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precisely.

DESIGN CONSIDERATIONS FOR HIGH-STABILITY PULSED LIGHT SYSTEMS

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Abstract

Understanding and characterizing the behavior of Xenon flashlamps is addressed together with discussion on the electro-optics of integrated systems. Flashlamp stability and efficiency as a function of arc plasma size, discharge energy, sampling rate, wavelength, operating life and the design or selection of the trigger and power supplies is described. Also treated are optics, component selection, the impact and importance of radiation collection efficiency, accuracy and referencing techniques and limitations. In-depth sharing of past development experiences will prove invaluable to the novice professional as well as the veteran engineer.

The flashlamp was invented by Dr. Harold Edgerton (fondly referred to as Papa Flash) of MIT in the late 30's and subsequently developed by PerkinElmer, Inc. (formerly Edgerton, Germeshausen and Grier, Inc.), for a wide variety of commercial applications such as high intensity beacons, motion stopping strobe systems, high speed photography and more recently, in the last decade in medical/clinical analytical systems. Basically, the flashlamp is a device which emits radiation generated by a confined, controlled explosion between two electrodes in an inert gas. The important word to note here is *controlled*, which makes the flashlamp an important component as the light source in modern day absorption spectroscopy and analytical fluorimetry.

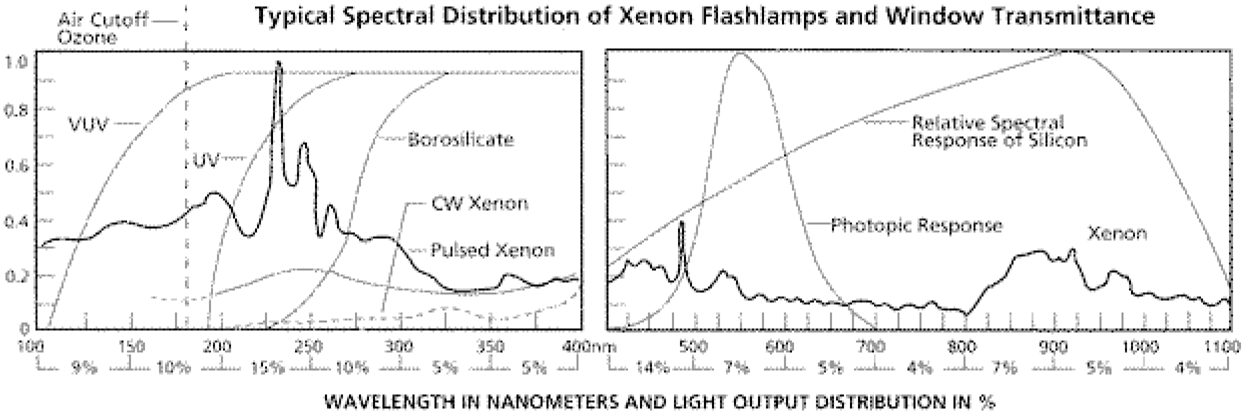

Figure A.

Efficiency

A primary characteristic of the xenon flashlamp is its capability of generating wideband radiation (< 50 nanometers to > 4 microns) with high efficiency...especially in the ultraviolet spectral region from 180 nanometers (air-cutoff) to 400 nanometers. In the visible, efficacies of today's lamps are in the range of about 150 to 250 lumens/watt. [For those who are unfamiliar with the term, percent efficacy (or efficiency) is defined as broadband (radiometric) TOTAL light output energy emitted into a 4p steradian solid angle (sphere) divided by the electrical input energy (x 100). In casual discussion, the two are often used interchangeably.]

The efficacy for a typical set of operating parameters of a xenon flashlamp as a function of wavelength is illustrated in Figure A, and is normalized relative to 1.0 at the 236 nanometer peak. Measurements were made with a 5 nanometer half power bandwidth resolution (i.e., angstrom-width line structure is obscured). **Note that the abscissa also allows the designer to determine the percentage of the total energy of the emitted radiation 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 included for convenience are the relative responses of the photopic curve, silicon detector responsivity and (3) three of the envelope window materials commonly employed in flashBULB fabrication by EG&G. [The context of this dissertation pertains to the xenon flashBULB.]

