ORIEL

ORIEL PRODUCT TRAINING

Spectral Irradiance

SECTION ONE FEATURES

- Optical Radiation Terminology and Units
- Laws of Radiation
- Pulsed Radiation
- Light Collection and System Throughput
- Spectral Irradiance Data
- Using the Spectral Irradiance Curves
- Calculating Output Power

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There are many systems of units for optical radiation. In this catalog we try to adhere to the internationally agreed CIE system. The CIE system fits well with the SI system of units. We mostly work with the units familiar to those working in the UV to near IR. We have limited the first part of this discussion to steady state conditions, essentially neglecting dependence on time. We explicitly discuss time dependence at the end of the section.

RADIOMETRIC, PHOTOMETRIC AND PHOTON QUANTITIES

The emphasis in our catalog is on radiometric quantities. These are purely physical. How the (standard) human eye records optical radiation is often more relevant than the absolute physical values. This evaluation is described in photometric units and is limited to the small part of the spectrum called the visible. Photon quantities are important for many physical processes. Table 1 lists radiometric, photometric and photon quantities.

Table 1 Commonly Used Radiometric, Photometric and Photon Quantities

Radiometric			Photometric			Photon		
Quantity	Usual Symbol	Units	Quantity	Usual Symbol	Units	Quantity	Usual Symbol	Units
Radiant Energy	Q_e	J	Luminous Energy	Q_v	lm s	Photon Energy	N_p	*
Radiant Power or Flux	ϕ_e	W	Luminous Flux	ϕ_v	lm	Photon Flux	$\Phi_p = \frac{dN_p}{dt}$	s^{-1}
Radiant Exitance or Emittance	M_e	W m^{-2}	Luminous Exitance or Emittance	M_v	lm m^{-2}	Photon Exitance	M_p	s^{-1} m^{-2}
Irradiance	E_e	W m^{-2}	Illuminance	E_v	lx	Photon Irradiance	E_p	s^{-1} m^{-2}
Radiant Intensity	I_e	W sr^{-1}	Luminous Intensity	I_v	cd	Photon Intensity	I_p	s^{-1} sr^{-1}
Radiance	L_e	W sr^{-1} m^{-2}	Luminance	L_v	cd m^{-2}	Photon Radiance	L_p	s^{-1} sr^{-1} m^{-2}

* **Photon quantities are expressed in number of photons followed by the units, eg. photon flux (number of photons) s^{-1}. The unit for photon energy is number of photons.**

The subscripts e,v, and p designate radiometric, photometric, and photon quantities respectively. They are usually omitted when working with only one type of quantity.

Symbols Key:

J: joule	lm: lumen
W: watts	s: second
m: meter	cd: candela
sr: steradian	lx: lux, lumen m^{-2}

Table 2 Some Units Still in Common Use

Units	Equivalent	Quantity
Talbot	lm s	Luminous Energy
Footcandle	lm ft^{-2}	Illuminance
Footlambert	cd ft^{-2}	Luminance
Lambert	cd cm^{-2}	Luminance

Sometimes "sterance", "areance", and "pointance" are used to supplement or replace the terms above.

- Sterance, means, related to the solid angle, so radiance may be described by radiant sterance.
- Areance, related to an area, gives radiant areance instead of radiant exitance.
- Pointance, related to a point, leads to radiant pointance instead of radiant intensity.

SPECTRAL DISTRIBUTION

"Spectral" used before the tabulated radiometric quantities implies consideration of the wavelength dependence of the quantity. The measurement wavelength should be given when a spectral radiometric value is quoted.

The variation of spectral radiant exitance ($M_{e\lambda}$), or irradiance ($E_{e\lambda}$) with wavelength is often shown in a spectral distribution curve. Pages 16 to 32 show spectral distribution curves for irradiance.

In this catalog we use mW m^{-2} nm^{-1} as our preferred units for spectral irradiance. Conversion to other units, such as mW m^{-2} μm^{-1}, is straightforward.

For example:

The spectral irradiance at 0.5 m from our 6333 100 watt QTH lamp is 12.2 mW m^{-2} nm^{-1} at 480 nm. This is:

0.0122 W m^{-2} nm^{-1}
1.22 W m^{-2} μm^{-1}
1.22 μW cm^{-2} nm^{-1}

all at 0.48 μm and 0.5 m distance.

With all spectral irradiance data or plots, the measurement parameters, particularly the source-measurement plane distance, must be specified. Values cited in this catalog for lamps imply the direction of maximum radiance and at the specified distance.

Wavelength, Wavenumber, Frequency and Photon Energy

This catalog uses "wavelength" as spectral parameter. Wavelength is inversely proportional to the photon energy; shorter wavelength photons are more energetic photons. Wavenumber and frequency increase with photon energy.

The units of wavelength we use are nanometers (nm) and micrometers (μm) (or the common, but incorrect version, microns).

1 nm = 10^{-9} m = 10^{-3} μm
1 μm = 10^{-9} m = 1000 nm
1 Angstom unit (Å) = 10^{-10} m = 10^{-1} nm

Fig. 1 shows the solar spectrum and 5800K blackbody spectral distributions against energy (and wavenumber), in contrast with the familiar representation (Fig. 4 on page 1-5).

Table 2 below helps you to convert from one spectral parameter to another. The conversions use the approximation 3 x 10^8 m s^{-1} for the speed of light. For accurate work, you must use the actual speed of light in medium. The speed in air depends on wavelength, humidity and pressure, but the variance is only important for interferometry and high resolution spectroscopy.

TECH NOTE

Irradiance and most other radiometric quantities have values defined at a point, even though the units, mW m^{-2} nm^{-1}, imply a large area. The full description requires the spatial map of the irradiance. Often average values over a defined area are most useful. Peak levels can greatly exceed average values.

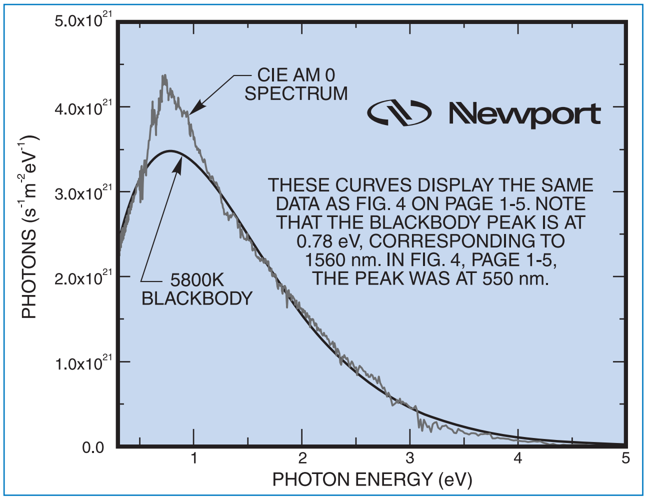


Fig. 1 Unconventional display of solar irradiance on the outer atmosphere and the spectral distribution of a 5800K blackbody with the same total radiant flux.

Expressing radiation in photon quantities is important when the results of irradiation are described in terms of cross section, number of molecules excited or for many detector and energy conversion systems, quantum efficiency.

Monochromatic Radiation

Calculating the number of photons in a joule of monochromatic light of wavelength λ is straightforward since the energy in each photon is given by:

$$E = hc/\lambda \text{ joules}$$

Where:
h = Planck's constant (6.626 x 10^{-34} J s)
c = Speed of light (2.998 x 10^8 m s^{-1})
λ = Wavelength in m

So the number of photons per joule is:

$$N_{p\lambda} = \lambda \times 5.03 \times 10^{15} \text{ where } \lambda \text{ is in nm}^{+}$$

Since a watt is a joule per second, one Watt of monochromatic radiation at λ corresponds to $N_{p\lambda}$ photons per second. The general expression is:

$$\frac{dN_{p\lambda}}{dt} = P_\lambda \times \lambda \times 5.03 \times 10^{15} \text{ where } P_\lambda \text{ is in watts, } \lambda \text{ is in nm}$$

Similarly, you can easily calculate photon irradiance by dividing by the beam impact area.

+ We have changed from a fundamental expression where quantities are in base SI units, to the derived expression for everyday use.

Table 3 Spectral Parameter Conversion Factors

	Wavelength	Wavenumber*	Frequency	Photon Energy**
Symbol (Units)	λ (nm)	υ (cm^{-1})	ν (Hz)	E_p (eV)
Conversion Factors	λ	$10^7/\lambda$	$3 \times 10^{17}/\lambda$	$1{,}240/\lambda$
	$10^7/\upsilon$	υ	$3 \times 10^{10}\upsilon$	$1.24 \times 10^{-4}\upsilon$
	$3 \times 10^{17}/\nu$	$3.33 \times 10^{-11}\nu$	ν	$4.1 \times 10^{-15}\nu$
	$1{,}240/E_p$	$8{,}056 \times E_p$	$2.42 \times 10^{14}E_p$	E_p
Conversion Examples	200	5×10^4	1.5×10^{15}	6.20
	500	2×10^4	6×10^{14}	2.48
	1000	10^4	3×10^{14}	1.24

When you use this table, remember that applicable wavelength units are nm, wavenumber units are cm^{-1}, etc.

*** The S.I. unit is the m^{-1}. Most users, primarily individuals working in infrared analysis, adhere to the cm^{-1}.**

**** Photon energy is usually expressed in electron volts to relate to chemical bond strengths.The units are also more convenient than photon energy expressed in joules as the energy of a 500 nm photon is 3.98 x 10^{-19} J = 2.48 eV**

Example 1

What is the output of a 2 mW (632.8 nm) HeNe laser in photons per second?

$$2 \text{ mW} = 2 \times 10^{-3} \text{ W}$$
$$\phi_p = 2 \times 10^{-3} \times 632.8 \times 5.03 \times 10^{15}$$
$$= 6.37 \times 10^{15} \text{ photons/second}$$

Broadband Radiation

To convert from radiometric to photon quantities, you need to know the spectral distribution of the radiation. For irradiance you need to know the dependence of $E_{e\lambda}$ on λ. You then obtain the photon flux curve by converting the irradiance at each wavelength as shown above. The curves will have different shapes as shown in Fig. 2.

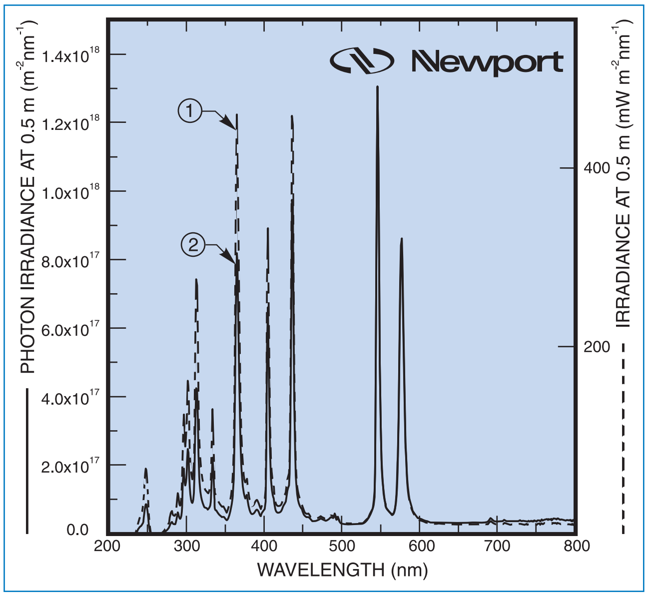


Fig. 2 The wavelength dependence of the irradiance produced by the 6283 200 W mercury lamp at 0.5 m. (1) shown conventionally in mW m^{-2} nm^{-1} and (2) as photon flux.

CONVERTING FROM RADIOMETRIC TO PHOTOMETRIC VALUES

You can convert from radiometric terms to the matching photometric quantity (Table 1 on page 1-2).The photometric measure depends on how the source appears to the human eye.This means that the variation of eye response with wavelength, and the spectrum of the radiation, determine the photometric value. Invisible sources have no luminance, so a very intense ultraviolet or infrared source registers no reading on a photometer.

The response of the "standard" light adapted eye (photopic vision) is denoted by the normalized function V (λ). See Fig. 3 and Table 4. Your eye response may be significantly different!

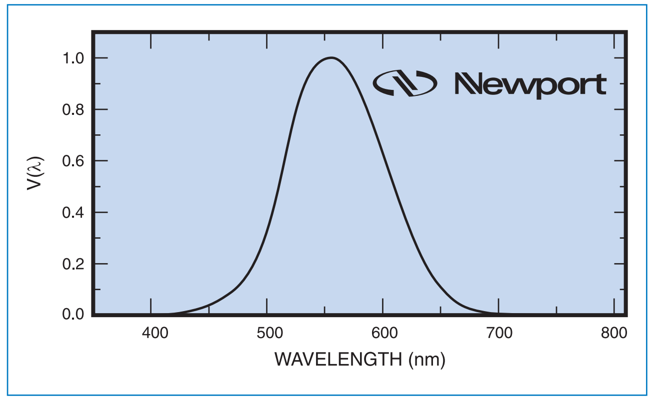


Fig. 3 The normalized response of the "standard" light adapted eye.

Table 4 Photopic Response

Wavelength (nm)	Photopic Luminous Efficiency V(λ)	Wavelength (nm)	Photopic Luminous Efficiency V(λ)
380	0.00004	580	0.870
390	0.00012	590	0.757
400	0.0004	600	0.631
410	0.0012	610	0.503
420	0.0040	620	0.381
430	0.0116	630	0.265
440	0.023	640	0.175
450	0.038	650	0.107
460	0.060	660	0.061
470	0.091	670	0.032
480	0.139	680	0.017
490	0.208	690	0.0082
500	0.323	700	0.0041
510	0.503	710	0.0021
520	0.710	720	0.00105
530	0.862	730	0.00052
540	0.954	740	0.00025
550	0.995	750	0.00012
555	1.000	760	0.00006
560	0.995	770	0.00003
570	0.952		

To convert, you need to know the spectral distribution of the radiation. Conversion from a radiometric quantity (in watts) to the corresponding photometric quantity (in lumens) simply requires multiplying the spectral distribution curve by the photopic response curve, integrating the product curve and multiplying the result by a conversion factor of 683.

Mathematically for a photometric quantity (PQ) and its matching radiometric quantity (SPQ).

$$PQ = 683 \int (SPQ_\lambda) \bullet V(\lambda)d\lambda$$

Since V(λ) is zero except between 380 and 770 nm, you only need to integrate over this range. Most computations simply sum the product values over small spectral intervals, $\Delta\lambda$:

$$PQ \approx \left(\Sigma_n(SPQ_{\lambda n}) \bullet V(\lambda_n)\right) \bullet \Delta\lambda$$

Where:

$(SPQ_{\lambda n})$ = Average value of the spectral radiometric quantity in wavelength interval number "n"

The smaller the wavelength interval, $\Delta\lambda$, and the slower the variation in SPQ_λ, the higher the accuracy.

Example 2

Calculate the illuminance produced by the 6253 150 W Xe arc lamp, on a small vertical surface 1 m from the lamp and centered in the horizontal plane containing the lamp bisecting the lamp electrodes. The lamp operates vertically.

The irradiance curve for this lamp is on page 1-23. Curve values are for 0.5 m, and since irradiance varies roughly as r^{-2}, divide the 0.5 m values by 4 to get the values at 1 m. These values are in mW m^{-2} nm^{-1} and are shown in Fig. 4. With the appropriate irradiance curve you need to estimate the spectral interval required to provide the accuracy you need. Because of lamp to lamp variation and natural lamp aging, you should not hope for better than ca. ±10% without actual measurement, so don't waste effort trying to read the curves every few nm. The next step is to make an estimate from the curve of an average value of the irradiance and V(λ) for each spectral interval and multiply them. The sum of all the products gives an approximation to the integral.

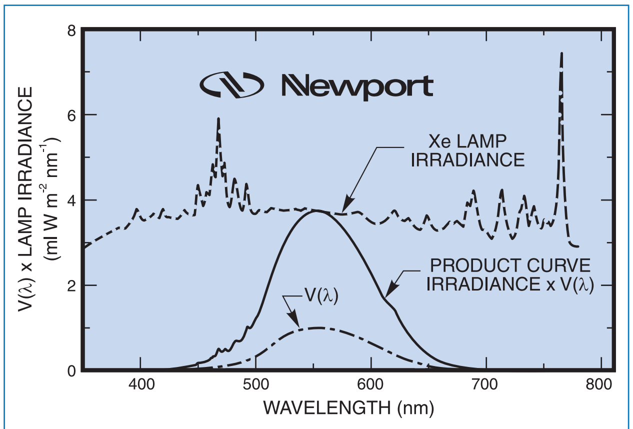


Fig. 4 Lamp Irradiance, V (λ), and product curve.

We show the "true integration" based on the 1 nm increments for our irradiance spectrum and interpolation of V(λ) data, then an example of the estimations from the curve.

Fig. 4 shows the irradiance curve multiplied by the V(λ) curve. The unit of the product curve that describes the radiation is the lW, or light watt, a hybrid unit bridging the transition between radiometry and photometry. The integral of the product curve is 396 mlWm^{-2}, where a lW is the unit of the product curve.

Estimating:

Table 5 shows the estimated values with 50 nm spectral interval. The sum of the products is 392 mlWm^{-2}, very close to the result obtained using full integration.

Table 5 Light Watt Values

Wavelength Range (nm)	Estimated Average Irradiance (mW m^{-2} nm^{-1})	V(λ)	Product of cols 1 & 2 x 50 nm (mlW m^{-2})
380 - 430	3.6	0.0029	0.5
430 - 480	4.1	0.06	12
480 - 530	3.6	0.46	83
530 - 580	3.7	0.94	174
580 - 630	3.6	0.57	103
630 - 680	3.4	0.11	19
680 - 730	3.6	0.0055	1.0
730 - 780	3.8	0.0002	0.038

To get from lW to lumens requires multiplying by 683, so the illuminance is:

396x683 mlumens m^{-2} = 270 lumens m^{-2} (or 270 lux)

Since there are 10.764 ft^2 in a m^2, the illuminance in foot candles (lumens ft^{-2}) is 270/10.8 = 25.1 foot candles.

TECH NOTE

The example uses a lamp with a reasonably smooth curve over the VIS region, making the multiplication and summation easier. The procedure is more time consuming with a Hg lamp due to the rapid spectral variations. In this case you must be particularly careful about our use of a logarithmic scale in our irradiance curves. See page 1-18. You can simplify the procedure by cutting off the peaks to get a smooth curve and adding the values for the "monochromatic" peaks back in at the end. We use our tabulated irradiance data and interpolated V(λ) curves to get a more accurate product, but lamp to lamp variation means the result is no more valid.

Everything radiates and absorbs electro-magnetic radiation. Many important radiation laws are based on the performance of a perfect steady state emitter called a blackbody or full radiator. These have smoothly varying spectra that follow a set of laws relating the spectral distribution and total output to the temperature of the blackbody. Sources like the sun, tungsten filaments, or our Infrared Emitters, have blackbody-like emission spectra. However, the spectral distributions of these differ from those of true blackbodies; they have slightly different spectral shapes and in the case of the sun, fine spectral detail. See Fig. 1.

Any conventional source emits less than a blackbody with the same surface temperature. However, the blackbody laws show the important relationship between source output spectra and temperature.

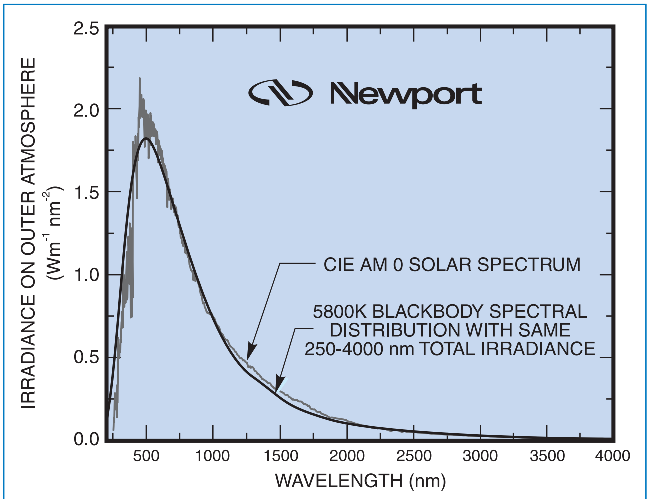


Fig. 1 The spectrum of radiation from the sun is similar to that from a 5800K blackbody.

PLANCK'S LAW

This law gives the spectral distribution of radiant energy inside a blackbody.

$$W_{e\lambda}(\lambda,T) = 8\pi hc\lambda^{-5}(e^{ch/k\lambda T} - 1)^{-1}$$

Where:

T = Absolute temperature of the blackbody
h = Planck's constant (6.626×10^{-34} Js)
c = Speed of light (2.998×10^{8} m s^{-1})
k = Boltzmann's constant (1.381×10^{-23} JK^{-1})
λ = Wavelength in m

The spectral radiant exitance from a non perturbing aperture in the blackbody cavity, $M_{e\lambda}(\lambda,T)$, is given by:

$$M_{e\lambda}(\lambda,T) = (c/4)W_{e\lambda}(\lambda,T),$$

$L_{e\lambda}(\lambda,T)$, the spectral radiance at the aperture is given by:

$$L_{e\lambda}(\lambda,T) = (c/4\pi)W_{e\lambda}(\lambda,T)$$

The curves in Fig. 3 show $M_{B\lambda}$ plotted for blackbodies at various temperatures.The output increases and the peak shifts to shorter wavelengths as the temperature,T, increases.

STEFAN-BOLTZMAN LAW

Integrating the spectral radiant exitance over all wavelengths gives:

$$\int M_{e\lambda}(\lambda,T)d\lambda = M_e(T) = \sigma T^4$$

σ is called the Stefan-Boltzmann constant

This is the Stefan-Boltzmann law relating the total output to temperature.

If $M_e(T)$ is in W m^{-2}, and T in kelvins, then σ is 5.67×10^{-8} $Wm^{-2} K^{-4}$.

At room temperature a 1 mm^2 blackbody emits about 0.5 mW into a hemisphere. At 3200 K, the temperature of the hottest tungsten filaments, the 1 mm^2, emits 6 W.

WIEN DISPLACEMENT LAW

This law relates the wavelength of peak exitance, λ_m, and blackbody temperature,T:

$\lambda_m T$ = 2898 where T is in kelvins and λ_m is in micrometers.

The peak of the spectral distribution curve is at 9.8 µm for a blackbody at room temperature. As the source temperature gets higher, the wavelength of peak exitance moves towards shorter wavelengths. The temperature of the sun's surface is around 5800K. The peak of a 6000 blackbody curve is at 0.48 µm, as shown in Fig. 3.

EMISSIVITY

The radiation from real sources is always less than that from a blackbody. Emissivity (ε) is a measure of how a real source compares with a blackbody. It is defined as the ratio of the radiant power emitted per area to the radiant power emitted by a blackbody per area. (A more rigorous definition defines directional spectral emissivity $\varepsilon(\theta,\phi,\lambda,T)$. Emissivity can be wavelength and temperature dependent (Fig. 2). As the emissivity of tungsten is less than 0.4 where a 3200 K blackbody curve peaks, the 1 mm^2 tungsten surface at 3200 K will only emit 2.5 W into the hemisphere.

If the emissivity does not vary with wavelength then the source is a "graybody".

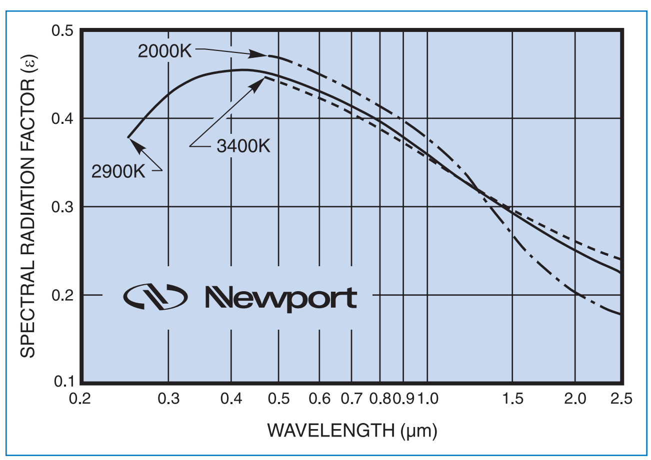


Fig. 2 Emissivity (spectral radiation factor) of tungsten.

