PerkinElmer®
precisely.

Xenon: The Full Spectrum vs. Deuterium Plus Tungsten

by Robert A. Capobianco

Abstract

Analytical techniques employed in modern methods of substance analysis are essentially derived from the foundation science of atomic and molecular absorption spectroscopy which deals with the theory and interpretation of optical spectra (a.k.a. the quantitative and qualitative study of elements and compounds). Some of the familiar technologies which are based in spectroscopy are: Clinical Chemistry, High Performance Liquid Chromatography, Fluorimetry, Timed-Flight Fluorimetry, Phosphorimetry, Immunoassay Testing, and many others. Instrumentation designed to support these technologies require four fundamental constituents: an appropriate light source, a spectrally dispersive optical element, a detector system and signal processing electronics. The latter three components may be a variety of devices in different configurations such as ruled/holographic gratings or discrete optical filters; photomultipliers, photodiode and CCD arrays; transimpedance amplifiers, or logarithmic voltage converters, using analog to digital or voltage to frequency converters, generally with a CPU/microprocessor based dedicated computer.

The selection of the light source is more distinct. The most commonly employed wide band spectral sources are, pulsed and continuous arc type lamps, hollow cathode lamps and filament lamps. Some specific applications still effectively use the methods of flame, RF-induction and arc-spark spectroscopy. Yet others introduce the sample to be analyzed into the radiative emission such as with plasma-jet and chemiluminescence emission spectroscopy.

This dissertation will deal only with the more commonly used xenon, tungsten and deuterium radiation sources and a comparison of their implementation in analytical instrumentation, and, speculations of requirements of the future. This is not a research oriented thesis, but merely a paper constructed to review and assist people in understanding an important tool which offers broad potential in the realm of the analytical sciences and illumination technology.

Introduction

Absorption spectroscopy is the study of radiated energy as a function of wavelength, which is *absorbed* by the atoms of an element of compound under excited conditions. (Conversely, emission spectroscopy is a study of radiated energy as a function of wavelength, which is *emitted* by the atoms of an element or compound under excited conditions). Essentially, spectroscopy is an empirical method which enables the researcher to identify and quantitize a material and its composition to great precision.

Basically, a sample to be analyzed is bombarded by a high intensity, high density radiation which may be visible light or **UV** or thermal in nature. An atomic vapor is created which initially emits photons upon incidence and eventually absorbs photons in recombination in a lower energy field. The wavelength at which the photons are emitted or absorbed are very precisely and uniquely characteristic to infinitesimal bandwidth dimensions (i.e. , 1 Å ~ 0.1 nanometer) of the sample being analyzed.

This scientific phenomenon was originally discovered by Wallaston and Fraunhofer circa 1812 who noticed dark lines in the sun's spectrum and luminous vapors of various elements, when produced by a prism and a narrow slit. Each and every one of the 103+ elements known to man emit or absorb many very specific wavelengths of radiation which are related to its atomic structure and the *intensity density* of the exciting source.

The words intensity density are emphasized because it is important to the design of spectroscopic instrumentation that the selection of the exciting source becomes most important in deciding the specifications and limitations of the analytical system… especially with future trends in UV analysis, fluorescence, resolution, trace analysis, microsampling and quantitative sensitivity. For example, a high resolution grating will spread the spectrum over a wider linear dispersion (e.g., 1 nanometer/mm to 0.01 nanometer/mm) to allow the distinguishing of absorption lines of different elements, but in doing so will inadvertently diminish the contrast of those lines because the total excited energy is spread over a larger area.

To reiterate, selection of the excited source is critical in the design of spectroscopic systems. Specifically, source energy density is paramount to efficient design, especially with respect to future expectations and obsolescence. A 300 watt generator which produces 4 optical watts into a 12 millimeter half power focus offers no advantage whatsoever to a 20 watt source producing a 0.5 optical watt into a 5 millimeter half-power beam, when employed in a typical 1.0 nanometer resolution system with a 16 nanometer/millimeter dispersion.

Systems Overview

Absorption spectroscopy is most commonly employed in the biological sciences. Systems include analytical research, blood-gas analyzers, HPLC-high performance liquid chromatography, gas chromatography, immunoassay analyzers and others whose spectral region of interest (for the present) extends nominally between 330 nm and 700 nm with a bandwidth resolution of about 10 nm. They may be the scanning type with motor driven grating or the spectrograph type with motor driven grating or the spectrograph type which employ photodiode or linear CCD arrays complete with integrated rapid signal processing electronics on a microchip. Researchers exploring and developing systems for fluorimetry, timed-fluorimetry, phosphorimetry and the unknown have extended the range of the shorter wavelength down to 250 nm and lower.

Other methods using basically the same electro-optical elements in commercial applications are colorimetry, chromaticity evaluation, ultra-violet analysis, color temperature rendering, photography, actinic filter development, et al. The spectral range of these systems are bounded by practicality between 1100 nm which is the long wavelength limit of sensitivity of a silicon detector, and 180 nm because of air-cutoff and ozone generation. Prior to the advent of the holographic grating, especially the concave type, short wavelength spectral analysis was limited to about 400 nm, and with poor accuracy and resolution at that.

Prior to the late 80's, most of the analytical systems mentioned above employed both tungsten and deuterium continuous lamps as the source. Certain specific applications used gas flame, argon plasma jet, spark and RF excitation methods, and some still do.

