Technical Guide 101

ATLAS
MATERIAL TESTING SOLUTIONS
AMETEK
MEASUREMENT, COMMUNICATIONS
& TESTING

Basics of Irradiance and Radiant Energy in Weathering Testing

Introduction

In exposure tests it is important to know both the amplitude of the radiation impinging on a test specimen's surface as well as the accumulated energy dose over the exposure period. Following Newton's inverse square law, with a constant point source output, that amplitude at the test specimen surface will decrease with the square of the distance[Note 1]. Therefore, describing the intensity only in terms of the emission power of the source is not useful. We need to know the amplitude at the test specimen surface, from which we can calculate the accumulated exposure dose over time.

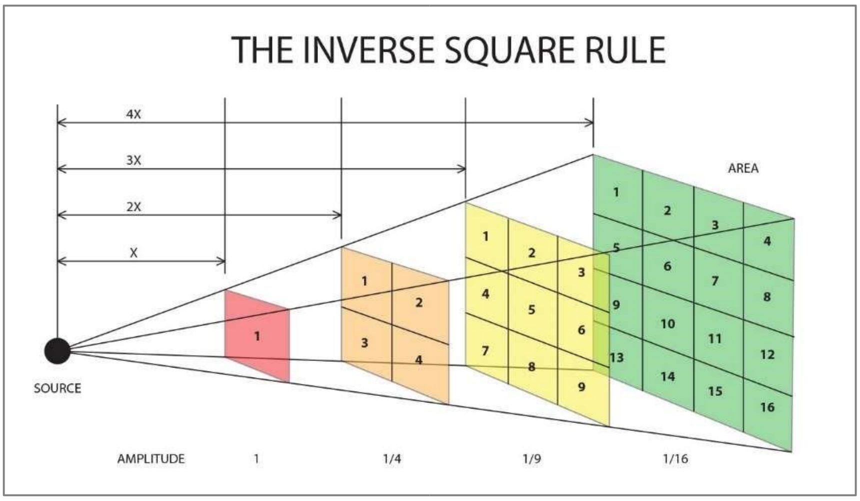


Figure 1. The inverse square rule.

Terminology and definitions

There are two measurement systems in use. Photometry involves measuring the visible-to-human portion of the electromagnetic spectrum, which we call "light". The measurements are skewed to the response of the human eye, which perceives green light as brighter than other colors. Radiometry involves measuring energy over the entire electromagnetic spectrum in equal and absolute units, and radiometric measurements are used in weathering.

Amplitude

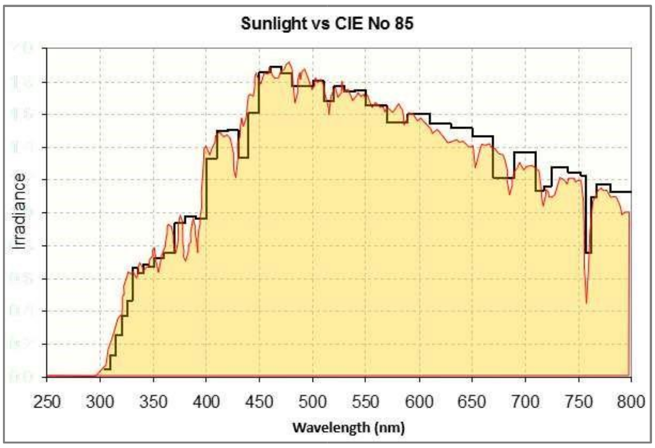
Radiant flux (W) is the total amount of radiant energy emitted, transmitted or received over a unit of time. The Radiant flux density (W/m^2) is the radiant flux (Watt) incident per unit of area, in this case a square meter. Therefore, the Irradiance (W/m^2) is the radiant flux density incident on a surface such as our test specimen. However, in weathering we are concerned with measuring the irradiance (E) at a specific wavelength (λ) such as 340nm, or over a wavelength range, such as 300-400nm or 295-385nm in the ultraviolet region of the terrestrial solar spectrum, or over a larger range of UV/Visible/Infrared radiation such as 295-2500nm. When defining the radiant flux density, or irradiance, in terms of a specific spectral wavelength region, the units become Radiant spectral flux density and Spectral irradiance ($W\ m^{-2}\ nm^{-1}$), often commonly expressed as $W/m^2 \bullet nm$ or W/m^2 @ nm. Note that the measurement wavelength (or wavelength range) must always be specified when a spectral radiometric value is quoted.

