Photoflash fundamentals

Introduction

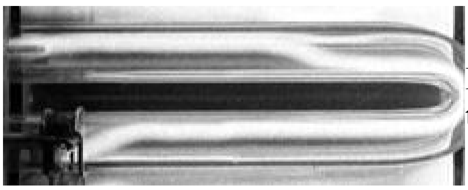
At the heart of any electronic flash system is a Xenon discharge tube, which belongs to the class of triggerable gas discharge devices known as 'Thyratrons'. Other types of thyratron once found service in situations where the light output was not important, i.e., they were used as switches, but were replaced by the semiconductor equivalent: the 'Thyristor' (AKA 'Silicon Controlled Rectifier' or 'SCR'). Development of the Xenon tube as a synchronised photographic light source is mainly due to the work of Prof. Harold Edgerton of MIT in the 1930s. Prof. Edgerton formed part of the scientific team which sailed with J Y Cousteau on the Calypso expeditions, in which environment he was known as 'Papa Flash'.

Flash tubes

A basic gas discharge tube is simply a glass bulb or tube, with two electrodes inserted into it, which has been evacuated and filled with an appropriate gas at somewhat less than atmospheric pressure. All such tubes have the property that, as the voltage applied across the electrodes is increased, there comes a point called the 'strike voltage', at which the gas in the tube ionises, and due to an avalanche effect, a low resistance current path is formed. Once an arc has struck, the tube resistance remains low until the applied voltage falls below a point called the 'extinction voltage'. The extinction voltage is usually considerably lower than the strike voltage, i.e., the arc is difficult to get going, and then difficult to stop once started.

If the gas pressure is very low, the tube emits light at one or more characteristic wavelengths associated with transitions between electronic states of the gas atoms or molecules. Devices with such spiky spectra (e.g. yellow sodium-vapour street lights) are no use as photographic light sources because they give poor or non-existent colour rendering, but as the gas pressure is increased, the spikes become broader. This 'pressure broadening' is a direct consequence of the Heisenberg Uncertainty Principle, and stems from the fact that as the pressure increases, the gas molecules undergo more and more collisions, thus reducing the average time for which a molecule can remain in a given electronic state. The Heisenberg principle states that as the lifetime of given state decreases, its energy becomes less and less well defined, the net result being that the characteristic emission wavelengths are smeared-out into bands. Xenon gas discharge tubes can be operated at a pressure at which the characteristic wavelengths are sufficiently smeared out, that the output approximates pure daylight; or more specifically, black-body radiation with a colour temperature of about 6000K.

A discharge tube becomes a Thyratron upon the addition of a third electrode. Such devices are operated by applying, across the main electrodes, a voltage which is above the extinction voltage but below the strike voltage. The device is triggered by applying a voltage pulse between the third electrode and one of the main electrodes, the resulting small discharge starting an avalanche which then spreads to the whole tube. In Xenon tubes, it is usually sufficient to apply a high voltage trigger pulse (3-6KV) to the outside of the glass envelope. As the tube is operated closer and closer to it strike voltage, it can also be triggered by radioactive particles[1], and by the light from other flash tubes being fired in its vicinity. Flash tubes are usually operated sufficiently well away from the strike voltage that accidental triggering is rare.



Early streamer in a Xenon tube. As the avalanche progresses, the arc grows to fill the whole tube.

1 A Geiger-Müller tube is a discharge tube to which an electron-capture agent (usually bromine) has been added to prevent the discharge from spreading

Photographic Flash

When used as a photographic light source, the Xenon tube is connected across a large high-voltage capacitor, which is charged from a mains or battery power supply. The device that produces a high voltage output from a low-voltage battery is known as an 'inverter', but may also be referred to as a 'DC to DC converter'. Common preferred operating voltages are 330, 360, 400 and 600V, depending on the application, whereas the pressure dependant strike voltage of the tube is considerably in excess of 1000V. The tube extinction voltage is usually about 50V. When the tube is triggered, its resistance drops to something in the order of 1Ω. Consequently, the discharge current may peak at several hundred Amps, before it ceases abruptly as the capacitor voltage falls to 50V. Note that ordinary electrolytic capacitors are not designed to withstand being discharged by short-circuit, and special 'Photoflash' grade electrolytics are used.