Tungsten lamps are used to cover the spectral range from about 340 nm to 1100 nm; the deuterium generates the ultraviolet radiation from about 400 nm down to 180 nm. The systems are generally the dual-beam scanning type where at a selected crossover wavelength during a scan, data processing is paused and the focussed beams of the lamps are opto-mechanically switched by lens/mirror and motor. The scanning dual beam method essentially alleviates the requirements and nuisance of order sorting filter correction (grating harmonic blocking). **It works**; **it has its limitations.**

In the late 1980's, PerkinElmer, Salem, MA began working with many companies in the successful development of a variety of systems which use a single pulsed Xenon arc source to cover the full spectral ranged from 180 nm to 1100 nm (or any selected bandwidth within) in a spectrographic configuration, and complete with dispersion optics, reference channels and signal processing electronics. All systems are customer-specific in parameters, operation and application and surprisingly, all are different and unique to a specific market feature individually. Quantity OEM production of these systems and sub-systems extends from 1990 to present with 2nd and 3rd generation designs in progress.

During the early development period PerkinElmer expended a considerable R&D effort concentrated in successfully redesigning the Xenon flashlamp, trigger module and OEM power supply circuits for ultimate performance in flash repeatability and temporal, spatial and spectral stability. EMI/RFI reduction, extended lamp life, increased efficiency, *experience and knowledge* were important additional by-products. (See [Design Considerations for High-Stability Pulsed Light Systems](#) by Robert Capobianco).

Again, with more than a factor of ten in increased efficiency x energy density, a single Xenon flashlamp covering the full spectral range will replace the tungsten and deuterium lamps and all the extra mounting and opto-mechanical switching hardware. Further, the PerkinElmer 1100 Series offer a 20 watt flashlamp with an outer metal sleeve accurate to arc location within < 0.008 inch which, in many designs, eliminates the need for XYZ and q adjustments for field replacement. Various arc sizes and window transmitting glasses are available.

Even further, the PerkinElmer 1160 Series Flashlamps, which are identical in package size, incorporate an internal integrated reflector (F*/0.7) which reflects rear emitted radiation back through the arc to increase the output **and eliminate the optical noise inadvertently generated by backscattering off the pin press.**

The remainder of this publication will deal with the case for xenon, replacing the tungsten + deuterium source, or, any other intensity comparable source.

Spectral Considerations

There is a profound distinction between the spectral response distribution between CW (continuous wave) and pulsed xenon lamps regardless of the manufacturer. That difference is in the order of a factor of 5 to 10 in the total energy radiated below 400 nm. For a pulsed xenon flashbulb approximately 40% of the total optical energy is radiated below 400 nm and abut 25% is in the visible. For CW xenon, about only 4% to 8% is converted to radiation below 400 nm, and only < 1% is distributed below 250 nm, making CW xenon

very unattractive where interest in the UV is essential, especially with an eye toward the future. However, pulsed xenon is especially rich and unequaled in the UV, but engineers who are familiar with CW sources have an aversion to designing with pulsed sources for a whole variety of unfounded reasons: EMI/RFI, repeatability and stability, cost, high voltage, high frequency amplifier requirements, drifting offsets and whatever. It is still not uncommon to encounter someone who has gone form a 5 watt tungsten lamp to a 100 watt halide just to obtain a fractional increase of emission in the blue. It is one of the intentions of this paper to alleviate that aversion.

Some have asked, What about mercury, krypton, argon and metal halide lamps? Briefly, all have long warm up times; argon is less efficient than xenon, krypton distributes much of its spectral energy output in the 750 nm to 900 nm bandwidth (which is more ideal for pumping YAG lasers); mercury is too line structured rather than spectrally continuous, and metal halides are deficient in the UV. Xenon is relatively flat with the exception of a couple of inconsequential (actually useful) blips between 225 nm and 250 nm, and requires no warm up time or preflash.

For further clarity, refer to Figures 1 through 3. Figures 1 and 2 are identical except that they y-ordinate is logarithmic in Figure 1 and linear in Figure 2 for perspective.
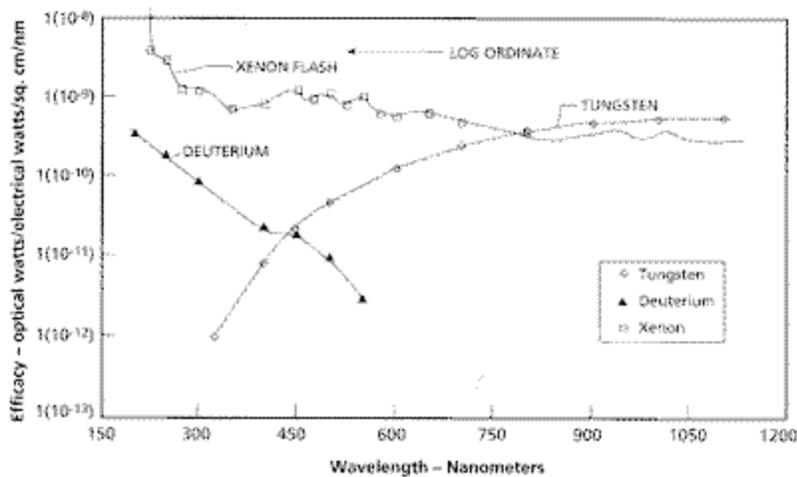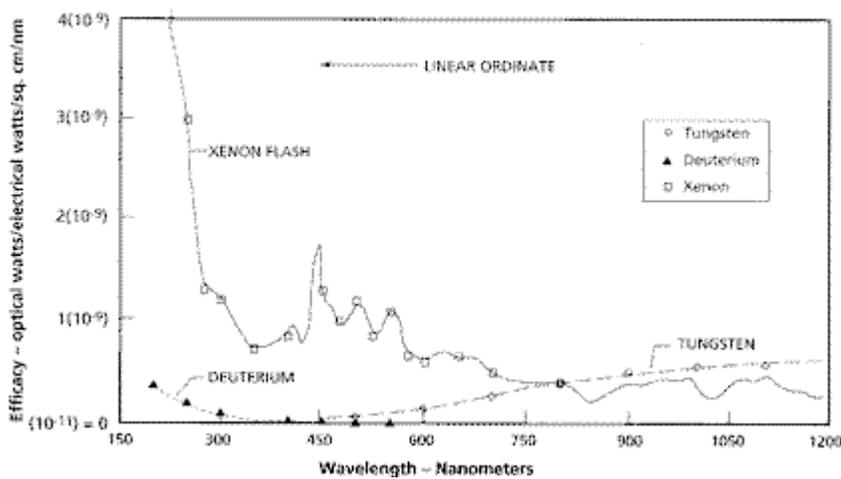