> The flashbulb is distinguished from the *linear* flashlamp in that they differ in construction configuration, and operate in somewhat different modes of plasma formation. In general, the flashbulbs are low energy (<1.0 joule), unconfined or guided - arc *point* sources, where the linear flashlamp employs the principles of the confined or pinched higher power *line* source. Although the spectral plots are somewhat dissimilar, the energy distributions per bandwidth are pretty much the same for operating conditions less than about 10% explosion energy levels. (See the 1300 Series Lamp Technical Brief for more information.)

More than often, the question What is the efficiency of the flashlamp? confronts the manufacturer, the customer, the sales person and especially the veteran designer, ... and with some frustration, answers varying as much as one or two decades may be obtained. Of course, there is only one correct answer, but it does require explanation and conditions, and it is vital to distinguish between flashlamp efficacy, source efficiency, and system/application efficiency.

The efficacy of a flashlamp is the ratio of output optical energy to input electrical energy over:

- The entire radiation bandwidth
- into total 4p (ideally) steradian space (total in all directions), and
- referenced to PEAK operating conditions or derated accordingly (to be fully explained later)
-

The substantiated research of numerous sources bracket this basic conversion of electrical to optical energy of the xenon plasma between 50% to 60%, and it is this percentage which is represented as the total integrated area under the xenon curve (limited to 100 nm to 1100 nm) in Figure A. As examples, the efficacy of a flashlamp in the bandwidth region between 250 nm to 400 nm would be about

(10% + 5% + 5%)(55% *average)* » 11%

if it were measured with a flat response detector.

In the spectral region defined by a detector with a photopic response (which can be roughly estimated by a triangular response with a base 400 nm to 700 nm and a peak at 550 nm); the efficacy would be about

(14% + 7% + 5%)(½)*triangle*(55% *average)* » 7%

That is, the efficacy measurement of a xenon flash when convolved with a photopic filter response is only about 7% (and will be reduced further by non-optimum operating conditions - to be explained subsequently). Of course, this implies that the measurement was made correctly with an overfilled detector and without head vignetting or other interference.

Again, the radiation which is emitted is in all directions (4p steradian ideally) with the exception of that which is blocked and/or reflected by the electrodes. Knowing the shape and size of the electrodes, their solid angle interference may be readily calculated and subtracted, but for simplicity, a total radiance solid angle of 10 steradian would be a consistent approximation.

As an example, in an application where collection is by an f#/1 lens, the solid angle subtended by the lens is:

$$y = 4p \sin^2 (F/2) = 0.663 \text{ steradian}$$

where arc tan F = 0.5,

and the optical collection efficiency, e_c, would be only

$$e_c = 0.663/10 = 0.066 = 6.6\%$$

From the previous example with the photopic response, the 7% is further reduced to

$$(7\%)(6.6\%) = 0.5\%$$

Further, the above calculations are valid only when the flashlamp is operated at optimum or peak efficiency conditions and must be derated accordingly. Refer to Figure B which shows flashlamp OPERATING efficiency as a function of input energy for 1.5 and 3.0 millimeter arc flashlamps. Be advised that these curves have been generated for certain flashlamps, and are included here only as a guideline and are NOT representative of every application. The designer must create their own data empirically for a specific application and pulse energy level. The y ordinate should not be misconstrued as percentage but only as a relative number. Again, as an example, if a 3.0 mm arc were flashing at 20 millijoules per pulse, the OPERATING efficiency read on the y axis is about 8 which is about ½ that of optimum peak efficiency (16 at 0.25 joule). In the example with the photopic response, the efficiency now reduces to (0.5%)(½) = about 0.25%. Although profoundly reduced, flashlamps have considerably higher conversion efficacies than the popular laser... which is generally pumped with flashlamps.