The burst of energy from a typical photographic flash tube lasts for about 1 millisecond (1ms). This time can be reduced by minimising the resistance in the tube - capacitor circuit, or by interrupting the current in the tube. The flash duration can be increased by inserting an inductance or 'delay coil' in series with the tube. The delay coil is used particularly in TTL and auto flash systems, where, by spreading the discharge over a longer interval, it permits more accurate determination of the point at which the light-burst should be terminated for proper exposure.

X-Sync

Because the burst of energy from a flash unit is very short, the level of film exposure cannot be controlled by a mechanical camera shutter. Exposure is controlled instead by the camera aperture and the (fixed or variable) guide-number of the flash. For this system to work however, the camera shutter must be fully open when the flash is fired, and this triggering regime is known, for historical reasons, as "X-Synchronisation". In focal-plane shutter systems (film cameras), X-synchronisation, is achieved by placing a switch at the end of travel of the first shutter curtain. Note however, that for high shutter speeds in focal-plane systems, the second curtain is released before the first curtain has finished travelling, and the film is exposed by the slit between the moving curtains. Consequently, in mechanical cameras, X-sync is not possible above a certain shutter speed. For a given camera, the highest shutter speed at which the shutter opens fully is called the "X-sync speed". Synchronisation at speeds below the X-sync speed is of course possible.

The 'Ready' Signal

Photographers using completely manual flash systems must suffer the irritation of spoiling photographs by forgetting to reduce the shutter speed to something below the X-sync limit. The single most important ergonomic improvement for a film camera system is therefore to provide a signal from the flash unit to the camera, which forces the camera to the X-sync speed if a higher speed has been selected. This signal is known as the "Flash Ready" signal, and is a feature of all modern automatic flash systems.

Auto and TTL exposure control

Photographic exposure is the product: Intensity × time. Automatic control of the instantaneous intensity of a flash is difficult, but the duration of the flash can be curtailed in one of two ways:

- Dump the remaining energy in the capacitor by switching a low resistance device across it. The device in question is usually a small Xenon trigger-tube with high electrode area and small inter-electrode distance, called a 'Quench Tube'. A quench tube does emit light, but it is placed inside the flash-unit electronics compartment and cannot contribute to the exposure. The disadvantage of the charge-dump system is that it wastes the unused energy and results in a system which must recharge the capacitor from scratch after each firing.
- Interrupt the current in the tube using a series control element, originally a 'Gate Turn-Off Thyristor' (GTO-SCR), but nowadays an Insulated-Gate Bipolar Transistor (IGBT) or a power FET (field-effect transistor). The idea was originally patented by Vivitar Inc. This is the modern system,

which results in reduced recycling time after a partial discharge.

In order to determine the correct point at which to quench the flash, It is necessary to integrate the amount of light falling on the recording medium over time. In film TTL and auto systems, this is done by using the current passing through a phototransistor to charge a capacitor. The capacitor is connected to a comparator, which changes state when the capacitor voltage crosses over a threshold set by the ISO film-speed control.

In TTL digital camera systems, a controlled pre-flash is fired and the level of exposure obtained is found by reading data from the sensor and averaging it. This information is used to calculate a suitable burst time for the main flash, using stored data relating to the time vs intensity profile of the flash output.

OK

The signal sent from the camera to the flash unit to terminate the light burst is called the 'Quench', 'Q' or 'TTL Stop' signal. If there is insufficient light to complete the exposure, a quench signal will not be sent. Many flash units have an 'OK' indicator, often a green lamp, which tells the user that a quench signal has been received.

Afterglow

A potentially serious problem in high-power flash system design is afterglow, which can occur intermittently, and may cause the circuit to self-destruct if not controlled. Afterglow occurs when the charging circuit has sufficient output to keep the capacitor charged to a point above the tube extinction voltage while the gas is conducting. In this case, the gas continues to glow indefinitely after triggering, and system meltdown will occur unless preventative measures are taken. In TTL and automatic exposure flash systems, afterglow can be prevented by sending a late quench pulse to the series-control element (i.e., by waiting to see if the camera sends a quench signal, and switching-off the current anyway if nothing is received after several milliseconds). In full-output systems, one possible solution is to sense the tube current and inhibit power-supply output (stop the inverter) while the tube is conducting.