Figure 1

Figure 2

Typical Spectral Distribution of Xenon Flashlamps and Window Transmittance

WAVELENGTH IN NANOMETERS AND LIGHT OUTPUT DISTRIBUTION IN %
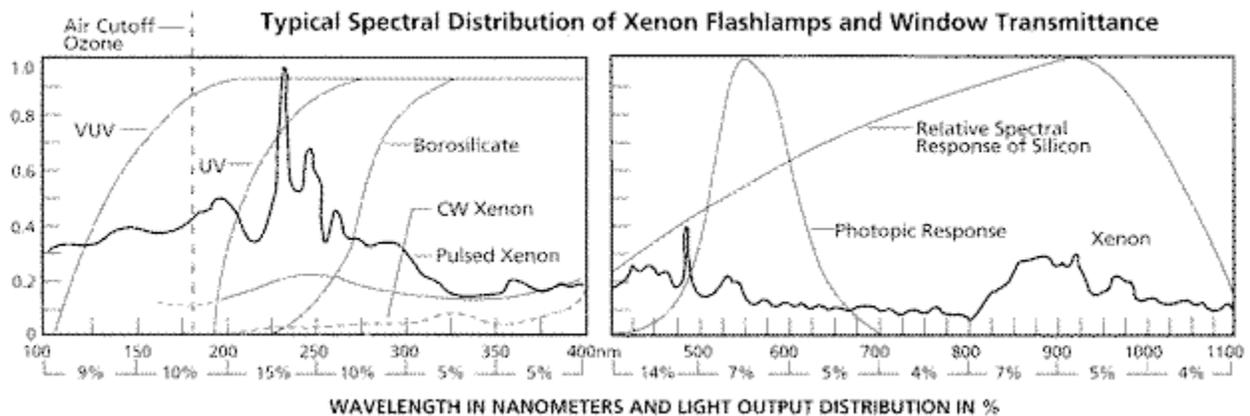
Figure 3

Figure 3 graphs the efficacy for a typical set of operating parameters of a xenon flashlamp normalized relative to 1.0 at a 236 nm peak. Note especially the dashed line in the UV region below 400 nm which indicates the spectral response of CW xenon. Measurements were made with a 5 nm half power bandwidth resolution. Note that the abscissa also allows the designer to determine the percentage of the total energy of the emitted radiation (pulsed xenon only) which falls within a bandwidth division. The infrared energy - 1100 nm to about 4 or 5 microns - would be on the order of about 5% to 10% of the total but has been ignored in this treatment for clarity. Also indicated for convenience are the relative responses of the photopic curve, silicon detector sensitivity and (3) three of the envelope window materials commonly employed in flashbulb fabrication by EG&G.

Although not directly pertinent here, another feature of xenon is that its spectral response closely resembles that of 5500°K sunlight especially in the visible between 400 nm and 700 nm. See Figure 4.
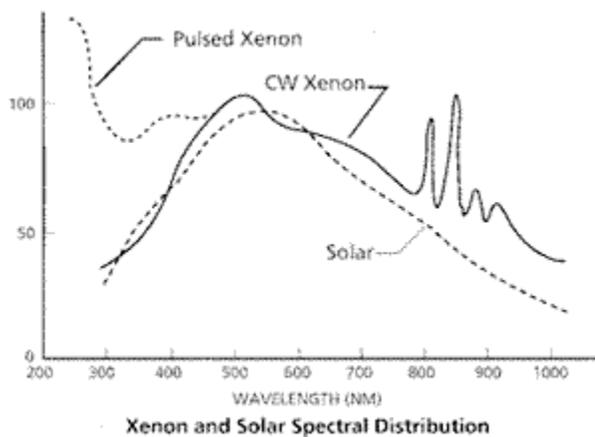

WAVELENGTH (NM)

Xenon and Solar Spectral Distribution

Figure 4

Energy Density Transfer

In optical imaging with lenses and reflectors, it can be shown that maximum energy density (not intensity) occurs when the magnification (M) is equal to one. (M = 1 is also a condition

where the distance between image and object is a minimum). This can present a limitation dilemma in energy density transfer design. For example, in developing a system which will efficiently focus the light from a tungsten filament lamp which may be 2 mm x 5 mm in dimension onto a 0.5 mm x 12 mm slit or 10 mm diameter fiber optic bundle, the designer may elect to use compound aspheric or condenser lenses, or much better yet an ellipsoidal reflector or even a toroidal mirror. However, as long as the combined transverse and axial resultant magnification exceeds the ratio of 1:1 (target dimension/source dimensions) or if the source is larger than the target, energy and system performance are then painfully compromised and wasted.

