASTM "because they are representative of average conditions in the 48 contiguous states of the United States."

Fig. 5 shows typical differences in standard direct and global spectra. These curves are from the data in ASTM Standards, E 891 and E 892 for AM 1.5, a turbidity of 0.27 and a tilt of 37° facing the sun and a ground albedo of 0.2.

Table 1 Power Densities of Published Standards

Solar Condition	Standard	Power Density (Wm^{-2})		
		Total	250 - 2500 nm	250 - 1100 nm
	WMO Spectrum	1367		
AM 0	ASTM E 490	1353	1302.6	1006.9
AM 1	CIE Publication 85, Table 2		969.7	779.4
AM 1.5 D	ASTM E 891	768.3	756.5	584.7
AM 1.5 G	ASTM E 892	963.8	951.5	768.6
AM 1.5 G	CEI/IEC* 904-3	1000	987.2	797.5

* Integration by modified trapezoidal technique.
CEI = Commission Electrotechnique Internationale.
IEC = International Electrotechnical Commission.

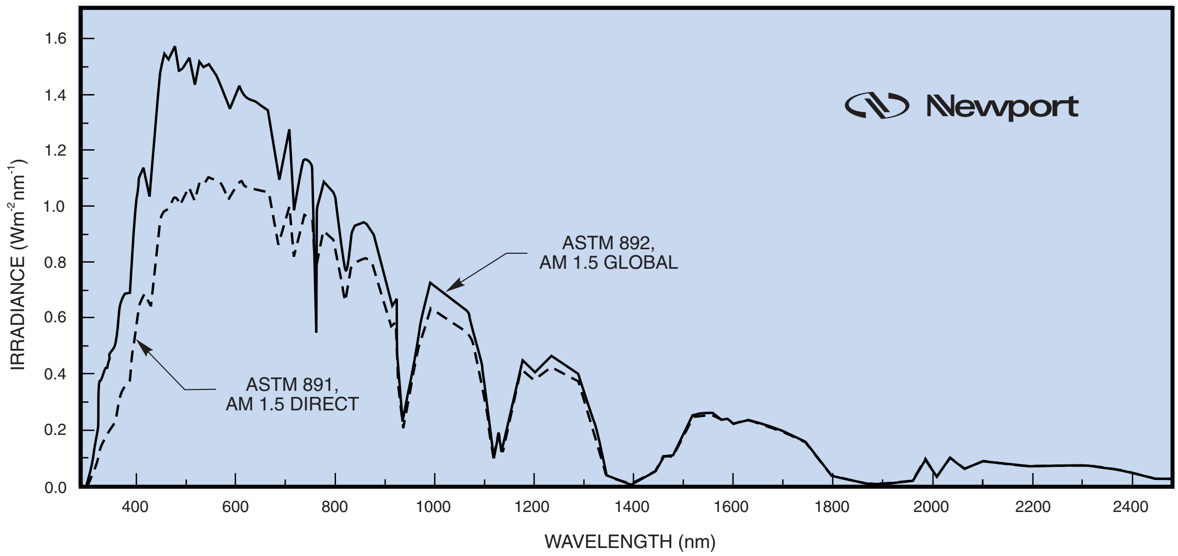


Fig. 5 Standard spectra for AM 1.5. The direct spectrum is from ASTM E891 and global ASTM E892.

The appearance of a spectrum depends on the resolution of the measurement and the presentation. Fig. 1 shows how spectral structure on a continuous background appears at two different resolutions. It also shows the higher resolution spectrum smoothed using Savitsky-Golay smoothing. The solar spectrum contains fine absorption detail that does not appear in our spectra. Fig. 2 shows the detail in the ultraviolet portion of the WMO (World Metrological Organization) extraterrestrial spectrum. Fig. 2 also shows a portion of the CEI AM 1 spectrum. The modeled spectrum shows none of the detail of the WMO spectrum, which is based on selected data from many careful measurements.

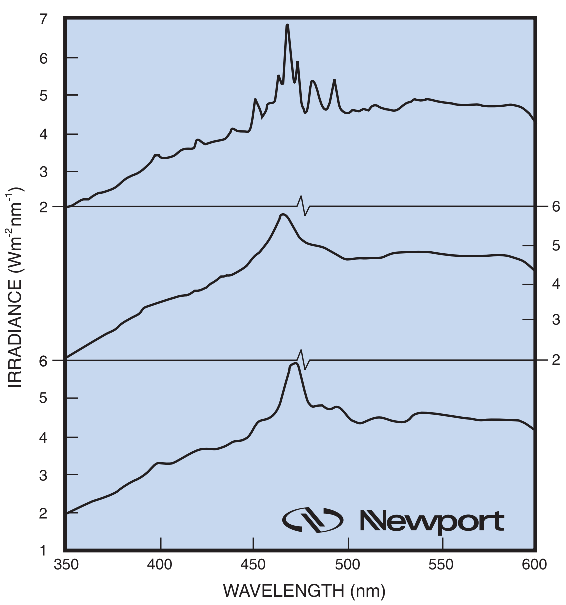


Fig. 1 Top: Actual scan of a simulator with resolution under 2 nm; high resolution doesn't enhance these Doppler broadened lines. Middle: Scan of same simulator with 10 nm resolution. Bottom: Smoothed version of top curve. We used repeated Savitsky-Golay smoothing. We use this technique for the curves on page 30 where we're comparing simulator and solar curves.

The spectra we present for our product and most available reference data is based on measurement with instruments with spectral resolutions of 1 nm or greater. The fine structure of the solar spectrum is unimportant for all the applications we know of; most biological and material systems have broad radiation absorption spectra.

Spectral presentation is more important for simulators that emit spectra with strong line structure. Low resolution or logarithmic plots of these spectra mask the line structure, making the spectra appear closer to the sun's spectrum. Broadband measurement of the ultraviolet output results in a single total ultraviolet irradiance figure. This can imply a close match to the sun. The effect of irradiance with these simulators depends on the application, but the result is often significantly different from that produced by solar irradiation, even if the total level within specified wavelengths (e.g. UVA, 320 - 400 nm) is similar. See page 7-16 for information on effectiveness spectra relevant to this discussion.

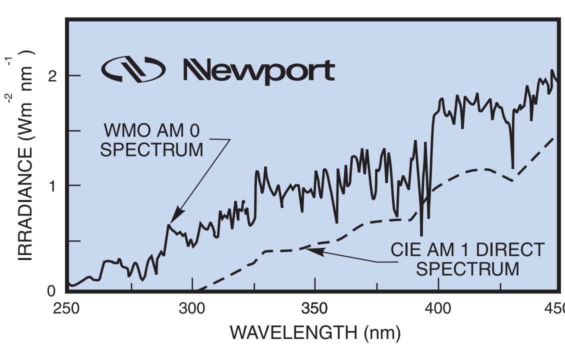


Fig. 2 Comparison of the UV portion of the WMO measured solar spectrum and the modeled CIE AM 1 direct spectrum. All the modeled spectra, CIE or ASTM, used as standards, omit the fine details seen in measured spectrum.

GEOMETRY OF SOLAR RADIATION

The sun is a spherical source of about 1.39 million km diameter, at an average distance (1 astronomical unit) of 149.6 million km from earth. The direct portion of the solar radiation is collimated with an angle of approximately 0.53° (full angle), while the "diffuse" portion is incident from the hemispheric sky and from ground reflections and scatter. The "global" irradiation, the sum of the direct and diffuse components, is essentially uniform.

Since there is a strong forward distribution in aerosol scattering, high aerosol loading of the atmosphere leads to considerable scattered radiation appearing to come from a small annulus around the solar disk, the solar aureole. This radiation mixed with the direct beam is called circumsolar radiation.

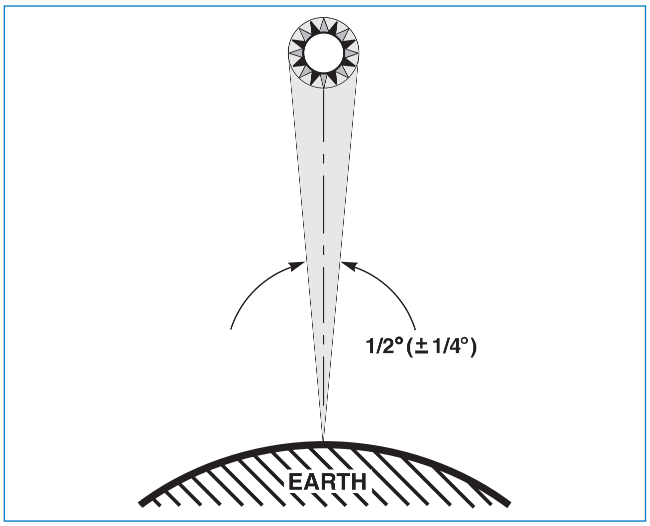


Fig. 6 The solar disk subtends a 1/2° angle at the earth.

DIRUNAL AND ANNUAL VARIATION

Figs. 7 and 8 show typical diurnal variations of global solar radiative flux. Actual halfwidth and peak position of the curve shape depend on latitude and time of year. Fig. 7 shows a cloudless atmosphere. Fig. 8 shows the impact of clouds. Fig. 9 shows the global solar irradiance at solar noon measured in Arizona, showing the annual variation.

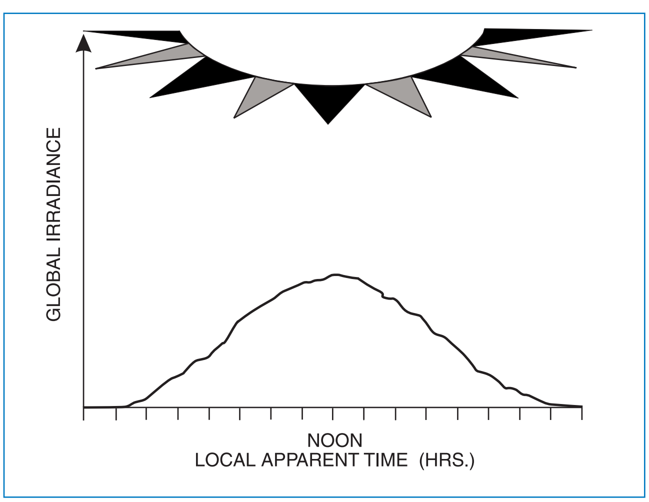


Fig. 7 Diurnal variations of global solar radiative flux on a sunny day.

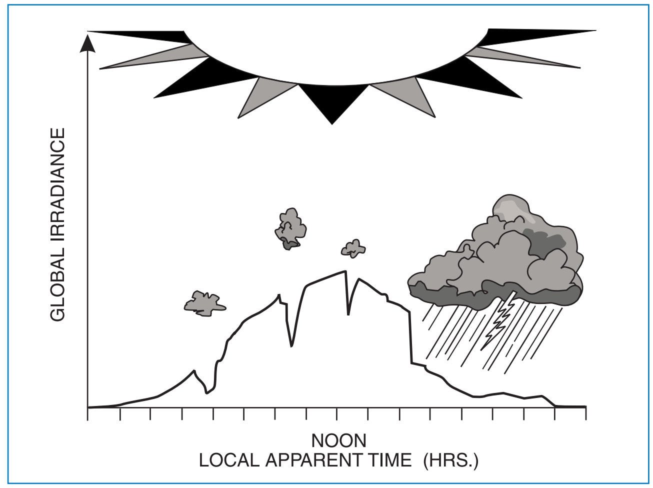


Fig. 8 Diurnal variations of global solar radiative flux on a cloudy day

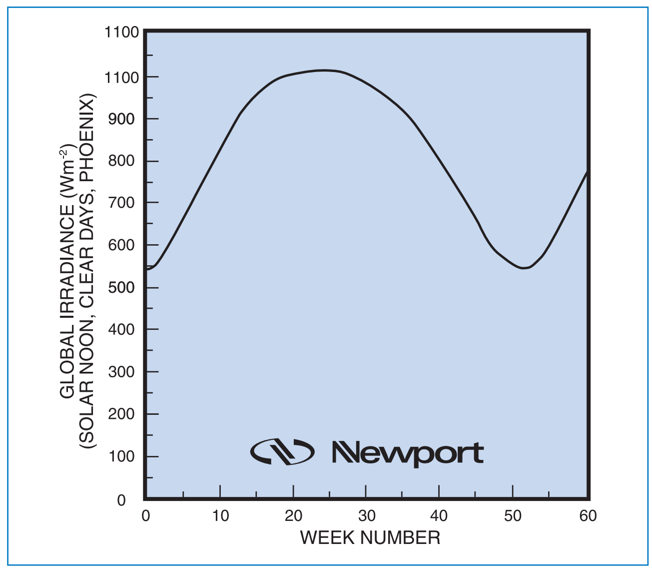


Fig. 9 The global solar irradiance at solar noon measured in Arizona, showing the annual variation.

SIMULATION OF SOLAR IRRADIATION

Light sources developed and used to simulate solar radiation are called solar simulators. There are several types with different spectra and irradiance distributions. Here we list some advantages of simulators and then explain why Newport's Oriel Xenon Solar Simulators approach the ideal. We are in the final development stages of Class A Solar Simulators. See page 7-32 to 7-35 in the Oriel Light Resource Catalog, for details.

ADVANTAGES OF SIMULATORS; PREDICTABLE, STEADY OUTPUT

Outdoor exposure is the ultimate test of the weather resistance for any material or product. Solar simulators offer significant advantages because of the unpredictable variation and limited availability of solar radiation. With a simulator you can carry out tests when you want to, and continue them 24 hours a day, and you can control the humidity and other aspects of the local environment. You can repeat the same test, in your laboratory or at any other site and you can relate the exposure to the internationally accepted solar irradiation levels. As with direct solar irradiance, you can concentrate the beam for accelerated testing.

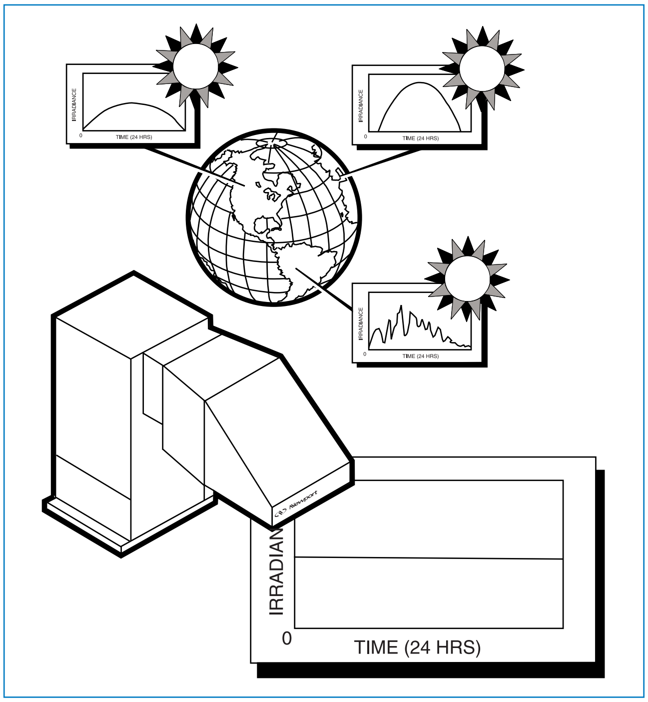


Fig. 10 Simulators let you simulate various solar conditions any time of the day, during any weather condition.

TYPES OF SIMULATORS

There are several types of solar simulators, differing in spectral power distribution and irradiance geometry. The type of lamp determines the spectral power distribution, although the spectrum may be modified by optical filters. The beam optics determine efficiency and irradiance geometry.