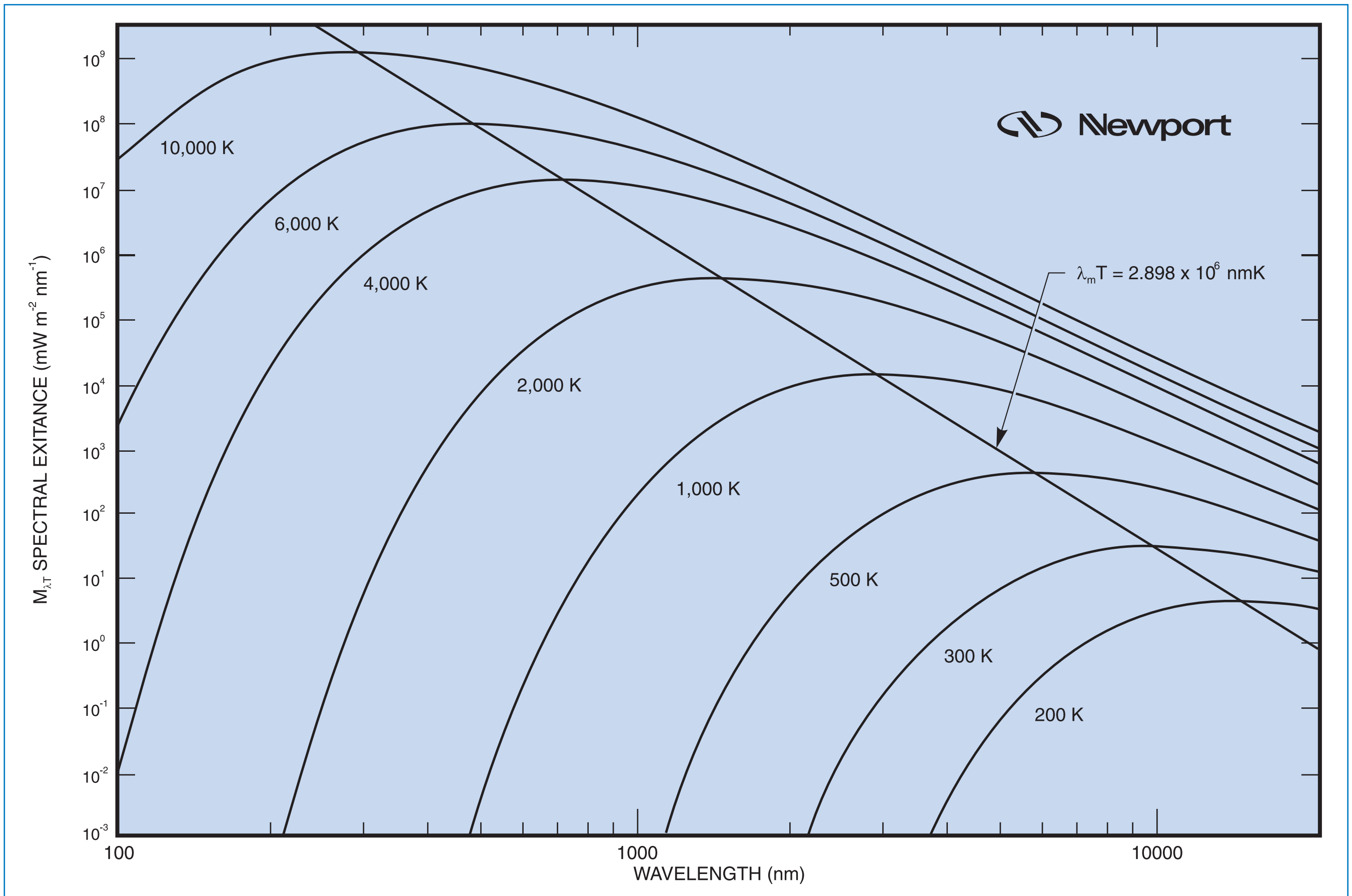


Fig. 3 Spectral exitance for various blackbodies

TECH NOTE

Sometimes you prefer to have low emissivity over a part of the spectrum. This can reduce out of band interference. Our Ceramic Elements (page 5-31) have low emissivity in the near infrared; this makes them more suitable for work in the mid IR. Normally one wants a high blackbody temperature for high output, but the combination of higher short wavelength detector responsivity and high near IR blackbody output complicates mid infrared spectroscopy. Because of the emissivity variation, the Ceramic Elements provide lower near IR than one would expect from their mid IR output.

KIRCHOFF'S LAW

Kirchoff's Law states that the emissivity of a surface is equal to its absorptance, where the absorptance (α) of a surface is the ratio of the radiant power absorbed to the radiant power incident on the surface.

$$\int_T \alpha(\lambda,T)d\lambda = \int_T \varepsilon(\lambda,T)d\lambda$$
$$\alpha = \varepsilon$$

LAMBERT'S LAW

Lambert's Cosine Law holds that the radiation per unit solid angle (the radiant intensity) from a flat surface varies with the cosine of the angle to the surface normal (Fig. 4). Some Oriel Sources, such as arcs, are basically spherical. These appear like a uniform flat disk as a result of the cosine law. Another consequence of this law is that flat sources, such as some of our low power quartz tungsten halogen filaments, must be properly oriented for maximum irradiance of a target. Flat diffusing surfaces are said to be ideal diffusers or Lambertian if the geometrical distribution of radiation from the surfaces obeys Lambert's Law. Lambert's Law has important consequences in the measurement of light. Cosine receptors on detectors are needed to make meaningful measurements of radiation with large or uncertain angular distribution.

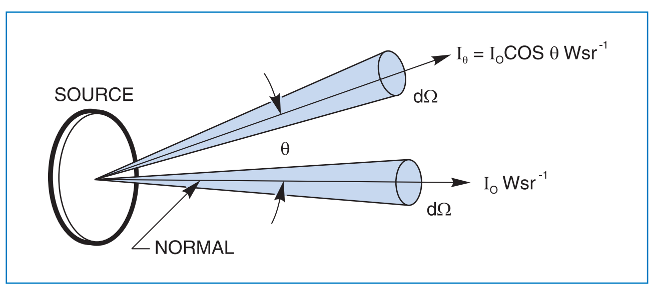


Fig. 4 Lamberts cosine law indicates how the intensity, I, depends on angle.

TIME DEPENDENCE-PULSED RADIATION

So far we have omitted the time dependence of the radiation, assuming that the radiation level was constant. Now we briefly extend the treatment to cover radiation of varying level. This requires consideration of the dependence on t, time, so that irradiance becomes $E_{e\lambda}$ (λ,t).

Most displays of radiation pulses show how the radiant power (radiant flux) $\Phi_e(\lambda,t)$ varies with time. Sometimes, particularly with laser sources, the word "intensity" is used instead of radiant flux or radiant power. In this case intensity often does not represent the strict meaning indicated in Table 1, but beam power.

Single Pulse

Fig. 1 shows a typical radiation pulse from a flash lamp (page 4-50) or laser. Microsecond timescales are typical for flashlamps, nanosecond timescales are typical for Q-switched or fast discharge lasers, and picosecond or femto-second timescales are typical of mode locked lasers. Pulse risetimes and decay times often differ from each other, as the underlying physics is different.

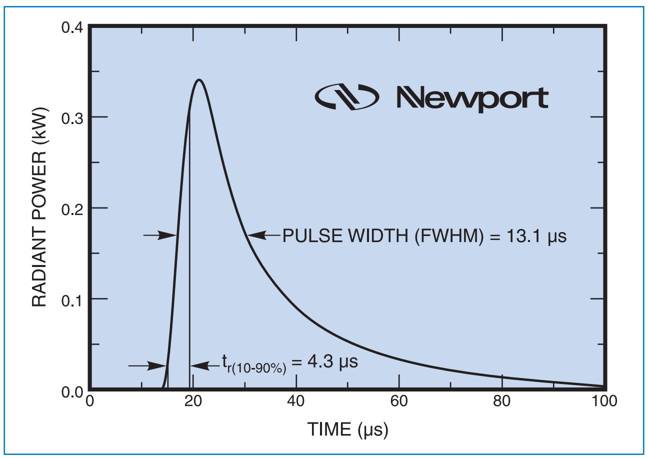


Fig. 1 Typical optical radiation pulse shape.

TECH NOTE

When recording pulses you should ensure that the detector and its associated electronics are fast enough to follow the true pulse shape. As a rule of thumb, the detection system bandwidth must be wider than $1/(3t_r)$ to track the fast risetime, t_r, to within 10% of actual. A slow detector system shows a similar pulse shape to that in Fig.1, but the rise and fall times are, in this case, characteristic of the detector and its electronic circuitry. If you use an oscilloscope to monitor a pulse you will probably need to use a "termination" to reduce the RC time constant of the detection circuitry and prevent electrical signal reflections within a coaxial cable. For example, an RG 58/U coaxial cable requires a 50 ohm termination.

The pulse shape shows the dependence of radiant power, with time. The radiant energy in a pulse is given by:

$$Q_e = \int Q_e(\lambda)d\lambda = \iint_{\Delta t} \Phi_e(\lambda,t)\, dtd\lambda$$

$$Q_e = \int_{\Delta t} \Phi_e(t)dt = \iint_{\Delta t} \Phi_e(\lambda,t)\, dtd\lambda$$

$\Phi_e(\lambda,t)$ represents the flux per unit wavelength at wavelength λ and time t; $\Phi_e(t)$ represents the total flux (for all wavelengths), at time t. $\Phi_e(\lambda)$ is the spectral distribution of radiant energy, while Q_e represents the total energy for all wavelengths.

For $\Phi_e(t)$ in Watts, Q_e will be in joules.

Δt, is the time interval for the integration that encompasses the entire pulse but in practice should be restricted to exclude any low level continuous background or other pulses.

The pulse is characterized by a pulsewidth. There is no established definition for pulsewidth. Often, but not always, it means halfwidth, full width at half maximum (FWHM). For convenience average pulse power is often taken as the pulse energy divided by the pulsewidth. The validity of this approximation depends on the pulse shape. It is exact for a "top hat" pulse where the average power and peak power are the same. For the flashlamp pulse shown in Fig.1, the pulse energy, obtained by integrating, is 6.7 mJ, the pulse width is 13.1 µs, so the "average power" computed as above is 0.51 kW. The true peak power is 0.34 kW and thus a nominal inconsistency due to arbitrary definition of pulse width.

Repetitive Pulses

Fig. 2 shows a train of pulses, similar to the pulse in Fig.1. Full characterization requires knowledge of all the parameters of the single pulse and the pulse repetition rate. The peak power remains the same, but now the average power is the single pulse energy multiplied by the pulse rate in Hz.

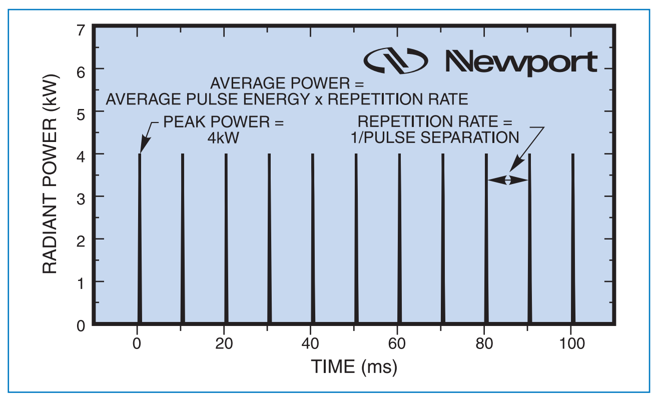


Fig. 2 Typical pulsetrain display. In this figure, the repetition rate is 100 Hz, the peak power 4 kW. Pulse energy can be easily measured by pyroelectric detectors or, if repetition rate is too high, average power of the pulsetrain, as measured by a thermopile detector, can be divided by pulse repetition rate to obtain average pulse energy.

On the following pages we hope to help you select the best optical system for your application. This discussion is restricted to general use of sources such as arc lamps or quartz tungsten halogen lamps. Diffraction and coherent effects are excluded. The emphasis through this section will be on collection of light.

TOTAL SYSTEM CONSIDERATIONS

A system can include a source, collection optics, beam handling and processing optics,delivery optics and a detector. It is important to analyze the entire system before selecting pieces of it. The best collection optics for on application can be of limited value for another. Often you find that collecting the most light from the source is not the best thing to do!

F-NUMBER AND NUMERICAL APERTURE

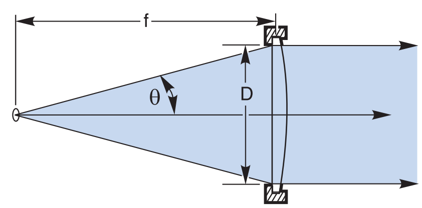


Fig. 1 Lens collecting and collimating light from a source.

Fig.1 shows a lens of clear aperture D, collecting light from a source and collimating it. The source is one focal length, f, from the lens. Since most sources radiate at all angles, it is obvious that increasing D or decreasing f allows the lens to capture more radiation.The F-number concept puts these two together to allow a quick comparison of optics

F-number is defined:

$$F/\# = \frac{1}{2\,n\,\sin\,\theta}$$

Where:

n = Refractive index of space in which the source is located

θ = Half angle of the cone of radiation as shown in Fig. 1

Though valid only for small angles (<15°), f/D, the paraxial approximation, is widely used as F/#.

$$F/\# \approx f/D$$

The smaller the F-number the greater the radiant flux, ϕ_C, collected by the lens.

The flux ϕ_C increases as the inverse of the square of the F/#.

$$\phi_C \propto \frac{1}{(F/\#)^2}$$

In the jargon of photography, the F/# denotes the "speed" of the optics, with fast lenses having low F/#. The aperture control on a camera changes the F/# by using an iris diaphragm to change D.

Numerical Aperture

In microscopy and the world of fiber optics,"numerical aperture",rather than F/#, is used to describe light gathering capability. In a medium of refractive index n, the numerical aperture is given by:

$$N.A. = n \sin \theta$$

The larger the N.A., the more flux is collected. In air, the maximum N.A. is 1. Microscope objectives are available with N.A. of 0.95.

N.A. and F/# are related by:

$$N.A. = \frac{1}{(2F/\#)}$$

Numeric aperture is a more valuable concept for optical systems with high cone angles.

F-Number of Mirrors

Concave spherical mirrors are also used to collect light and focus. We use them for our Monochromator Illuminators on pages 6-2 to 6-11. The focal length of a lens can vary with wavelength due to chromatic aberration, while mirror systems are truly wideband in application. The concepts of F/# and numerical aperture also apply to mirrors. When elliptical reflectors are used, as in PhotoMax™ (page 4-37), F/# is used to describe the ratio of the reflector aperture to the distance between that aperture and the focus outside the ellipse.

F-Number of Non Circular Optics

We use square and rectangular mirrors in some of our products. The F/# we quote is based on the diameter of the circle with area equal to that of the mirror. This F-number is more meaningful than that based on the diagonal when light collection efficiency is being considered.

COLLECTED LIGHT AND USEFUL LIGHT

Since light collection varies as $1/(F/\#)^2$, decreasing F/# is a simple way to maximize light collection. However, note there is a difference between total radiant flux collected and useful radiant flux collected. Low F/# lenses collect more flux but the lens aberrations determine the quality of the collimated output. These aberrations go up rapidly with decreasing F/#. Though more light is collected by a very low F/# lens, the beam produced is imperfect. Even for a "point source" it will include rays at various angles, far from the collimated ideal. No optical system can focus a poor quality beam to a good image of the source. So, while a low F/# singlet lens (<F/4) may be an efficient collector, you will get such a poor output beam that you cannot refocus it efficiently. Our Aspherabs™ (page 9-10) address this problem and we use doublet lenses to reduce aberration in our F/1 condensers. In applications where image quality or spot size is important, a higher F/# condenser may give better results.

It is important to understand this fundamental concept, for though it is relatively easy to collect light, the quality of the beam produced and your application determine whether you can use the light collected. Our PhotoMax™ Systems are efficient collectors but the output beams have their own limitations. This is discussed in the section on PhotoMax™ (page 4-37)

FOCUSING : F-NUMBER AND THE MINIMUM SPOT SIZE

When focusing a beam with a lens, the smaller the F-number, the smaller the focused spot from a collimated input beam which fills the lens. (Aberrations cause some significant exceptions to this simple rule.)

MINIMUM PRACTICAL F-NUMBER FOR LENSES

The practical limit for F/# for singlet spherical lenses depends on the application. For high performance imaging, the limit is about F/4. F/2 - F/1.5 is acceptable for use as a condenser with arc lamps.The lens must be properly shaped and the correct side turned towards the source. Our F/1.5 plano convex condensers have much poorer aberration performance if reversed. We discuss spherical aberration on the right, and on page 9-10 where we describe our Aspherab® Lenses.

The number of elements must increase for adequate performance at lower F/#. F/1 camera lenses have five or six components. Our F/0.7 Aspherabs® use four. Microscope objectives approach the limit of F/0.5 with ten or more elements, and they have good performance only over very small fields.

REAL SOURCES AND CONDENSERS

Here are some of the major considerations in selecting and using a condenser:

Transmittance

The material of any condensing lens has a limited range of spectral transmittance. Sometimes these limits are useful, for example in blocking the hazardous ultraviolet (UV). Another example when working in the IR, is the use of a germanium lens with a VIS-IR source such as a quartz tungsten halogen lamp. The lens acts as a long pass filter and absorbs the visible.

The ultraviolet transmittance of condensers and other optical elements is important when trying to conserve the limited ultraviolet components from our sources. The ultraviolet transmittance of "quartz"* or "fused silica" is very dependent on the origin of the material and on the cumulative exposure to short wavelength radiation (solarization). Our condensers are made from selected UV grade synthetic silica for best ultraviolet transmittance.

* Quartz is the original natural crystalline material. Clear fused silica is a more precise description for synthetically gene-rated optical material.

Thermal Problems

Although refractive index, and therefore focal length, depend on temperature, the most serious thermal problem in high power sources is lens breakage. The innermost lens of a low F/# condenser is very close to the radiating source. This lens absorbs infrared and ultraviolet. The resultant thermal stress and thermal shock on start-up, can fracture the lens. Our high power Lamp Housings with F/0.7 condensers use specially mounted elements close to the source. The elements are cooled by the Lamp Housing fan, and the element closest to the source is always made of fused silica. Even a thermal borosilicate crown element used in this position fractures quickly when collecting radiation from a 1000 or 1600 W lamp.

Collimation

All real sources have finite extent. Fig. 2 exaggerates some of the geometry in collecting and imaging a source. Typical sources have dimensions of a few mm. Our 1 kW quartz tungsten halogen lamp has a cylindrical filament of 6 mm diameter by 16 mm long. With the filament at the focus of an ideal 50 mm focal length condenser, the "collimated beam" in this worst case includes rays with angles from 0 to ~9° (160 mrad) to the optical axis.

Most lenses have simple spherical surfaces; focusing a highly collimated beam with such a spherical optic also has limitations.

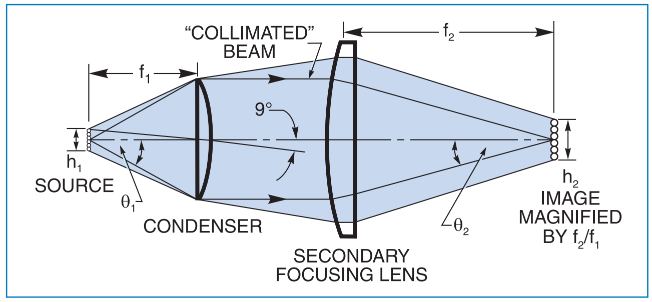


Fig. 2 Imperfect collimation for sources of finite size.

Spherical Aberration

Fig. 1 on the previous page shows an ideal lens. With real single element condensers, spherical aberration causes the rays collected at high angle to converge even though the paraxial rays are collimated (Fig. 3a). You might do better by positioning the lens as shown in Fig. 3b. The best position depends on the lens, light source, and your application. Our Condensers have focus adjust which allows you to find the best position empirically.

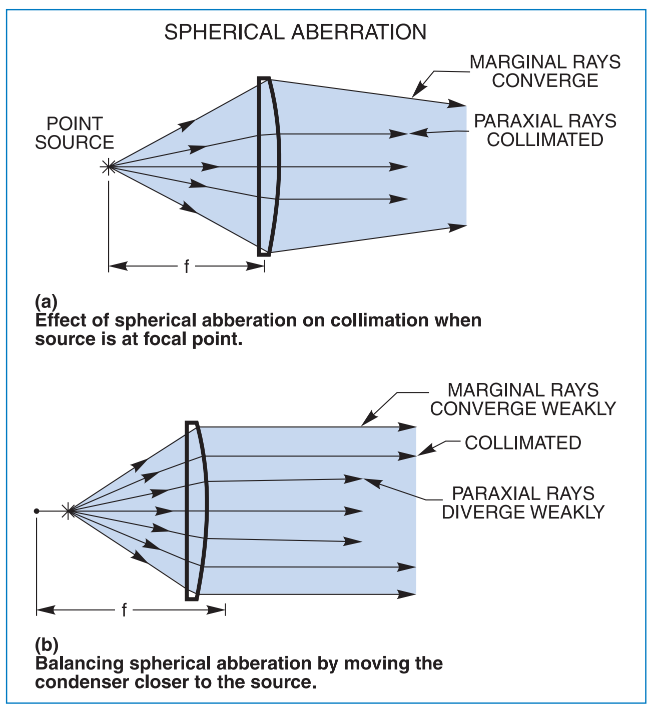


Fig. 3 (a) shows the effects of spherical aberration in a single element condenser. (b) shows how moving the lens toward the source can be a useful compromise.

Chromatic Aberration

The focal length of any lens depends on the refractive index of the lens material. Refractive index is wavelength dependent. Fig 4 shows the variation of focal length and light collection of silica lenses with wavelength. The refractive index of borosilicate crown glass and fused silica change by 1.5% and 3% respectively through the visible and near infrared, but change more rapidly in the ultraviolet. Because of this, simple lens systems cannot be used for exact imaging of the entire spectrum, nor can a simple condenser lens produce a highly collimated beam from a broad band point source. (Fig. 5). Most practical applications of light sources and monochromators do not require exact wideband imaging, so economical, uncorrected condensers are adequate. Our lamp housing condenser assemblies have focus adjust to position the lens for the spectral region of interest. We also provide a special version of the F/0.7 condensers for use in the deep ultraviolet.

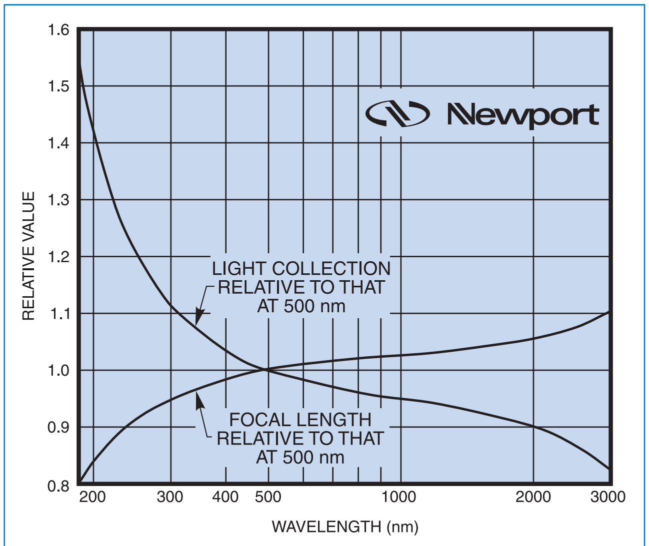


Fig. 4 The effect of refractive index variation on focal length and $(1/F\#)^2$ with wavelength for fused silica lenses. $(1/F\#)^2$ is a measure of light collection by a collimating condenser when the lens is 1 focal length from the source. Since the focal length is shorter at low wavelengths, the lens must be moved towards the source to collimate these wavelengths. When you move it closer you also collect more light.