Dose

The accumulated radiation dose deposited on a sample surface is irradiance integrated over time and is the Radiant exposure (H), usually expressed in units of J/m^2 nm^{-1} where J is Joules and nm^{-1} is the same wavelength or range of the spectral irradiance value. Therefore, the general shorthand formula used is:

$$H\ (J/m^2\ nm^{-1}) = E\ (W/m^2\ nm^{-1})\ X\ t\ (seconds) \qquad \text{Equation 1.}$$

While not shown, the units convert correctly since 1 Joule = 1 Watt-second. Frequently the radiant exposure will be stated in terms of kilojoules (J X 10^3) or Megajoules (J X 10^6) and, although frequently omitted, is always at the same wavelength or wavelength range as the spectral irradiance value. Note that spectral ranges cannot be mixed in Equation 1. Also, time is more commonly expressed in hours (3,600 seconds). Therefore, factors such as hours X 3.6 (to convert to kiloJoules/m^2) or hours X 0.0036 (to convert to Megajoules/m^2) are often substituted for time (t) in seconds in this equation. Note that this is the radiation exposure time only, as some test cycles have dark periods.

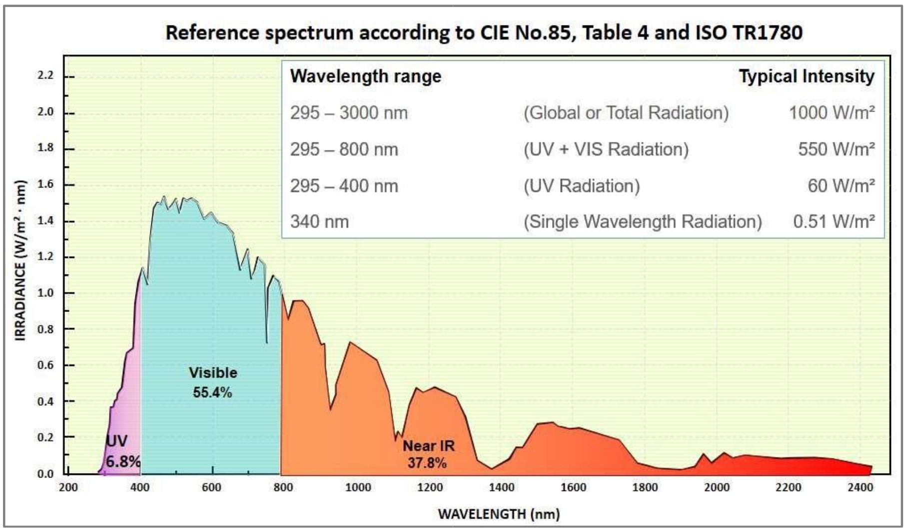


Spectral Power Distribution

The spectral power distribution (SPD) describes the power per unit area per unit wavelength of a radiation source.

Figure 2. Example of target CIE SPD versus sunlight.

While terrestrial solar radiation constantly varies, standard spectra such as those defined in reference documents such as CIE (International Commission on Illumination) Publication 85, and others, are commonly used. An example is shown in Figure 2 showing the UV and visible wavelengths in the range of 300 – 800nm. These are the targets for laboratory solar simulation and weathering applications. The exact spectral curve shape for sunlight depends on several factors, while that for sources such as xenon arc solar simulators are determined by the lamp and any optical filters.



Wavelength range		Typical Intensity
295 – 3000 nm	(Global or Total Radiation)	1000 W/m²
295 – 800 nm	(UV + VIS Radiation)	550 W/m²
295 – 400 nm	(UV Radiation)	60 W/m²
340 nm	(Single Wavelength Radiation)	0.51 W/m²

Figure 3. CIE/ISO reference spectrum for terrestrial solar radiation showing equivalent irradiance values integrated over different wavelength ranges.