ORIEL XENON ARC LAMP SOLAR SIMULATORS

Our Oriel Solar Simulators provide the closest spectral match to solar spectra available from any artificial source. The match is not exact but better than needed for many applications. Our curves (see pages 30 to 32) clearly show the differences for the various solar Air Mass spectra. (We can produce more exact matches over limited spectral ranges.)

Fig. 11 shows the optics of the Oriel Simulators. The xenon arc lamp at the heart of the device emits a 5800K blackbody-like spectrum with occasional line structure. The small high radiance arc allows efficient beam collimation. The system design features low F/# collection, optical beam homogenization and filtering and finally, collimation. The result is a continuous output with a solar-like spectrum in a uniform collimated beam. Beam collimation simulates the direct terrestrial beam and allows characterization of radiation induced phenomena.

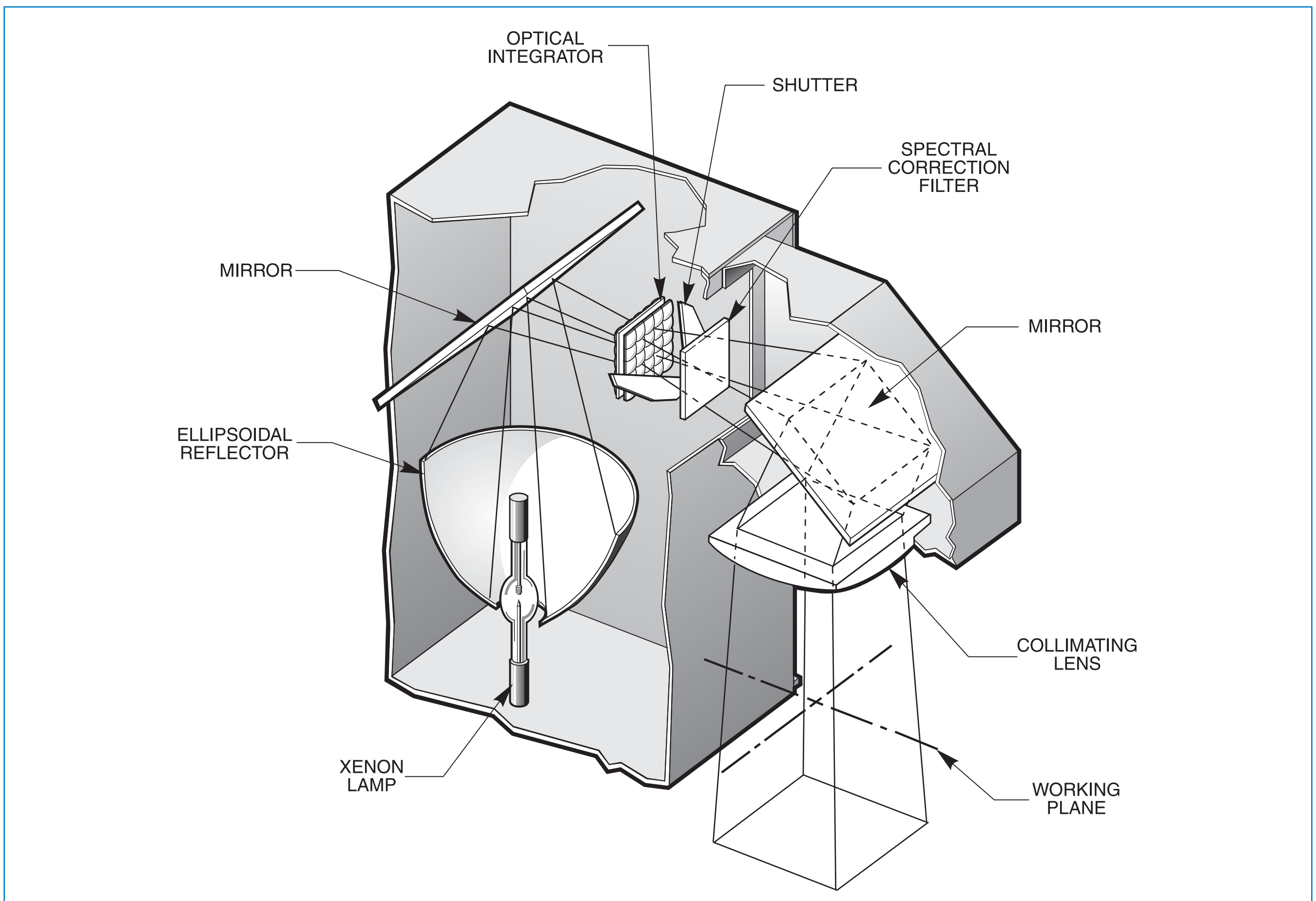


Fig. 11 Cut-away view of an Oriel Solar Simulator.

Beam Size Sets Irradiance Level, Not The Spectrum

Our simulators are available with several beam sizes. The magnitude (sun value, total irradiance in W m^{-2} or spectral irradiance at any wavelength in W m^{-2} nm^{-1}), but not the shape of the spectral curve, depends on the beam size. That is, the shape of the curve of any Newport's Oriel Solar Simulator with the same Air Mass filters, is essentially the same.

EXAMPLE

The 91291 kW (4 x 4 inch) Solar Simulator, with AM 0 filter has a typical integrated irradiance of 3575 W m^{-2} compared with the "1 sun" value of 1367 W m^{-2} of the AM 0 standard. The 91290 (2 x 2 inch) Simulator, with the same AM 0 filter has a typical integrated irradiance of 13400 W m^{-2}. Both use the same lamp, and have the spectrum shown on page 24.

Page 7-28 in the Light Resource Catalog, shows the output of our 300 W Simulator, model 91160 and explains how we normalize our curves - scale the measured output without changing the shape.

Output Control

You can reduce the magnitude of the simulator output by 15% using the power supply controls, and by more than 80% by adjusting lamp position and using optional apertures. Using apertures improves the output beam collimation.

The Role of The Filters

The xenon lamp spectrum differs from all solar spectra because of the intense line output in the 800 - 1100 nm region. We use our AM 0 filter to reduce the mismatch, but no reasonably economical filter can remove the line structure without severe modification of the remainder of the spectrum. The relevance of the residual infrared mismatch depends on the application.

Our AM 1, AM 1.5 and AM 2 filters also modify the visible and ultraviolet portion of the spectrum for a better match to the standard solar spectra. Many photobiological applications require very close simulation of the solar ultraviolet. On page 7-48 in the Light Resource Catalog, we describe a filter that shapes the ultraviolet cut-off of the simulator spectrum to match the atmospheric ozone layer.

Comparing Simulators' Spectra With Standard Solar Spectra

It is helpful to consider the solar spectral and simulator curves as having both a **shape** and **magnitude**. The easiest single number specifying the magnitude is the total irradiance, the integral of the curve (page 7-29).

$$\text{Total irradiance of standard} = \int E_{std}(\lambda)\, d\lambda$$
$$\text{Total irradiance of simulator} = \int E_{sim}(\lambda)\, d\lambda$$

For the AM 0 standard curves this value is the solar constant, 1367 W m^{-2}, equivalent to "1 sun." We measure the total irradiance in W m^{-2} for our simulators by integrating the spectral data with a calibrated broadband meter.

For some applications it is preferable to compare the integrated irradiance over a limited spectral region. For silicon photovoltaic research the integrated irradiance from 200 - 1100 nm, the sensitive range for these devices, is a better basis for comparison of the magnitude of a simulator irradiance with that of the corresponding standard curve.

If you know the spectral response of the effect you wish to create R_λ, then comparing the effective exposure rates, the integrated product of the solar and simulator spectra, with the responsivity curve, gives a better measure of how the simulator relates to standard solar exposure.

$$\text{Effective exposure rate} = \int E_{std}(\lambda)\, R_\lambda\, d\lambda$$
For the standard curves

$$\text{Effective exposure rate using the simulator} = \int E_{sim}(\lambda)\, R_\lambda\, d\lambda$$

ASTM document E-927-85 "Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing" classifies simulators on the basis of beam uniformity, temporal stability and spectral match to the ASTM standard solar spectra. Our simulators have Class B, or better, performance. However, we are in the final development phase of Class A Solar Simulators. See page 7-32, in the Oriel Light Resource Catalog for details.

Temporal Behavior of Simulator Output

The sun is a relatively constant source, though the terrestrial irradiance level and spectrum changes with daily and annual cycles and with unpredictable atmospheric conditions. Our simulator power supplies have superb regulation against line or load changes and internal filtering to reduce short term noise and ripple. Even so, the output of our simulators falls gradually and the spectrum changes slightly as the lamp ages (see Fig. 12). Changes in local temperature can affect the simulator output by a few percent. We can provide initial test data (on a special order basis) but recommend regular measurement of total or relative simulator output for long term assurance of irradiation level.

We select and age our filters, and the design locates them in a moderate intensity zone of the beam. With these and other precautions we find no significant post processing filter heating or filter aging effects.

For precise quantitative work, you should stabilize the output in the spectral region of interest using the optional Light Intensity Controller. For repetitive monitoring, as in a quality assurance application, a standard test cell can be simpler than spectroradiometry for monitoring simulator performance and stability.

(Note that changes in radiometer responsivity in the UV due to radiometer filter or detector changes can imply that the simulator output is changing. The UV irradiance of some of our simulators can quickly change untreated filter transmittance and UV detector spectral responsivity.)

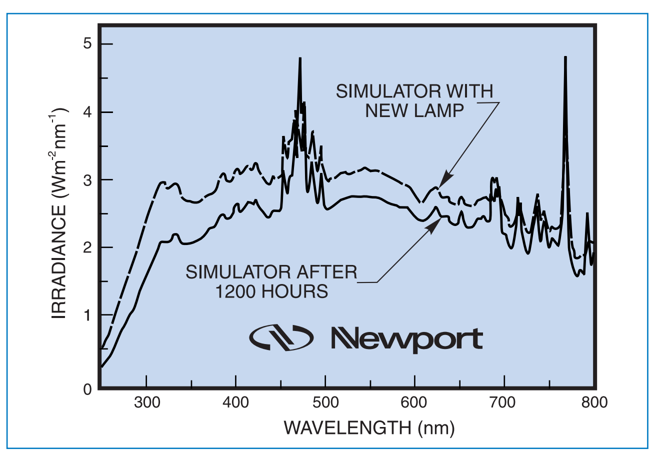


Fig. 12 Actual spectral irradiance of a Solar Simulator with a new lamp, and a lamp after 1200 hrs. (Light intensity controller was not used.)

SIMULATION WITH OTHER KINDS OF LAMPS

Solar simulators based on lamps other than high pressure xenon arcs produce spectra that are poorly matched to the solar spectrum (with the exception of the impractical carbon arc simulator).

Simulation With Tungsten Lamps

The brightest tungsten lamps operate at color temperatures of 3200K. (The solar spectrum has a brightness temperature of 5600 - 6000K depending on the spectral region.) Filters allow you to modify the tungsten lamp spectrum for a reasonable match to portions of the solar spectrum. The low UV and shortwave visible output prevents an efficient match in these key regions. You can use a filtered tungsten lamp for a good match to the infrared solar spectrum.

Fig. 13 shows typical solar spectrum and tungsten lamp spectrum. Filters may be used to modify the spectrum to make a reasonable, but inefficient match in the visible.

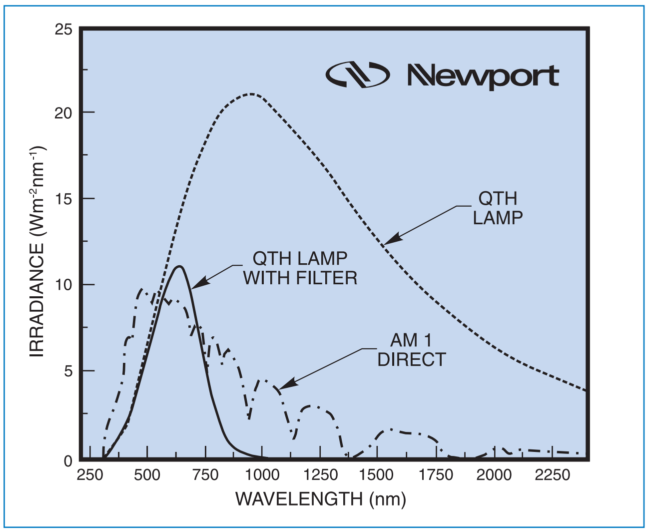


Fig. 13 Spectrum of a 3300K tungsten halogen lamp. Filtering removes a lot of the excess IR, but is inefficient and leaves a UV defecit.

Simulation with Mercury Lamps

There are many kinds of mercury lamps from low pressure lamps (germicidal) to high pressure short arc lamps. The strong line spectra in the ultraviolet prevent a close spectral match. You can successfully use these lamps to simulate solar UV for any application that is totally insensitive to source spectral distribution (i.e. having a flat action spectrum) and for some relative test. Most UV action spectra are far from flat, so results with mercury lamp simulators can be misleading.

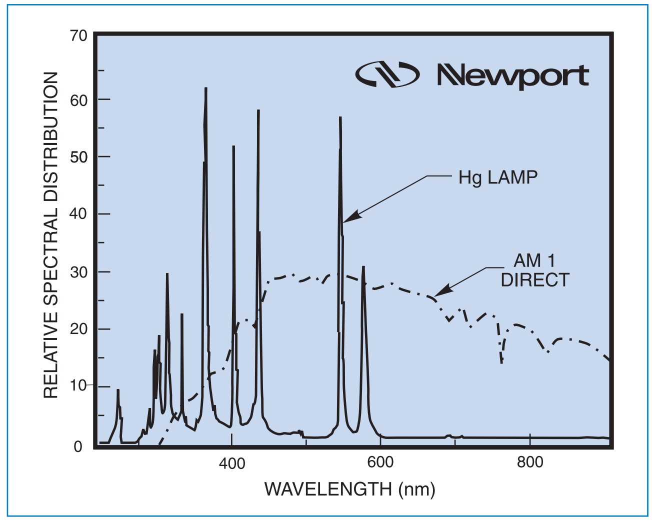


Fig. 14 Mercury lamp output and AM 1 direct solar spectrum.

Simulation with Metal Halide Lamps Lamps

Metal halide lamps are efficient sources, rich in ultraviolet and visible output. Like mercury lamps, the spectrum is dominated by strong lines that invalidate quantitative data for most UV activated photoeffects.

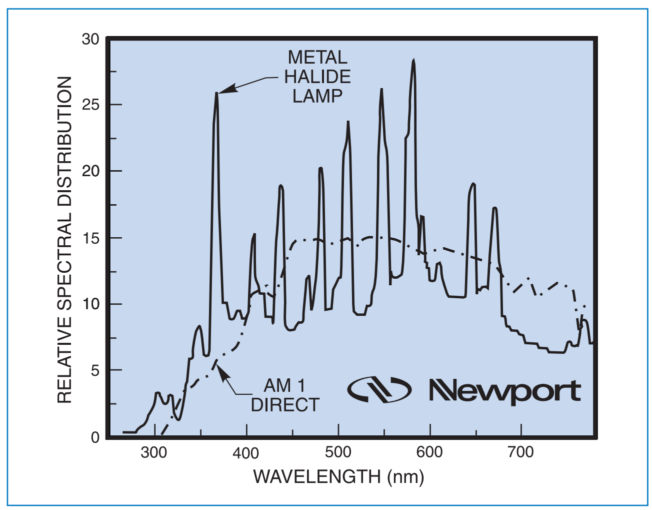


Fig. 15 Metal Halide lamp output and AM 1 direct solar spectrum.