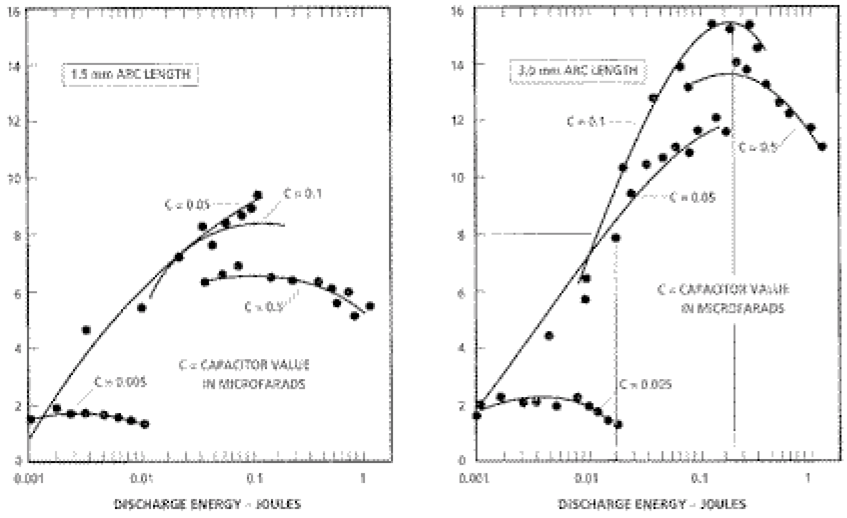

Figure B. Percent Efficiency as a function of input energy for 1.5 and 3.0 mm arc flashlamps

Note: The graphs represent conservative results since the total bandwidth of the measuring radiometer is a limiting factor (approximately 350 to 1100 nm). Actually, the xenon spectrum extends from below 75 nm (far UV) to well above 4000 nm (mid-IR).

In summary then, the source energy incident upon a target is the input energy in electrical joules times approximately 55% for conversion to optical energy, multiplied by the percentage of energy within the bandwidth of interest (i.e., if less than 100 nm to 1100 nm), multiplied by the collection efficiency of the optics (some fraction of 4p steradian), and finally corrected for non-optimum operating conditions.

In attempting to calculate system efficiency and source requirements without empirical measurements, the best that one can hope to do is to estimate the energy levels within about half an order of magnitude and realize the impact or priority of each of the individual thruput coefficients.

Flashlamp Energy Conversion

$E_{\text{OPTICAL OUT JOULES}} = (E_{\text{ELEC IN JOULES}})(e_{\text{CONV}})(e_{\text{IBW}})(e_{\text{COLL}})(e_{\text{OPT}})$

$E_{\text{ELEC IN}} = \frac{1}{2}CV^2$

- EELEC IN = Joules (or Watt-Sec)
- C = Capacitance in microfarads
- V = Voltage in volts

$e_{\text{CONVERSION}}$ » 50% to 60% when optimized
e_{IBW} = %/100 of the bandwidth of interest
$e_{\text{COLLECTED}}$ = %/100 of the radiation collected by optics
$e_{\text{OPTIMIZED}}$ = Adjusted for less than peak efficiency operation

Stability

Arc (plasma) stability, also commonly referred to as flash-to-flash efficiency, repeatability, reproducibility, or S/N (signal-to-noise ratio), may be separated into essentially four components:

1. Repeatability: pulse-to-pulse efficacy repeatability; the variation in broadband intensity of flashes
2. Temporal: variation of optical pulse initiation relative to trigger excitation; commonly referred to as jitter
3. Spatial: sporadic arc movement; or variation in arc location from flash-to-flash
4. Spectral: wavelength relative to wavelength inconsistency; or variation in intensity for a given wavelength or bandwidth from flash-to-flash

It is most important to emphasize that the stability of a xenon flashlamp light source cannot be attributed to any one specific component, but to the combination or synergy of all components: the flashlamp, the arc-initiating or trigger circuitry, the power supply, and not to be considered lightly, the design of the energy discharge capacitor. Maximum source stability can only be expected when each of these components is operating at peak performance conditions.