Note that in Figures 2 & 3 the standard solar spectrum will have a different amplitude value depending on the individual wavelength number. If we imagine Figure 3 to be printed on high resolution graph paper, the sum of the individual squares in any vertical single-wavelength column will be the irradiance value for that wavelength, such as at 340nm. If we choose a range of wavelengths, such as 300-400nm, the total irradiance will be the sum total of all of the graph squares in all of the columns within that range.

Figure 3 shows that if we integrate the area under the spectral curve over various wavelength ranges that the irradiance values will change, even though the amplitude and shape of the curve have not changed. In other words, we can use different wavelength ranges (and their corresponding irradiance values) to describe the exact same SPD. This is why spectral irradiance must always include the wavelength range to be meaningful. This ability to have different irradiance values for the same exact SPD is often a source of confusion, especially for those new to weathering, or when comparing different test methods or test results using different irradiance measurements. If the spectral curve shape is fixed (as with a xenon lamp/filter combination), then there is also a fixed mathematical relationship between all wavelengths, and we can convert spectral irradiance values to any wavelength or range. However, these fixed relationships are SPD dependent, meaning that different xenon lamp and filter combinations with even slightly different spectra will have different irradiance conversion factors. This also requires precision spectral measurements, preferably with ≤ 1.0nm resolution.

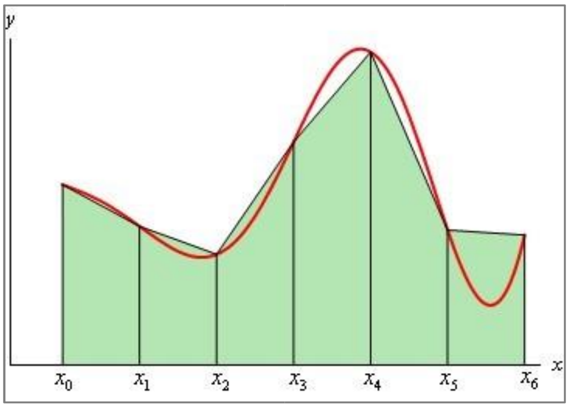


Figure 4. Trapezoidal approximation method of area integration under a curve.

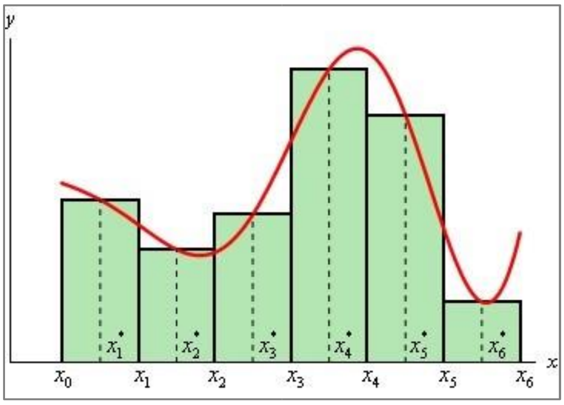


Figure 5. Rieman (center justified approach shown) approximation method of area

Unfortunately, Microsoft® Excel does not provide an "integration (∫)" function in its math library. Alternatively, many mathematics software packages do provide one. Also, approximations can be made using the trapezoidal method (Figure 4) or the Rieman sums method (Figure 5), using left, right or center (shown) justification. If data is of high resolution, i.e., in 1nm or better increments, a simple sum (∑) of the values over the desired wavelength range may be a sufficient approximation for many purposes.

Normalization

As the amplitude and shape of the spectral curve will vary, for example between solar radiation and different laboratory light source simulations, it is often desirable to compare SPD's based on a common reference point. The process of normalization adjusts data sets by commonizing the curves to a specific irradiance value at a particular wavelength. This can only be performed when the curve shape changes linearly with irradiance, as in filtered xenon arc solar simulators such as Atlas xenon weathering instruments. An example of normalization to an irradiance of 0.55 W/m2 • 340nm is shown in Figure 6. Terrestrial solar radiation data should not be adjusted, since the SPD from the sun will constantly change due to the sun's position in the sky and atmospheric conditions. Therefore, the shape of solar SPD does not remain constant at different amplitudes during the day. It is recommended that only the artificial simulation spectra be normalized relative to the natural solar radiation, and not to adjust natural values relative to an artificial one.