(By geometric definition, the magnification of a finite source by an ellipsoidal reflector is always greater than one and directly related to the spacing between foci and the ellipse angle e = arc tan (a/f) where a is the minor axis and f is the focal length. As the spacing between focal points reduces to zero, the ellipsoidal reflector reduces to a hemispherical mirror with, of course, a magnification equal to one.)

In arc-plasma sources such as the xenon flashlamp or CW arc lamp, the electrode spacing is typically only 0.030 to 0.060 inches (0.75 to 1.50 mm) mainly because arc lamps with lesser spacing operate at much reduced efficacies and arc lamps with larger dimensions operate at greater power but have strike and stability problems and in general, shorter lifetimes. It becomes clear then that this type of source will replace the filament lamp to great advantage and accommodate the shorter wavelengths (UV) as well with far greater efficiency and ...*energy density.*

A slight but pertinent digression:

The problem becomes considerably more complicated when the customer, the application and the market demand even greater light concentration into the sample size or fiber optic equal or smaller than the diameter of the source (i.e.; < 1 mm and magnification less than 1) with the same conservation of efficiency. The use of a hemispherical (a.k.a. spherical) concave mirror offers one compact solution, where the arc source and image are equally separated on both sides of a radial bisector of the mirror as in Figure 5. However, this design has its problems and limitations which evolve around the collective F#, the proximity of the source and image and size, alignment and replacement considerations, aberrations and losses and cost. Gattling type multiple lamp arrays have been proposed and demonstrated, but again are too large, cumbersome and costly for industrial use.
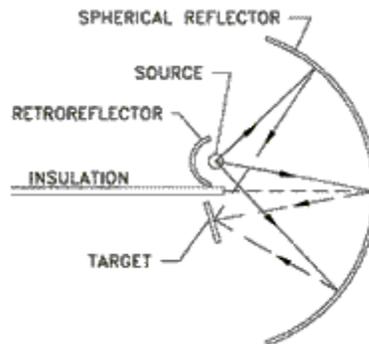

Figure 5

There must be a simpler, less expensive method of increasing the energy density or PEAK intensity per area incident to a target. However, the best instruments reviewed to date employ what some call the brute-force method which form a 300 to 500 watt **CW** lamp system will deliver only a few optical watts of visible light; less than a fraction of that in the UV; and more IR per steradian than the Chicago fire, **plus** enough dissipated heat to challenge a local room air conditioner. Again, with circumspect design, a pulsed xenon system will out perform any other source for a broadband application.

It is important to keep in mind that the above proposition pertains to applications and analytical systems where the sampling time or spectral scanning time is preeminent in system design and performance as in immunoassay testing and machine vision instrumentation. It does not (necessarily) impact in the same manner when applied to continuous visible lighting functions such as the surgeon's headlight and remote endoscopic illumination.

Further discussion in this area is beyond the scope intended for this review and will be the subject of another interesting paper; which ill include results of experiments with the Blondel-Rey Effect and the Phi Phenomena.

Is there another way? How can the flashlamp be used to greater advantage over that of the CW lamp, particularly in the ultraviolet where research and applications are persistently extending the state-of-art in the direction of shorter wavelengths?

A Case for Xenon Flash

Medical and industrial analytical systems commonly employ tungsten, deuterium and xenon lamps for sources for reasons elaborated upon earlier in this report. The tungsten and deuterium lamps must be continuous by physical nature and require substantial warm-up times on the order of about 20 to 30 minutes for stabilization of emission.

> *(Some inroads have been made in simmer-pulsed operation of deuterium, but not enough to matter in significantly extending most design concepts)*

Although tungsten lamps may be capable of long life, deuterium lamps have a very finite lifetime on the order of about 500 to 1000 hours with a constant (even predictable) deterioration of light output usually specified as down to the 50% level. Furthermore, even if the deuterium lamp is used only for a fraction of a spectral scan, it must be kept operating and ready during the full on time of the instrument, which in busy laboratories is often 8 or more hours a day. The replacement of the deuterium lamp generally determines the frequency of system maintenance. Xenon flashlamps operating at intensities and efficiencies of greater than a factor of 10 in comparison are readily known and specified to exceed 10^9 to 10^{11} pulses depending upon energy and power levels, which translates to lifetimes measured in years, rather than hours or months. This is not conjecture, but the case for over a decade worth of experience, research and process control.

Flash-to-flash repeatability, reproducibility, and stability (see [Design Considerations for High-Stability Pulsed Light Systems](#)) are specified by the flashlamp manufacturer and are limited, at least to date, by still unknown phenomena in pulsed arc-plasma formation. Actually, when compare to so called stable steady-state (CW) arc lamps, PerkinElmer xenon flashlamps offer the designer less stability design problems! CW lamps often require very

long thermal (or other) stabilization periods (typically ½ hour or more), are less efficient, have shorter life per energy characteristics and generate continuous EMI/RFI. Not unlike flashlamps, CW lamps also exhibit sporadic arc wander, peak-to-peak noise, flicker and even other essentially inexplicable error phenomena designated/grouped into a category called fliers which are usually contended with by statistical exclusion. When using the flashlamp, however, the light or energy pulse (in the order of μsecs) is only initiated for the measurement and is off for the remainder of the duty cycle.

Any analytical system requiring an accuracy and repeatability of less than ± 0.5% requires a **reference channel** to correct for short and long term variations in flashlamps and CW lamps. The main beam is optically split into two channels, one which traverses through the sample under analysis, the other unobstructed beam is the reference which is divided/ratioed with the sample beam for the normalization of source variations over a fairly wide range limited only by second order errors.