The terrestrial solar ultraviolet amounts to about 5% of the total insolation, but because of its impact on the biological environment and on materials used outdoors, the ultraviolet requires special attention. Unfortunately the ultraviolet spectral insolation is not well characterized. Atmospheric turbidity and surface albedo have a strong influence on total UV, stronger than that of the ozone layer. The ozone layer, however, protects us from the most energetic, most damaging radiation.

ATMOSPHERIC GASES BLOCK UV <290 nm

The column of absorbing gas in the path of incoming radiation includes atomic and molecular nitrogen and oxygen and their products. These gases block all short wave ultraviolet radiation. Molecular oxygen in the stratosphere (10 to 48 km) absorbs short wave (up to 242.4 nm from the ground state and with very strong bands from 50-100 nm, and 140-175 nm) ultraviolet and photodissociates. The atomic oxygen produced leads to the production of ozone. Ozone strongly absorbs longer wave ultraviolet in the Hartley and Huggins bands from 200 - 360 nm (Fig. 16), and has additional weak absorption bands in the visible (Chappius bands from 450 - 750 nm) and infrared.

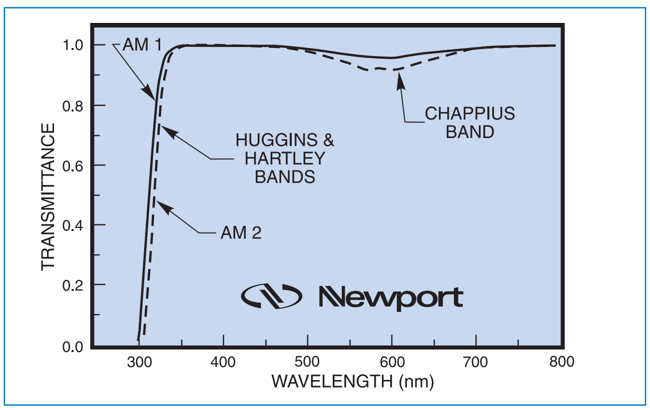


Fig. 16 Transmittance of ozone layer.

Absorption in the Herzberg continuum of the abundant molecular oxygen blocks most ultraviolet up to ca. 250 nm. Rayleigh scattering by air molecules (Fig. 17) and the strong ozone absorption from 200 - 290 nm determine the terrestrial ultraviolet edge at around 290 nm. Ozone absorption is variable however, since the amount of ozone in the upper atmosphere depends in a complex manner on formation and circulation patterns of the ozone and of the long lived catalytic chemicals that destroy ozone.

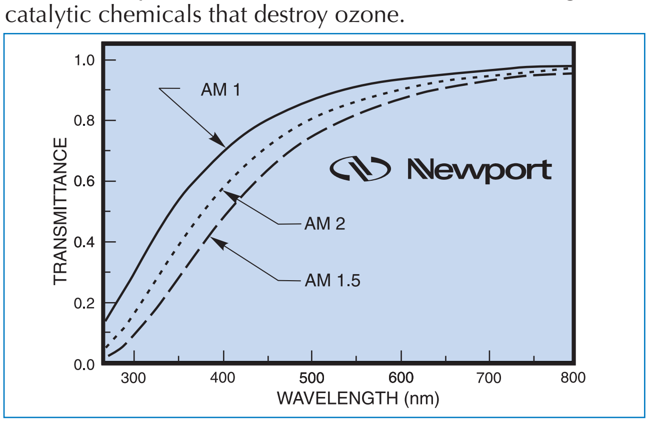


Fig. 17 Rayleigh scattering; impact on transmittance.

VARIABLE OZONE LEVEL MEANS VARIABLE ABSORPTION EDGE

The ozone level is quantified as the corresponding path length of the gas at standard temperature and pressure (STP) or in Dobson units (D.U.), the number of milliatmosphere centimeters of ozone at STP. Typical ozone levels vary from 2.4 mm (STP) or 240 D.U. at the equator increasing with latitude to 4.5 mm at the north pole. Seasonal variation is highest at the poles. Prior to the report of the ozone hole, the ozone level at the north pole was known to drop to ~2.6 mm (STP) in October. Antarctic levels as low as 1.1 mm (STP) have been reported and attributed to chemical destruction of ozone. The ASTM standard spectra shown on page 7-29 use 3.4 mm ozone in the computation as this is the expected average value for the U.S.

Since ozone is the principal absorber of solar radiation in the 250 - 300 nm region with the strong slope shown in Fig. 18, ozone depletion leads to increased levels of UVB. We discuss some of the implications of this in the section on Photochemistry and Photobiology. Ironically, ground level ozone, a pollutant in heavily industrialized or populated areas, seems to reduce UV irradiation there.

Fig. 19 shows how the calculated terrestrial ultraviolet at 50° latitude changes with ozone depletion. This figure is based on data taken from Vol. I of the UVB Handbook by Gerstl et al. of Los Alamos National Laboratory.

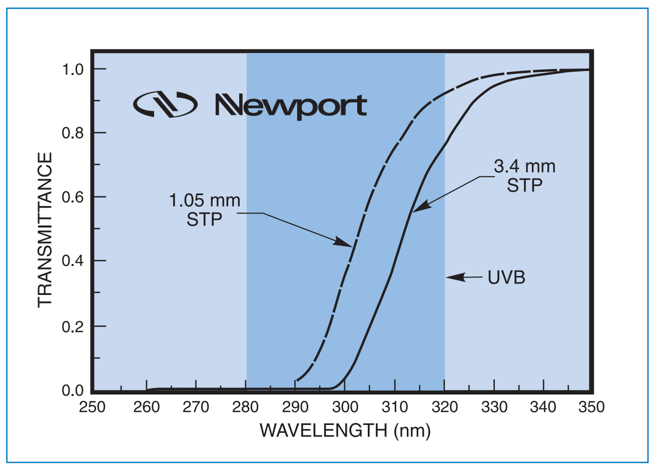


Fig. 18 UV transmittance of normal and depleted ozone layer.

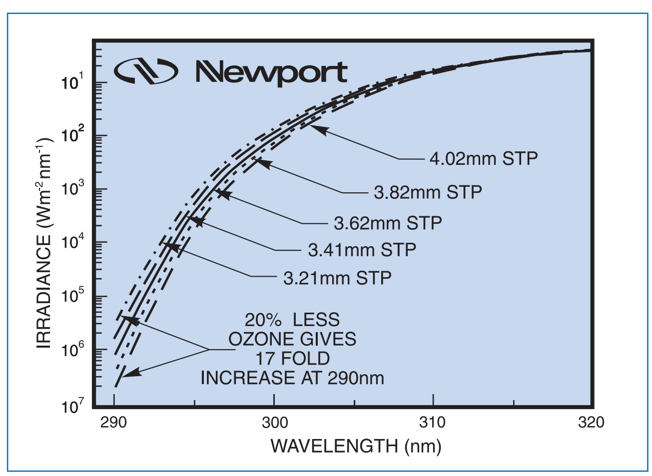


Fig. 19 UV irradiance and ozone depletion.

The sun provides 1 kW m^{-2} of free, non polluting, power for several hours every day. Thermal and photovoltaic systems take advantage of this as does the biomass. Coal, oil, plant ethanol, and wood are all forms of stored solar energy.

While each energy conversion process has a unique spectral responsivity curve most laboratory development work has concentrated on photovoltaic (PV) systems. Fig. 31 shows the response of some important PV solar cells. Detailed knowledge of solar irradiance through the VIS and near IR is needed for cell optimization and economic viability assessment. Development and production testing requires the availability of high quality solar simulators.

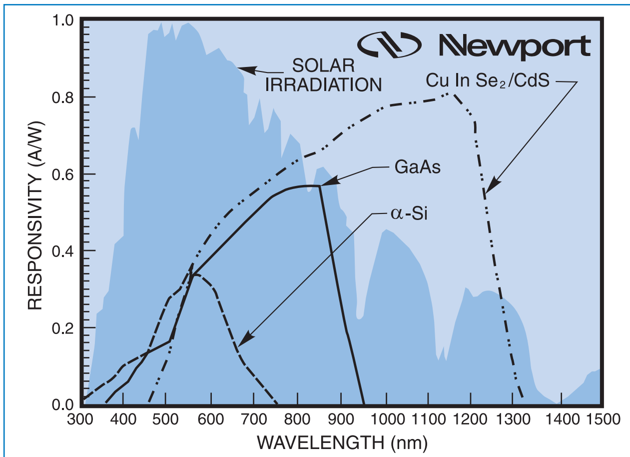


Fig. 31 Responsivity of photovoltaic solar cells.

COMPARISON OF PHOTOVOLTAICS

Characterization of photovoltaics involves measurement of current voltage relationships under standard illumination and temperature conditions. Surface reflectance, deep level traps, carrier diffusion, crystalline structure and boundaries, junction type depth and temperature, optical absorption and scattering, series and shunt resistance and photon degradation all influence efficiency. The spectral responsivity curve takes many of these fundamental effects into account, but should record the temperature and intensity level and other measurement conditions for completeness. For example, voltage sweep rates and direction and contact resistivity also affect I-V measurements. Simulator pulse duration is important for some herterojunction and electrochemical cells.

The photovoltaic conversion efficiency, η, is the most important comparative measure for a photovoltaic device. It is defined as the maximum power produced by the photovoltaic device divided by the incident light power under standard light conditions. Our Simulators provide repeatable light conditions close to the specified standards.

$$\eta = \frac{P_{out}}{P} = \frac{V_{oc} J_{sc} FF}{P}$$

Where:

P_{out} = output power density produced by the device
P = the incident power density
V_{oc} = the open circuit voltage
J_{sc} = the short circuit current
FF = the fill factor

The definitions assume illumination with the standard irradiation.

STANDARD LIGHT CONDITIONS

The actual performance of any solar energy converter under irradiation depends on the intensity and spectrum of the incident light. The short circuit current density, J_{sc}, is especially sensitive to the spectral distribution of the source. The significance of spectral mismatch depends on the device responsivity curve, $S_{pv}(\lambda)$, and the differences between the simulator spectrum, $E_{sim}(\lambda)$, and the standard spectrum $E_{std}(\lambda)$.

$$J_{sc} = \int E_{std}(\lambda)\, S_{pv}(\lambda)\, d\lambda$$
$$J_{sc(sim)} = \int E_{sim}(\lambda)\, S_{pv}(\lambda)\, d\lambda$$

Spectral differences at wavelengths where the responsivity is small, are less significant.

The AM 1.5 Direct and AM 1.5 Global standard spectra are the U.S. standards for solar energy applications (ASTM E948). CEI IEC 904-3 provides an international AM 1.5 standard for silicon photovoltaic matching the ASTM 1.5 Global data. Actual terrestrial solar spectra differ from the standard conditions so outdoor measurements, while fundamentally important, don't provide the basis for repetitive comparison. Even when you make measurements at a single site, and over the course of a few clear days, the efficiency measured as the ratio of power output to total power input will change due to the spectral changes through the day. These spectral changes can produce apparent efficiency changes of up to 20% for conventional photovoltaics (the actual value depends largely on the responsivity curve for the device). This is in addition to expected changes in output power due to solar zenith angle and environmental conditions.

THE IMPORTANCE OF INTENSITY LEVEL

It is important to know how the efficiency of the solar converter changes with incident intensity. Low (fractional-sun) test irradiation levels may hide some saturation, thermal, or degradation problem at field intensities. High intensity (multi-sun levels) tests are sometimes desirable for photovoltaics to be used with optical concentrators and for accelerated testing. Linearity measurements can validate both low and high level testing and extend understanding of device operation.

The total incident power for the ASTM AM 1.5 Direct standard is 768 W m^{-2} with 580 W m^{-2} below 1100 nm, the useful spectral region for silicon photovoltaics. The figures are 1000 W m^{-2} and 797 W m^{-2} respectively for AM 1.5 Global. Actual output varies from product to product. Prolonged testing at these levels, with whatever cover glass or filter will be used and with the device in its normal thermal environment, is needed for any conventional solar cell.

We list the typical output of our simulators throughout this section. You should monitor the intensity of any simulator you use for photovoltaic testing. While you can reduce the intensity level without significant spectral changes by moving the lamp position in the reflector, you should consider using aperture or mesh grids inside the simulator for spectrally neutral intensity reduction without any impact on uniformity. Using the combination of a simple aperture and a broadband power meter, allows you to determine the linearity of your devices to reasonable accuracy. Consider simultaneous irradiation with a simulator and a chopped beam from one of our monochromator sources for more detailed studies of device physics.

WHY ORIEL SOLAR SIMULATORS ARE PREFERRED FOR PHOTOVOLTAIC TESTING

Filtered xenon arc simulators are acknowledged to provide the closest match to standard light conditions. Oriel Simulators were used for some of the earliest development of photovoltaics for spacecraft, and we've improved them continuously. The high color temperature of the xenon arc is particularly important for devices with blue responsivity. The small bright arc allows the collimation required for test purposes. Our beam homogenizers ensure output beam uniformity over the entire beam area, important for credible testing of any photovoltaic. Our power supplies alleviate concerns of output stability; arc wander is minimized. Optional Light Intensity Controllers reduce temporal variations even more. (Fig. 32) You will find a full description of the best simulators available on pages 7-36 to 7-47, in the Oriel Light Resource Catalog.

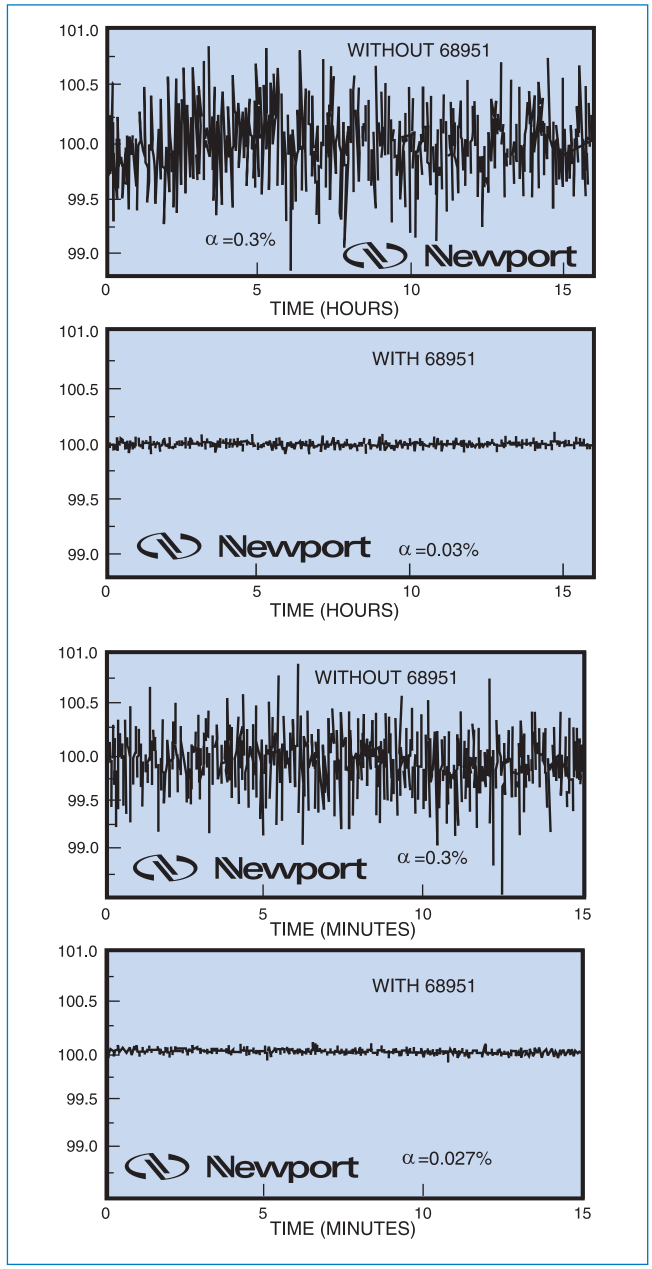


Fig. 32 Typical variation of the output of a kW simulator with time:

1. Data taken every minute; 16 hour period under power supply control.
2. Data taken every minute; 16 hour period with Light Intensity Controller (page 7-50, in the Oriel Light Resource Catalog).
3. Data taken every second; 15 minute period under power supply control.
4. Data taken every second; 15 minute period with Light Intensity Controller.