With radiation sources such as full-spectrum filtered xenon arc lamps, the amplitude (irradiance) can be adjusted by manipulating the power applied to the lamp, without changing the overall spectral curve shape, i.e. the irradiance changes by an equal percentage for all wavelengths. Note that this uniform change does not hold true for all radiation sources, such as metal halide lamps where the spectral balance changes with the applied power.

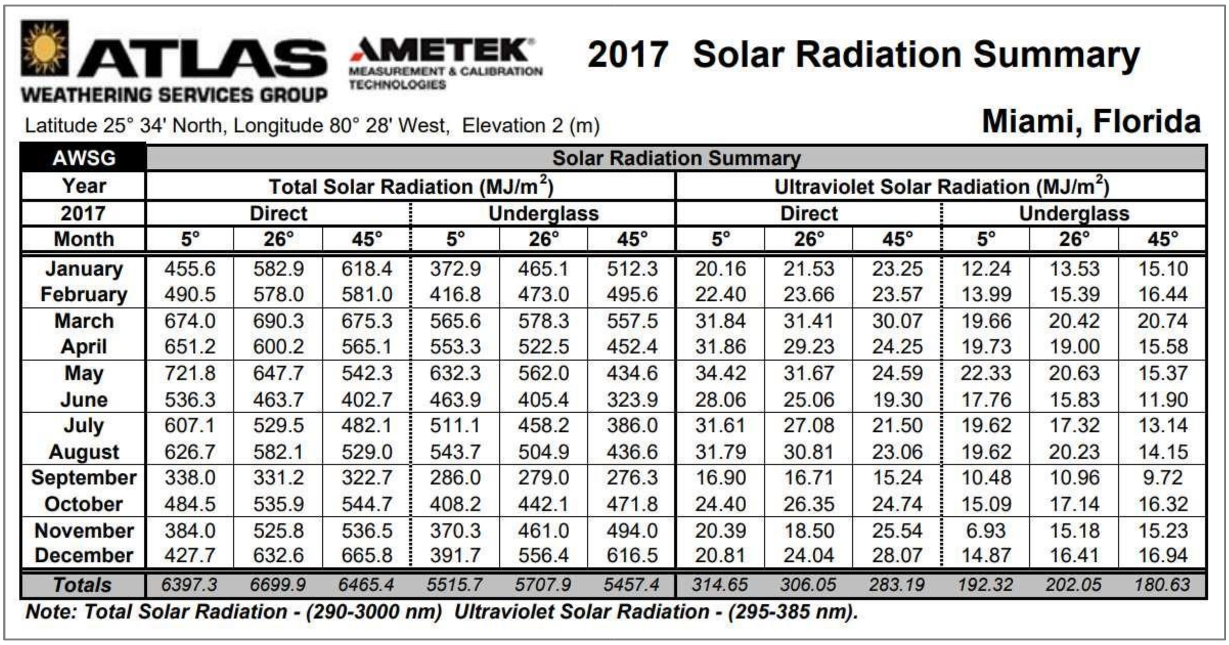
Irradiance will also change as the source to test specimen distance is altered, but will not affect the spectral balance.

Radiant exposure (H)

Radiant exposure, the energy dose the test surface receieves, obviously accumulates only during the light portions of an outdoor diurnal cycle or laboratory test cycle, so dark time is not included. This must be taken into consideration when basing laboratory exposure endpoints on duration. For cycles with dark periods, the total test time will be longer than for a continuous light exposure to reach the same radiant energy. Timing and comparing tests based on radiant energy is typically preferred over chronological timing e.g., hours).

Exposure “equivalences”

A very common question is “how long do I need to run laboratory test method “X” to equal “Y” years exposure outdoors in location “Z”? The issues of exposure correlation and specific material degradation are very complex and there are no simple answers to this question. Also, the answer is different for different test condition/test material combinations. Actual correlation can only be established by comparing the outdoor and laboratory test results for a specific material formulation and a specific property change. However, this presents a “which came first, the chicken or the egg?” problem in that often the very reason for laboratory testing is because there is no real-time outdoor test data for the material, and/or it will take too long to produce.