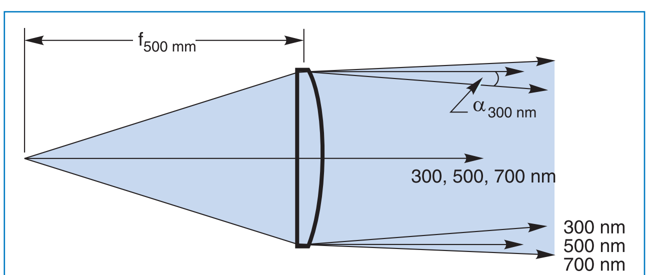


Fig. 5 The effects of chromatic aberration on a collimating condenser. The angles are exaggerated in the drawing. For an F/1.5 Fused Silica condenser, at 300 nm, the divergence of the marginal ray (assuming no spherical aberration) is only 0.33°.

Achromatic Lenses

Achromatic lenses reduce the effects of chromatic aberration. Most are designed only for the visible, and include elements cemented together with optical cement. This cement will not withstand the levels of ultraviolet and infrared flux from our high intensity arc sources. The material darkens and absorbs light. If you need the imaging performance of these lenses, you should collect the light from the source using a standard condenser. Then remove the ultraviolet and infrared, and use a secondary focusing lens and pinhole to create a bright, well defined image for use as a secondary source. This secondary source may then be imaged by the achromat. Camera lenses and other achromats are valuable with low intensity or distant visible sources. We list achromats on page 9-33.

Directionality in Source Radiance

Real sources also do not radiate equally in all directions. By design, our quartz tungsten halogen lamps have strongest irradiance normal to the plane of the filament. We designed our lamp housings so that the optical axes of the condensers lie in the direction of highest radiance. Our 6333 100 watt quartz tungsten halogen lamp emits about 3600 lumens. If this was uniformly radiated into all space, then our F/1.5 condenser would collect only 94 lumens (2.6%). In fact, the lens collects about 140 lumens.

MIRRORS, AN ALTERNATIVE METHOD

Curved mirrors suffer from many of the same problems that plague lens systems such as thermal considerations, limited field of view, and spherical aberration. Nevertheless, there are advantages that make reflective optics useful in place of lenses for some collection, focusing, and imaging applications. For this reason we use mirrors in our 7340/1 Monochromator Illuminators and new Apex Illminators on pages 6-2 to 6-11, and in PhotoMax™ on page 4-37.

Mirrors Do Not Have Chromatic Aberration

Because reflection occurs at the surface of these optics, the wavelength dependent index of refraction does not come into play. Therefore, there is no variation in how a mirror treats different incident wavelengths. Some care must be taken in choosing the mirror's reflective coating as each coating exhibits slightly varying spectral reflectance (see Fig. 6). However, mirrors eliminate the need for refocusing during broadband source collection or imaging. Simple spherical reflectors such as front surface concave mirrors are suitable as condensers in many applications.

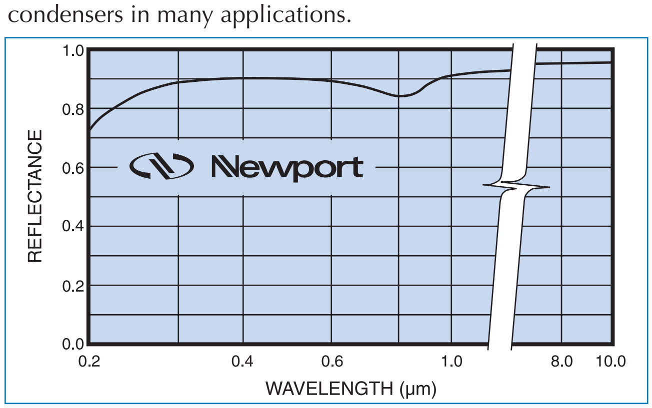


Fig. 6 Reflectance of an AlMgF$_2$ coated Front Surface Reflector.

Paraboloidal Reflectors

These reflectors collect radiation from a source at the focal point, and reflect it as a collimated beam parallel to the axis (Fig. 7). Incoming collimated beams are tightly focused at the focal point. Our off-axis paraboloidal reflectors are a circular segment from one side of a full paraboloid. The focal point is off the mechanical axis, giving full access to the reflector focus area (Fig. 8). There are no shadowing problems if you place a detector or source at the focus. Note that these mirrors do introduce significant aberrations for extended sources.

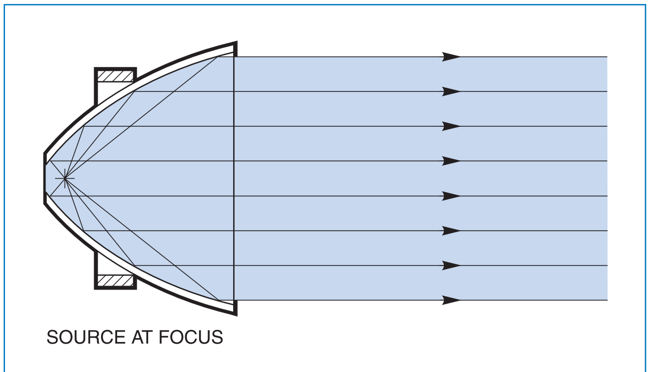


Fig. 7 A paraboloidal reflector reflects light from the focus into a collimated beam, or refocuses a collimated beam at the focus.

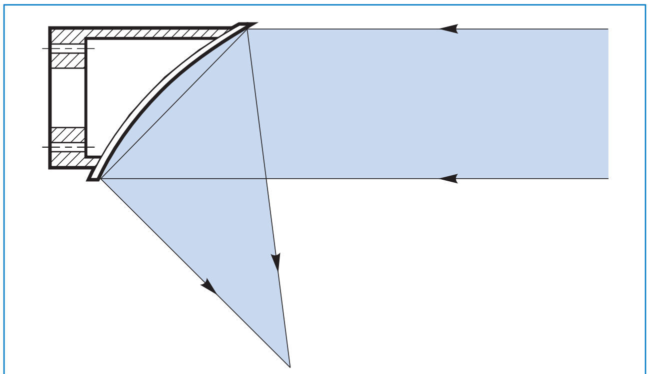


Fig. 8 The focus of an off-axis paraboloidal reflector is off the mechanical axis.

Ellipsoidal Reflectors

These reflectors have two conjugate foci. Light from one focus passes through the other after reflection (Fig. 9). Deep ellipsoids of revolution surrounding a source collect a much higher fraction of total emitted light than a spherical mirror or conventional lens system. The effective collection F/#'s are very small, and the geometry is well suited to the spatial distribution of the output from an arc lamp. Two ellipsoids can almost fully enclose a light source and target to provide nearly total energy transfer.

More significant perhaps is the ellipsoid's effect upon imaging of extended sources. For a pure point source exactly at one focus of the ellipse, almost all of the energy is transferred to the other focus. Unfortunately, every real light source, such as a lamp arc, has some finite extent; points of the source which are not exactly at the focus of the ellipse will be magnified and defocused at the image. Fig. 10 illustrates how light from point S, off the focus F_1, does not reimage near F_2 but is instead spread along the axis. Because of this effect ellipsoids are most useful when coupled with a small source and a system that requires a lot of light without concern for particularly good imaging.

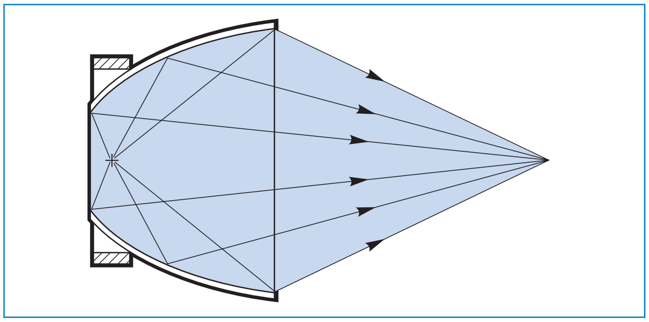


Fig. 9 Ellipsoidal reflectors reflect light from one focus to a second focus, usually external.

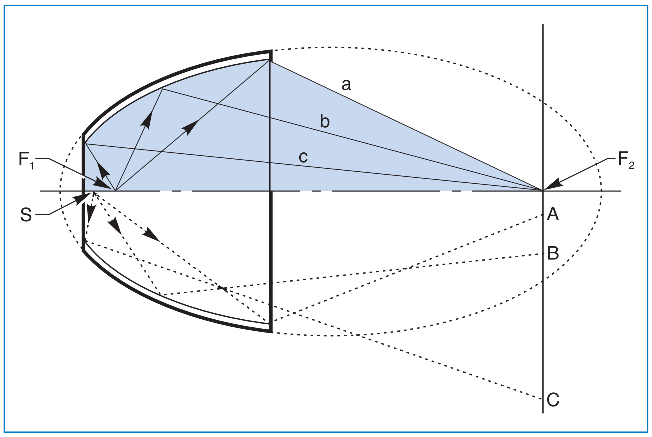


Fig. 10 A section of an ellipsoidal reflector. Rays a, b and c, shown in the top half of the ellipse, are all from F_1 and pass through F_2, the second focus of the ellipse. Rays A, B and C, in the bottom half of the ellipse are exact ray traces for rays from a point close to F_1. They strike the ellipse at equivalent points to a, b and c, but do not pass through F_2. For a small spot (image) at F_2 you need a very small source.

SOME LIMITATIONS OF THE F-NUMBER CONCEPT

Beam Quality

The beam quality concept mentioned earlier is one of the dangers of using F/# as the only quality measure of a condenser or other optical system.

Definition Depends on Application

Fig. 11 shows the same lens at three different distances from a source. According to the definition of Fig.1 (page 1-9, the F/# of the lens is f/D but obviously the light collected by the same lens differs significantly for each position. The description should include the F/# for collection and the F/# for imaging.

A single F/# is sometimes defined for the particular optical configuration. We use f/D throughout this catalog to compare collimating condensers. For condensers not at a focus, or other imaging systems, we use the higher of the ratios of image distance to optic diameter and source (object distance) to optic diameter. This incorrect use of F-number is somewhat legitimized as it states the "worst case" parameters for a system. Our descriptions of PhotoMax™, Apex, and our 7340/1 Monochromator Illuminators are examples of this usage.

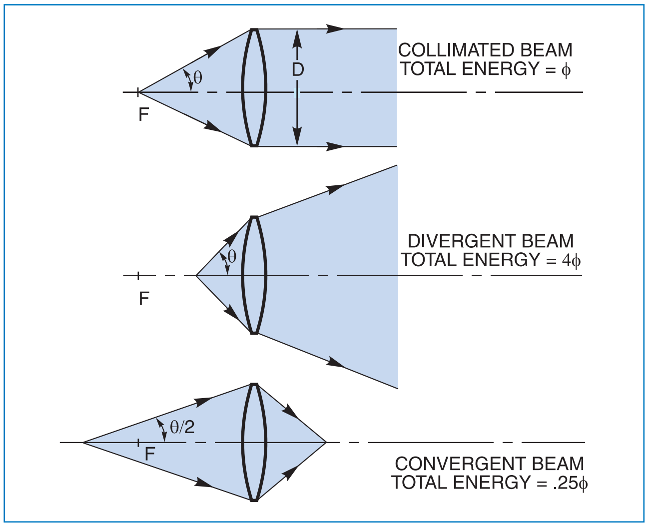


Fig. 11 Light collection by a lens at three different distances from a source.

Throughput Optimization Requires More Than F-Number

Matching F/# is important through an optical system. For example, in a system using a fiber optic input to a monochromator (Figs. 12a and 12b), the output of the fiber optic, characterized by a numerical aperture or F/# value, should be properly matched to the input of the monochromator. Consideration of F/# alone does not however give a simple way of optimizing such a system. This is because F/# contains no information on source, image, or detector area. In the example, matching of F/# alone does not take into account the consequential change in irradiance of the monochromator input slit. If the F/# of the beam from the fiber is increased to match the acceptance F/# of the monochromator, the beam size on the slit increases and less light enters the monochromator. The concept of "optical extent" gives a better sense of what is attainable and what is not.

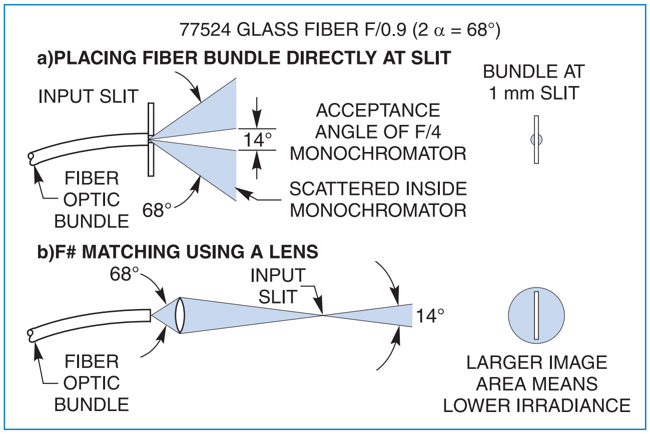


Fig. 12 Fiber Optic input to a monochromator. Simply matching F/#'s does not guarantee optimum performance.

GEOMETRICAL EXTENT, OPTICAL EXTENT, AND LINEAR INVARIANT

Very often the goal in optical system design is to maximize the amount of radiant power transferred from a source to a detector. Fig. 13 shows a source, an optical system, and an image. The optical system is aberration free and has no internal apertures which limit the beam.The refractive index is 1. Using paraxial optical theory, we can prove that:

$$A_s\Omega_S = A_i\Omega_i$$

Where:

A_s = Source area
A_i = Image area
Ω_s = Solid angle subtended at the source by the entrance aperture of the optical system
Ω_i = Solid angle subtended at the image by the exit aperture.

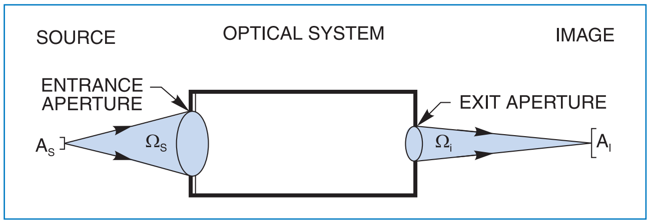


Fig. 13 A source, optical system and an image.

The quantity G = AΩ is the same for the source and the image, and for any other image plane in the system. G is called the **geometrical extent.**

If the surfaces are in media of different refractive indices, then $n^2\Omega$, the **optical extent**, replaces G. If the source has uniform (or average) radiance L, then the radiant flux which reaches the image, (often at a detector) is:

$$\phi = tGL^*$$

Where:

t ≡ transmittance (t will include reflection losses and component transmittances)

*** Again, an aberration free optical system is assumed. When aberrations are present, tGL becomes an upper limit on achievable flux: $\phi \leq tGL$.**

The concept of optical extent has been widely applied, though under a variety of names. These include etendue, luminosity, light-gathering power and throughput.

The one dimensional version of the optical extent is applicable to rotationally symmetric systems and is easier to work with. Fig. 14 defines h_1, h_2, θ_1, and θ_2.

$$h_1\theta_1 = h_2\theta_2$$

For equal refractive index, the product $\theta_1 h_1$ is invariant through an optical system. The product has several names including the optical invariant, Lagrange invariant, and Smith-Helmoltz invariant. When sin θ is substituted for θ, the equation is called the “Abbe sine condition”.

Any system has two values of the one dimensional invariant, one for each of two orthogonal planes containing the optical axis. Obviously for an instrument with slits it is simplest to use planes defined by the width and height of the slit. In this case it is important to remember that the two values of optical extent for the orthogonal planes are usually different as input and output slits are usually long and narrow. This complicates the selection of a coupling lens for optimizing the throughput.

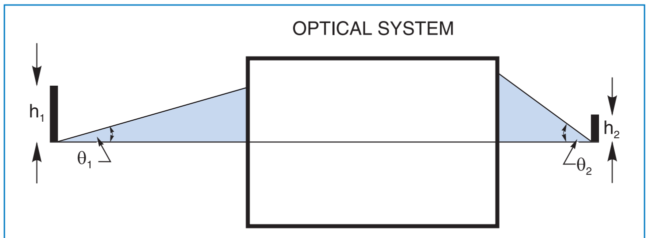


Fig. 14 Optical invariant

IMPORTANCE OF OPTICAL EXTENT

In introducing the concept of G, we required that the optical system in Fig.13 had no internal limiting apertures. This meant that G was determined by the source area and input acceptance angle of the optical system. In this case, for more total flux through the system from a source of fixed size and radiance, all that is needed is to increase G. This is equivalent to decreasing condenser F/# as previously discussed.

Every real optical system has something in it which limits G. It could be space or economic constraints. Frequently, G_{lim} is determined by a spectrometer. In some systems a small detector area[1] and the practical constraint on the maximum solid angle of the beam accepted by the detector, limit G. When a system uses fiber optics, the aperture and acceptance angle of the fiber optic may determine G_{lim}.

[1] Complete system modeling requires attention to detector noise. Often this is related to detector area.

Whatever limits G, fixes the maximum throughput, and no amount of clever optical design can improve on that limit.

The radiant flux through the system becomes:

$$\phi = t\, G_{lim} L$$

or at a specific wavelength λ:

$$\phi_\lambda = t_\lambda\, G_{lim\,\lambda}\, L_\lambda$$

(Frequently, G can be considered independent of wavelength.)

HOW TO MAXIMIZE THE LIGHT THROUGH THE SYSTEM

First look through the proposed system, beyond the light source and condensers, for the component which limits G and, if possible, replace it with a component with a higher G. When you have finally fixed the limiting G, you can then sensibly select other components, to minimize cost. (Optics cost usually increase with aperture.)

Light Source and Condenser

Select the source and collection optics to:

1. Match G_{lim}
   The collection optics should have a value of G that is as large as G_{lim}. At smaller values, the collection of light from the source limits the total flux transfer.You can use a higher value of G. More radiation is collected, but this cannot pass through the optical system. If G_{lim} is due to a spectrometer, the excess radiation will be lost at the slit or scattered inside the spectrometer leading to possible stray light problems.
2. Maximize $G_{lim}L$
   G_{lim} determines the product of source area and collection angle. These can be traded off within the limitation of source availability and maximum collection angle (1.17 sr for F/0.7 Aspherab®, 0.66 sr for F/1). For a given source area, you get more radiation through the system with a higher radiance (L) source. (See Table 1) (For spectroscopy, use the spectral radiance at the wavelength you need.)

Note: Aberrations introduced by the optical elements will lead to lower flux through image deterioration. Use of aberration corrected optics like Aspherabs® lead to significantly higher G_{lim}.

Table 1 Average Spectral Radiance of Various Sources

Source Type	Model No.	Input Power	Nominal Source dimensions (mm)	Average Spectral Radiance* ($W\ cm^{-2}\ sr^{-1}\ nm^{-1}$)			
				300 nm	400 nm	500 nm	633 nm
Quartz Tungsten Halogen	6333	100 W	4.2 x 2.3	0.0015	0.013	0.034	0.065
Xenon Arc	6253	150 W	0.5 x 2.2	0.085	0.16	0.21	0.24
3400 K Blackbody				0.0037	0.03	0.08	0.15
Sun**			1.4×10^{12}	0.75	2.1	2.9	2.2
HeNe Laser	79200	2 mW***	0.63 diameter	0	0	0	108****

*** Over the nominal area. Small regions may have a higher radiance.**
**** Based on extraterrestrial solar radiation.**
***** This is output power. Conventionally, lamps are rated by input power, lasers by output power.**
****** Based on a 4×10^{-3} nm line width.**

EXAMPLES OF USE OF INVARIANTS

Source Magnification

Since θh is invariant, we can easily relate source and image size. Fig.15 shows this for a simple condenser/ focusing lens arrangement, and Fig. 14 for any optical system.

Fig. 1 (page 1-9) shows a condenser collecting and collimating the light from one of our sources. In many applications it is convenient to have a collimated path which is used for placement of beam filtering or splitting components. Fig.15 shows a short collimated path, and a secondary focusing lens reimaging the source. As θh is invariant, the image size, h_2, will be given by:

$$h_2 = h_1\, \theta_1 / \theta_2$$

From the geometry:

$$h_2 = h_1\, f_2 / f_1 \text{ (small angles assumed)}$$

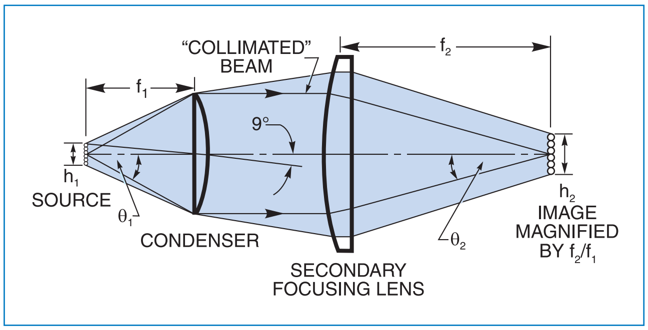


Fig. 15 Secondary focusing lens reimaging the source.

Monochromators and Filters With an Extended Source

Invariants are of particular value when designing systems in spectroscopy. Monochromators have acceptance angles, slit heights, and slit widths set to give desired resolution. These define the value of the optical extent G, of the monochromator, and allow comparison of different systems and selection of light source optics. The comparison is no longer simply based on F/# of the monochromator. A low F/# monochromator may have lower optical extent, i.e., less throughput, than a monochromator with higher F/#, but which uses larger slits to give the desired resolution. For example, our 1/8 m and our 1/4 m Monochromators have approximately the same F/# but the 1/4 m has a higher G_{lim} for the same resolution.

The advantages of an optical filter are quickly apparent in the following example:

Example

Compare the 56430 Narrow Band Filter with the 77250 1/8 m Monochromator for isolation of a 20 nm bandwidth at 365 nm from an extended source. The monochromator has a standard 1200 l/mm grating.

The acceptance angle of this filter for the 20 nm bandwidth is approximately 15°. The corresponding solid angle is 0.21 sr. If the filter holder reduces the aperture to 0.9 inch (22.9 mm), the area is 4.1 cm^2 and

$$G_{fil} = 0.86 \text{ sr cm}^2$$

We must multiply this by the filter transmittance of 0.2 for comparison of throughput.

$$G_{fil}\, T_{fil} = 0.17 \text{ sr cm}^2$$

The acceptance angle of the 77250 Monochromator is 7.7° and the corresponding solid angle is 0.57 sr. For a 20 nm bandwidth, the slit width is 3.16 mm. As the usable slit height is 12 mm, the area is 0.38 cm^2, so:

$$G_{mono} = 0.022 \text{ sr cm}^2$$

and

$$G_{mono}\, T_{mono} = 0.007 \text{ sr cm}^2$$

The optical filter isolating 20 nm from this extended source passes about 24 times as much light as the monochromator. If the light from the filter can be coupled to a detector, i.e. the detector does not restrict the system, then the filter is much more efficient.

This ratio does not apply to small asymmetrical sources such as the arcs of our arc lamps. Each source must be examined individually.

The radiometric data on the following pages was measured in our Standards Laboratory. The wavelength calibrations are based on our spectral calibration lamps. Irradiance data from 250 to 2500 nm is based on an NIST traceable calibrated quartz tungsten halogen lamp of the type found on page 2-3. We validated the measurements using calibrated detectors. We used a calibrated deuterium lamp (page 2-3) for wavelengths below ~300 nm. In both cases we use interpolation to infer the irradiance of the calibrated lamp at other than the discrete NIST calibration wavelengths. We measured each of the lamps to be calibrated, in the most favorable orientation.

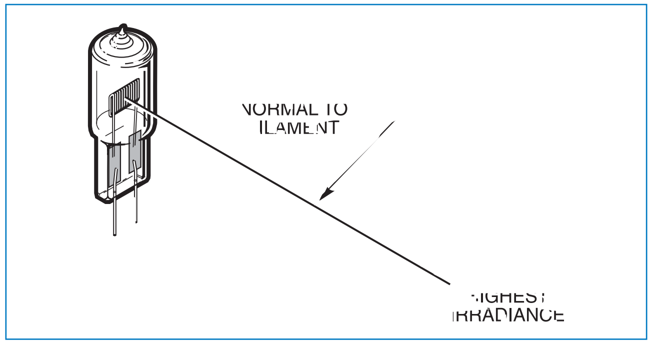


Fig. 1 QTH lamps with dense flat filaments have highest irradiance along the axis normal to the filament plane through the filament center. We orient the arc lamp so the seal-off tip and, in some cases, the starter wire does not interfere with the measurement.