NATIONAL RENEWABLE ENERGY CENTER

The National Renewable Energy Center (NREL) in Golder, CO has published extensively on photovoltaic testing and solar radiation. We would like to acknowledge the extensive assistance of the Center over many years, while pointing out that the opinions expressed in this catalog are entirely those of the Newport staff.

Simulators offer the possibility of projecting how solar radiation will affect materials and finishes intended for outdoor use. Assessment of long term environmental effects is important for plastics, paints, and fabrics. Changes due to outdoor exposure are collectively described as "weathering."

Pollutants, moisture, wind, temperature (cycling), and the ultraviolet fraction of global solar irradiation are the major "weathering" factors. Metals, such as copper domes, are more susceptible to pollutants, but many plastics, paints, and fabrics suffer primarily from photochemical reactions caused by the short wavelength ultraviolet. Fig. 33 shows the solar ultraviolet in terms of photon flux against photon energy in electron volts. Ionization potentials for organic bonds are typically ≥5 eV. Absorbance increases for high energy photons but the quantum yields for any weathering effect may be much less than that for absorbance. The ultraviolet causes chain scission and crosslinking in polymers, plastics become brittle and change color, and paints and fabrics fade. Gloss retention is a key concern for outdoor paints and decorative plastics exposed to ultraviolet radiation.

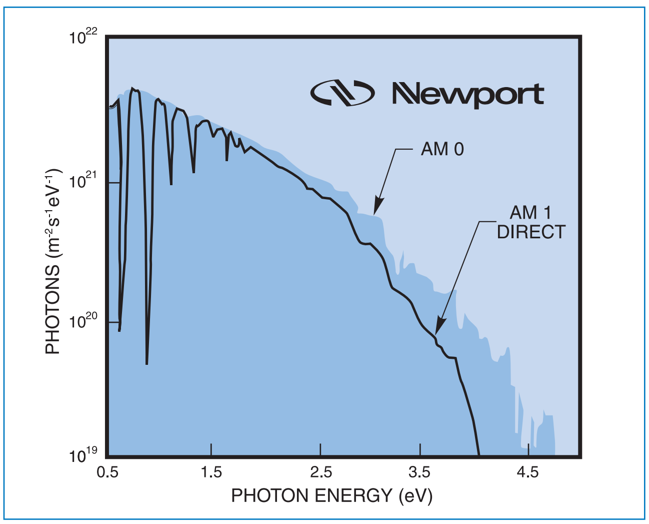


Fig. 33 Solar spectrum.

Weathering is a complex topic. In some circumstances, combined attack, for example by UV and ozone, is more serious than separate exposures to the same aggressors. Moisture level often plays an important role. In some polymer materials, thin, UV induced, crosslinked surface layers provide partial protection against further damage. In others the UV creates "color centers" that enhance the effect of subsequent radiation. Absorbing "UV stabilizers" can afford some protection for plastics.

ORIEL SOLAR SIMULATORS FOR WEATHERING

In all cases the collimated and carefully spectrally characterized output of our simulators helps you unravel the complex interplay. The round-the-clock availability of high intensity levels allows accelerated testing. You can subject a test sample to the equivalent of many years of solar UV in a matter of days. Simple dose control using the shutter and shutter timer allows determination of the relationships between exposure dose and color change or change in mechanical properties.

RECIPROCITY

Most accelerated weathering tests rely on the response (the weathering) being independent of irradiation rate; the response must depend linearly only on the total radiant exposure (or "dose").

Effects that depend on dose rather than dose rate, are said to follow the law of reciprocity. Accelerated tests are simplest for materials with reciprocity, you can easily relate the results of these test to expected lifetime outdoors. (In principle, characterization of the dose rate dependence of degradation for a sample that does not exhibit reciprocity will also allow estimation of lifetime, but you need extensive data on the variation of the solar irradiation level).

Fig. 35 illustrates two of the simplest types of departure from reciprocity. The top graph shows an effect that "saturates" at high flux levels; this may be due to sample heating. This type of behavior limits the rate of acceleration. For other processes the rate increases, i.e. the curve swings upwards, at higher fluxes, due to increasing sample temperature.

The lower graph is typical of a weathering change where a simple conversion takes place. The upper curve and the left axis show the cumulative dose as time progresses. (The UV flux from this simulator is ca. 143 W m^{-2}. In one minute the dose is 60s x 143 W m^{-2} = 8580 J m^{-2}, or 8.58 kJm^{-2}.) The cumulative dose eventually becomes high enough to have converted a significant fraction of the material and subsequent irradiation has lowered efficiency.

We have used these two simple examples for clarification. Identification of the cause of reciprocity failure may not be so simple. For example, saturation at high flux levels may also be due to cumulative dose saturation shown in the lower figure.

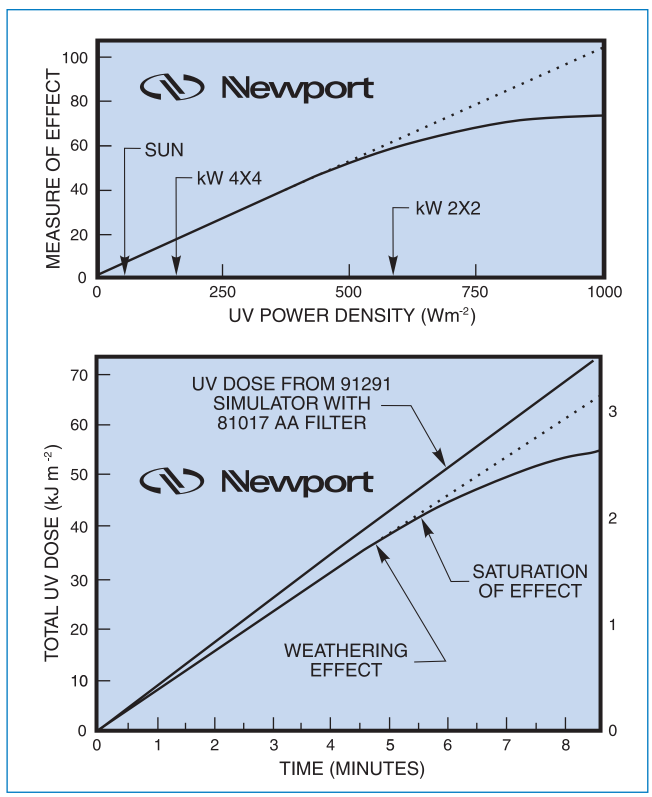


Fig. 34 Two different types of reciprocity failure.

BE CAREFUL OF OTHER EFFECTS

Effects other than the one under study may set a limit on accelerated testing. The maximum irradiation rate must not damage the sample (or cause non-linear response, Fig. 34). Absorbed visible and infrared radiation in intense solar radiation or simulator beams can quickly char dark fabrics, even though the ultraviolet induced weathering effects is still following the law of reciprocity. We offer simulators which have greatly reduced visible and infrared output. This allows realization of high ultraviolet intensities without complications from visible and infrared heating.

THE IMPORTANCE OF SPECTRAL MATCHING

When the action spectrum for the weathering effect is not precisely known, as is often the case, it is important that the test spectrum closely simulates the expected spectrum for deployment. Using a total ultraviolet level for tests can be misleading if the simulator spectrum isn't a reasonable approximation to a time weighted outdoor spectrum. This is particularly true for highly variable action spectra.

We describe the concept of effectiveness spectrum on page 17. Any weathering effect following reciprocity will be proportional to the total effective dose; the wavelength integrated product of the action spectrum and the dose spectrum. The appropriate dose spectrum should take into account the diurnal and annual dependence of the outdoor spectrum and may be expressed as "worst case" annual irradiance, or for materials like those making up patio furniture, the local spectrum for total summertime dose. Reliable information is gradually becoming more available on UV dose spectra for various sites throughout the world.

EXAMPLE

For our example we use the summer noon UV spectrum from page 7-14, and a “weathering action spectrum” based on the ultraviolet absorption of polycarbonate resin. We compute the effect at each wavelength (in arbitrary units) for the solar spectrum by multiplying the value of the solar irradiance by the value for the action spectrum. Integrating the values gives the total weathering effect for this action spectrum and that solar spectrum.

We repeat this process for the simulator with atmospheric attenuation (AA) filter, and a metal halide based simulator. For both of these we scale the output to match the total solar irradiance from 280 - 400 nm. The results are tabulated.

Table 1

Source	UV Spectrum	Integrated Effect (Relative)
Sun	Noon, summer Spectrum, page 7-14	1
91260 UV Simulator with AA Filter	Page 7-38 scaled to 1 sun	0.97
Metal Halide Simulator	Page 7-11 scaled to 1 sun	1.1

The integrated effectiveness spectrum indicates how effective each source is in producing weathering. In the example we are able to compare the sources because we used a known action spectrum. The simulator based on the metal halide lamp produces 10% more weathering than expected from power measurement.

BROADBAND POWER OR ENERGY METERS

When the action spectrum is not known, the closer the spectral match between the simulator and the average solar irradiance, the easer it is to extrapolate simulator results to outdoor reality. This is particularly important when comparing new product formulations with possible differences in action spectra.

Broadband power or energy meters are sensitive to a broadband of wavelengths. The meter described on page 7-49 in the Oriel Light Resource Catalog, is sensitive to all wavelengths from 190 - >3µm; typical UV meters are sensitive from 250 - 400 nm, but unlike our meter, have a response that depends on wavelength.

Broadband UV meters are useful when working with a single source or two sources with similar spectral content. Using a meter to measure solar UV and then comparing this value with simulator output can lead to serious errors. In biological applications, Sayre[1] showed errors of factors of twenty!

For valid comparison of sources with different spectral outputs using a broadband meter either:

The sources must have similar spectral content

or

The meter spectral response must have the same shape as the action spectrum

1. Sayre, R. and Kligman L., Photochem. Photobiol. 55:1:141

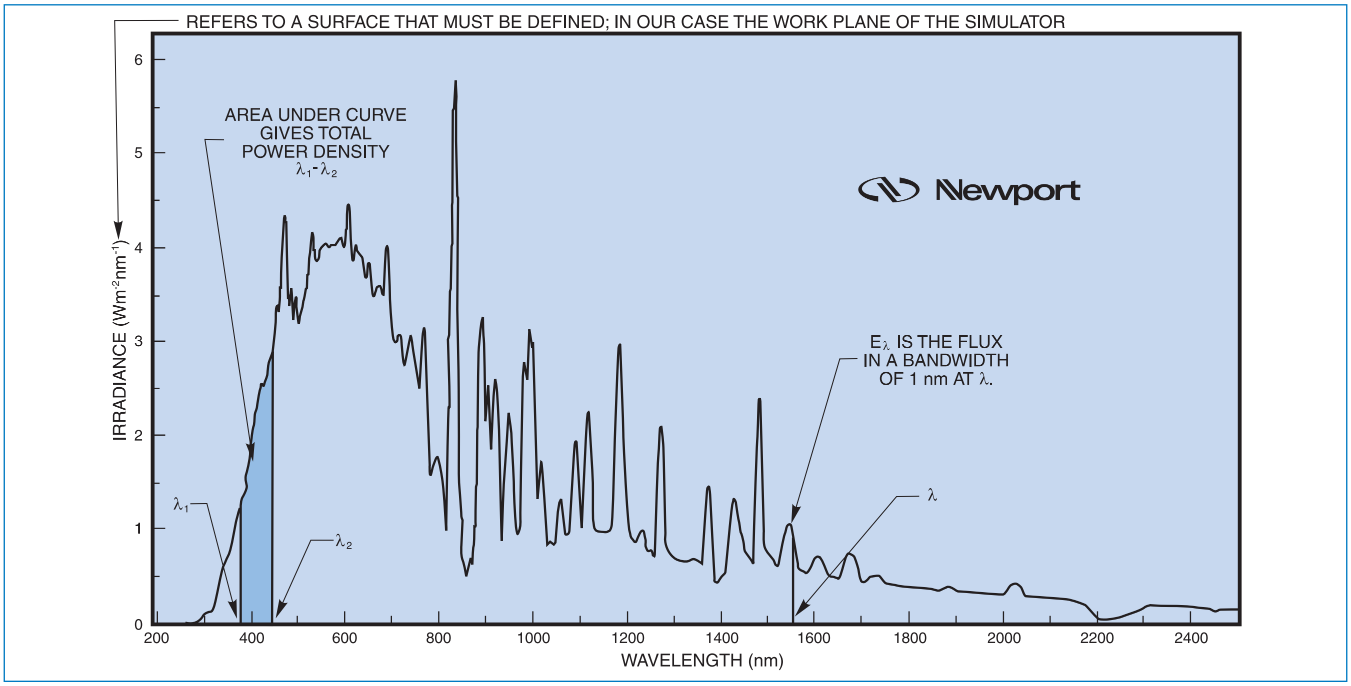


Fig. 1 Example of the spectral output curves we show for each solar simulator, on pages 7-24 to 7-27

The spectral irradiance at any wavelength, E_λ, is in units of watts per square meter per nm (W m^{-2} nm^{-1}). The value is a measure of the flux per nm at the specified wavelength incident normally onto an element of the surface divided by the area of the surface element in square meters. The value can be expressed in other units such as W cm^{-2} nm^{-1} or W m^{-2} μm^{-1}. For example, 1.23 W m^{-2} nm^{-1} is equivalent to 0.000123 W cm^{-2} nm^{-1} or 0.123 W cm^{-2} μm^{-1}.

Finding the Irradiance on a Sample of Known Area

If a beam of irradiance E_λ (W m^{-2} nm^{-1}) falls on a sample of area A square meters, the total irradiance on the sample will be A E_λ (W nm^{-1}).

Finding the Total Irradiance in a Wavelength Interval

The total irradiance between two wavelengths λ_1 and λ_2 is equal to the integral of the E_λ curve between λ_1 and λ_2. This is the area of the curve between λ_1 and λ_2 and the units will be in W m^{-2}. Our simulator spectral irradiance curves (pages 7-24 to 7-27) include tabled values of the percentage of the total radiation. We compute the data for these tables and the total irradiance, using trapezoidal integration of our measurement data. The data is a series of discrete irradiance/wavelength pairs. These tables allow you to calculate the irradiance for any wavelength ranges coinciding with the tabulated values.

Since the curves pages also include the total irradiance for each simulator beam size you can find the irradiance for tabulated wavelength ranges for any of our simulators.