ATLAS WEATHERING SERVICES GROUP
AMETEK MEASUREMENT & CALIBRATION TECHNOLOGIES

2017 Solar Radiation Summary

Latitude 25° 34' North, Longitude 80° 28' West, Elevation 2 (m)

Miami, Florida

AWSG	Solar Radiation Summary											
Year	Total Solar Radiation (MJ/m^2)						Ultraviolet Solar Radiation (MJ/m^2)					
2017	Direct			Underglass			Direct			Underglass		
Month	5°	26°	45°	5°	26°	45°	5°	26°	45°	5°	26°	45°
January	455.6	582.9	618.4	372.9	465.1	512.3	20.16	21.53	23.25	12.24	13.53	15.10
February	490.5	578.0	581.0	416.8	473.0	495.6	22.40	23.66	23.57	13.99	15.39	16.44
March	674.0	690.3	675.3	565.6	578.3	557.5	31.84	31.41	30.07	19.66	20.42	20.74
April	651.2	600.2	565.1	553.3	522.5	452.4	31.86	29.23	24.25	19.73	19.00	15.58
May	721.8	647.7	542.3	632.3	562.0	434.6	34.42	31.67	24.59	22.33	20.63	15.37
June	536.3	463.7	402.7	463.9	405.4	323.9	28.06	25.06	19.30	17.76	15.83	11.90
July	607.1	529.5	482.1	511.1	458.2	386.0	31.61	27.08	21.50	19.62	17.32	13.14
August	626.7	582.1	529.0	543.7	504.9	436.6	31.79	30.81	23.06	19.62	20.23	14.15
September	338.0	331.2	322.7	286.0	279.0	276.3	16.90	16.71	15.24	10.48	10.96	9.72
October	484.5	535.9	544.7	408.2	442.1	471.8	24.40	26.35	24.74	15.09	17.14	16.32
November	384.0	525.8	536.5	370.3	461.0	494.0	20.39	18.50	25.54	6.93	15.18	15.23
December	427.7	632.6	665.8	391.7	556.4	616.5	20.81	24.04	28.07	14.87	16.41	16.94
Totals	*6397.3*	*6699.9*	*6465.4*	*5515.7*	*5707.9*	*5457.4*	*314.65*	*306.05*	*283.19*	*192.32*	*202.05*	*180.63*

Note: Total Solar Radiation - (290-3000 nm) Ultraviolet Solar Radiation - (295-385 nm).

Figure 7. Atlas Miami test site solar radiation data summary for calendar 2017.

Despite the above caveats, a starting point is often needed, if for no other reason than to estimate the end date of the test. The first step is to select an appropriate testing method and test conditions, whether following a standard, or a proprietary or even a custom test, as appropriate for the combination of test material(s), specific service use environments(s) and the objective(s) of the test. Test method and criteria selection, and overall test planning, including analytical measurements and measurement intervals, specimen replicates, specimen form factor (size and shape), is a critical step, and is beyond the scope of this document.