In the PerkinElmer 1100 Series of Flash Source Components, the flashlamps have been designed and engineered with improved electrode materials, precise alignments and optimized fill gas pressures and mixes to achieve exceptional stability:

- **Repeatability:** results in the order of ± ½% to ± 1% can be realized depending upon operational parameters
- **Temporal:**is generally less than 200 nanoseconds and is almost always inconsequential when accommodated for in signal processing electronics
- **Spatial:** arc movements of less than 0.1 millimeter are obtainable at moderate to low energy discharge levels
- **Spectral:** is directly related to full power bandwidth and is wavelength dependent but generally less than ½% over a ± 10 nm bandwidth.

Basic System Design

In the realm of system design perhaps the (3) most important basic *technical* questions to resolve are:

1. How much flashlamp energy is required to make a sample analysis?
2. What is the system stability/accuracy required?
3. What is a reasonable flashlamp lifetime?

In addressing the question - how much energy? - the answer is either forthcoming from previous experience, or in the case of a new instrument, must be determined empirically. The latter requires the use of a working model which would consist of a flashlamp source, application related optics (lenses, fiber optic bundles, filters), an inexpensive radiometer, the sample component and a darkroom.

The flashlamp source implies the flashbulb, a trigger module, the power supply and includes the discharge capacitor(s). The PerkinElmer 1100 Series Flashpac has been designed to incorporate all of these components into a packaged light source which produces exceptional arc stability of microsecond duration pulses of broadband light.

With these elements, the ballpark energy level required from the flashlamp source is determined to establish feasibility, flashlamp type, optical configuration and thruput, detector type and sensitivity, and general design direction. Initial consultation with a flashlamp systems applications engineer is highly recommended. The object of the experimentation is to determine what energylevels for specific wavelength bandwidths are necessary to achieve the chemistries or absorption/fluorescent measurements intended. Once accomplished, the optics and detector(s) are selected, optical collection efficiencies and thruput are estimated, response time and circuit sensitivity are confronted, the basic selection of the flashlamp source is established and the system design refinement process can be outlined and prepared. At this level, it is also convenient and judicious to investigate the most effective operating conditions of the flashlamp source in interaction with the sample studies (i.e., pulse-burst averaging to be explained subsequently).

Having become familiar with the above basics, the next major considerations to contend with are - *system stability and accuracy* - which will substantially influence system design and configuration.

Flash-to-flash repeatability is specified by the flashlamp manufacturer and is limited, at least to date, by still unknown phenomena in pulsed arc-plasma formation. Actually, when compared to so-called stable steady-state (CW) arc lamps, 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, generate continuous EMI/RFI, exhibit sporadic arc wander, peak-to-peak noise, and flicker. At the least in favor of the flashlamp, the light or energy pulse of a microsecond or so, is only initiated for the measurement and is off for the remainder of the duty cycle.

Although flash-to-flash repeatability of the PerkinElmer 1100 Series Short Arc Xenon Flashlamps is limited to about ± ½% to ± 1%, there are complimentary optical design techniques which significantly correct for the variation.

In a wide variety of tested applications, the implementation of a reference channel or bichromatic normalization with pulse-burst averaging, has reduced the coefficient of variation of measurement (Cv) to ± 0.02% (approximately 0.1 milliabsorption unit) for wavelengths in the 300 nm to 700 nm spectral range.

$$Cv\% = [\text{Standard Deviation } (100)]/\text{Mean}$$

These design techniques are application specific and must be investigated accordingly, where some of the variables are: energy per pulse, voltage, pulse rate, number of pulses per average measurement, sample and reference beam bandwidth, and the system optical f number and magnification.