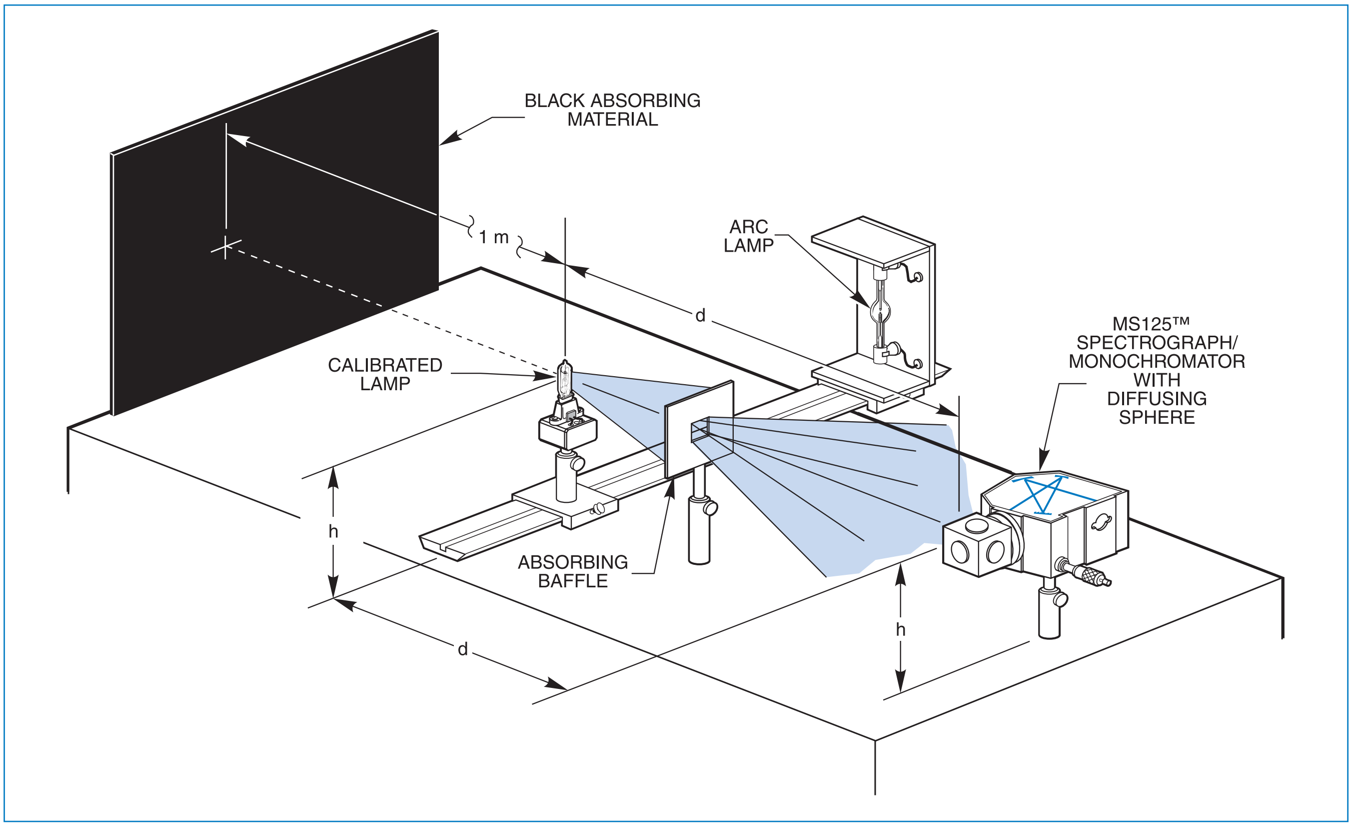


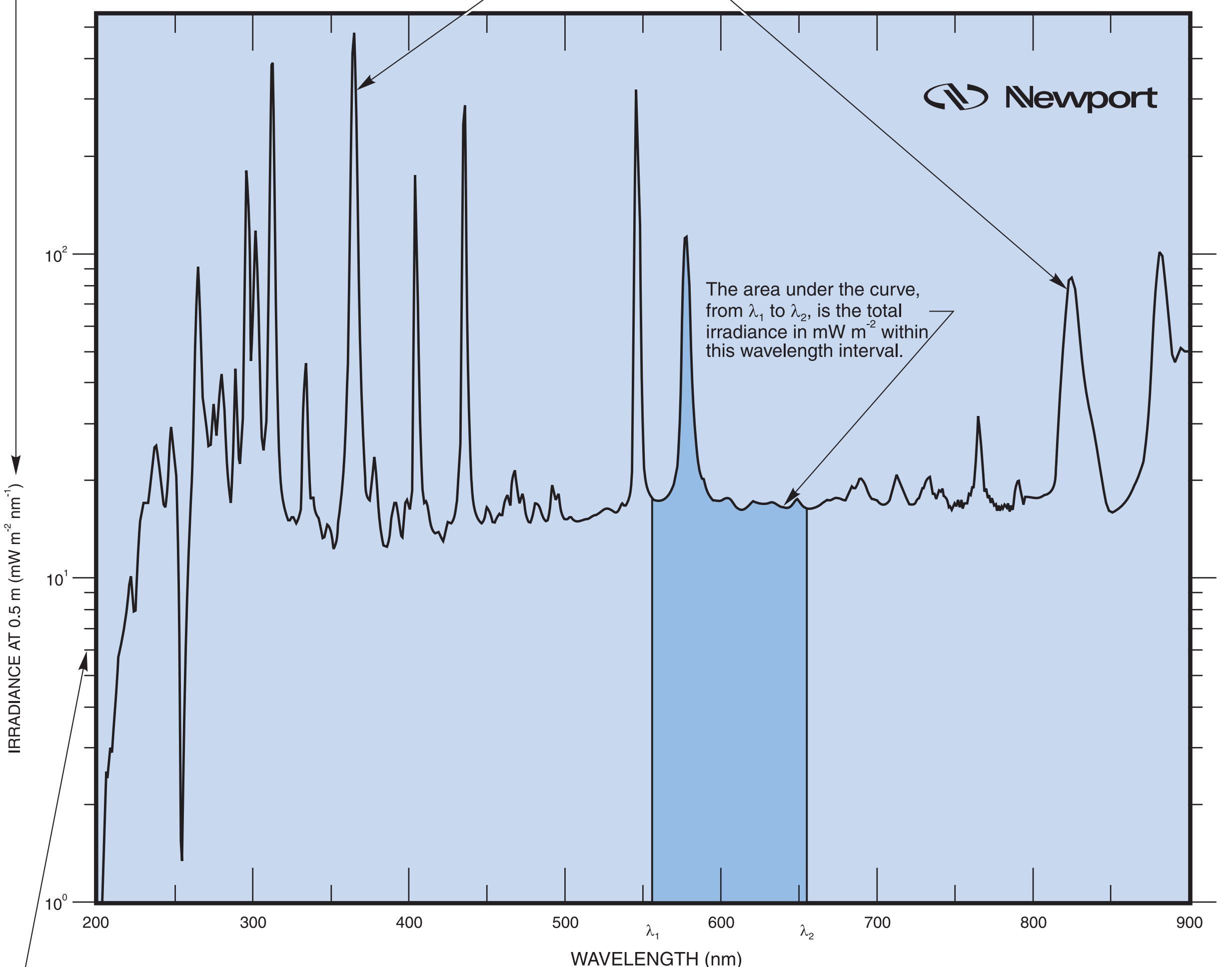
Fig. 2 Set-up for a radiometric measurement.

The lamps are operated vertically and the measurement is made in the horizontal plane through the center of the radiating filament or arc. The lamps are rotated for maximum flux at the measurement site. This is particularly important for our planar filament quartz tungsten halogen lamps. At 0.5 m the flux density of all our lamps is uniform over at least a 25 x 25 mm^2 area. As you move out of the plane but still maintain the same 0.5 m distance and face the source, the recorded power should in principle fall according to Lambert's Law for a planar source and remain constant for a point source. Measurements show something in between, with the arc lamps resembling point sources up to the electrode shadowing limit (page 4-26).

As you change the measuring distance from 0.5 m, the irradiance follows the inverse square law providing the distance, d, is larger than 20 to 30 times the radiating element size. The shortest distance we use in our measurements is 300 mm.

The spectral irradiance $E_{e\lambda}$ is the radiant flux in a small band of wavelengths, $\Delta\lambda$, at wavelength λ falling on a small element of a surface located 0.5 m from and facing the source, divided by the area ΔA (in m^2) of the surface element and divided by $\Delta\lambda$ (in nm). See page 1-2 for conversion to other units.

Actual peak shapes are a convolution of the true peak shape with the measurement instrument response function.



The logarithmic scale allows display of the lamp output over several orders. You can clearly see that there is UV output and you can estimate it. The linear display of the same graph (Fig. 4 on the following page) doesn't make this clear and because of the large dominant peaks, a lot of detail is lost over the rest of the spectrum. The logarithmic display suppresses the high peaks. We mention a disadvantage of the semi-log display on the next page.

We use wavelength as a spectral variable. The symbol is λ. See page 1-3 for a conversion to other spectral quantities, wavenumber, frequency and photon energy. When you convert, the shape of the spectrum will change. The displayed range covers the most popular wavelengths for the lamps. We show 200-2400 nm irradiance for each type of lamp on pages 1-22 to 1-29.

Fig. 3 Example of the spectral irradiance curves we show for our arc, quartz tungsten halogen, and deuterium lamps, on pages 1-22 to 1-30.

WORKING WITH SEMI-LOG DISPLAYS

The advantage of the semi-log display is the range our graphs cover, from very low levels to large peaks. Fig. 4 shows the linear display of the graph on the previous page. You get a much better sense of the height of the peaks but the values at lower levels are lost.

The logarithmic compression can be deceptive when it comes to estimating the area under a portion of the curve, to determine the total irradiance from λ_1 to λ_2, for example. You cannot rely on a rapid visual comparison unless you remember that the area at the bottom must be discounted appropriately. The peaks are much more important than they seem! So, you should calculate the area using the data values you read from the curve.

The logarithmic scale complicates estimation of the amount of irradiance in any peak. The half maximum is no longer halfway between the peak top and the bottom of the graph. You can easily find the half maximum by measuring the distance from 1 to 2, or 10 to 20, etc., on the logarithmic axis scale. Moving down this distance from the peak locates the half maximum (Fig. 5). We discuss the spectral peaks in the discussion on "Calculating the Output Power," pages 1-33 to 1-35.

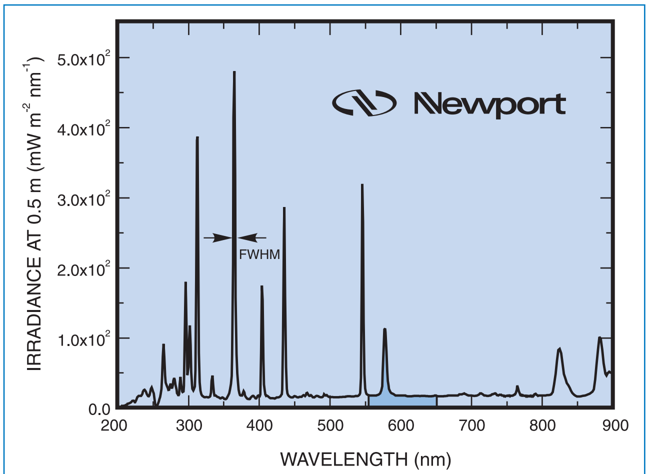


Fig. 4 Linear display of the graph shown in Fig. 3.

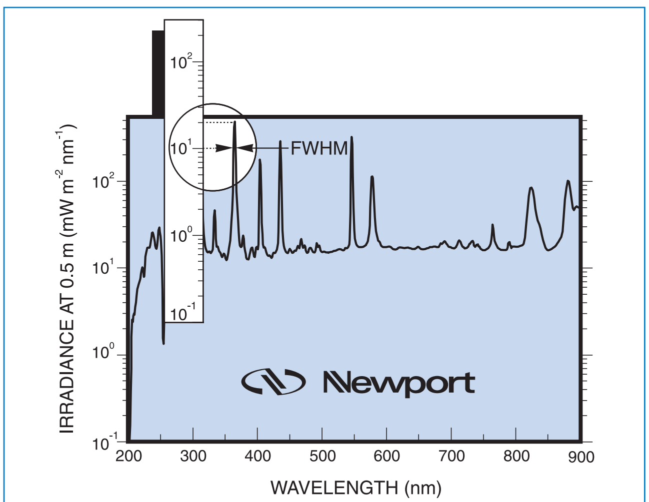


Fig. 5 Calculating the FWHM from a log graph.

HOW GOOD ARE THE DATA?

We measured the irradiance data on all our lamps using both multichannel detectors with our MS257™ Spectrograph, and scanning monochromators.

We used integrating spheres for most of the measurements. This effectively averages the polarization of the incoming radiation. Stress birefringence in the arc lamps and the filament structure of the lower power QTH lamps cause noticeable polarization of the output that may enhance or detract from your application.

We have a high degree of confidence in our data and cross check them with full radiant power meters and calibrated filters.

The measurements are of lamps early in their life, operated in open air. Thermal conditions are different for lamps operated in lamp housings, and the spectral distribution changes slightly as the lamps age. Mercury lamps are particularly sensitive to thermal changes.

We see ±15% variation in output from lamp to lamp even within the same batch of lamps. We see substantially more variation in the UV output (<ca. 280 nm). Envelope materials, both for standard and ozone free versions, are continuously changing, and envelope thicknesses are not subject to tight tolerance.

In short, we believe that this set of data is the most comprehensive and reliable you will find for lamps of this type and are an excellent resource for first estimates. But don't base a tightly toleranced system design on the data without additional characterization of the lamp in its intended operating environment.

FINDING THE RIGHT SPECTRAL IRRADIANCE CURVE

With nine pages of spectral irradiance graphs, and various curves per graph, you can easily miss your lamp data. Table 1 lists the page and figure number by lamp type. You'll also notice that we show the percentage of total irradiance in specific UV, VIS and NIR spectral ranges, for specific lamps on the following two pages.

Table 1 UV-IR Radiation Sources

Lamp Type	Usable Wavelength Range	Wattage/Power	Model No.	Spectral Irradiance Curves	
				Figure No.	Page No.
Deuterium	~160 to 400 nm	30 W, High Uniformity (Ozone Free)	63161 and 70620	2	22
		30 W, High Uniformity (Full Spectrum)	63162 and 70623	2	22
		30 W, High Irradiance (Ozone Free)	63164 and 70621	1	22
		30 W, High Irradiance (Full Spectrum)	63163 and 70624	1	22
		30 W, High Irradiance/stability (Ozone Free)	63165 and 70622	1	22
Xenon	200 to 2500 nm	75 W (Standard)	6251	3	23
		75 W (High Stability)	6247	3	23
		75 W (Ozone Free)	6263	3	23
		100 W (Ozone Free)	6257	6	24
		150 W (Standard)	6253	4	23
		150 W (Ozone Free)	6255	4	23
		150 W (UV Enhanced)	6254	4	23
		150 W (Compact)	6256	4	23
		300 W (Ozone Free)	6258	6	24
		450 W (Standard)	6261	7	25
		450 W (Ozone Free)	6266	7	25
		450 W (UV Enhanced)	6262	7	25
		500 W (Ozone Free)	6267	8	25
		1000 W (Standard)	6269	10	26
		1000 W (Ozone Free)	6271	10	26
		1600 W (Ozone Free)	62711	12	28
Mercury	200 to 2500 nm	50 W (Standard)	6282	3	23
		100 W (Standard)	6281	6	24
		200 W (Standard)	6283	7	25
		350 W (Standard)	6286	9	26
		500 W (Standard)	6285	9	26
		1000 W (Standard)	6287	10	26
Mercury (Xenon)	200 to 2500 nm	200 W (Standard)	6291	8	25
		200 W (Ozone Free)	6292	8	25
		500 W (Standard)	66142	11	27
		1000 W (Standard)	6293	11	27
		1000 W (Ozone Free)	6295	11	27
		1600 W (Ozone Free)	62712	12	27
EmArc™ Enhanced Metal Arc	200 to 2500 nm	200 W	6297	5	24
Pulsed Xenon	200 to 2500 nm	0.32 J (Guided Arc)	6426	17	33
		5J	6427	18	34
Quartz Tungsten Halogen	240 to 2700 nm	10 W	6318	13	29
		20 W	6319	13	29
		50 W (Short Filament)	6332	13	29
		50 W (Long Filament)	6337	13	29
		100 W	6333	14	30
		250 W	6334	14	30
		600 W	6336	15	31
		1000 W (FEL Type)	6315	16	32
		1000 W	6317	15	31
IR Sources	1 to 25 µm	140 W (IR Element)	6363	19	35
		22 W (Ceramic Element)	6575	19	35
		9 W (IR Element)	6580	19	35
		0.8 W (Miniature IR Element)	6581	19	35
		50 W (Silicon Carbide Source)	80030	19	35

	UVC		UVB	UVA		VISIBLE						INFRARED						
RANGE (nm) $\lambda_1 - \lambda_2$	<250	250-280	280-320	320-350	350-400	400-450	450-500	500-550	550-600	600-650	650-700	700-800	800-900	900-1000	1000-1100	1100-1500	1500-2000	2000-2400
% OF 200-2400nm C - λ_2	2.4	3.0	12.2	15.2	25.9	38.5	41.0	48.1	56.0	57.4	58.8	61.4	63.9	66.5	70.5	82.8	94.1	100
% OF 200-2400nm $\lambda_1 - \lambda_2$	2.4	0.6	9.2	3.0	10.7	12.6	2.5	7.1	7.9	1.4	1.4	2.6	2.5	2.6	4.0	12.3	11.3	5.9

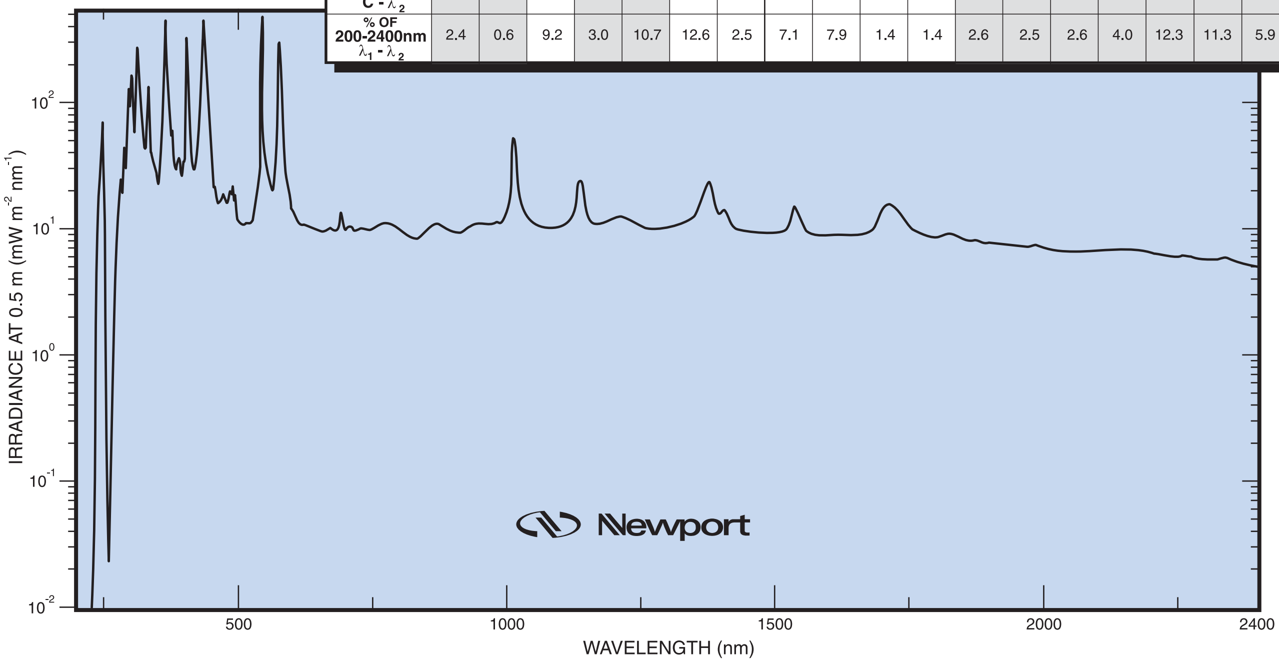


Fig. 1 Typical spectral irradiance of 6283 200 W Hg Lamp, showing % of total irradiance in specific UV, VIS and NiR spectral ranges.

	UVC		UVB	UVA		VISIBLE						INFRARED						
RANGE (nm) $\lambda_1 - \lambda_2$	<250	250-280	280-320	320-350	350-400	400-450	450-500	500-550	550-600	600-650	650-700	700-800	800-900	900-1000	1000-1100	1100-1500	1500-2000	2000-2400
% OF 200-2400nm C - λ_2	0.5	1.4	3.2	4.7	7.3	10.2	13.8	16.9	20.0	23.0	26.1	32.3	47.4	62.5	67.4	81.5	93.6	100
% OF 200-2400nm $\lambda_1 - \lambda_2$	0.5	0.9	1.8	1.5	2.6	2.9	3.6	3.1	3.1	3.0	3.1	6.2	15.1	15.1	4.9	14.1	12.1	6.4

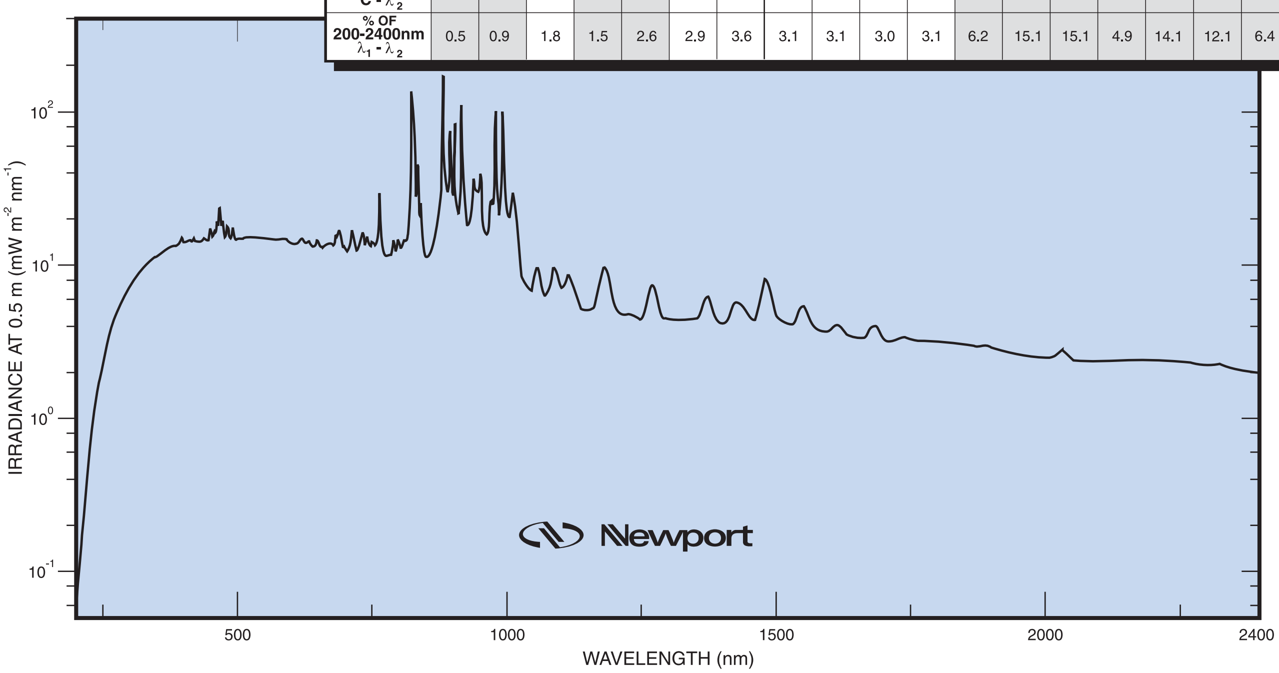


Fig. 2 Typical spectral irradiance of 6253 150 W Xe Lamp, showing % of total irradiance in specific UV, VIS and NiR spectral ranges.