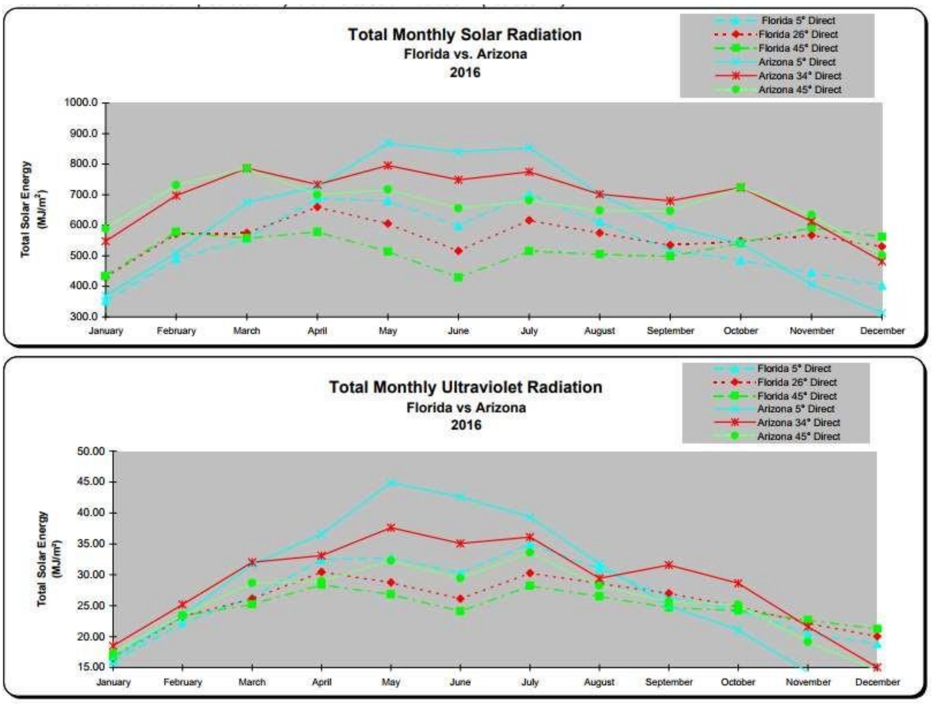


Figure 8. Graphical 2016 annual Miami total solar and total ultraviolet and radiation.

Second is determining the overall test duration. Lacking any correlation or other performance data, or knowledge regarding the degradation mechanisms, the approach most often used is to provide an "equivalent" exposure in the laboratory chamber (or other accelerated weathering device such as one of the EMMA or EMMAQUA solar concentrating outdoor exposures). "Equivalent" here means a) within the limits of the technology and b) knowledge that all accelerated and/or artificial tests will alter the natural stress balance, and not completely mimic the actual exposure. Atlas measures total solar and total ultraviolet radiation at several global outdoor test sites such as Miami, Florida and New River, Arizona in the USA. These measurements (both direct and under glass) are made at various test rack exposure angles and provide high resolution solar radiation data, which can then be averaged over multiple years to reduce yearly variability ("Climate is what you expect, weather is what your get"). Test site weather and solar radiation data is available at www.atlas-mts.com in both graphical and tabular form. An example of annual Miami test site solar radiation data is shown in Figures 7 & 8.

Common exposure angles, tilt being measured from the horizontal 0°, are 5°, at-latitude (e.g., 26° Miami, 34° Phoenix), 45°, and 90° North or South). Exposure racks face towards the equator (i.e., South facing in the Northern hemisphere); vertical exposures, such as paint panels, are also performed facing away from the equator for mold and mildew studies. As the ratio of UV versus total solar energy varies (Figures 7 & 8) with latitude and local climate (particularly atmospheric moisture), specific exposure angles may be optimal for particular exposures. In general, samples should be exposed simular to their in-service use, but there are exceptions.

The most common way of providing an initial estimate for an accelerated test radiant exposure "equivalence" to Miami (or any location for which reliable solar radiation data is available) is to deliver the "same" total solar or (more typically) the "same" total ultraviolet radiant energy averaged on an annual basis, within the capability of technology.

However, it is critical to understand that this is not correlation, does not account for the effects of other stresses such as temperature, moisture (or their natural cycles), or account for any specific material-related sensitivity to any stress. It is a “black box” approach and only approximates an outdoor exposure. However, lacking reliable correlation data, it is usually a reasonable, and often necessary, first approximation for determining a test duration endpoint. This also assumes that the testing methodology selected is appropriate for the material and service environment. This is generic guidance only, and may not apply to a specific material or situation.

Also, consider that product duty cycle, i.e., the actual time that in-service product will be exposed to optimum testrack equivalent exposure (such as due to partial shading, compass direction or orientation, etc.) may be used to adjust these equivalence estimations. A similar process can be used for building or automotive interior glass-filtered daylight situations. Atlas weathering experts can help advise regarding test method selection and test duration, or engage in consulting projects for more intensive involvement.

However, these estimates for accelerated artificial weathering should always be confirmed with real time exposures in the dessired service use climates.

Note 1. Newton’s inverse square law only directly applies to point light sources. Laboratory exposure devices typically use source geometries that are not point sources, or use multiple sources, so there is some deviation from the mathematical formula and the actual irradiance value should be measured rather than calculated. However, the concept of the relationship between source-to-specimen distance and irradiance still applies.

Author: Allen Zielnik, Atlas Material Testing Technology LLC, 16 February 2018