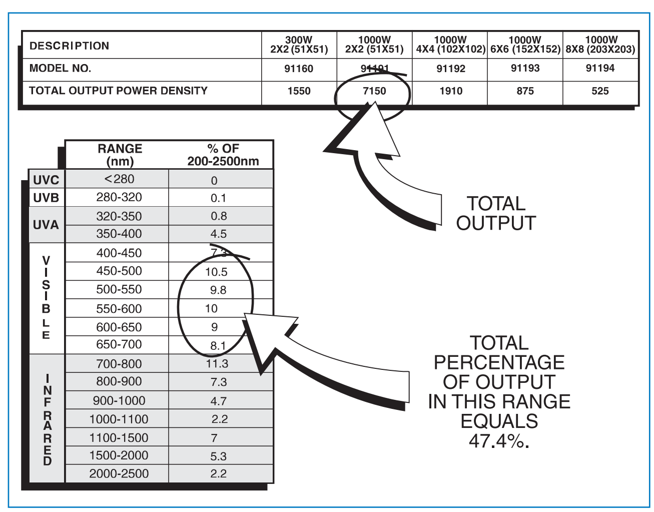
If you need to estimate the total irradiance in a wavelength interval not bounded by the tabulated values then you can use simple geometry to calculate the area under the curve for your wavelength interval. We give an example on the next page.

Finding the Total Dose in a Wavelength Interval for a Known Exposure Time

To find the total radiation dose within a specified wavelength range you first need to compute the irradiance for this wavelength interval. The result will be in W m^{-2}. When you multiply this by the exposure time in seconds the result is the dose in J m^{-2} (joules per meter squared). When you multiply this by the sample area you get the total dose on the sample. Note that you must use the sample area in square meters.

Finding Effective Dose

To find the effective dose you need to know the action spectrum for the effect and convolve this with the simulator spectrum. You then integrate the convolved spectrum. For absolute data you will need the absolute action spectrum; the relative spectrum is adequate to compare simulators with solar spectra.



DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY	1550	7150	1910	875	525

	RANGE (nm)	% OF 200-2500nm
UVC	<280	0
UVB	280-320	0.1
UVA	320-350	0.8
	350-400	4.5
VISIBLE	400-450	7.3
	450-500	10.5
	500-550	9.8
	550-600	10
	600-650	9
	650-700	8.1
INFRARED	700-800	11.3
	800-900	7.3
	900-1000	4.7
	1000-1100	2.2
	1100-1500	7
	1500-2000	5.3
	2000-2500	2.2

Fig. 2 Example of the data we show for each solar simulator.

Example 1

Find the irradiance in the wavelength range 450 - 700 nm from a 91191, 2 x 2 inch kW simulator with AM 1.5 Global Filter.

Step 1: Find what fraction of the output is in the specified range. (The curve and tabled data for simulators with AM 1.5 Global output is on page 7-26. Fig. 2 shows the tabled data.)

The total percentage of the output in this range = **47.4%**

Step 2: Multiply the fraction by the total power.

The top table in Fig. 2, and the top of the graph on page 7-26, shows the total output power density to be 7150 W m^{-2} for this model. Therefore the irradiance for the 450 - 700 nm range is:

0.474 x 7150 = 3389 W m^{-2}

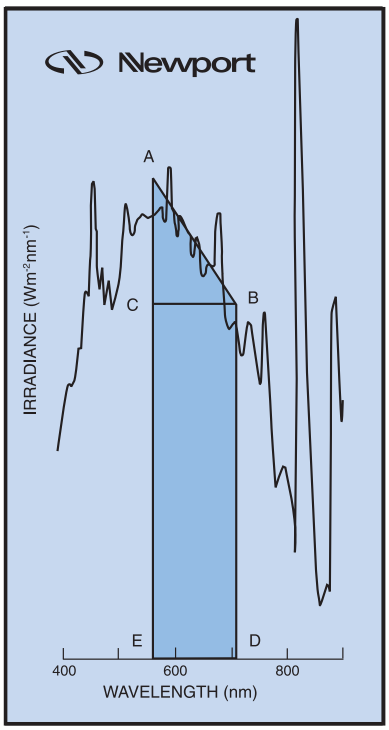


Fig. 3 Selected section of the AM 1.5 D simulator output curve.

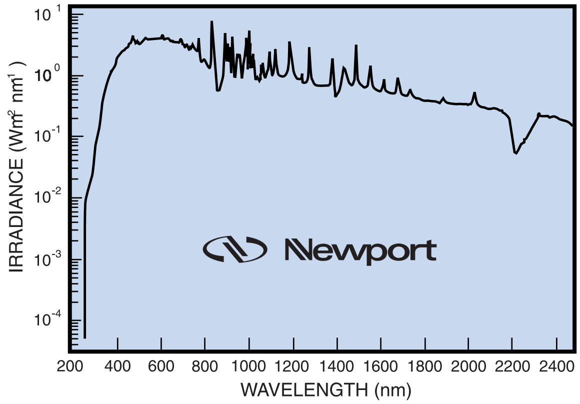


Fig. 4 Logarithmic display of Fig. 1.

Example 2

Determine the total 680 - 720 nm radiation dose on a 2 cm^2 sample in the work plane of the AM 1.5 D simulator with irradiance curve shown in Fig. 3, when the shutter is opened for 1.5 minutes.

Step 1: Determine the irradiance in the specified spectral region by measuring the area under the curve over the specified wavelength range. We use the curve shown. **Note that this curve like all of those on pages 7-24 to 7-26 is for a simulator with a 4 x 4 inch (102 x 102 mm) beam. Our example is for a 2 x 2 inch (51 x 51 mm) beam.**

We drew the line AB as best estimate of the average of the curve from 680 - 720 nm. Use a photocopier with magnification to make this area measurement easier. The area under the curve is approximately the sum of the area of the triangle ABC and the rectangle CBDE. We use simple scaling of the axes to find CE, and AC.

Area ABC = 140 x 0.5 x 0.82 = 57.4 W m^{-2}
Area CBDE = 140 x 3.16 = 442 W m^{-2}
Total area, ABC + CBDE, = 499 W m^{-2}

The total irradiance or power density is 499 W m^{-2} for a 4 x 4 inch simulator. Since our example deals with a 2 x 2 inch model we must multiply the output by the relative outputs of these two models, i.e. 10360/2765 = 3.75

499 W m^{-2} x 3.75 = 1871 W m^{-2}

Step 2: Find out how much power falls on the sample. The irradiated area is 0.02 m x 0.02 m = 0.0004 m^2, so the total radiation falling on the sample is

0.0004 m^2 x 1871 W m^{-2} = 0.75 W

Step 3: Calculate the dose, i.e. the total energy that falls on the sample in 1.5 minutes. The dose is the power multiplied by the exposure time, 90 seconds

0.75 W x 90 s = 67.5 J (1 Ws = 1 J)

Logarithmic Plots of Irradiance

Most of the plots in this catalog are linear plots. Log-lin plots are useful to illustrate the fall-off of the irradiance at the atmospheric edge because the log scale enhances the low value data and compresses the high value data. Plotting Fig. 1 as a log-lin plot makes the entire spectrum look flatter as the peaks are reduced. When two plots, such as solar and simulator irradiance are both plotted on the same log-lin grid, differences appear less.

Convenient definitions of spectral regions include UVA, UVB, UVC, visible and infrared (also sometimes divided into IR-A and IR-B). The exact boundaries of these regions remain the subject of debate. See page 2 - 3 for the definitions we use.

DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY (Wm^{-2})	3620	17120	4565	2100	1250

	RANGE (nm)	% OF 200-2500nm
UVC	<280	0.3
UVB	280-320	1.0
UVA	320-350	1.2
	350-400	2.9
VISIBLE	400-450	4.2
	450-500	5.6
	500-550	5.2
	550-600	5.2
	600-650	4.9
	650-700	4.7
INFRARED	700-800	8.1
	800-900	14
	900-1000	16.4
	1000-1100	5.9
	1100-1500	11.7
	1500-2000	6.3
	2000-2500	2.6

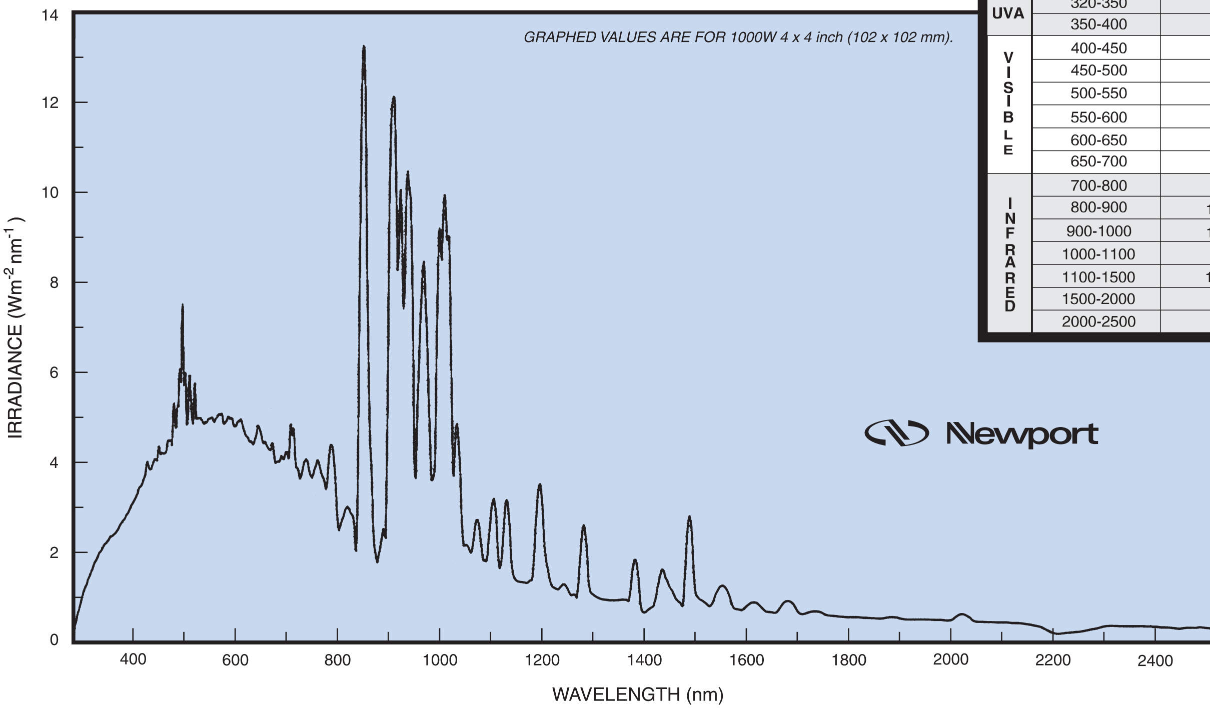


Fig. 1 The unfiltered output of the 91192, 1000 W Solar Simulator. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY (Wm^{-2})	2805	13406	3575	1640	980

	RANGE (nm)	% OF 200-2500nm
UVC	<280	0.11
UVB	280-320	0.6
UVA	320-350	1.0
	350-400	3.9
VISIBLE	400-450	5.4
	450-500	6.7
	500-550	6.7
	550-600	6.7
	600-650	6.5
	650-700	6.2
INFRARED	700-800	10.1
	800-900	8.3
	900-1000	6.9
	1000-1100	4.2
	1100-1500	15.2
	1500-2000	8.2
	2000-2500	3.5

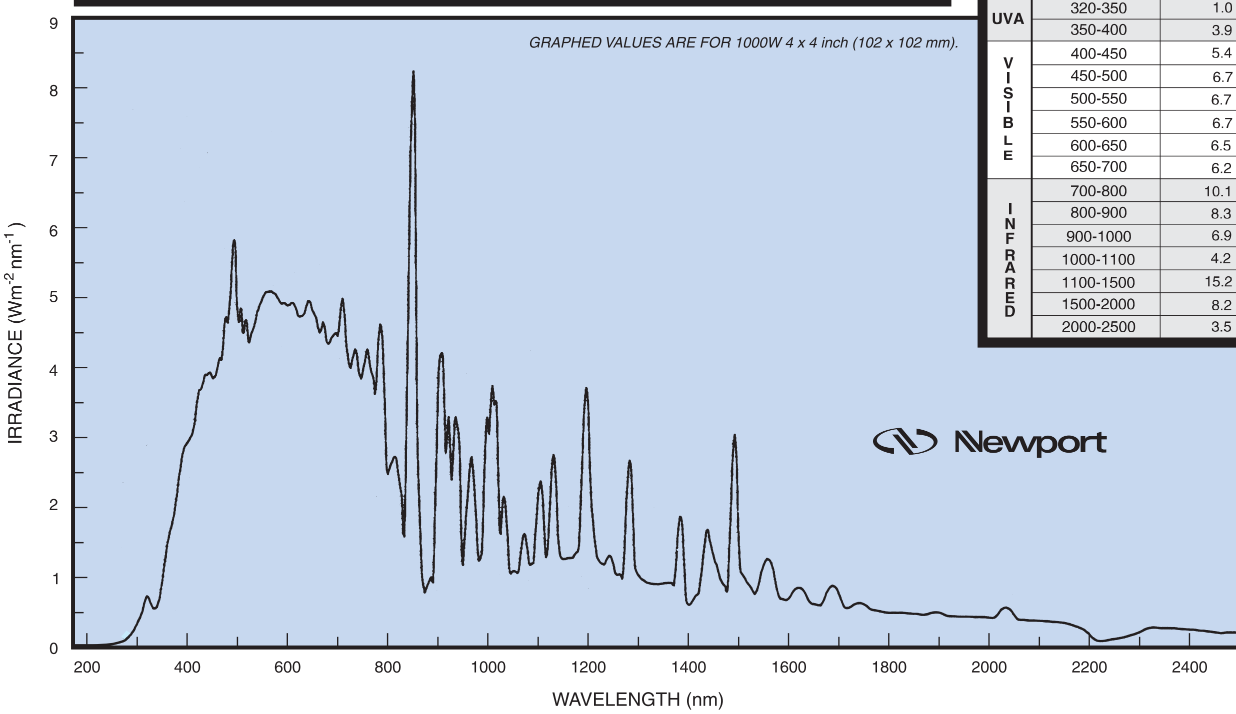


Fig. 2 The output of the 91192, 1000 W Solar Simulator, with AM O filter. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY (Wm^{-2})	2551	11475	3060	1400	850

	RANGE (nm)	% OF 200-2500nm
UVC	<280	0.01
UVB	280-320	0.18
UVA	320-350	0.62
	350-400	2.7
VISIBLE	400-450	4.8
	450-500	6.3
	500-550	6.5
	550-600	6.8
	600-650	6.7
	650-700	6.4
INFRARED	700-800	10.1
	800-900	8.3
	900-1000	7.5
	1000-1100	4.6
	1100-1500	16
	1500-2000	9.1
	2000-2500	3.9