In the spectral scanning instrument, reference correction proceeds simultaneously as the wavelength changes. In the spectrograph-array system, referencing becomes more complicated (but not insurmountably so) where one or many reference channels may be used to cover the spectral bandwidth, and then most expeditiously processed with a microprocessor. The spectrograph type system may also require the addition of optical sorting filters in the focal plane at the detector array depending upon design and performance factors.

A concise and generalized overview of a typical system design from source to readout/computer is illustrated with more definition in the PerkinElmer Toolbox brochure available from PerkinElmer Optoelectronics.

Again, bear in mind that, in general, all analytical instruments employing any type of radiation source, specifically tungsten plus deuterium versus xenon, require incorporation of reference optics and electronics whether addressed initially in prototype design or eventually after a great deal of time, effort, expenditure, and frustration have been expended. The contention here is that for the more sensitive and accurate system design, it is easier to implement referencing with a pulsed system whether it be a scanning or a spectrographic configuration. Designing a spectrographic instrument with a single dual element source presents an interesting challenge primarily because of spatial anomalies; however, even with a dual element emitter, lamp life is still limited by the deuterium element where cost and replacement source availability becomes a constraining consideration.

EMI/RFI and signal noise have always, universally, and consistently been a nuisance in the design of any electronic development. Engineers have always balked at the idea of containing a high voltage trigger and discharge device in the same box with a detector circuit that is processing literally dozens of signals in the picoampere level; but, it is done accurately and successfully every day. Much has transpired in that technology in the last decade or so primarily because of necessity and the understanding of the physics of EMI/RFI, and the development of instruments to analyze and trace it, and most significantly, the invention of materials to reduce, control and confine it. All PerkinElmer 1100 Series Flashlamps, trigger units and power supplies have been redesigned with the virtual elimination of EMI/RFI as a mandate. The extent to which this was accomplished involved modification of flashlamp electrode, pin and socket construction and materials, suppression elements to eliminate intrinsic resonance, proprietary topography and miniaturization, and many other changes and options, including opto-isolators and fiber

optic links. Modularization also played an important role in that each element (e.g., trigger unit) was treated individually to a limiting specification.

As a consummate example, the PerkinElmer Series LS-1130 Flashpacs, complete compact flash sources, are basically a Faraday Cage box with two small openings, i.e., one for light output and one for two wires to connect to power. Also, a library of application specific Flashpacs with a variety of options have evolved to facilitate rapid development of custom requirements including size and shape. These products are low cost, tested, burned-in and ready to simply connect and experiment with for prototype studies or production installation… all are EMI/RFI FREE and easy… no contending with elusive interference. CW signals are simple to process electronically. *What about the extra complexities in dealing with high frequency pulse amplifier circuitry and signal-to-noise levels therein?* There are none, and it can be shown that CW signal processing in sensitive sampling systems can be more difficult than pulse detection.

Analytical absorption analysis is governed by Beer's Law: transmittance of a stable solution is an exponential function of the concentration of the absorbing solute. Analytical transmission analysis relates to Lambert's Law: transmittance of a solution, or the internal transmittance of a transparent solid, is an exponential function of the thickness of the layer. A sample may be in the form of a solution (or a gas) contained in a flow cell, a capillary column, a cuvette cell or just an optical glass/filter or reflective surface. A light beam of any bandwidth is transmitted through (or reflected from) the sample, the exitant beam is detected, referenced and correlated to some known standard. The sensitivity and the speed of the instrument are related to the intensity of the source (watts) and the time interval (seconds) for which the sample is exposed. As an example of comparison, if a 10 watt/continuous source required 10 milliseconds to affect a design goal detection objective, the (10 watts)(0.010 seconds) = 0.10 watt-sec or 0.10 joule of energy. The same measurement can be made with a flashlamp operating at 0.10 joule (typically low level) energy pulse in one μsec or 10^{-6} seconds. The average power of a flashlamp is given by (joule/pulse) times the flash repetition rate, which means that the flashlamp can be pulsed 100 times before the average power dissipation equals that of the CW lamp, i.e., 10 watts. Of course, both systems would be operating at 10 watts, but the pulse source need not generate more than 0.01 watt to make the exact same measurement and still have the option of a dynamic range of 100 to 1. The sensitivity of pulsed units can be increased by multiple pulsing if elected, while the CW source burns away at a fixed 10 watts. Reflecting upon that, consider the ramifications or realistic numbers in an instrument which is to be used to analyze a trace solution in a fluorescent excited sample in the far UV (or high opacity 6 cavity blocking filter around 185 nm), and, … the fact that pulsed xenon is capable of at least a decade more optical power output in that range.

Regarding Pulse Amplifiers

A complete dissertation and all the details of integrator design would occupy about 2-3 chapters in a textbook, and those are abundant. In this brief introduction paper, it must suffice to elucidate upon only a few parameters which are sometimes overlooked or unfamiliar.