	UVC		UVB	UVA		VISIBLE						INFRARED						
RANGE (nm) $\lambda_1 - \lambda_2$	<250	250-280	280-320	320-350	350-400	400-450	450-500	500-550	550-600	600-650	650-700	700-800	800-900	900-1000	1000-1100	1100-1500	1500-2000	2000-2400
% OF 200-2400nm C - λ_2	8.0	14.9	23.8	24.9	32.1	38.7	40.2	44.7	48.2	49.6	51.2	54.5	60.7	66.8	70.6	83.1	94.3	100
% OF 200-2400nm $\lambda_1 - \lambda_2$	8.0	6.9	8.9	1.1	7.2	6.6	1.5	4.5	3.5	1.4	1.6	3.3	6.2	6.1	3.8	12.5	11.2	5.7

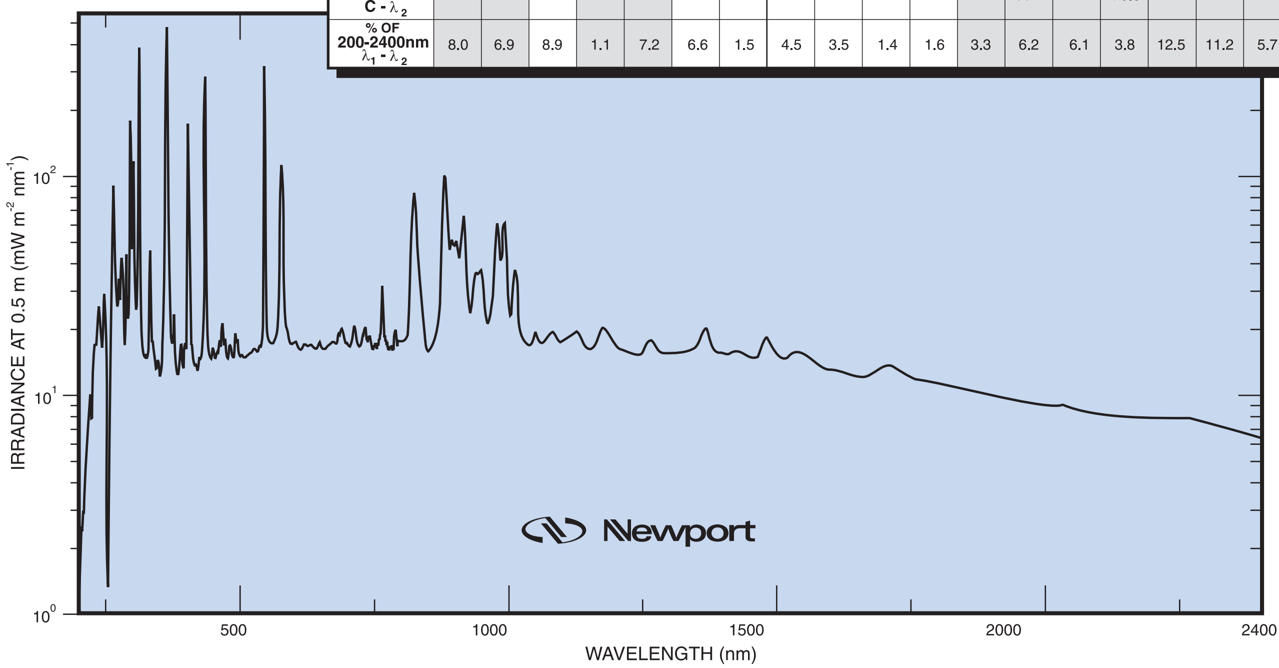


Fig. 3 Typical spectral irradiance of 6291 200 W Hg(Xe) Lamp, showing % of total irradiance in specific UV, VIS and NiR spectral ranges.

	UVC		UVB	UVA		VISIBLE						INFRARED						
RANGE (nm) $\lambda_1 - \lambda_2$	<250	250-280	280-320	320-350	350-400	400-450	450-500	500-550	550-600	600-650	650-700	700-800	800-900	900-1000	1000-1100	1100-1500	1500-2000	2000-2400
% OF 250-2400nm C - λ_2	—	0.005	0.035	0.14	0.4	1.0	2.1	3.7	5.9	8.7	12.0	19.8	28.4	37.1	45.5	72.3	91.5	100
% OF 250-2400nm $\lambda_1 - \lambda_2$	—	0.005	0.03	0.1	0.3	0.6	1.1	1.6	2.2	2.8	3.3	7.8	8.6	8.7	8.4	26.8	19.2	8.5

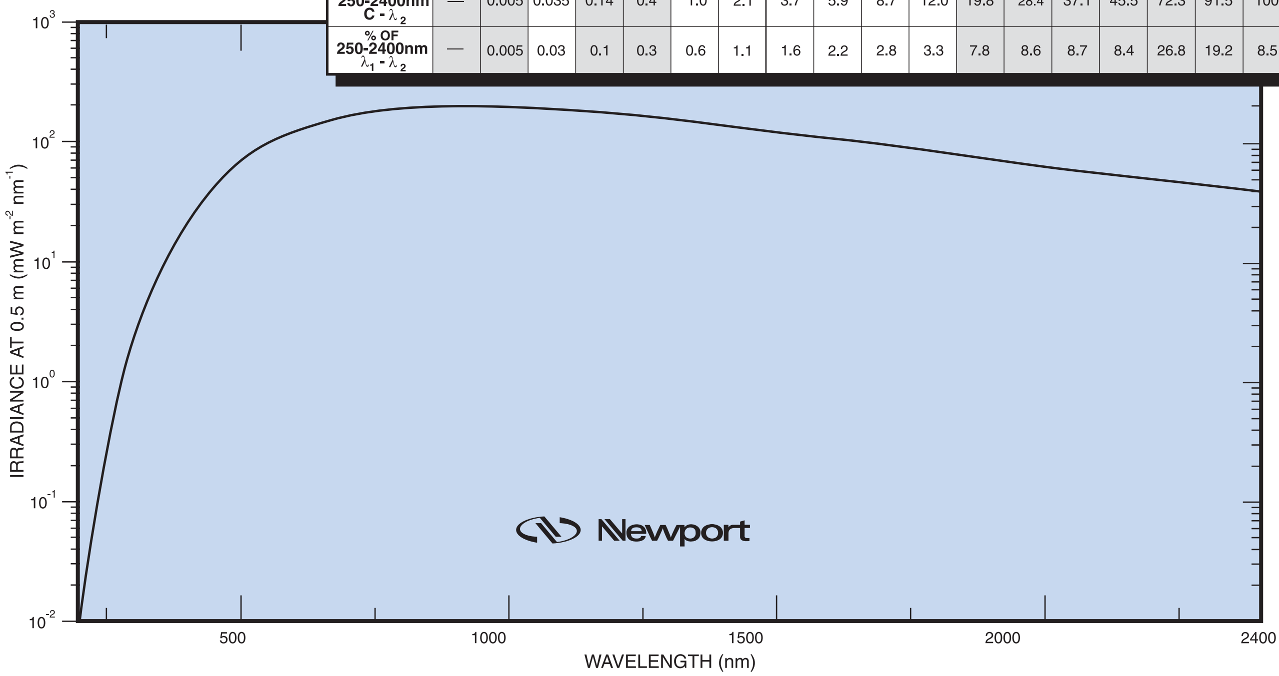


Fig. 4 Typical spectral irradiance of 6315 1000 W QTH Lamp, showing % of total irradiance in the specific UV, VIS and NiR spectral ranges.

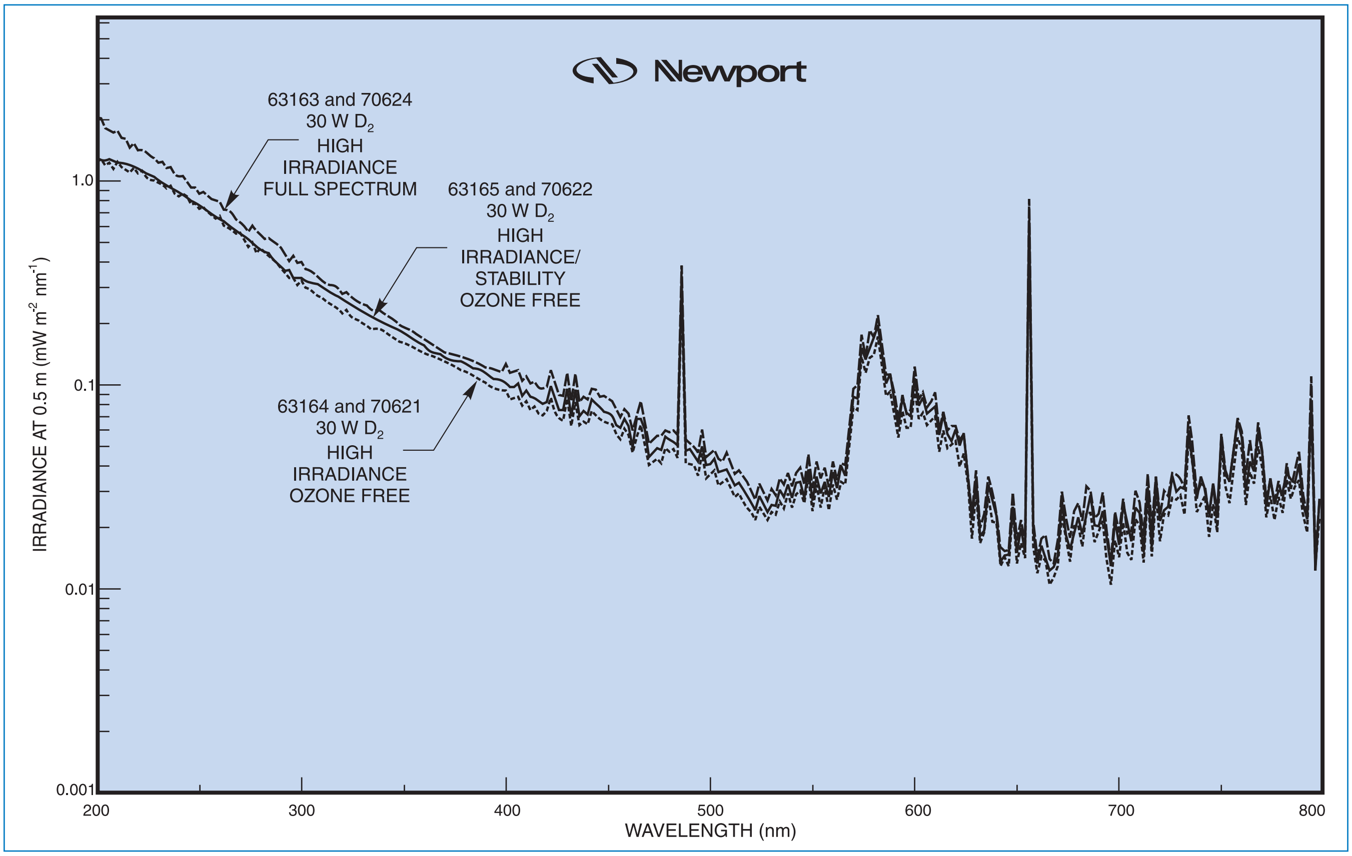


Fig. 1 Spectral irradiance of various Deuterium Lamps.

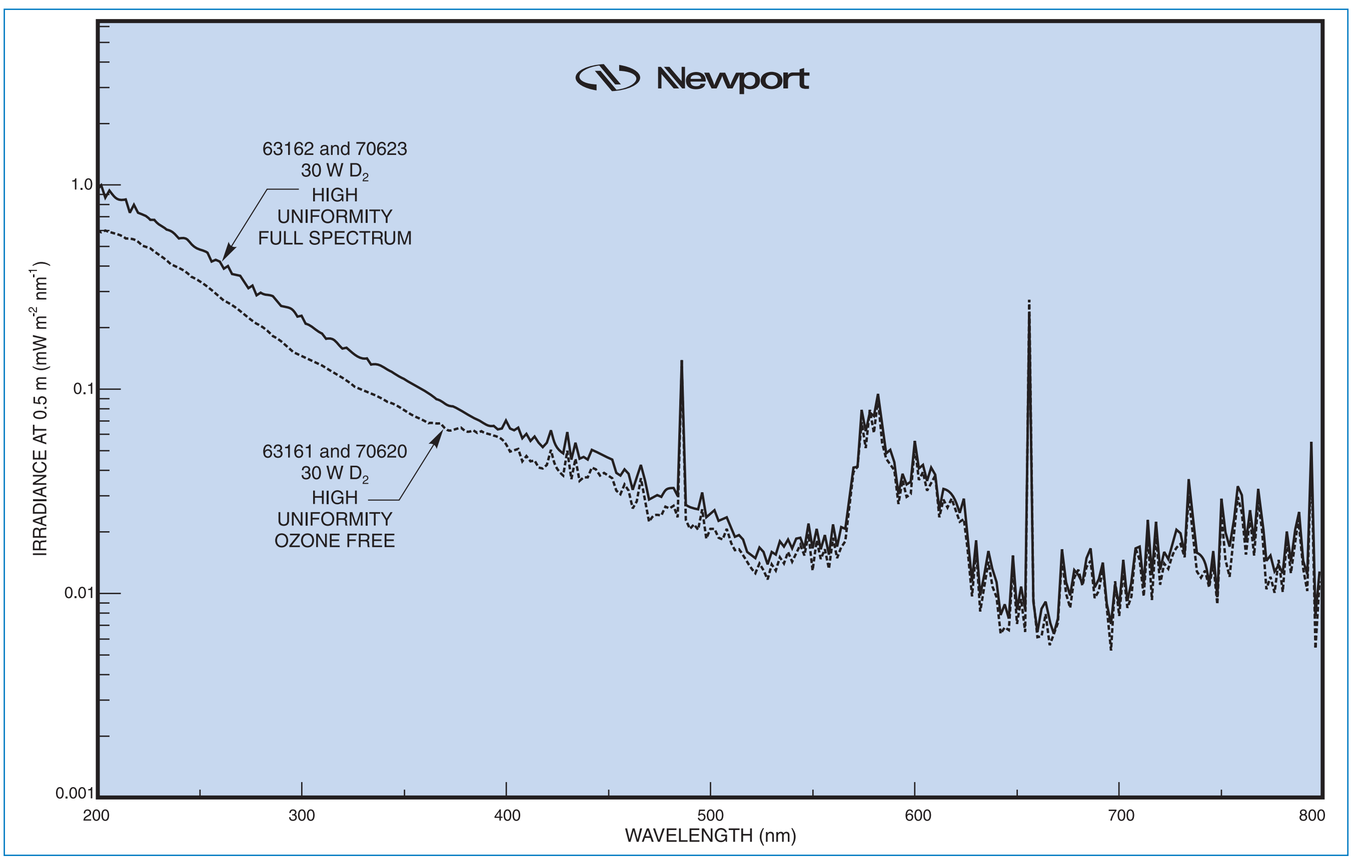


Fig. 2 Spectral irradiance of various Deuterium Lamps.

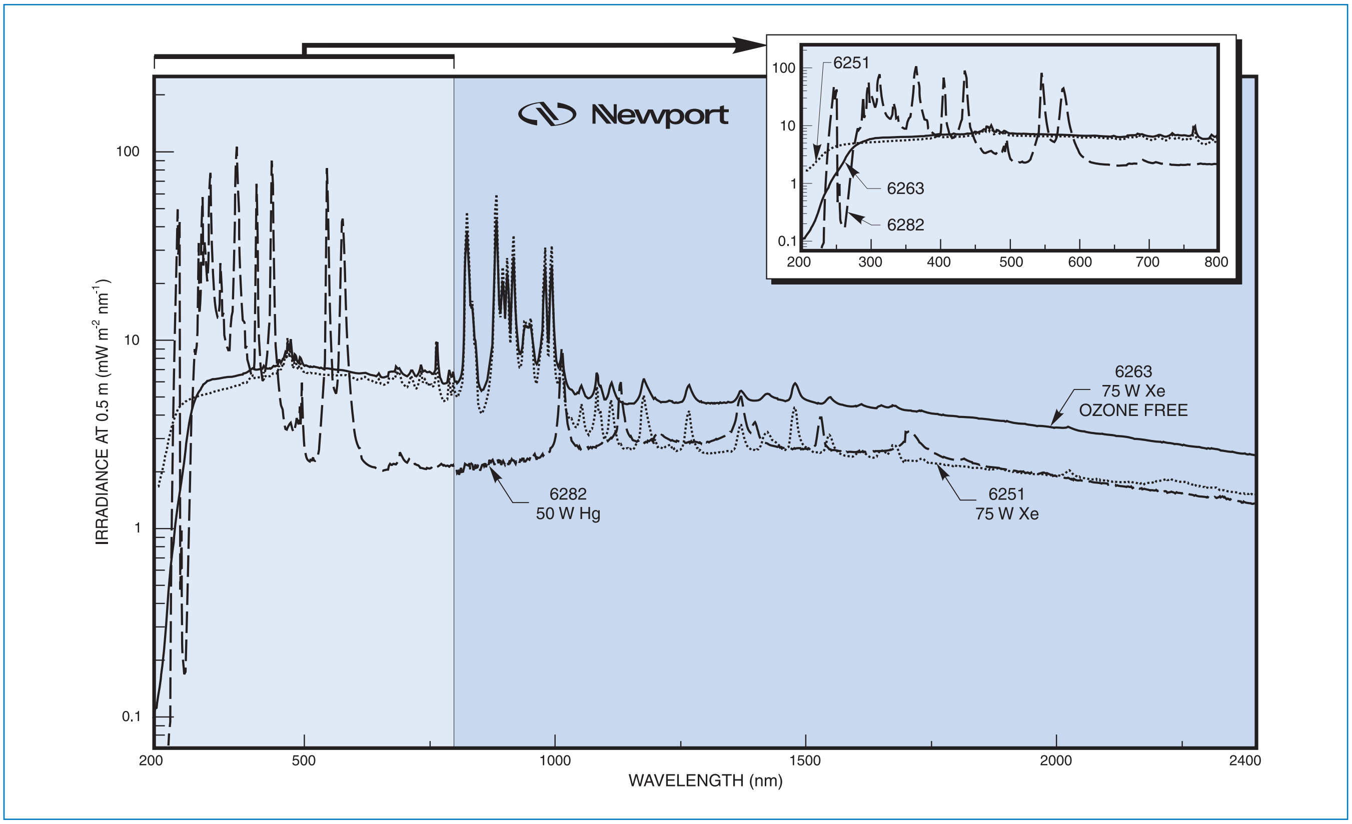


Fig. 3 Spectral irradiance of various Arc Lamps.

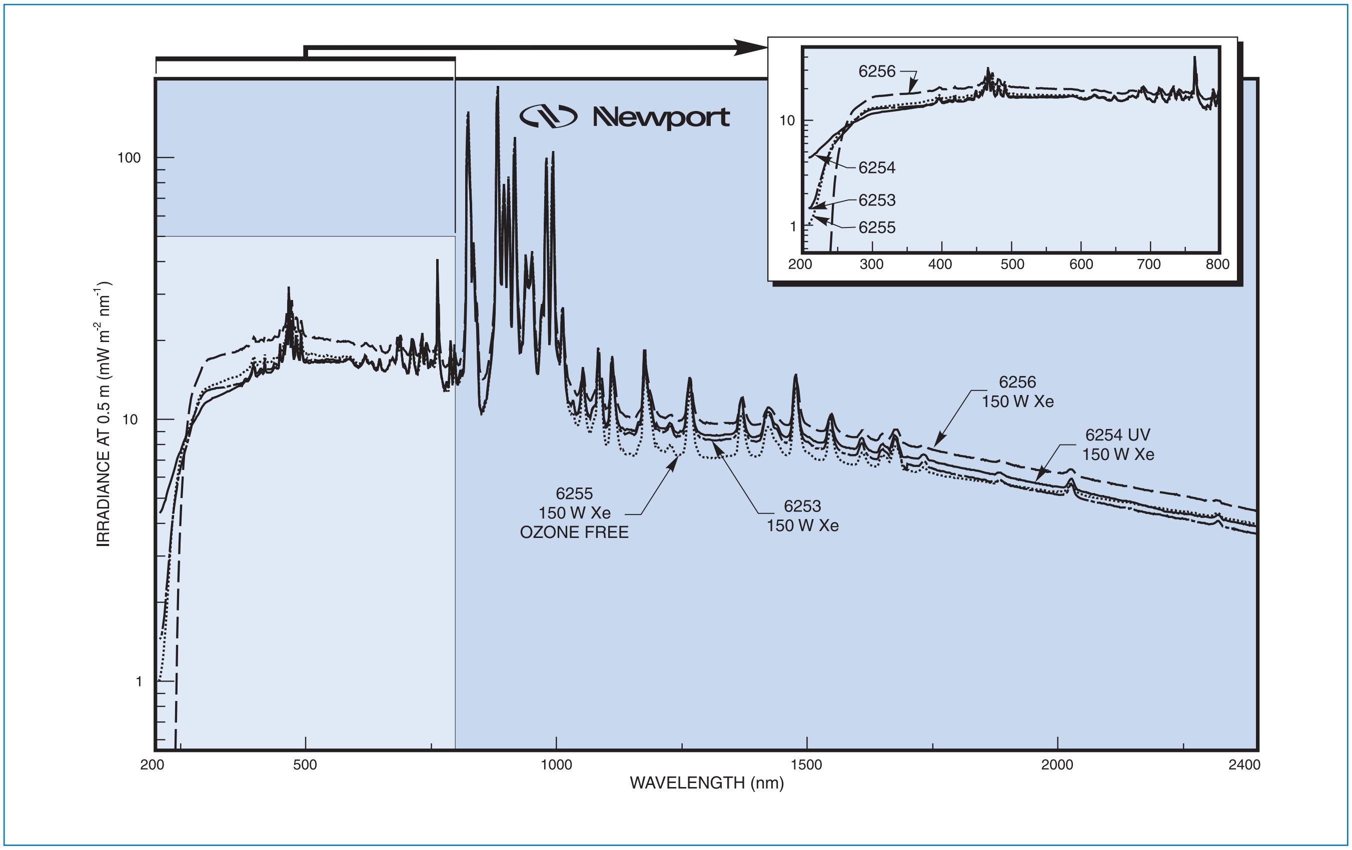


Fig. 4 Spectral irradiance of various Arc Lamps.