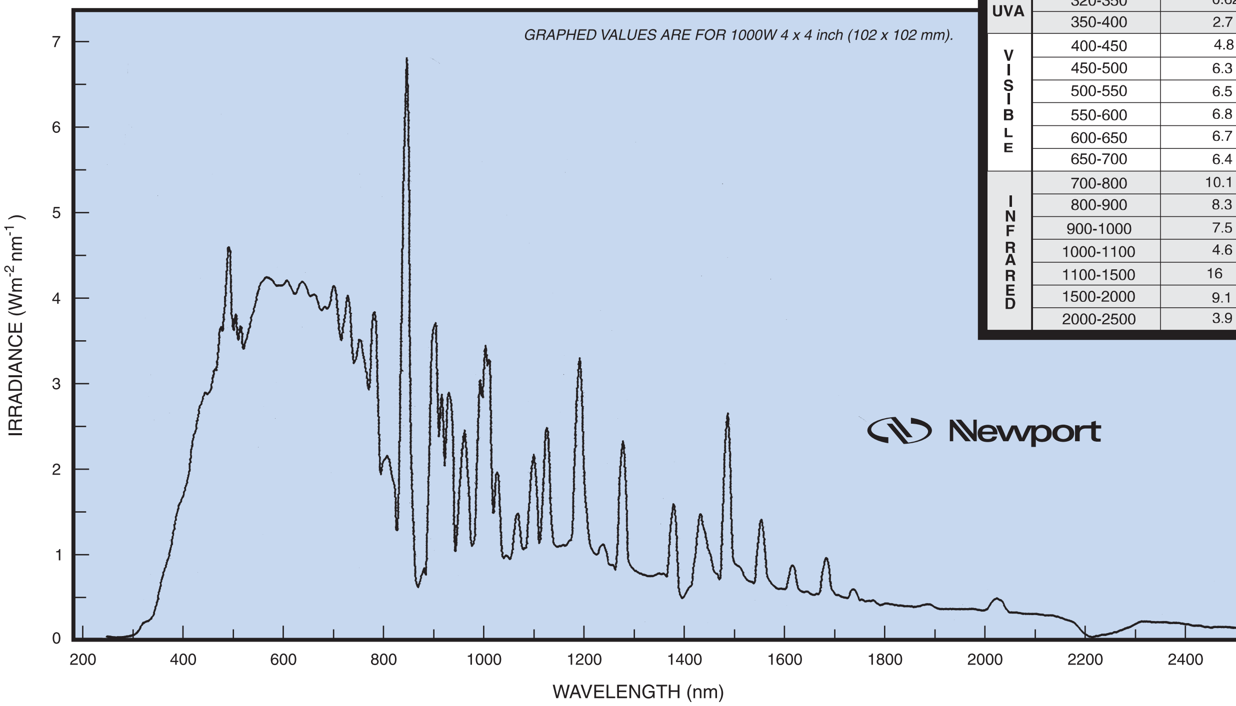


Fig. 3 The output of the 91192, 1000 W Solar Simulator, with AM 1 filter. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY (Wm^{-2})	2270	10360	2765	1270	760

	RANGE (nm)	% OF 200-2500nm
UVC	<280	0.01
UVB	280-320	0.12
UVA	320-350	0.5
	350-400	2.3
VISIBLE	400-450	4.6
	450-500	6.5
	500-550	6.8
	550-600	7.3
	600-650	7.2
	650-700	6.5
INFRARED	700-800	9.4
	800-900	7.7
	900-1000	7.5
	1000-1100	4.7
	1100-1500	15.8
	1500-2000	9.3
	2000-2500	3.8

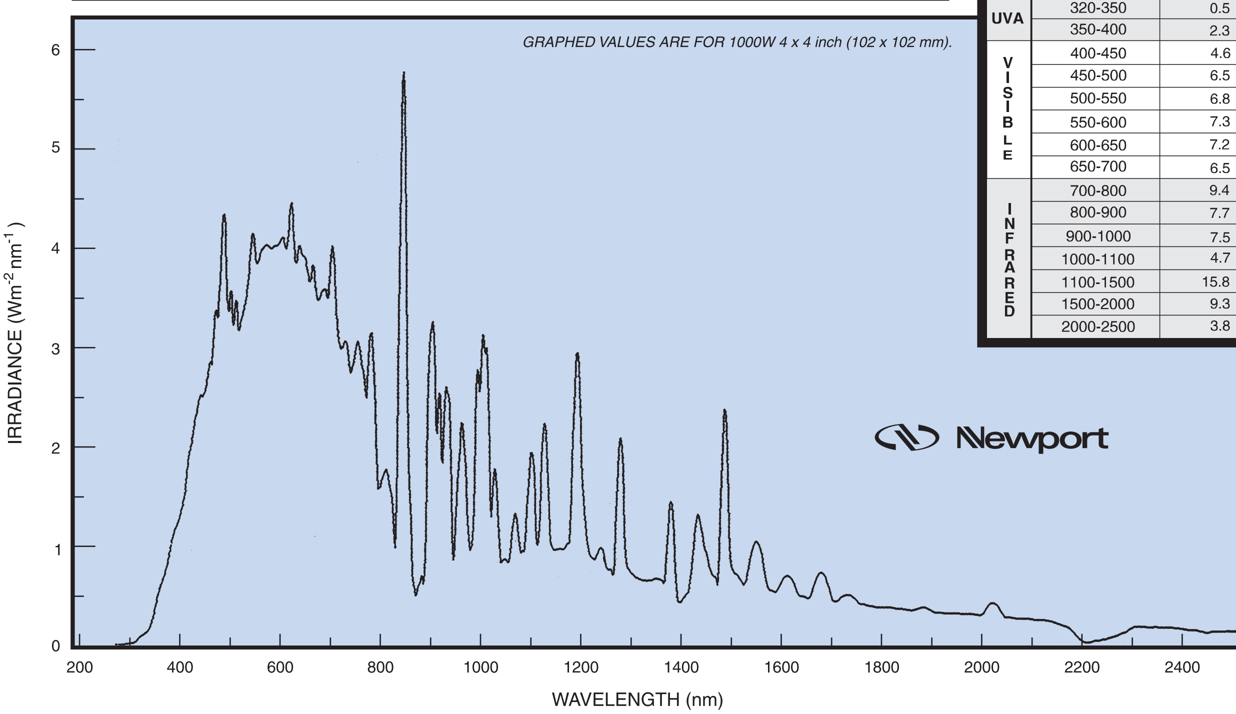


Fig. 4 The output of the 91192, 1000 W Solar Simulator, with AM 1.5 Direct Filter. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY (Wm^{-2})	1550	7150	1910	875	525

	RANGE (nm)	% OF 200-2500nm
UVC	<280	0
UVB	280-320	0.1
UVA	320-350	0.8
	350-400	4.5
VISIBLE	400-450	7.3
	450-500	10.5
	500-550	9.8
	550-600	10
	600-650	9
	650-700	8.1
INFRARED	700-800	11.3
	800-900	7.3
	900-1000	4.7
	1000-1100	2.2
	1100-1500	7
	1500-2000	5.3
	2000-2500	2.2

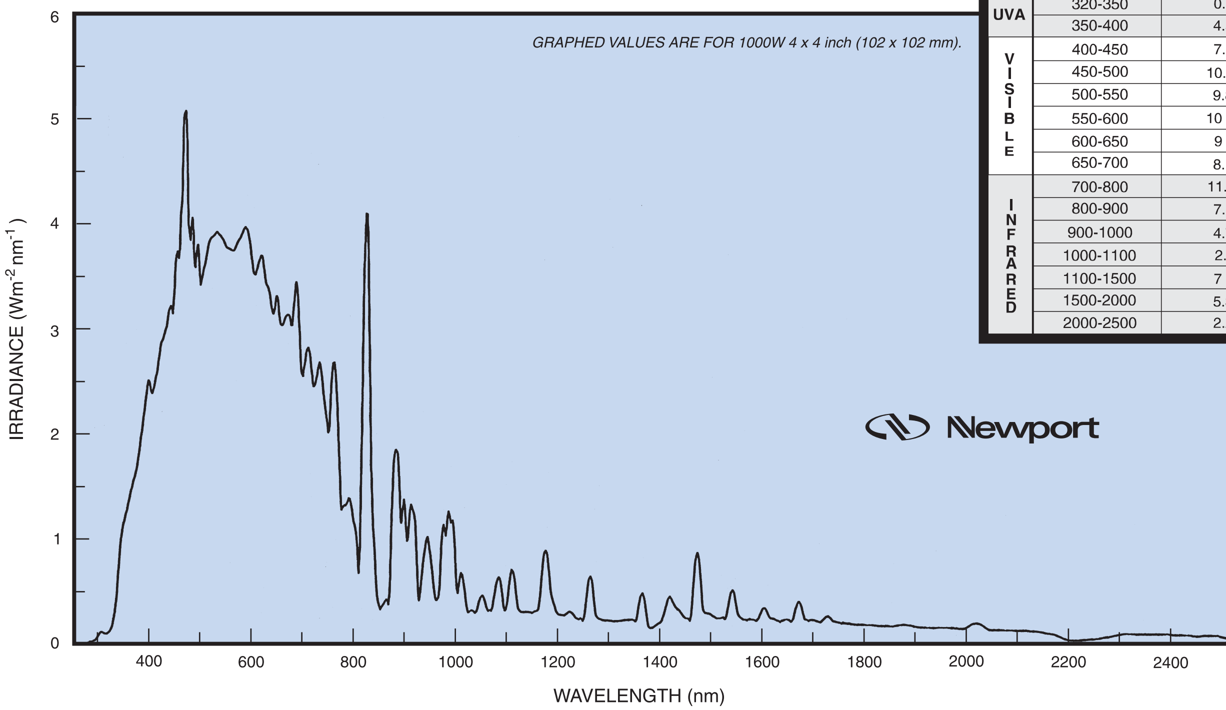


Fig. 5 The output of the 91192, 1000 W Solar Simulator, with AM 1.5 Global Filter. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY (Wm^{-2})	2100	9750	2600	1200	720

	RANGE (nm)	% OF 200-2500nm
UVC	<280	0.01
UVB	280-320	0.07
UVA	320-350	0.16
	350-400	1.3
VISIBLE	400-450	3.7
	450-500	5.7
	500-550	6.2
	550-600	7
	600-650	7.1
	650-700	6.4
INFRARED	700-800	10.3
	800-900	8.5
	900-1000	8.1
	1000-1100	5.1
	1100-1500	16.8
	1500-2000	9.6
	2000-2500	4

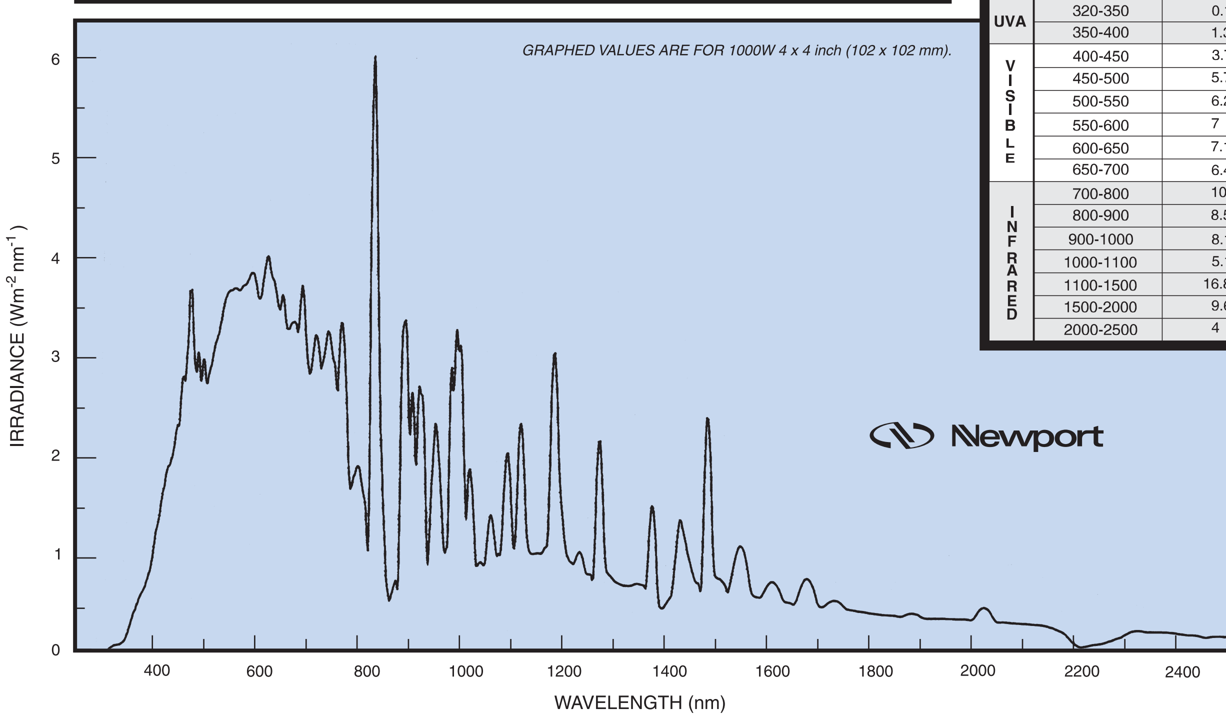


Fig. 6 The output of the 91192, 1000 W Solar Simulator, with AM 2 Filter. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91260	91291	91292	91293	91294
TOTAL OUTPUT POWER DENSITY (Wm^{-2})	730	3400	915	490	290

	RANGE (nm)	% OF 200-2500nm
UVC	<280	1.6
UVB	280-320	8.3
UVA	320-350	8.6
	350-400	17.6
VISIBLE	400-450	8.3
	450-500	3.9
	500-550	2.6
	550-600	3
	600-650	2.9
	650-700	2.3
INFRARED	700-800	4.1
	800-900	8.5
	900-1000	11.1
	1000-1100	3.9
	1100-1500	7.2
	1500-2000	4.5
	2000-2500	1.5

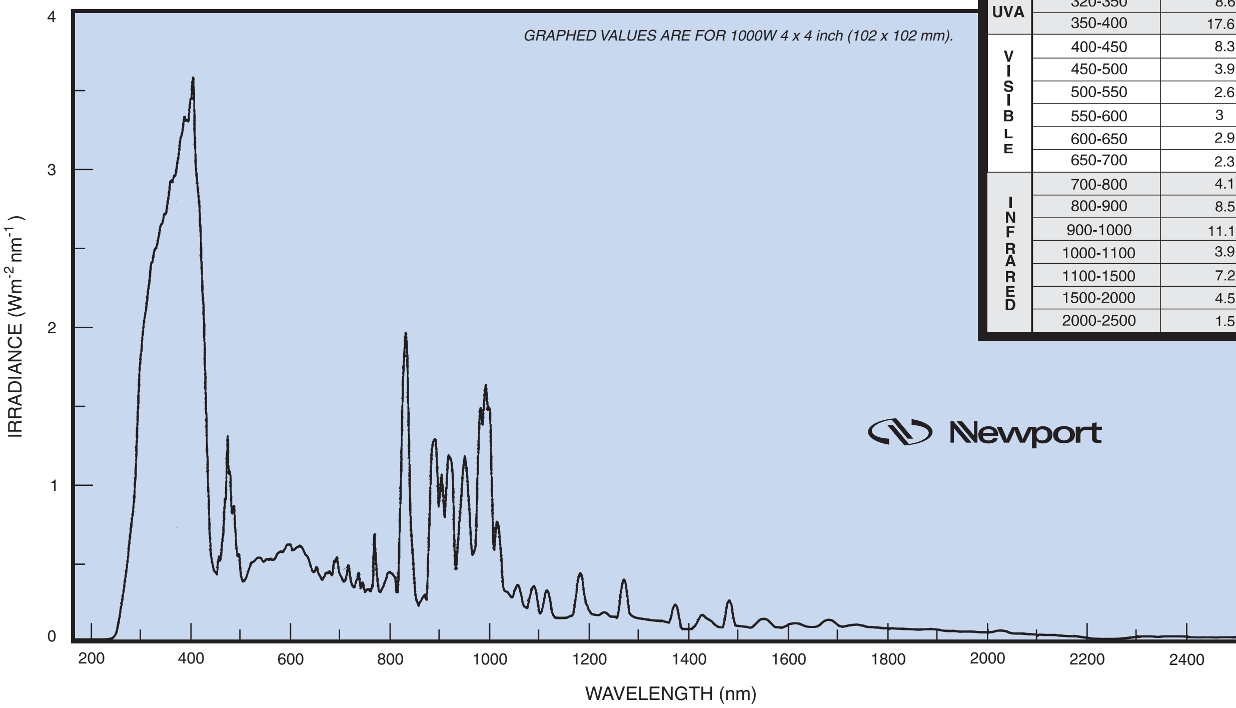


Fig. 7 The unfiltered output of the 91291, 1000 W Solar UV Simulator. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	91260	91291	91292	91293	91294
TOTAL OUTPUT POWER DENSITY (Wm^{-2})	730	3400	915	490	290