Equally important to emphasize at this point is the advantage of pulse-burst averaging in sample analysis where accuracy increases nearly exponentially as a function of the number of flashes per sample and the number of samples. For example, instead of obtaining an absorption/fluorescence measurement from a single 1.0 joule energy flash with a sample rate of 1 second, the designer would achieve considerably more reliability/accuracy by performing the same measurement by accumulating the results of 10 x 0.1 joule flashes at a 10 Hz burst rate, or perhaps 100 x 0.01 flashes at the 100 Hz rate. One might discover that the same measurement could be made with still better statistical results if it were the average of 10 individual sets of 0.01 joule flashes at 100 Hz, all still within the 1.0 second interval. It should be additionally noted that arc stability is better at the lower energy and flash rate levels.

Multiple pulse and multiple sample averaging always improves analytical results if performed within the threshold/saturation limits of absorption/fluorescence phenomena, and, the limits of the flashlamp flash rate. PerkinElmer 1100 Series Flashlamps are specified to 300 Hz (pulses per second). Incidentally, this imposes no additional constraints on the signal processing electronics. The integrator window is kept open to accumulate the pulse burst and reset only in between averaging sets. Any increase in integrator drift is corrected or subtracted out.

Temporal stability or jitter is simply dealt with by ensuring that the initiation of the signal integration interval of the detector/amplifier precedes the light pulse. Usually, 500 nanoseconds is more than adequate.

Spatial stability requires more thought in initial system design. As in every flashlamp source, there will always be some amount of arc perturbation which may be consistent, erratic, or sporadic, but through devoted engineering can be made somewhat more predictable and as minimal as possible. Arc stability can be greatly improved by flashbulb pre-conditioning and burn-in methods devised by PerkinElmer per lamp type per operating parameters. The PerkinElmer 1100 Series Flashlamps specify that spatial arc movements of less than 0.1 millimeter from flash-to-flash can be obtained with proper operating conditions and control. At this stage, it is most important that the system designer investigate and contend with arc movement in the prototype.

For a given set of operating conditions, arc stability can be observed by projecting the arc image onto a target with a lens with appropriate magnification. More sophisticated instrumentation such as a laser beam profiler is required to measure actual spatial/energy variation as a function of wavelength; and more importantly, for certain cross-sections of the arc-plasma. This data can be provided as a customer-assist service by PerkinElmer engineering once operating conditions have been decided.

In an analytical instrument, the arc is optically imaged onto the sample area, collected and eventually, re-imaged onto a detector element.

More specifically by design, it is *some* fractional part of the arc gradient, or *most* of the arc gradient or *all* of the arc and the electrodes and some of the background, which is what really becomes imaged by the optics. The optical parameters which enter into design consideration are sample size, depth, velocity and tolerance; the magnification, depth of field, and f# of the optics and detector; bi-refringence, polarization and chromatic aberrations which confound wavelength errors.

Problems encountered with the above are certainly not insurmountable, but suggest that the prototype optics be designed to allow for sampling of the arc (size and section) for the specific application. For example, in some circumstances, designers obtained best results with an image aperture (referred optically back to arc space) of about 2/3 arc width and 2/3 arc length; others have achieved design goal using the central half of the arc perpendicular to the arc axis; and, others operating at higher f# and simpler designs, experience no difficulty with spatial instability. Of course, if there are no imaging optics, arc movement becomes inconsequential and is only affected by the size of the collecting aperture (or sample) and its distance from the arc and alignment.

In any case, knowing the amount of spatial arc disturbance and designing such that the sample and detector collect all of the energy within the periphery of the perturbations, is the first step toward a sound and expedient design. Mechanically allowing for sampling of arc section and location would be most judicious (at least initially in the prototype). Providing for post-sample aperturing has solved many a problem as well. It is important to remember that increasing flashlamp input energy will increase arc cross-section and not necessarily increase image density linearly.