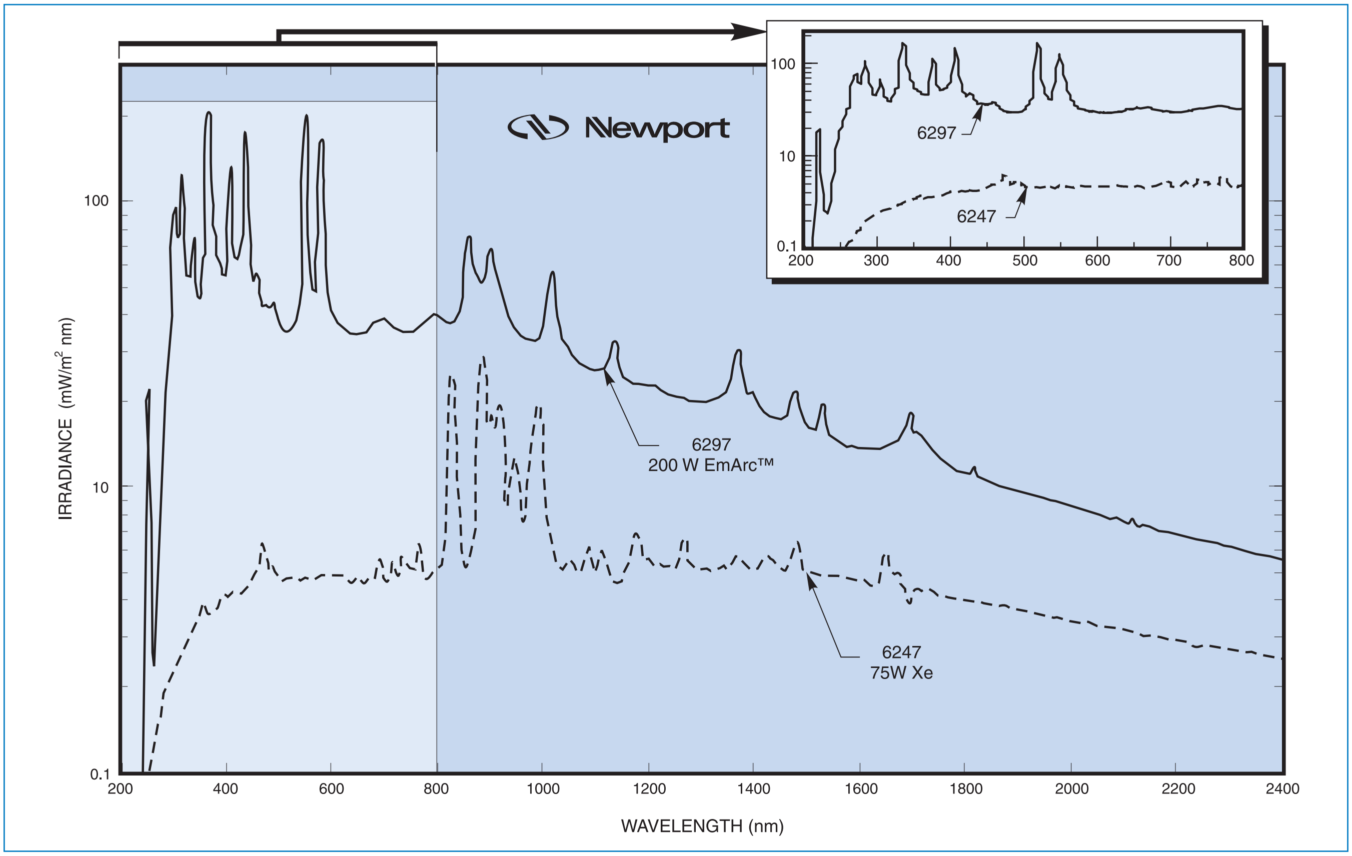


Fig. 5 Spectral irradiance of various arc lamps.

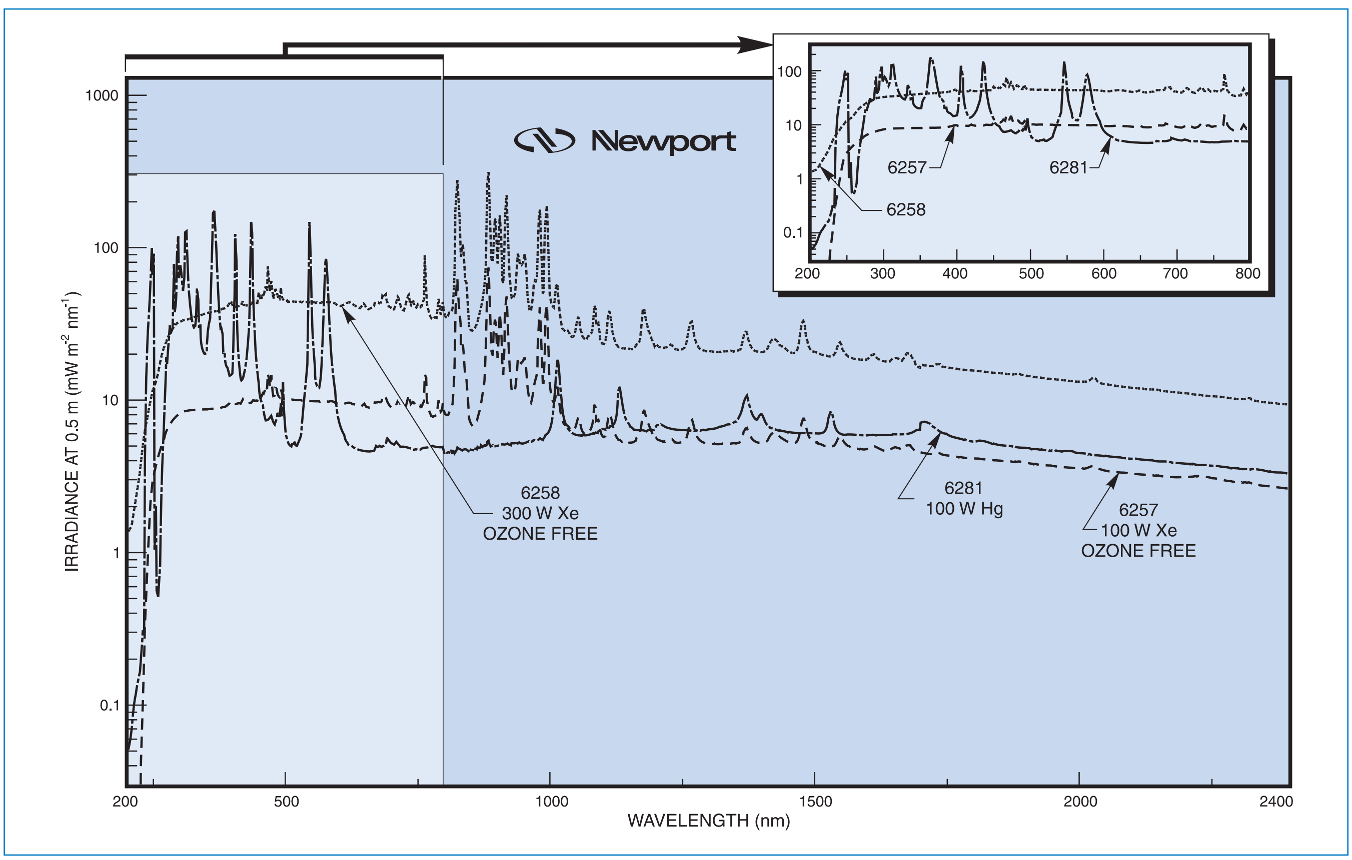


Fig. 6 Spectral irradiance of various Arc Lamps.

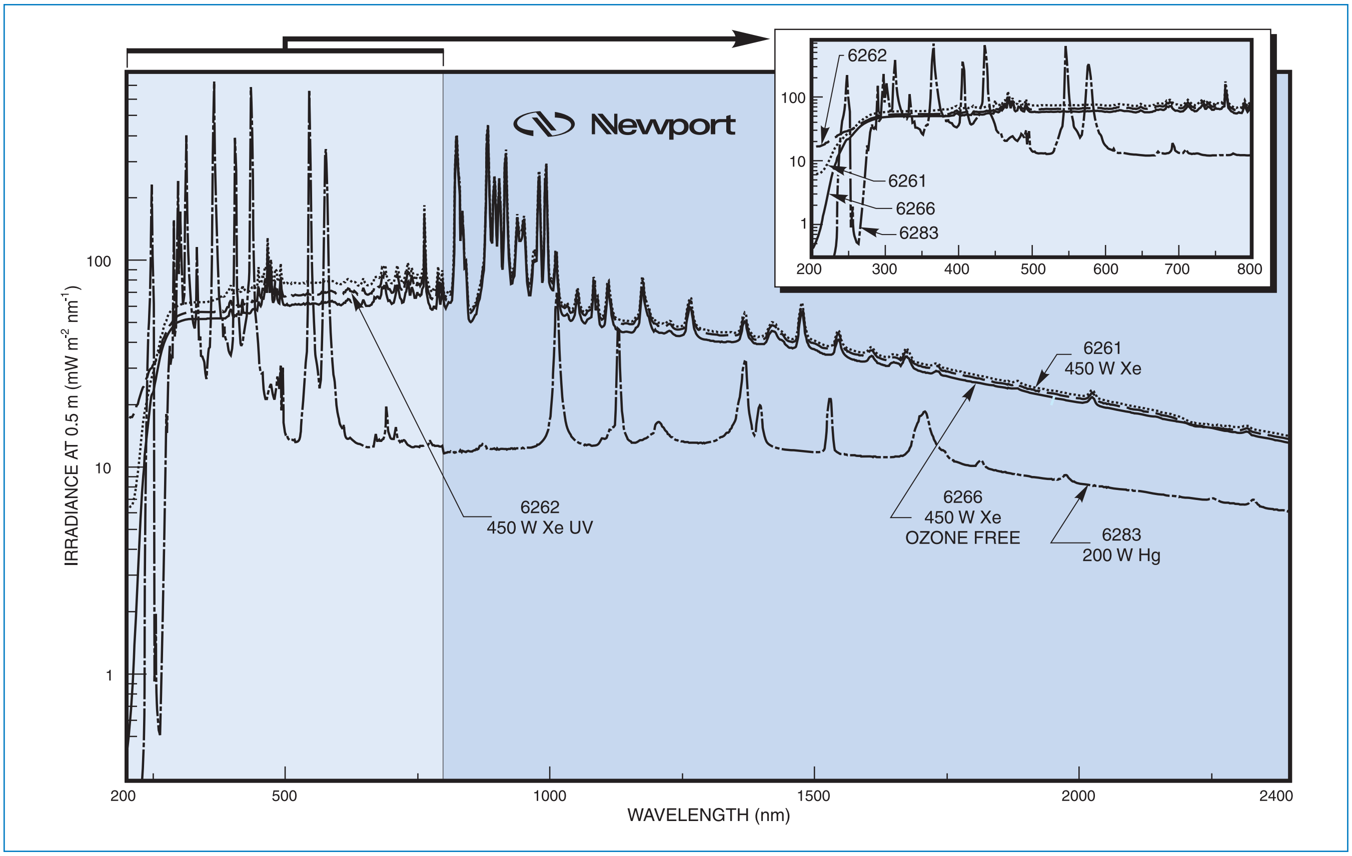


Fig. 7 Spectral irradiance of various Arc Lamps.

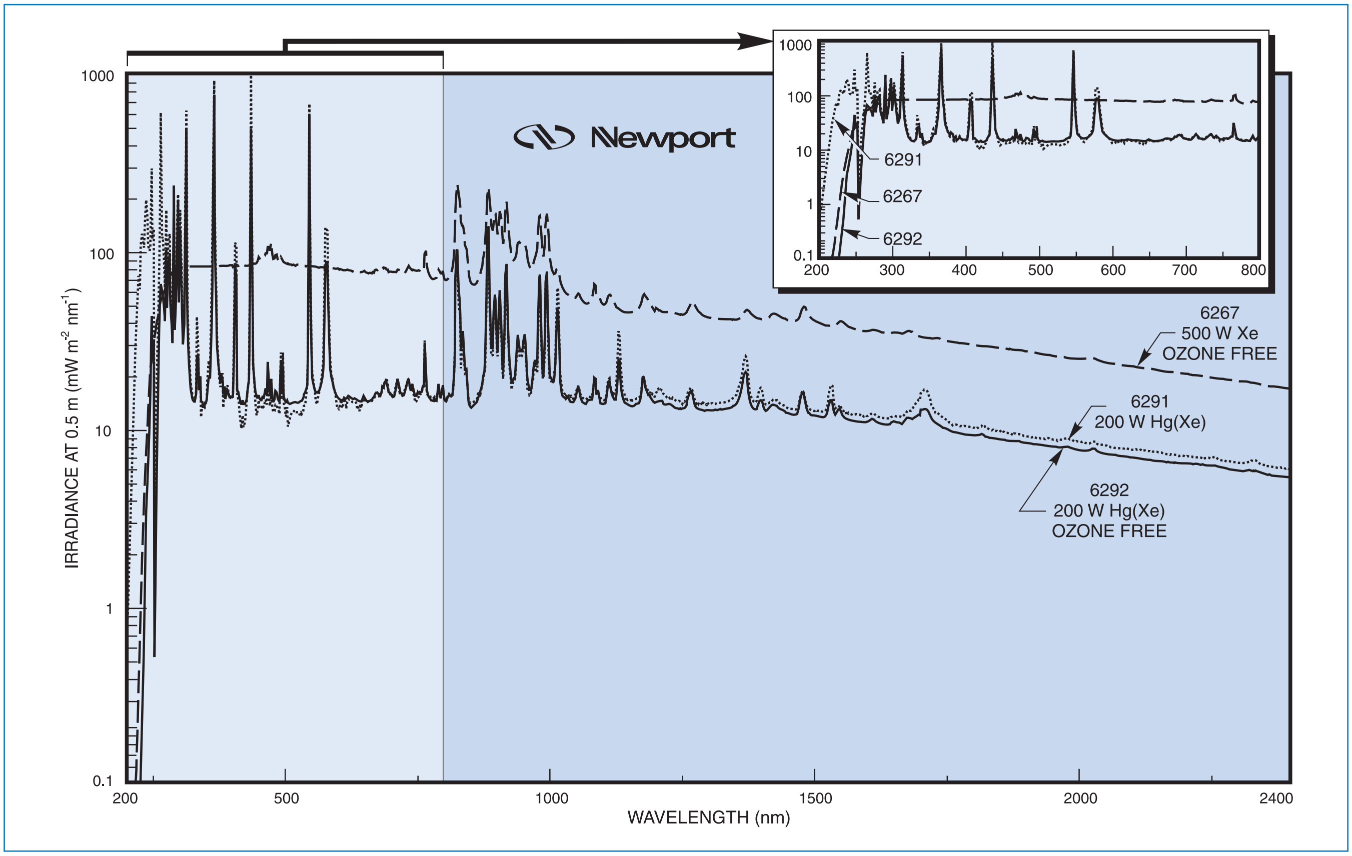


Fig. 8 Spectral irradiance of various Arc Lamps.

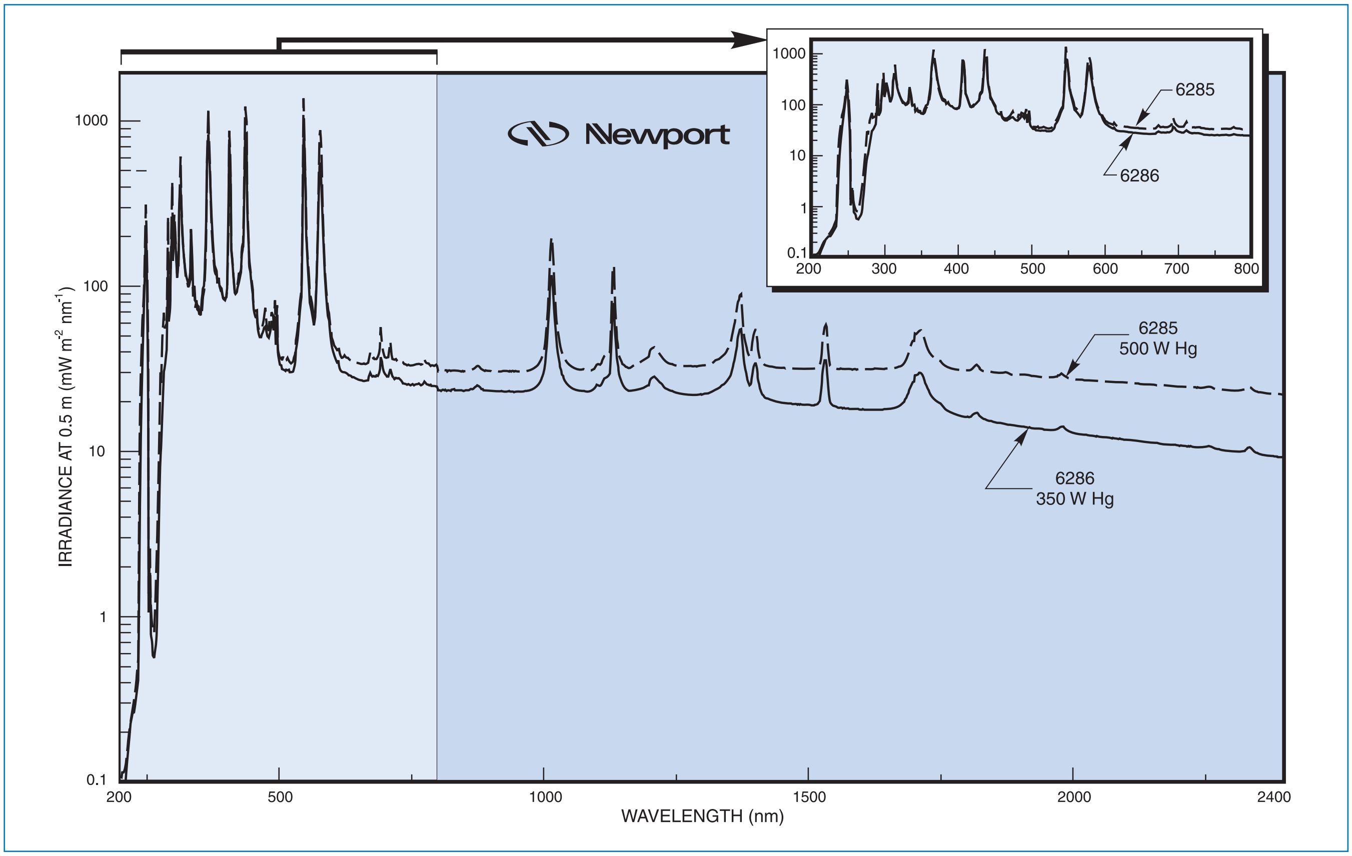


Fig. 9 Spectral irradiance of various Arc Lamps.

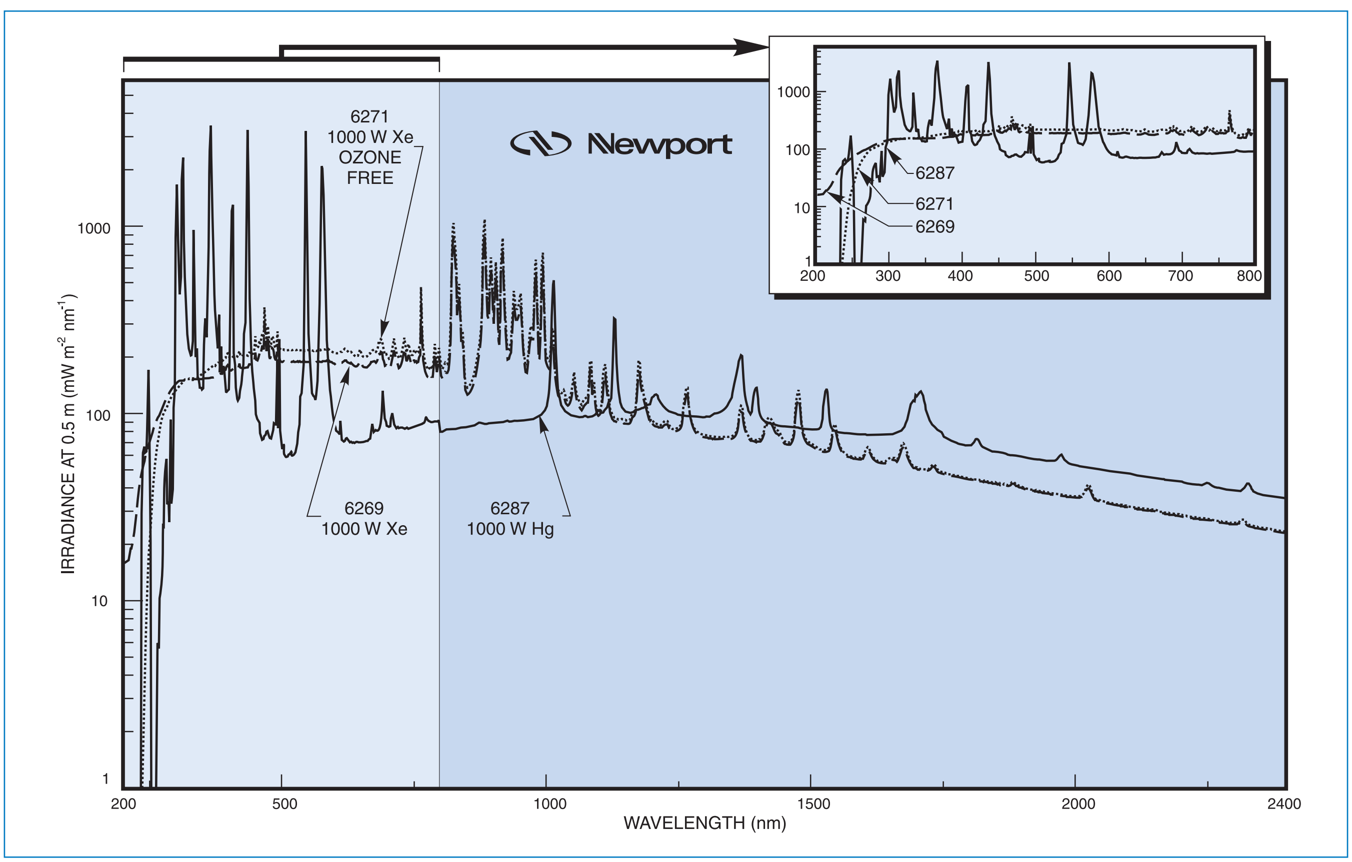


Fig. 10 Spectral irradiance of various Arc Lamps.

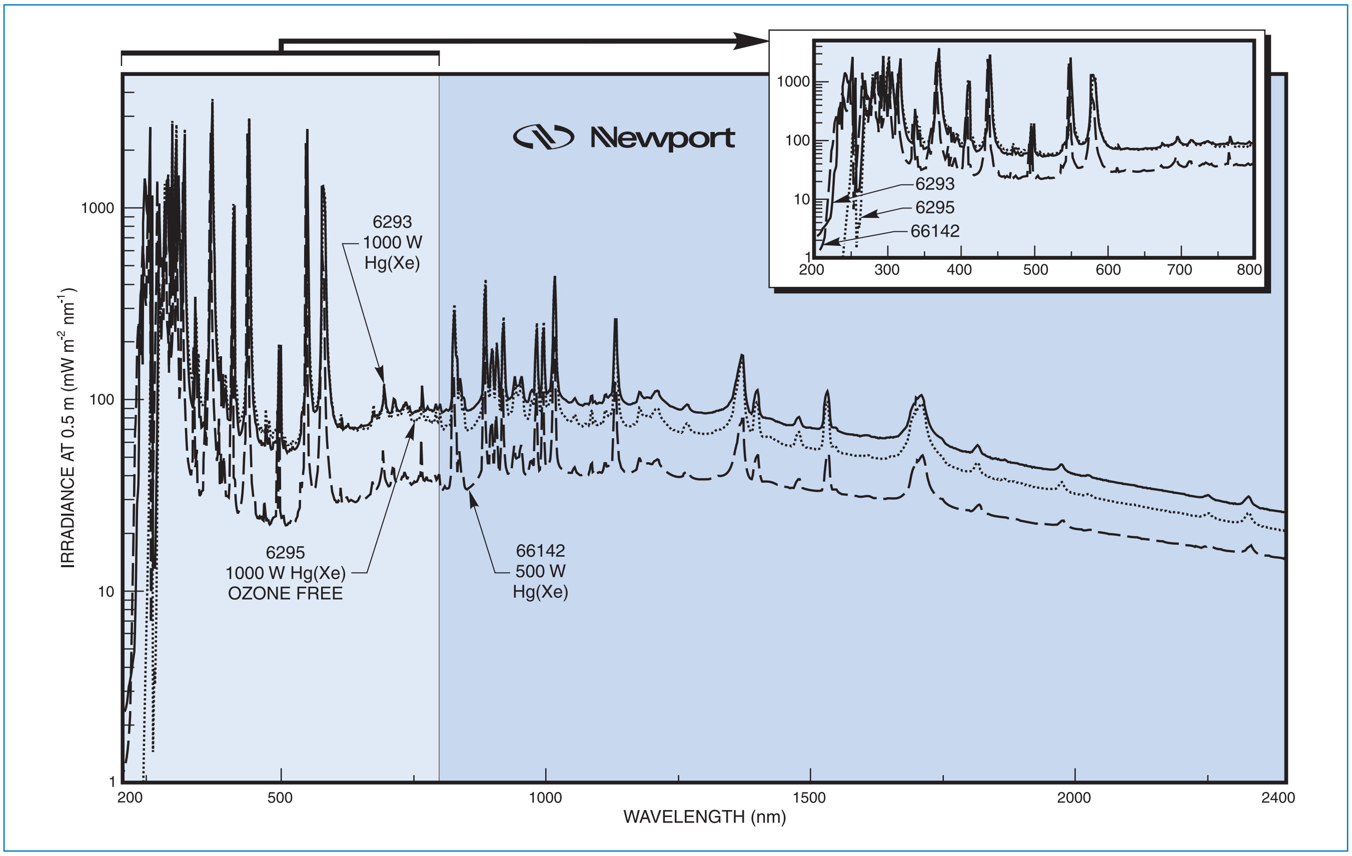


Fig. 11 Spectral irradiance of various Arc Lamps.