	RANGE (nm)	% OF 200-2500nm
UVC	<260	0.3
	260-280	1.3
UVB	280-290	1.4
	290-300	2.0
	300-310	2.3
	310-320	2.6
UVA	320-330	2.7
	330-340	2.9
	340-350	3.1
	350-360	3.2
	360-370	3.4
	370-380	3.6
	380-390	3.6
	390-400	3.8

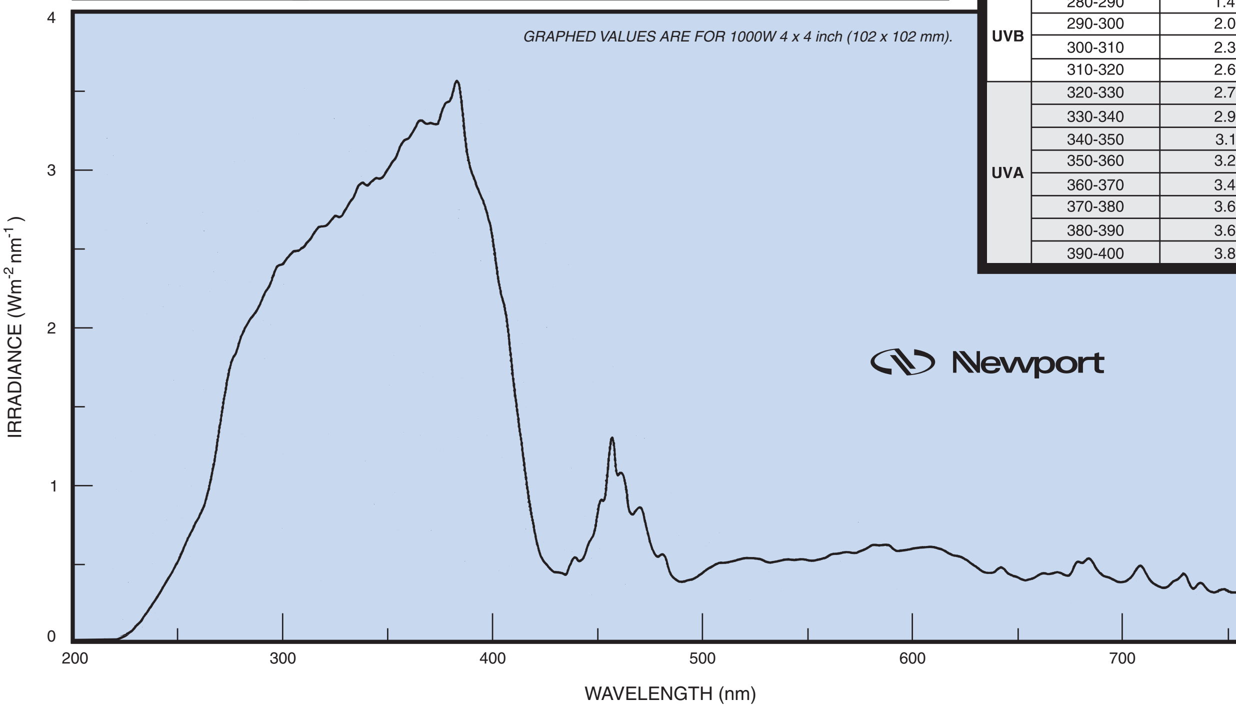


Fig. 8 The UV-VIS output of the 91291, 1000 W Solar UV Simulator. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

To simplify visual comparison of our simulators' curve shapes with the shapes of the standard solar spectra curves, we scale the measured simulator output, without changing the shape.

We use two types of normalization, one based on the total spectrum from 250 - 2500 nm, and the second based on 250 - 1100 nm. In each case, we calculate the normalization, or scaling factor, by comparing the total simulator irradiance with the total irradiance for the appropriate standard (ASTM or CIE) curve. Our comparison curves, on the following pages, show the simulator multiplied by the scaling factor so the displayed simulator curve has the same total irradiance as the relevant standard curve over the spectral region of interest.

On this page we show an example of a comparison between an actual measured output of a simulator to a standard spectrum, and a normalized simulator output to the same standard spectrum.

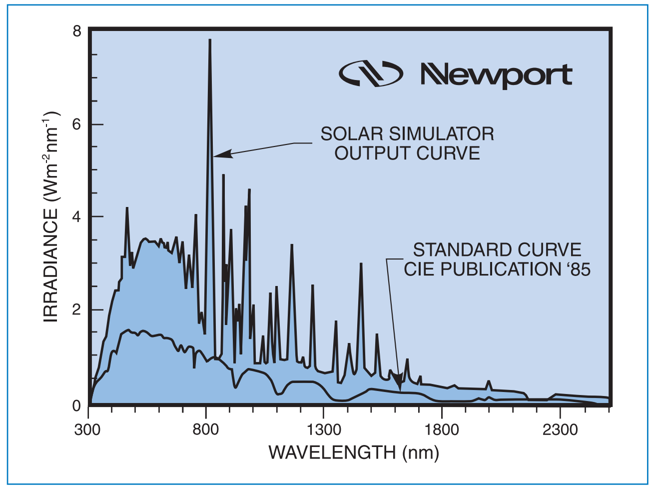


Fig. 1 Actual (not normalized) measured output of the Model 91160 300 W Solar Simulator with AM 1 Direct filter, and a CIE standard spectrum for AM 1 Direct. The total output (250 - 2500 nm) for the simulator is 2550 W m^{-2} while that for the standard is 970 W m^{-2}, i.e., the simulator is a 2.62 sun unit.

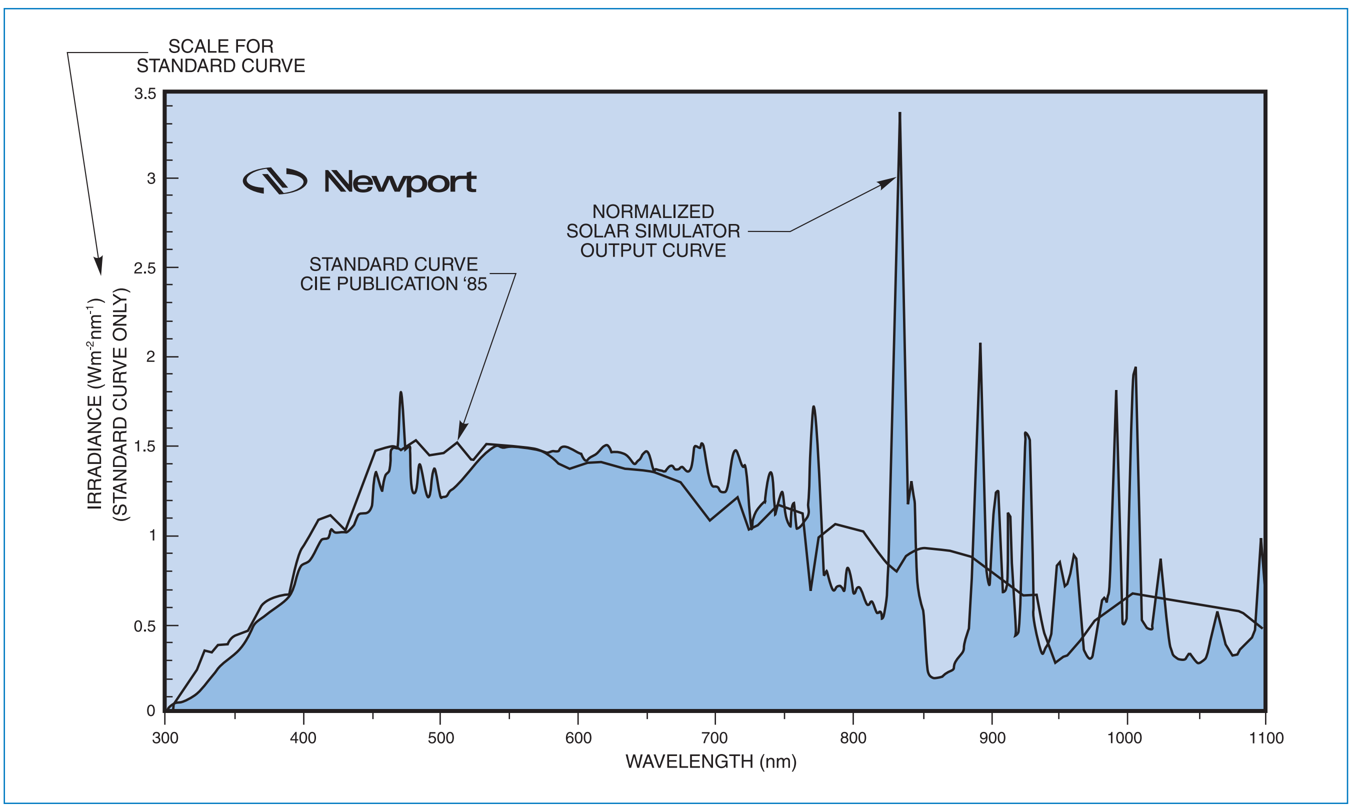


Fig. 2 Output from the same simulator shown in Fig. 1, from 300 - 1100 nm, normalized to match the CIE standard curve. (There is negligible output from 250 - 300 nm.) The total output of the simulator from 250 - 1100 nm was 1810 W m^{-2}, while that of the standard was 780 W m^{-2}. The graph shows the simulator curve multiplied by 780/1810, and the standard curve.

DESCRIPTION	ASTM E490	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	-	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY OVER 250 TO 2500nm (Wm-2)	1300	2805	13406	3575	1640	980

	RANGE (nm)	% OF 250-2500nm Newport	% OF 250-2500nm ASTM E490 A.M.O.
UVC	<280	0.11	0.6
UVB	280-320	0.6	1.7
UVA	320-350	1.0	2.4
	350-400	3.9	4.4
VISIBLE	400-450	5.4	6.6
	450-500	6.7	7.7
	500-550	6.7	7
	550-600	6.7	6.5
	600-650	6.5	6.7
	650-700	6.2	5.5
INFRARED	700-800	10.1	9.5
	800-900	8.3	7.6
	900-1000	6.9	6.3
	1000-1100	4.2	5.1
	1100-1500	15.2	12.7
	1500-2000	8.2	7.1
	2000-2500	3.5	2.9

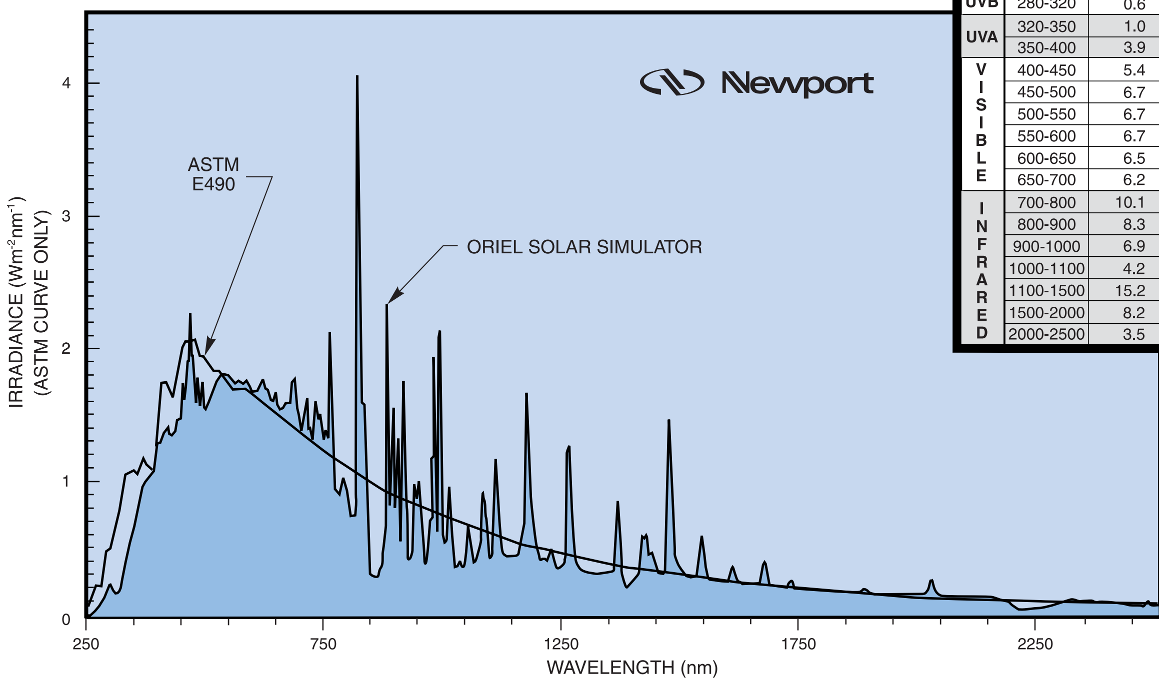


Fig. 1 Typical output spectral distribution of Oriel AM 0 Simulators normalized to the ASTM E490 standard spectrum by matching total power density from 250 - 2500 nm. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	ASTM E490	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	-	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY OVER 250 TO 1100nm (Wm-2)	1004	2050	9800	2640	1680	715

	RANGE (nm)	% OF 250-1100nm Newport	% OF 250-1100nm ASTM E490 A.M.O.
UVC	<280	0.15	0.8
UVB	280-320	0.8	2.3
UVA	320-350	1.5	3.2
	350-400	5.3	5.9
VISIBLE	400-450	7.4	8.9
	450-500	9.1	10.4
	500-550	9.1	9.4
	550-600	9.1	8.8
	600-650	8.9	8.4
	650-700	8.5	7.4
INFRARED	700-800	13.8	12.8
	800-900	11.3	10.2
	900-1000	9.3	8.5
	1000-1100	5.6	6.9

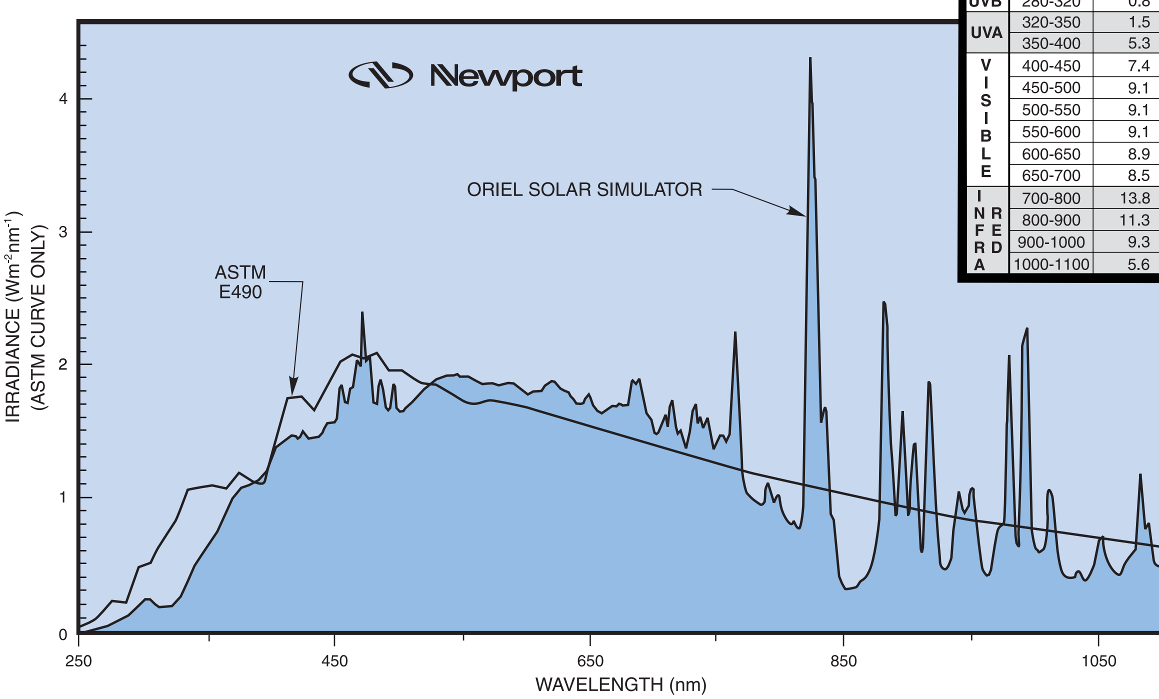


Fig. 2 Typical output spectral distribution of Oriel AM 0 Simulators normalized to the ASTM E490 standard spectrum by matching total power density from 250 - 1100 nm. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	ASTM E891	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	-	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY OVER 250 TO 2500nm (Wm^{-2})	757	2270	10360	2765	1270	760