Slew Rate vs. Bandwidth

Acquiring a 1 μsec pulse having a hypothetical rise/fall time of 10 nsec does not require a wide band amplifier with a $(0.35)/(10)(10^{-9})$ = 35 megahertz 3 db frequency response. The Beer-Lambert Laws relate absorption to the energy of the excitant beam (not the peak or a

level) and therefore the integral (energy = watts x time) of the sample and reference pulses is what is important and must be determined. Simply stated, the input amplifier becomes an integrator with a capacitive feedback, as illustrated in Figure 6.
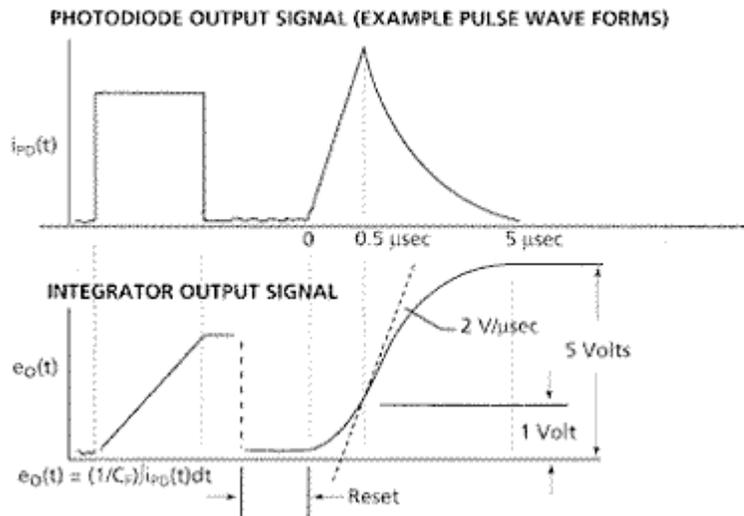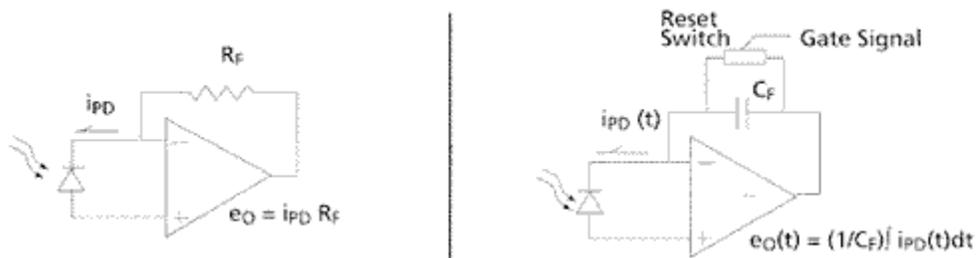
PHOTODIODE OUTPUT SIGNAL (EXAMPLE PULSE WAVE FORMS)

Figure 6a. Example of Integrator Amplifier Output

Figure 6b. Linear and Integrated Transimpedance Amplifiers

Measured Samples, Amplifier Output
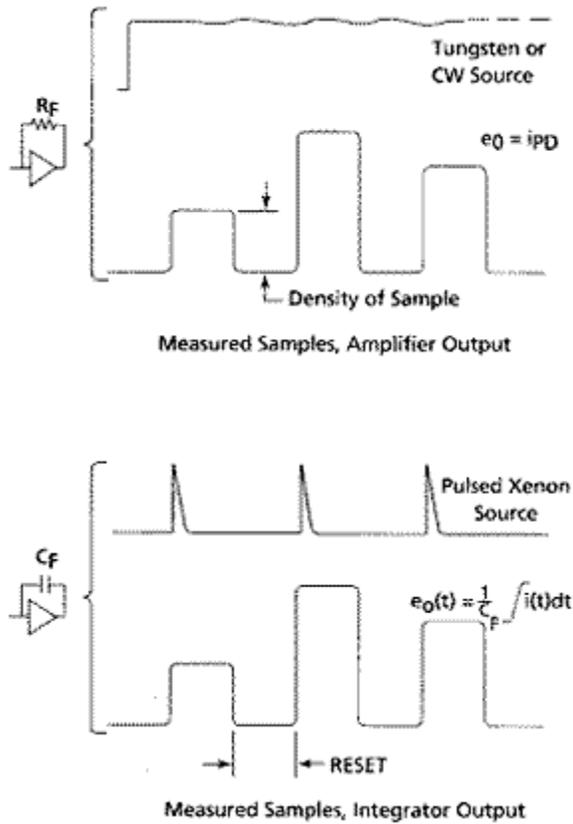
$e_0 = i_{PD}$

Tungsten or CW Source

Density of Sample

R_F

Measured Samples, Integrator Output

Pulsed Xenon Source

$e_0(t) = \frac{1}{C_F} \int i(t)dt$

RESET

C_F

Figure 6c. CW and Pulsed Measurement Results Compared

$e_0(t)$ Integrator Amplifier Signal Out
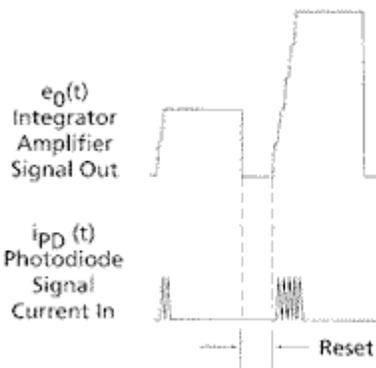
$i_{PD}(t)$ Photodiode Signal Current In

Reset

Figure 6d. Additional gain is obtained simply by multple pulsing during sample integrations

The integral of a square wave is a ramp in which its Fourier frequency content has nothing to do with the rise time of the square wave except that it is always slower. Therefore, what becomes important is the slew rate of the amplifier, not its frequency response.