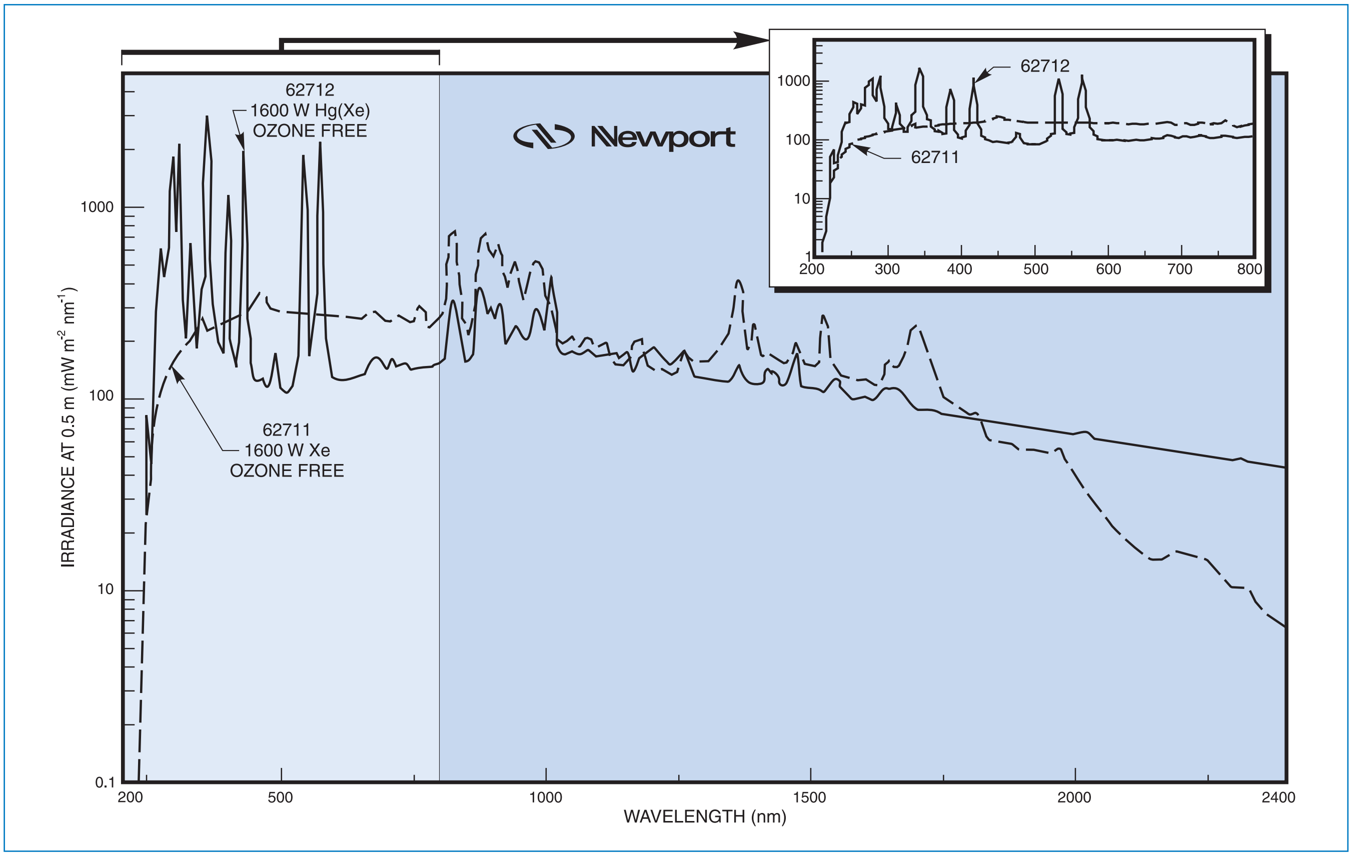


Fig. 12 Spectral irradiance of Arc Lamps.

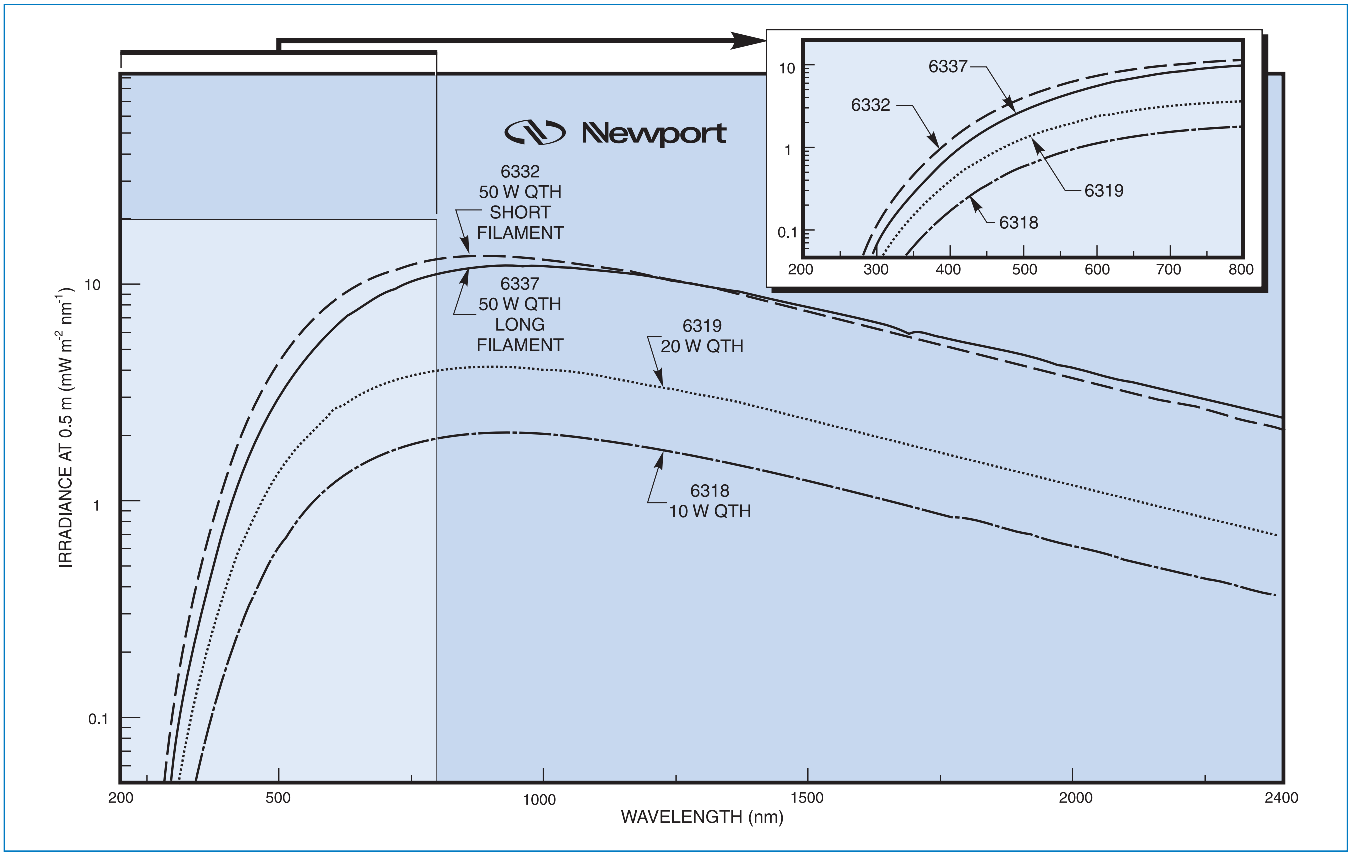


Fig. 13 Spectral irradiance of various Quartz Tungsten Halogen Lamps.

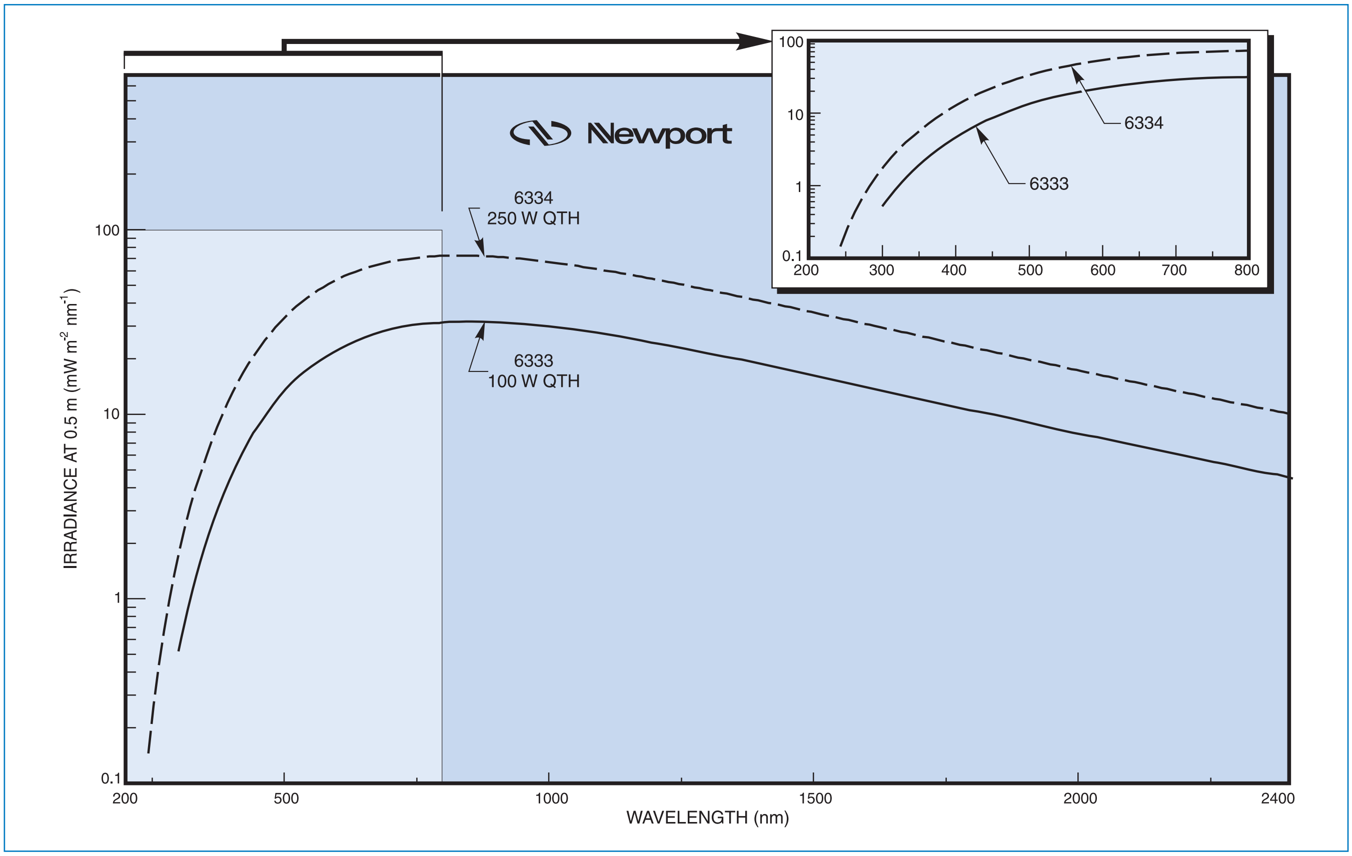


Fig. 14 Spectral irradiance of various Quartz Tungsten Halogen Lamps.

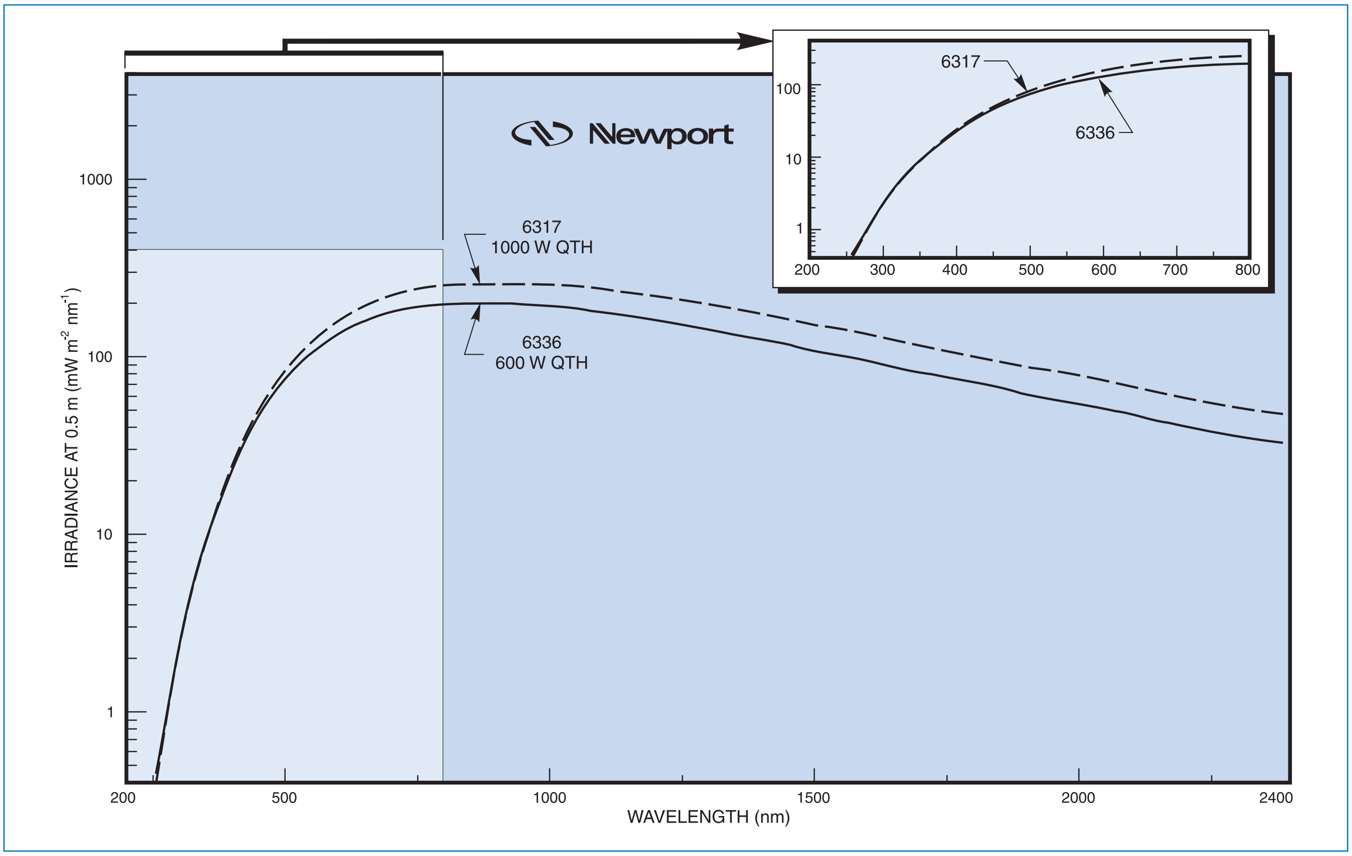


Fig. 15 Spectral irradiance of various Quartz Tungsten Halogen Lamps.

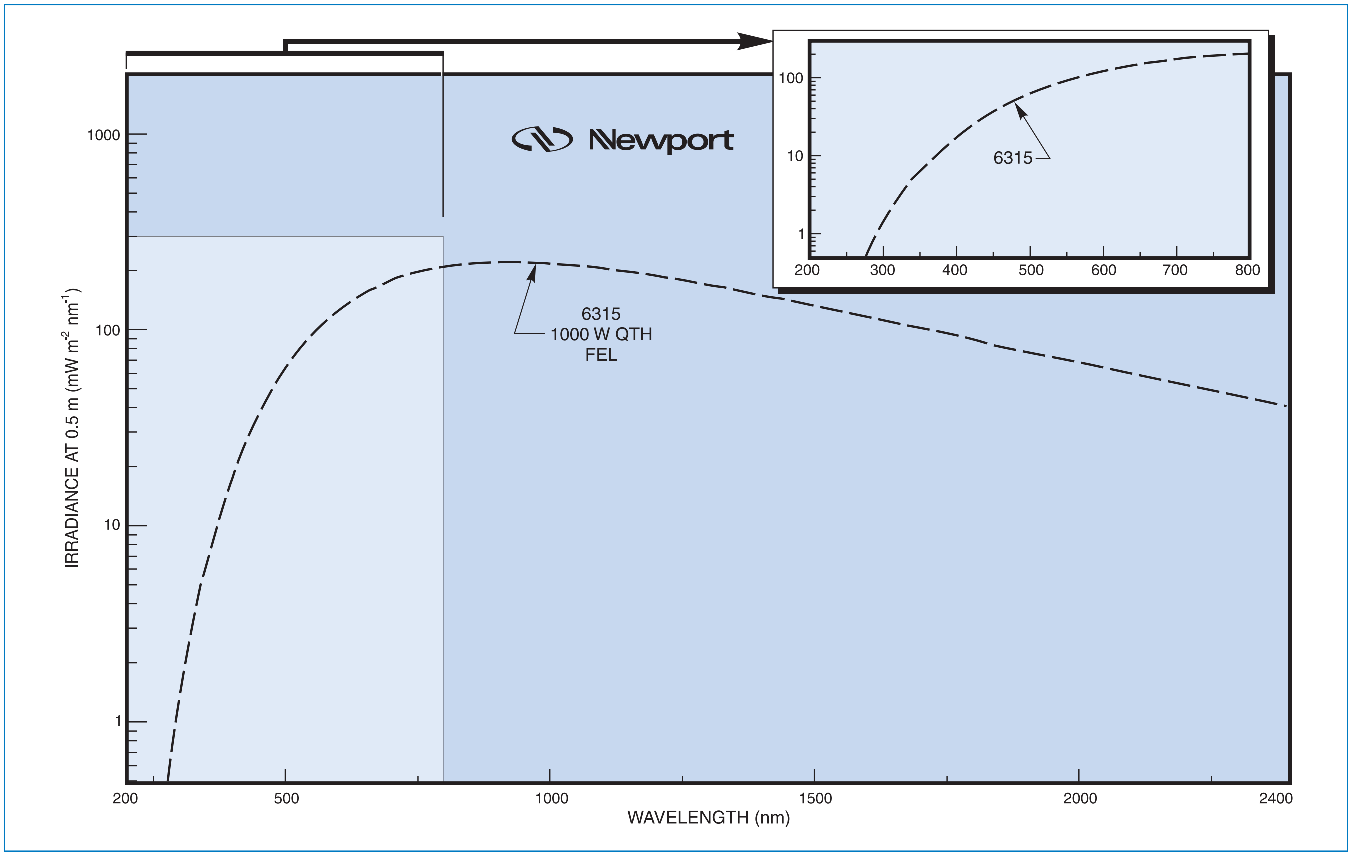


Fig. 16 Spectral irradiance of 6315 1000 W FEL Type Quartz Tungsten Halogen Lamp.

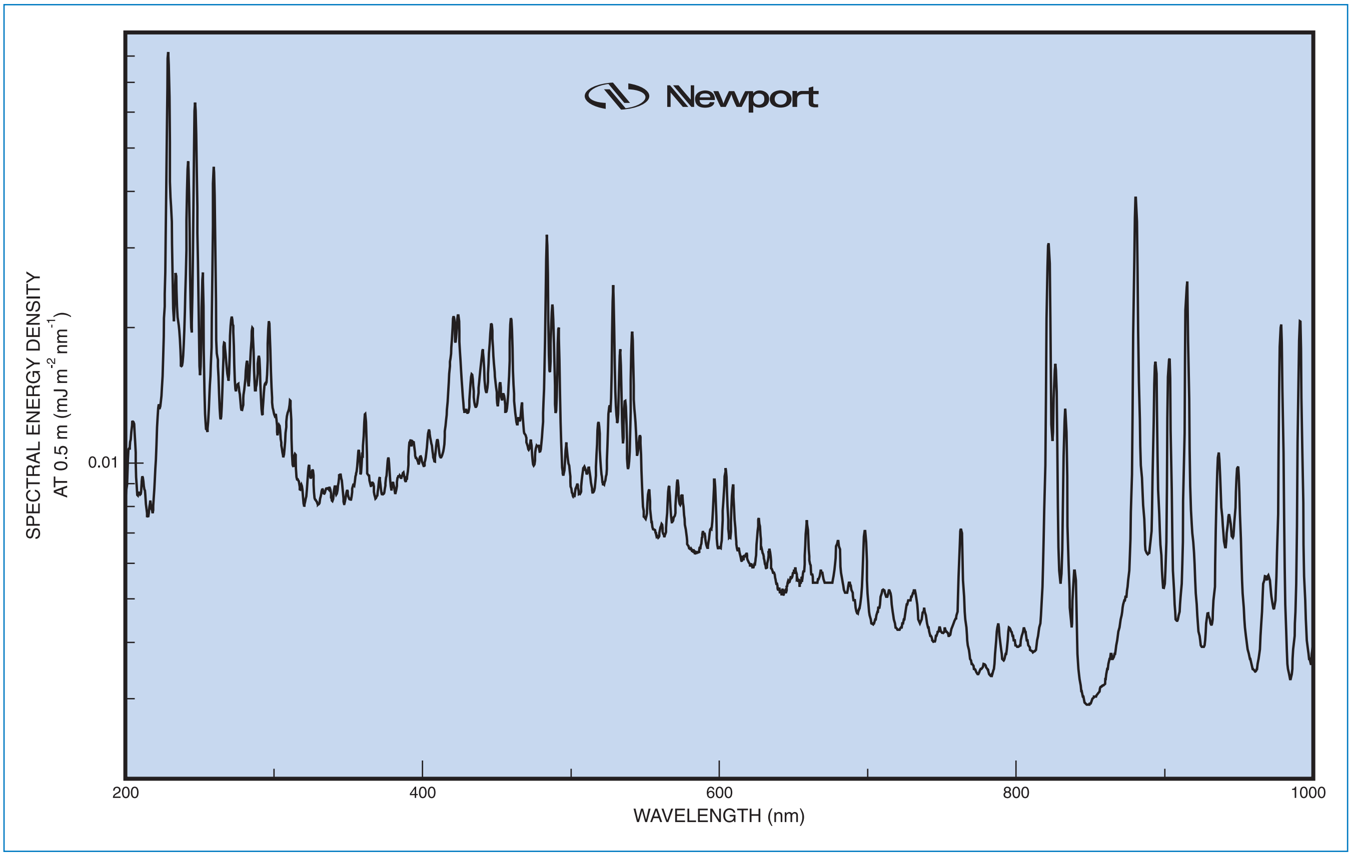


Fig. 17 Spectral energy density of a single pulse from the 6426 0.32 J Guided Arc Lamp at 0.5 m.