	RANGE (nm)	% OF 250-2500nm Newport	% OF 250-2500nm ASTM E891 A.M. 1.5 DIRECT
UVC	<280	0.01	0
UVB	280-320	0.12	0.06
UVA	320-350	0.5	0.6
	350-400	2.3	2.2
VISIBLE	400-450	4.6	4.7
	450-500	6.5	6.6
	500-550	6.8	7.0
	550-600	7.3	7.1
	600-650	7.2	7.1
	650-700	6.5	6.5
INFRARED	700-800	9.4	11.7
	800-900	7.7	10.1
	900-1000	7.5	9.5
	1000-1100	4.7	4.2
	1100-1500	15.8	10.9
	1500-2000	9.3	8.4
	2000-2500	3.8	3.7

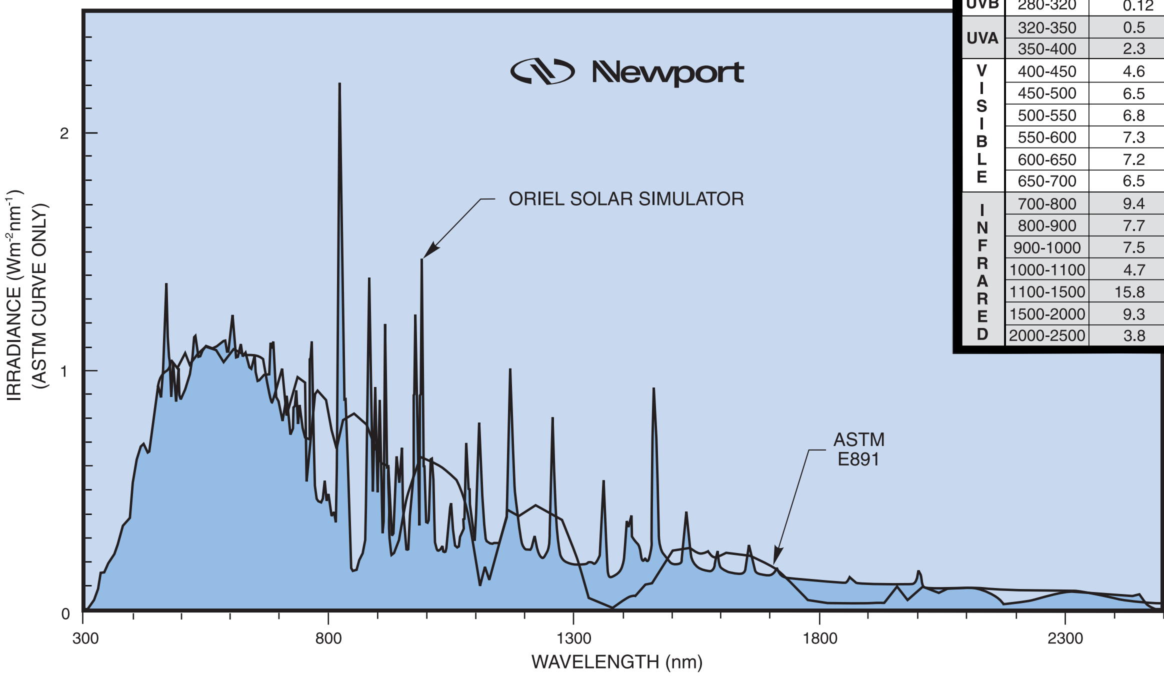


Fig. 3 Typical output spectral distribution of Oriel AM 1.5 Direct Simulators normalized to the ASTM E891 standard spectrum by matching total power density from 250 - 2500 nm. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	ASTM E891	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	-	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY OVER 250 TO 1100nm (Wm^{-2})	585	1614	7366	1966	903	540

	RANGE (nm)	% OF 250-1100nm Newport	% OF 250-1100nm ASTM E891 A.M. 1.5 DIRECT
UVC	<280	0.02	0.8
UVB	280-320	0.17	0.08
UVA	320-350	0.9	0.8
	350-400	3.2	2.9
VISIBLE	400-450	6.4	6.1
	450-500	9.1	8.6
	500-550	9.6	9.1
	550-600	10.3	9.2
	600-650	10.1	9.1
	650-700	9.2	8.4
INFRARED	700-800	13.2	15.2
	800-900	10.9	13.1
	900-1000	10.6	12.3
	1000-1100	6.5	5.4

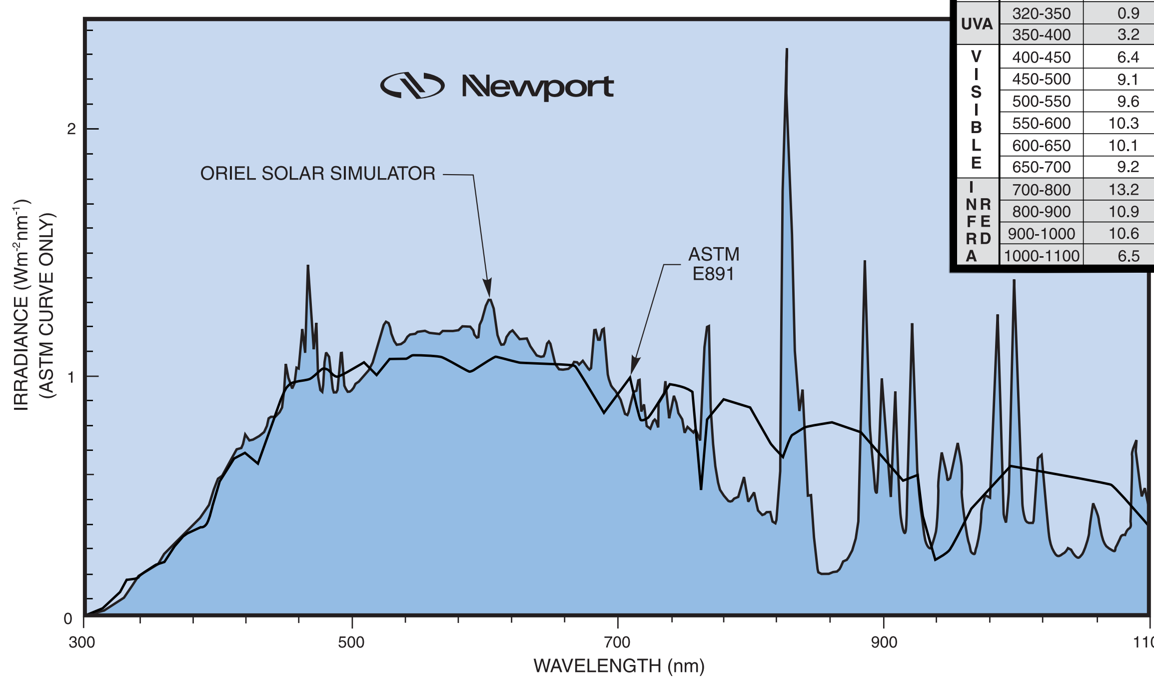


Fig. 4 Typical output spectral distribution of Oriel AM 1.5 Direct Simulators normalized to the ASTM E891 standard spectrum by matching total power density from 250 - 1100 nm. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	ASTM E892	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	-	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY OVER 250 TO 2500nm (Wm^{-2})	951	1550	7150	1910	875	720

	RANGE (nm)	% OF 250-2500nm Newport	% OF 250-2500nm ASTM E892 A.M. 1.5 GLOBAL
UVC	<280	0	0
UVB	280-320	0.1	0.13
UVA	320-350	0.8	1.1
	350-400	4.5	3.4
VISIBLE	400-450	7.3	6
	450-500	10.5	8
	500-550	9.8	7.9
	550-600	10	7.5
	600-650	9	7.3
	650-700	8.1	6.6
INFRARED	700-800	11.3	11.2
	800-900	7.3	9.3
	900-1000	4.7	5.7
	1000-1100	2.2	6.5
	1100-1500	7	3.1
	1500-2000	5.3	6.7
	2000-2500	2.2	9.4

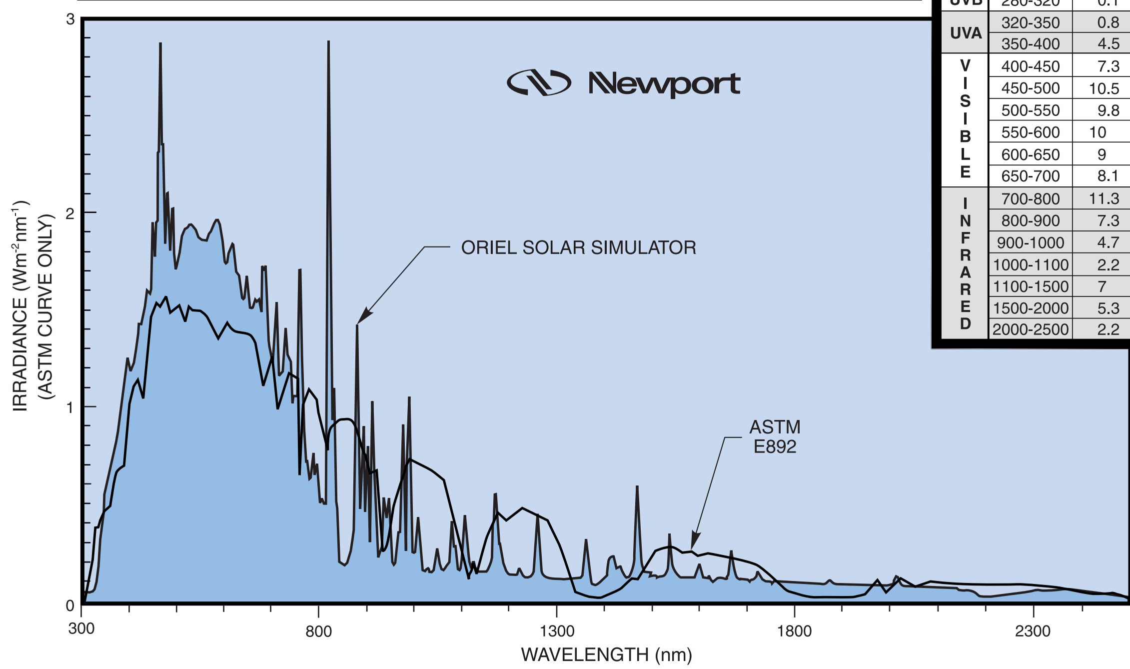


Fig. 5 Typical output spectral distribution of Oriel AM 1.5 Global Simulators normalized to the ASTM E892 standard spectrum by matching total power density from 250 - 2500 nm. The IEC 904-3 standard has the same shape as the ASTM E892. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.

DESCRIPTION	ASTM E892	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	-	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY OVER 250 TO 1100nm (Wm^{-2})	769	1325	6110	1630	750	450

	RANGE (nm)	% OF 250-1100nm Newport	% OF 250-1100nm ASTM E892 A.M. 1.5 GLOBAL
UVC	<280	0	0
UVB	280-320	0.11	0.16
UVA	320-350	0.6	1.4
	350-400	5.3	4.2
VISIBLE	400-450	8.6	7.4
	450-500	12.3	9.9
	500-550	11.5	9.8
	550-600	11.7	9.3
	600-650	10.6	9.1
	650-700	9.5	8.2
INFRARED	700-800	13.2	13.9
	800-900	8.6	11.5
	900-1000	5.5	7.1
	1000-1100	2.6	8.1

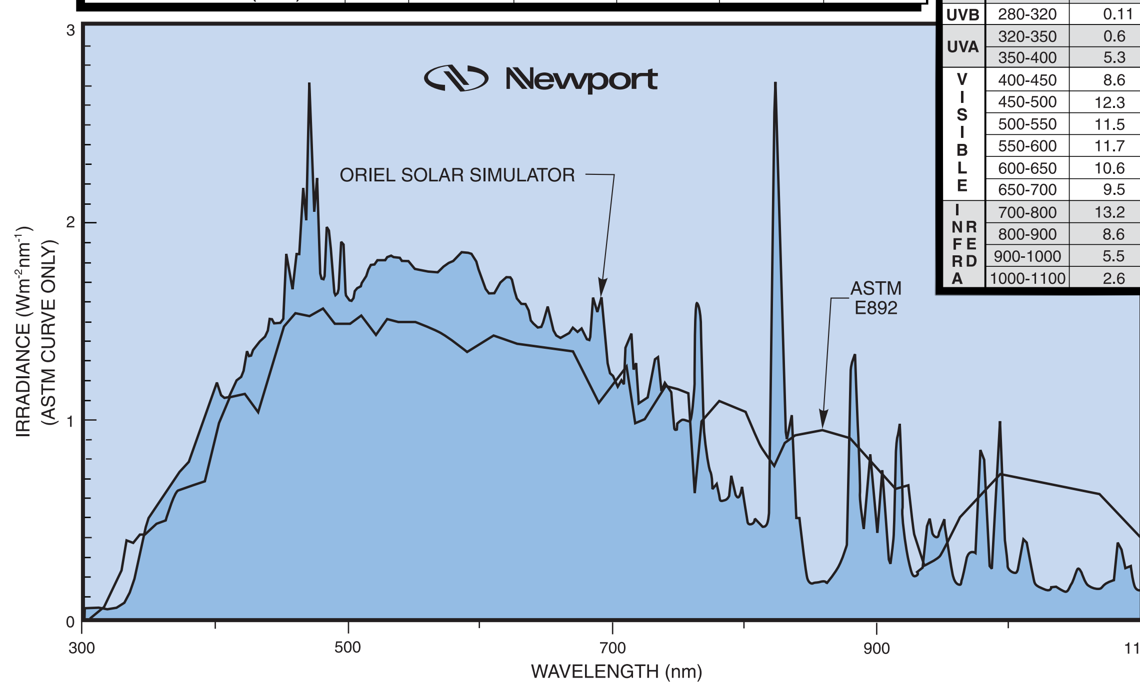


Fig. 6 Typical output spectral distribution of Oriel AM 1.5 Global Simulators normalized to the ASTM E892 standard spectrum by matching total power density from 250 - 1100 nm. The IEC 904-3 standard has the same shape as the ASTM E892. The 1600 W Solar Simulators have ~30% higher irradiance than equivalent 1000 W Simulators.