Spectral stability is a special case of repeatability that can still persist even though flash-to-flash reproducibility is hypothetically corrected exactly for a specific spectral range. That is, within a fixed spectral region, two consecutive flashes may emit the same total energy but, for example, in one of the flashes the energy in a 400 ± 10 nm BW may be slightly increased and at 500 ± 10 nm BW correspondingly decreased, while the total remained constant. The causes of spectral variations have been studied in great detail and most of them have been virtually eliminated in the PerkinElmer 1100 Series Flashlamps through innovation. However, like every imperfect phenomena in nature, source spectral variations are still evident, but only to the designer who is reaching beyond the present state-of-the-art and developing absorption systems which are accurate to less than 1 millabsorption unit for multichannel systems employing 10 and more simultaneous analyses. Yet there are system design techniques which will address that problem. As discussed earlier, the reference channel used to correct for flash-to-flash repeatability may be split or increased in number to monitor specific sections (using optical filters) of the total spectral range. Another technique used is bichromatic normalization which is essentially dividing one wavelength channel by another of clinical interest and correlating the ratio to absorption criteria. A more complex method would entail the use of a dual dispersive element (dual grating or dual LVF linear variable filter or combination of both). The flashlamp source beam would be split into two (not necessarily equal) segments; one which would transmit through the sample, and the other through some reference such as air or distilled water. The subsequent division of results corrects for both flash-to-flash repeatability and spectral errors simultaneously. Within certain specification limits, the entire complexity of the multichannel detection and signal processing electronics may be reduced to simplicity with the implementation of an PerkinElmer dual array complete with addressable registers, amplifiers, and readout multiplexers, all in a single available standard package.

And finally, it can be earnestly be said that, *further detailed discussion is well beyond the scope intended for this simple introductory primer.*

Flashlamp Life

Flashlamp life is generally expressed in term of the number of flashes which may be expected coincident with its radiometric output decreasing to a given percentage of initial value. PerkinElmer 1100 Series Flashlamps are so specified to also define end of life as a function of wavelength (especially in the UV spectral range) and/or loss of arc stability. Gradual electrode erosion and window transmission loss as a result of electrode sputtering are typical causes of end of life. Life performance is primarily a function of input energy per flash and is also related to average power and peak currents. Generally, the lower in value these parameters are, the longer the flashlamp life. The decline in radiometric light output is, however, not linear with respect to usage or wavelength. Initially, within several thousand flashes, a drop of less than 10% will occur. After this initial operating period, which can be a customized preconditioning or burn-in period, the slope of the light output curve becomes essentially flat.

Ordinarily, if a flashlamp source is designed within the limits and guidelines specified by the manufacturer, flashlamp life is not a problem, but an achievable goal which may sometimes require an additionalassist. At some time after satisfactory operating conditions have been 'optimized, at least 5 or 10 flashlamps should be placed on a life test system and monitored for radiometric output as a function of critical wavelengths and number of flashes. This degradation profile should also be studied closely initially (minutes and hours of operation) to gain further insight to stability conditioning as well.

If necessary, flashlamp life may be increased as a tradeoff for operating efficiency by reducing energy/flash and increasing optical energy thruput, or by modifying the operating conditions, or simply by reconsideration of flashlamp selection. Flashlamp life may also be extended by a pre-planned allowance for increasing the charge voltage by some moderate amount within specified limits of performance.

Other Considerations

The importance of the selection of the power supply, trigger module, and discharge capacitor must not be under estimated. The operation of these components substantially affect flashlamp arc stability as well as the total system performance and reliability. In any quality system, the power supply should have low ripple, good regulation and reasonable efficiency. Characteristics which are important, but not always obvious, include opto-isolation of the trigger circuits, EMI suppression, and the provision to delay recharging the capacitor(s) to ensure deionization of the flashlamp. The latter function prevents the possibility of what is know a holdover, which can occur if the capacitor voltage were to rise to the minimum lamp operating voltage before deionization is completed. The PerkinElmer 1100 Series Power Supplies and the FlashPac incorporate all of these features.

Consistent with the power supplies, the PerkinElmer 1100 Series Lite-Pac® Trigger Modules are designed with complementary EMI suppression control. And last, but certainly not least, the discharge capacitor must be selected with care. During flash operation, the flashlamp impedance becomes very low and discharge currents can exceed several hundred amperes peak during the few microseconds of discharge. The discharge capacitor must be selected for suitable power and response rating. In some applications it may even be advisable to parallel several capacitors of lower value to reduce the effects of peak current.