As an example, consider a typical flashbulb pulse, with a rise time of about 0.5 μsec and an exponential trailing edge out to about 5 μsec, and an amplifier design which is configured to produce an output signal of 5 volts; see Figure 6a. Assume that the area (integral) under

the signal waveform in the 0 to 0.5 µsec interval is about 1.4 that of the area between 0.5 µsec and 5 µsec. The integrated signal will rise to 1 volt during that interval, and then continue to rise to 5 volts in the remaining 4.5 µsec. The required slew rates of the integral signal of the respective intervals are 1 volt/0.5 µsec, and 4 volts/µsec for a maximum of 2 volts/µsec, a specification easily met with a simple, inexpensive microchip.

Note that in Figure 6b, a reset switch is shown across the feedback capacitor C_F to short it to zero and ready it for the next measurement. The reset should be a J-FET transistor or analog switch type with very low leakage (depending upon the capacitor isolation resistance) from source to drain and especially from gate to amplifier input which would cause integrator zero and output signal drift. A high impedance drain resistor can often replace the switch if the sampling duty cycle is such that if the RC_F drain constant is > 100 times the acquired signal risetime.

The Feedback Capacitor - Gain and Droop

The capacitor sets the integrator gain according to $E_{OUT} = (1/C_f)$ *integral* $I(t)$ *dt* and to eliminate droop, should be the low leakage, high insulation resistance type such as mylar, polycarbonate, polyester or even Teflon depending upon farad value and user environment. Droop is determined from:

$$e(t) = E_{out} \, e^{-t/RC} \text{ or}$$
$$ln_e[e(t)/E_{out}] = -t/RC \text{ and}$$
$$R = -t/\{Cln_e[e(t)]\} \text{ or}$$
$$R = +t/\{Cln_e[E_{out}/e(t)]\}$$

where E_{out} is the integrated output voltage and $e(t)$ is the E_{out} at some time after integration.

As an example: a design objective specifies that the maximum allowable droop of a 10 volt signal be < 0.25 millivolts in < 5 milliseconds following the integration interval:

$$e(t) = E_{out} = 9.99975/10.0 \text{ or,}$$
$$ln_e[e(t)/E_{out}] = -2.5 \, (10^{-5}).$$
$$\text{For a CF} = 1000 \text{ picofarad} = 10^{-9} \text{ farad}$$
$$R > -5(10^{-3})/(10^{-9})(-2.5)(10^{-5}) = 2(10^{11}) \text{ ohms}$$

R > a 200,000 Megohm isolation resistance is required for the capacitor.

Charge Injection

In low level, high sensitivity integrator design, charge injection may cause a confounding error which without understanding may lead to abandon. Charge injection is generated by small intrinsic capacitance usually in the feedback switch, the input stage of the amplifier or their connection. It is specified in analog switches in the unit of picocoulomb.
The equation for an integrator:

$$E_{OUT} = (1/C_f) \text{ } integral \text{ } I(t) \text{ } dt$$

may be arranged as

$$C_F E_{out} = integral \text{ } I(t) \text{ } dt = \text{coulomb charge}$$

Quality analog switches specify charge injection in the order of 10 to 1 picocoulombs and less. Translated to results, this means, for example, with a 1000 picofarad C_F, a one picocoulomb charge injection will, when switched, affect Eout $= (10^{-12}/C_F) = 10^{-12}/10^{-9} = 1$ millivolt, superimposed on the integrated signal - which may become a nuisance. Charge injection can be reduced considerably/eliminated by keeping the reset gate driver low and slow (use discrete RC spoiler); keeping the gate driver shorted to ground when the reset is open (NC type switch); by reducing the output load impedance of the amplifier to a minimum; and by counterinjection.

Understanding Closed Loop Gain for Integrator Accuracy

Integrator accuracy is a specification which places a demand on the open loop gain of the amplifier. Refer to the sketch in Figure 7. One way to visualize it is that the photodiode generates a current which generates a voltage V_{IN} across C_{Shunt}, which causes the amplifier to react with an output V_{OUT}, which balances the feedback loop.

$$V_{IN} = V_{OUT}[C_F/(C_F + C_S)] \text{ and closed}$$
$$\text{loop gain} = V_{OUT}/V_{IN} = (C_F + C_S)/C_F$$

C_S is the photodiode shunt capacitance and must be known as measured. C_S is a function of active area size and process; e.g., for reference only - a high quality PerkinElmer 1 cm^2 active area photodiode will have a C_S in the order of 1000 picofarad or less. Accuracy of an amplifier is determined/given by $G_{closed\ loop}/G_{open\ loop}$ in volts/volt.

Amplifier Accuracy = $\dfrac{\text{Closed Loop Gain}}{\text{Open Loop Gain}}$

$i_{PD}(t)$

C_F

C_S

$e_O(t) = (1/C_F)\int i_{PD}(t)dt$

Closed Loop Gain $= V_{OUT}/V_{IN} = (C_F + C_S)/C_F$
where C_F is the feedback (plus stray) capacitance,
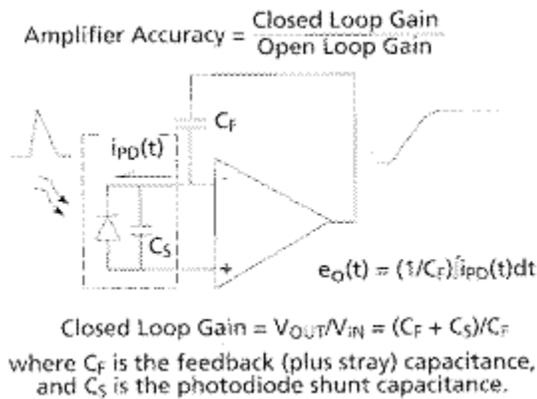and C_S is the photodiode shunt capacitance.