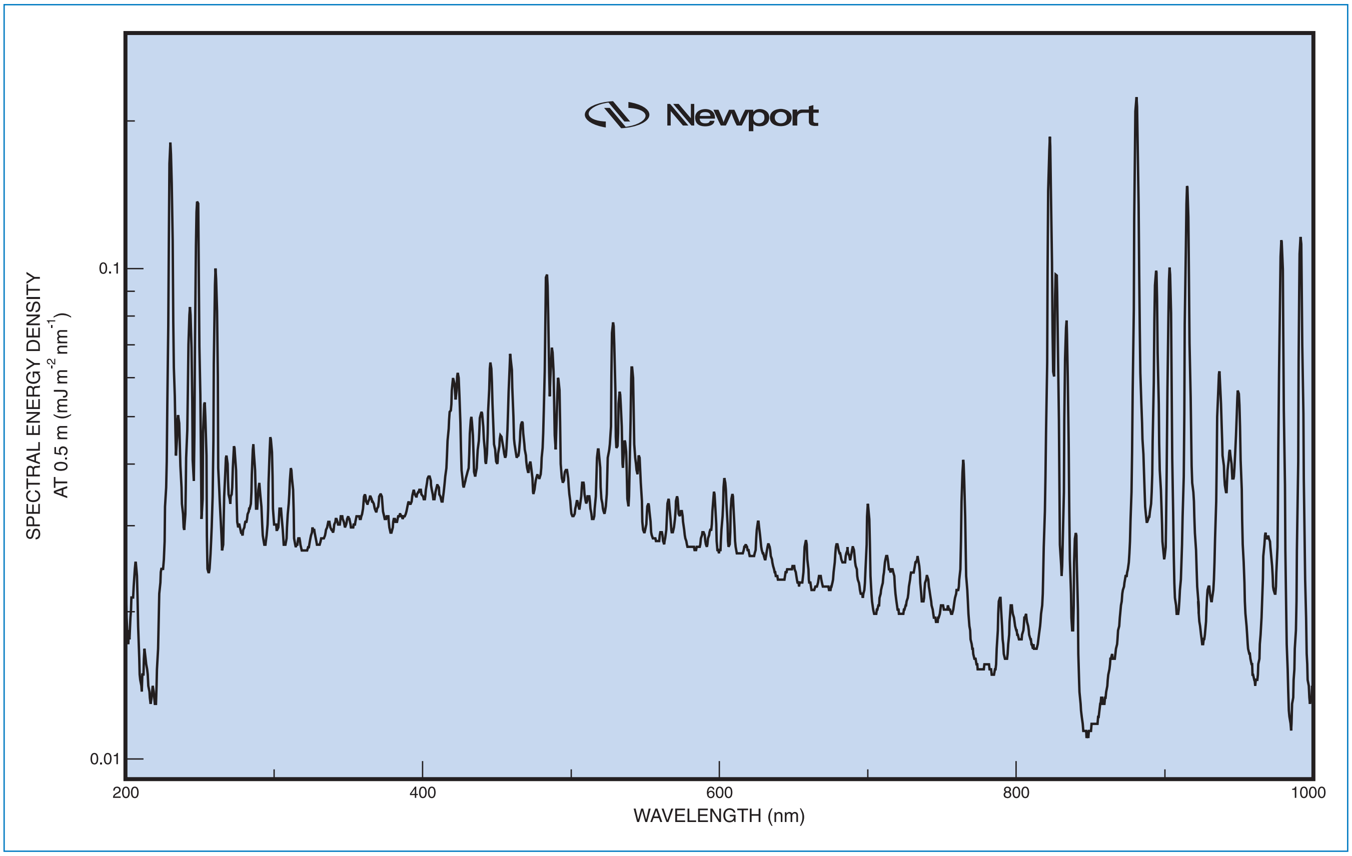


Fig. 18 Irradiance Pulse Spectrum from 6427 5 J Large Bulb. The values change with repetition rate.

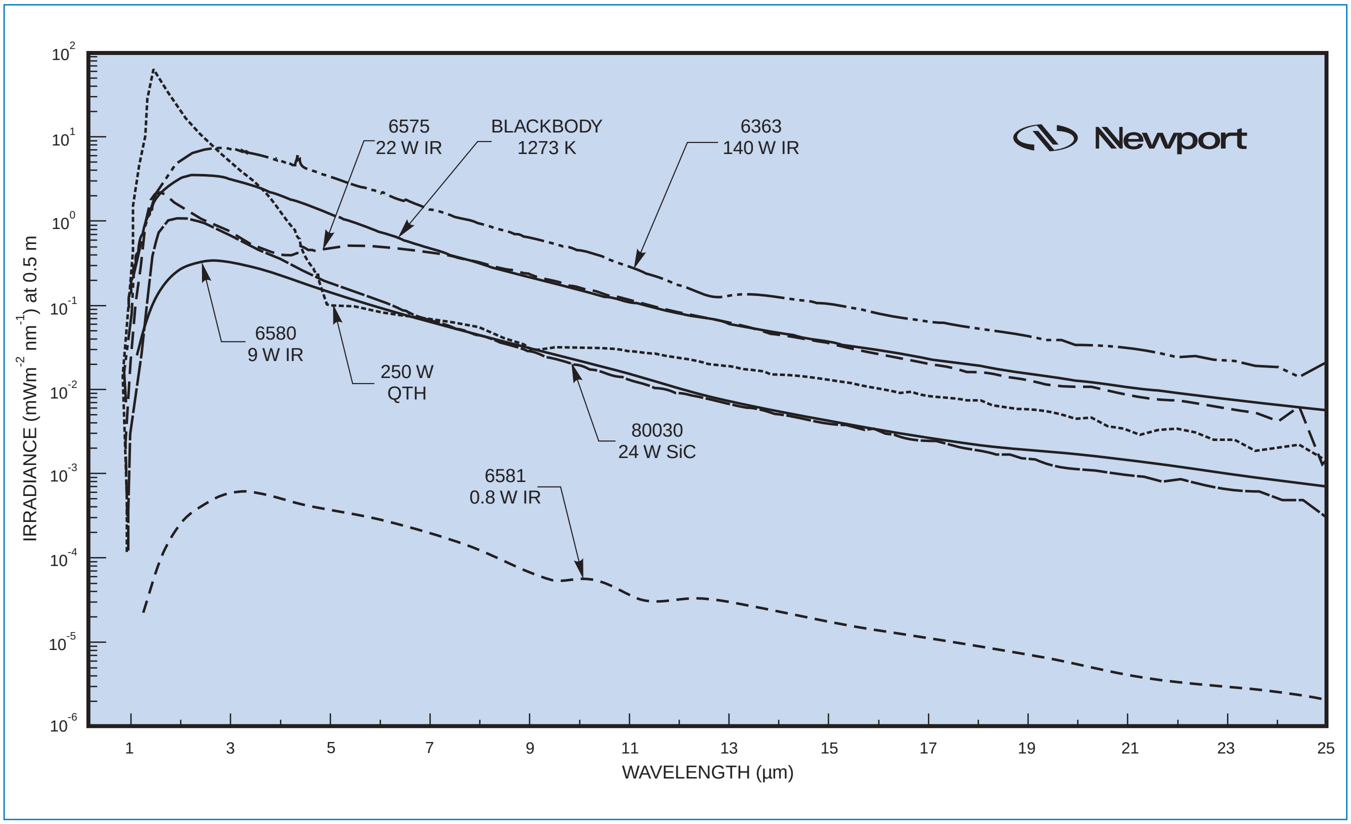


Fig. 19 Spectral irradiance of 6334 250 W QTH Lamp, and IR Elements.

We describe our spectral irradiance curves on pages 1-16 to 1-18. Again, we caution you on the need for testing of the final configuration particularly when the "total radiation budget" for the system, source to detector, is tight. On the next several pages we provide examples of the use of the data. First we discuss the importance of source size and describe the intense spectral lines from the arc lamps.

SOURCE SIZE

Our curves can be very misleading when it comes to selecting a lamp. A quick glance shows the irradiance increasing as we move up in lamp power. More irradiance is not necessarily better; lower power lamps have advantages.

1. A lot of applications require re-imaging of the source. The lower power lamps have small radiating areas, arcs or filaments. These are as bright, and in some cases brighter than, the larger arcs or filaments of the higher power lamps. You get as much flux density on target with a small lamp as with a large. If your target (a monochromator slit, fiber, sample, etc.) is small, then you won't do any better with a larger lamp. See pages 1-9 to 1-15 for more information on collection and focusing and the fundamental concept of optical extent, and 4-30 and 5-18 for the dimensions of the radiating element. Note, the smaller arcs of some of the xenon lamps make them more efficient, for many applications, than either the mercury or QTH lamps.
2. Smaller lamps are easier to operate. They require and produce less total power. In some cases, with high power lamps, you have to use a liquid filter to get rid of the high power to protect optical components. Apart from damage to optics, a continuously running kW source will heat the laboratory and your equipment. Therefore, it is a good idea to carefully analyze your optical system so that the lowest power lamp, that will serve your needs, can be selected.

Comparing the 6332 50 W and 6315 kW QTH lamps offers an extreme example. From the curves, the kW lamp produces about 20 times the irradiance of the smaller lamp. But the 6315 has a 6 x 16 mm filament while the 50 W lamp has a 3.3 x 1.6 filament. For a small target, several mm in dimension, the re-imaged smaller lamp actually produces significantly more power on target than the re-imaged kW lamp. When you need to irradiate a very large area, the kW lamp is better.

THE SPECTRAL LINES FROM ARC LAMPS

The intense UV lines make the mercury lamp the choice for many UV sensitive processes and for excitation of luminescence, particularly when you can efficiently excite with 313, 365, 404 or 436 nm radiation. (When you need to scan the wavelength of the excitation source you may be better off with the smoother xenon lamp spectrum. With the xenon lamp you have less worries about dynamic and linear range of a detection system. The rapid variation of the mercury lamp output with wavelength also puts demands on wavelength reproducibility in any application where you scan the source and where you ratio or subtract separate resulting scans.)

We publish the wavelengths for the lines from our mercury spectral calibration lamps on page 2-8. Some of these lines are extremely narrow while others show structural broadening. The wavelength values of these lines from the low pressure lamps, and the early alphabetical designation of some of them are still used as labels for all mercury lines.

i Line	h Line	g Line	e Line
365.01 nm	404.65 nm	435.84 nm	546.07 nm

Our irradiance data shows broader lines and some line shifting from these generic values. Doppler broadening and self reversal cause these changes. Since self reversal depends on the passage of radiation through colder mercury, the exact spectral profile depends somewhat on the lamp type and envelope temperature. Fig. 1 shows that the "254" line which dominates the output of the 6035 Spectral Calibration Lamp is substantially absorbed in the 350 W Hg lamp, model 6286, and in fact we should speak of a 250 nm line. This is important for selection of an interference filter for this and some of the other lines.

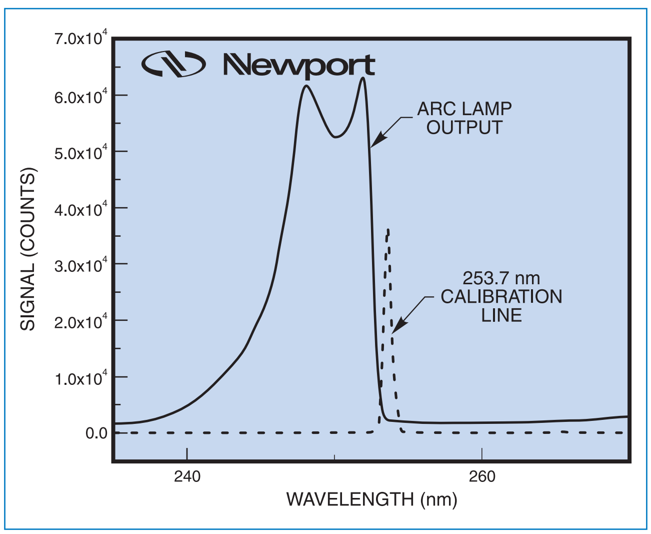


Fig. 1 "254" nm line from a 350 W Hg arc lamp shown with calibration line. The line width (FWHM) of the calibration line, as recorded by our MS257™ Spectrograph with a 1200 l/mm grating and 50 µm slit and photodiode array, was 0.58 nm, instrument limited.

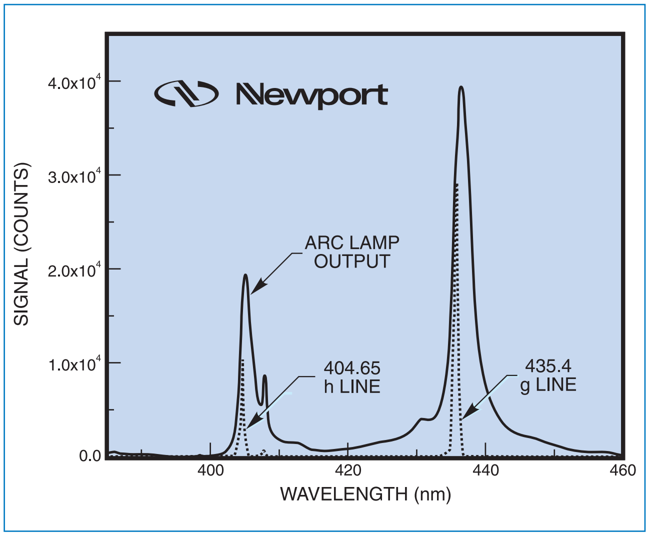


Fig. 2 The g and h lines from the 350 W Hg lamp shown with a calibration line recorded on the same equipment. These data were recorded with our MS257™ Spectrograph and a PDA, so the wavelength calibration is exact.

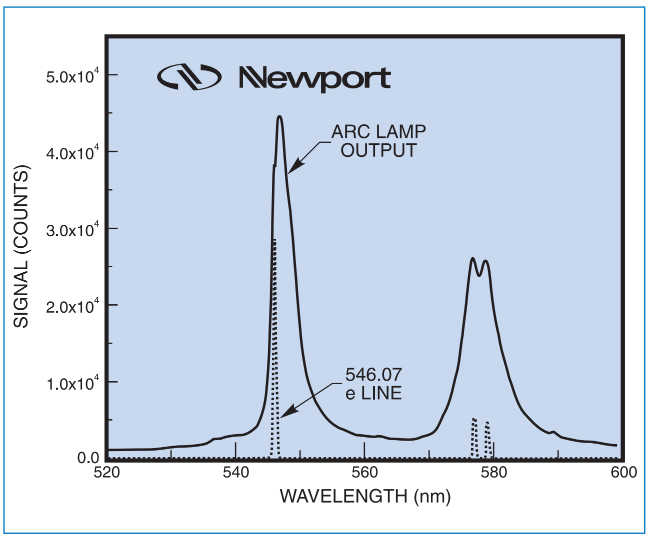


Fig. 3 The green 546.1 nm line and yellow doublet.

The high resolution scans of Figs. 2 and 3 also show the line broadening. For most calculation purposes the actual line shape is less important than the total irradiance in the band of wavelengths close to the line. This will be the same for a low resolution scan as for a high resolution scan. The line shape and height may differ but the area under the scans is the same to a good approximation.

Example 1 is an extension of the example on page 1-5 addressing the problem of the line output of the mercury lamps. On the following pages, we show how to calculate the output from our lamp housings.

Example 1

Calculate the illuminance, in ft candles, 8 ft from the 6285 500 W mercury arc lamp, along the direction of the highest illuminance.

The data on our curves are for the direction of highest irradiance which is of course the same as that for highest illuminance.

The curve for this lamp is on page 25. We describe the relationship between photometric and radiometric units on page 2, and briefly cover the principles of conversion on pages 3 and 4.

The steps are:

1. Convert the irradiance data to photometric values by multiplying the irradiance curve by the V(λ) data on page 1-4.
2. Convert the values in lux to values in foot candles.
3. Make the correction for the difference in source-target plane distance , 0.5 m vs. 8 ft in this example.

Step 1

Only visible radiation contributes to photometric value, so we work with the 400 - 750 nm portion of the spectrum. (We magnify this portion of the curve with a photocopier.) We first consider the four major visible lines, essentially cutting them off at a median background level, E_B, judged somewhat arbitrarily to be 50 mW m^{-2} nm $^{-1}$. We estimate the value at the peak and the linewidth from the (magnified) curves and tabulate the conversion:

λ (nm)	E_λ Estimate of E_λ from Curve (mW m^{-2} nm^{-1})	Δλ (nm)	V(λ)	Illuminance Due to Peak E_v (lux)
405	960	3.9	0.0008	2
436	1180	3.9	0.0173	54
546	1190	5	0.98	3983
580	750	8	0.87	3565
Total from Peaks				7604

We have used:

illuminance in lux, $E_V = E_\lambda \times \Delta\lambda \times 683 \times V(\lambda)$. Note the dominant contribution of the 546 and 580 nm peaks to the luminous total. The contribution from the background is:

$$E_B \times 683 \times \int V(\lambda)d\lambda = 0.05 \times 683 \times 107 = 3654 \text{ lux.}$$

The total illuminance from the peaks and background is about 11260 lux at 0.5 m.

Step 2

Since 1 lux is 1 lumen m^{-2} and 1 foot candle is 1 lumen ft^{-2}, we divide 11260 by 10.76 to get 1046 ft candles at 0.5 m.

Step 3

At 8 ft, 2.44 m, the value is 1046 x $(0.5)^2/ 2.44^2$ = 44 ft candles. (Integrating using our data files for the lamp gives 45 ft candles and we measure 48 ft candles using a Photometer.

GETTING FROM IRRADIANCE DATA TO BEAM POWER

You can estimate the power in the collimated beams* at any wavelength or in any wavelength range from our Series Q, Apex, or Research Lamp Housings with any of our CW and pulsed arc, quartz tungsten halogen or deuterium lamps. The procedure is similar to compute the output from the 7340 and Apex Monochromator Illuminators and PhotoMax™ (which produce focused outputs), but you must factor in the reflectance of the mirror (following page).

* The discussion covers the output from the condenser when operated to produce a collimated beam. You can produce more output in a diverging beam by moving the condenser in, and less by moving it out. See the discussion on Collection and Focusing of Light on page 1-9.

At a Single Wavelength

To find the total output power per nm at any wavelength for any of our Lamp Housings, you simply

1. Read the value of the irradiance from the curve for the lamp; the value will be in mW m^{-2} nm^{-1}.
2. Find the conversion factor for your Lamp Housing and condenser type (listed in Tables 1 and 2), and multiply this by the value from 1. The result will be in mW nm^{-1}.
3. Multiply the result by 1.6 when a rear reflector is used.

Table 1 Conversion Factors for Series Q and 250 and 500 W Research Housings

Condenser Type		Spectral Range	Condenser Aperture (mm)	Conversion Factor*
F/#	Lens Material			
F/1.5	Fused Silica	200 - 2500	33	0.06
F/1	Fused Silica	200 - 2500	33	0.11
F/0.85	Pyrex®	350 - 2000	33	0.13
F/0.7	Glass/Fused Silica	350 - 2000	69	0.18
F/0.7	Fused Silica	200 - 2500	69	0.20

* Measured at 500 nm

Table 2 Conversion Factors for 1000 and 1600 W Research Housings

Condenser Type		Spectral Range	Condenser Aperture (mm)	Conversion Factor
F/#	Lens Material			
F/1	Fused Silica	200 - 2500	48	0.13
F/0.7	Glass/Fused Silica	350 - 2000	69	0.18
F/0.7	Fused Silica	200 - 2500	69	0.20

THE REAR REFLECTOR

The rear reflector captures "backwards emitted radiation," and when properly adjusted, reflects it back through the source to contribute to the total output. This applies particularly to arc lamps which are transparent at most wavelengths. The factor of 1.6 decreases below 350 nm to about 1.2, at 250 nm.

You do get additional output from the QTH lamps but you must displace the re-imaged filament when using our closed packed planar filaments. This may limit the usefulness of the additional output. Re-imaging onto the filament does increase the collimated output a little and changes the power balance of the system.

You cannot use a rear reflector with our deuterium lamps.

WHERE DID THE CONVERSION FACTORS COME FROM?

We measured the output of our lamp housings and use the measured irradiance curves to determine the conversion factors at 500 nm. You can, in principle, use the irradiance curves to calculate factors for each condenser for an ideal point source as we know the collection geometry and transmittance. Since our lamps are neither point sources nor truly isotropic, the tabulated empirical values are better.

We list the values at 500 nm. Values at other wavelengths, within the transmission range of the condenser, will be similar.

Example 1

Find the output at 405 nm from the 66924 Arc Lamp Source operating the model 6293 1000 W Hg(Xe) lamp.

The curve for this lamp is on page 23, and the value at the peak of this line is 1000 mW m^{-2} nm^{-1}.

The conversion factor for the F/1 lens in this source is 0.11. Therefore, the output at 405 nm for the source will be:

$$1000 \times 0.11 = 110 \text{ mW nm}^{-1}$$

This lamp housing includes a rear reflector. This will increase the output by ca. 60%, to give 176 mW nm^{-1}.

Total Power in a Specified Spectral Range

To find the total output power in a wavelength range:

1. Find the curve for the particular lamp.
2. Calculate the total irradiance in your wavelength interval, λ_1 to λ_2, from the graph. The total is the area under the curve between λ_1 to λ_2. The result will be in mW m^{-2}.
3. This step only requires multiplying the total irradiance in mW m^{-2} from Step 2 by the conversion factor for your Oriel Lamp Housing and condenser. The result will be in mW.
4. Multiply the output by 1.6 when a rear reflector is used.

Example 2

Find the output from 520 - 580 nm from the 66908 Light Source operating the 6255 150 W xenon lamp.

1. From the graph at the bottom of page 1-23, the irradiance over this range is approximately 20 mW m^{-2} nm^{-1}. The range is 60 nm, so the total irradiance is 60 x 20 = 1200.
2. The conversion factor for the efficient Aspherab® is 0.18, so the total output in this spectral range is 1200 x 0.18 = 216 mW.
3. Since this lamp housing includes a rear reflector and these increase the output by ca. 60% when using an arc lamp, the final output will be close to 346 mW.

Monochromator Illuminators and PhotoMax™

We list the conversion factors at 500 nm for the 7340 and 7341 Monochromator Illuminator, Apex Monochromator Illuminators and PhotoMax™, below. You should multiply the factor from the tables below by the reflectance at the wavelength of interest, and divide by the reflectance at 500 nm. The conversion factor assumes no window in the PhotoMax™ (The 7340 and Apex Monochromator Illuminators do not use windows), so you should multiply by 0.92 if you use a window.

Table 3 Conversion Factors for Photomax™, at 500 nm

Reflector F/#	Reflector Coating	Conversion Factor
4.4	Rhodium or $AlMgF_2$	0.8
3.7	Rhodium or $AlMgF_2$	0.9
2	Rhodium or $AlMgF_2$	1.1

Table 4 Conversion Factor for Monochromator Illuminator, at 500 nm

Output F/#	Reflector Coating	Magnification	Conversion Factor
3.75	$AlMgF_2$	1.75	0.038

Table 5 Conversion Factor for Apex Monochromator Illuminator, at 500 nm

Output F/#	Reflector Coating	Magnification	Conversion Factor
4	$AlMgF_2$	1.75	0.038

Example 3

Find the output from PhotoMax™ at 275 nm operating the 6256 150 W Xe lamp. The PhotoMax™ has a fused silica window, the 60130 Beam Turner with the 60141 UV dichroic, and is configured with an F/3.7 Reflector.

From the curve at the bottom of page 1-23, the lamp irradiance at this wavelength is 15 mW m^{-2} nm^{-1}.

The tabulated conversion factor for 500 nm is 0.9. We multiply this by 0.96, the ratio we estimated by comparing the reflectance of the $AlMgF_2$ coating at 500 and 275 nm. We also need to multiply by 0.92 for the window transmission. So the output is:

$$15 \times 0.9 \times 0.96 \times 0.92 = 12 \text{ mW nm}^{-1} \text{ at 275 nm.}$$

The curve on page 9-9 shows the reflectance of the dichroic to be 0.83 at 275 nm, so the final output is:

$$12 \times 0.83 \sim 10 \text{ mW nm}^{-1}.$$

Example 4

Find the output from the 7340 Monochromator Illuminator at 600 nm operating the 6332, 50 W QTH lamp.

The curve on page 1-28 shows the irradiance from the 6332 to be 10 mW m^{-2} nm^{-1}. Since the reflectance of $AlMgF_2$ is the same at 500 and 600 nm, 95%, we multiply the 7340 Conversion factor, 0.038, by 95.

The total output from the 7340 is:

$$10 \times 0.038 \times 0.95 = 0.36 \text{ mW nm}^{-1} \text{ at 600 nm.}$$