Figure 7

As a typical example, the accuracy of an integrator circuit using an amplifier having an open loop gain of 80 db is:

for $C_F >> C_S$, ~ 1/80 db = 1/104 = 0.1 millivolt for a 1.0 volt V_{OUT}, or 1.0 millivolt for a 10 volt output signal;

for $C_S >> C_F$, e.g. 10:1 the accuracy reduces to $10^1/10^4$, or only 10 millivolts for a 10 volt output.

Other Xenon Particulars

In reiteration, pulsed xenon is especially rich and efficient in the UV below 400 nm. This spectral region is an experimental working ground for a large number or researchers, scientists and engineers that are exploring and developing analytical, machine vision and process control instrumentation and systems with vision for the near future and early next century. The UV region is often divided into bands referred to as:

Ozone generating	180 to 220 nm
Bacterial (germicidal)	220 to 300 nm
Erythemal	280 to 320 nm
Black Light	320 to 400 nm

A more common grouping in radiometric terms is:

UV-A (phototherapy)	315 to 400 nm
UV-B (sunburn)	280 to 315 nm
UV-C (carcinogenic)	100 to 280 nm

Studies in medical and industrial fluorescence induced phenomena range from 190 to 500 namometers. The quest for increased energy in the UV is incessant, as always. For pulsed xenon, about 45% to 50% of the input electrical energy is converted to optical energy, with an efficacy in the range of about 150 to 280 lumens/watt lamps when operated at optimum conditions.

In the IR, xenon lamps extend out to 6 microns and beyond, but CW xenon lamps cannot compare with the efficiency of tungsten, however, the flashlamp *does* offer a *pulsed* IR capability and a considerable increase in exitance or **flux/area of the source** for whomever may be interested (i.e., compare the size of the coiled tungsten filament with the 1 mm arc-plasma spot).

More so than most elements in the periodic table, pulsed xenon exhibits abundant atomic line structure from the far UV to the near IR. These lines become more distinct with increased (grating) dispersion, increased detection bandwidth resolution, and are dependent upon the plasma-exciting energy. Systems designers and optical laboratories are known to employ pulsed xenon lamps as wavelength calibration standards. Line peaks may vary with operating conditions and from pulse-to-pulse, but the wavelengths remain exact, in cooperation with the laws of the universe. Some of the applications include the wavelength calibration of vacuum UV radiometers, photoionization systems in the 100 to 130 nm region, and IR laser harmonics below 1000 nm. In the UV region, pulsed xenon supersedes mercury because it **can be pulsed** rapidly and is used conveniently in some cases as an intermittent background grid.

Another important characteristic of xenon (~ 5500°K) is that its spectral response closely resembles that of sunlight especially in the visible between 400 nm and 700 nm. Unlike other lamps mentioned, a little known feature of xenon is that its photometric spectral output changes imperceptibly, if any, with life.

Figure 4 compares a CW xenon arc lamp with sunlight. For a pulsed xenon flashlamp, the peaks in the 800 to 900 nm region disappear and the UV output below 400 nm increases profoundly as shown. By selecting the energy level, the discharge voltage and the charge capacitance, the xenon flashbulb may be operated at essentially any color temperature from below 3000°K to above 15,000°K depending upon the design objectives. A discussion of color temperature and its implications will not be included here, however, the reader is

urged to at lest make a cursory investigation of Planks Radiation Law, emissivity, and the Stefan-Boltzmann Law for a fairly comprehensive introduction and understanding.

Reality

Some of the details about integration discussed above are really more pertinent to the design of instruments and systems approaching the limits of ultra sensitivity, very high speed strobing and micro sampling in spectral regions - particularly in the UV - where signal-to-noise ratios need be contended with. That technology and the components to support it exist, the design techniques have moved out of the experimental and prototype laboratories and onto the production floor, and PerkinElmer Optoelectronics has served an important part of it.

Conclusion

One (subtle!) attempt of this paper is to awaken and stimulate the interest of tungsten and/or deuterium user advocates to the attributes of pulsed xenon technology, especially for what lies in the future for ultraviolet analysis as far down as 100 nm and below. For the most part, pulse detection is straightforward and integrator amplifiers are uncomplicated. Developing instrumentation in the ultraviolet below 400 nm requires careful, and more complicated, design decisions and considerations, **and knowledge supported by experience,** *unless of course*, you are considering employing a long life, modularized, high-stability, high efficiency, high-intensity, pulsed flashlamp…of PerkinElmer manufacture…of course.

Comparison between Array vs Scanning and Xenon vs Tungsten-Deuterium Lamp. deuterium lamp. Array versus Scanning. UV Vis instruments can be classified according to the geometry of the components that build up the optical system for the recording of spectra. The following configurations are generally used in UV Vis spectroscopy: Scanning spectrophotometer, usually equipped with a Tungsten-Deuterium lamp. Tungsten-Deuterium lamp spectrophotometers are considerably less efficient since two lamps are required to cover the UV Vis spectral range. Moreover, they must continue to operate during the entire instrument up-time. This contributes to shorter life-times and higher instrument maintenance costs. Xenon vs. Solar spectrum. FeOOH TiO2. Xenon: The Full Spectrum vs. Deuterium Plus Tungsten by Robert A. Capobianco, http://opto.perkinelmer.com/library/papers/tp9.asp. Experimental. lamp Cr. Full range of height values = 8.0 nm • RMS roughness = 1.47 nm. Fe nanoparticles prepared by heating FeOOH nanoparticles in H2. Height mode; 286 x 286 nm.