Flash Energy

The energy stored in a capacitor is given by the relationship:

$E = (½)\ C\ V^2$

(E in Joules, C in Farads, V in Volts)

Thus the energy dissipated by the tube (neglecting resistance losses) is:

$E = (½)\ C\ V_m^2 - (½)\ C\ V_x^2$

where V_m ("V-max") is the starting voltage, and V_x ("V-ex") is the extinction voltage.

The relationship between the flash energy and the photographic guide number G is given by:

$G = k\ \sqrt{E}$

i.e., the guide number is proportional to the square root of the flash energy.

k is a system constant which depends on the design of the reflector and any losses that may occur due to light absorption.

Voltage regulation

If a battery powered flash unit has no voltage regulation, it will have a lower guide number if NiCd or NiMH cells are used instead of standard Zn-MnO2 (alkaline) cells. The guide number will also drop off as the battery goes flat. If you want to estimate the effect of voltage drop-off; note that the output of an unregulated inverter is not proportional to the battery voltage, but to the voltage switched across the inverter transformer, i.e., to the battery voltage minus the saturation voltage of the switching transistor(s). The transistors used in inverters typically saturate at about 1V under dynamic conditions. Consequently, an inverter running on 6V will switch about 5V across the transformer primary, but if you run it on a 4.8V NiMH battery, it will only switch about 3.8V across the transformer. The proportional reduction in output voltage is therefore (approx.):

(4.8-1) / (6-1) = 0.76
i.e., the output voltage obtained using NiCd or NiMH cells is about ¾ of the output obtained using new alkaline cells. (The internal resistance of the battery affects the recycling time, but makes little difference to the final voltage, because the inverter current drops as the charging end-point is approached). Unfortunately, due to the square-law relationship between voltage and energy, the proportional reduction in energy output (in this example) will be 0.76^2, i.e., 0.58. The new guide number however, is simply 0.76× the original, i.e., if the (unregulated 6V) strobe has a guide no. of 22 with a 6V battery, it will have a guide no. of about 18 with a 4.8V battery.

Exposure calculation
When the flash tube is operated in air, the surrounding medium is so thin that it can be treated as a vacuum. In this case, insofar as the flash tube and reflector assembly can be regarded as a point source, the level of illumination produced is inversely proportional to the square of the distance. This results in a very simple rule for calculating exposure:
In metric countries, the flash guide number is the aperture setting required for ISO 100 film sensitivity when the flash to subject distance is 1m (In North America, the guide number is the 100ASA aperture setting for a distance of 1 foot. Divide the American guide number by 3.28 to get it in metres). Once the Guide number G has been determined (usually by trial and error), the required aperture for any ISO film speed and distance (in air) is obtained thus:

$$\text{Aperture} = \frac{G \times \sqrt{\dfrac{\text{film speed}}{100}}}{\text{distance}}$$

Where 'film speed' is the ISO index for the film or the ISO light sensitivity setting of a digital camera.
Thus, if a flash has a guide number of (say) 32, its guide table looks like this:

Flash to subject distance / metres

ISO	**1**	**1.4**	**2**	**2.8**	**4**	**5.6**	**8**	**11**	**16**
25	16	11	8	5.6	4	2.8	2	1.4	1
50	22	16	11	8	5.6	4	2.8	2	1.4
100	32	22	16	11	8	5.6	4	2.8	2
200		32	22	16	11	8	5.6	4	2.8
400			32	22	16	11	8	5.6	4
800				32	22	16	11	8	5.6
1600					32	22	16	11	8

Underwater "Guide Numbers"
Unfortunately, when flash lighting is used underwater, the guide number rules applicable in air break down; for two reasons: Firstly, the flash has to be fired at short range and so no longer acts as a point source, and secondly, the intervening medium absorbs light. An exposure guide table can still be constructed, but it has to be calculated in a different way or determined empirically, and it will usually be based on the assumption that the flash unit and the camera are both situated at about the same distance from the subject.

When a ray of light passes through an absorbing medium, the attenuation (reduction in intensity) over a given distance can be calculated using the Beer-Lambert law:
$I = I_0 \exp\{-\varepsilon L\}$
Where I is the final intensity, I_0 is the initial intensity, ε (epsilon) is the extinction coefficient, and L

is the path length in units compatible with ε (the quantity within the exponent brackets must be dimensionless, so if L is in metres, ε must be in metres-1, i.e., "per metre"). The Beer-Lambert law represents the fact that light intensity decays exponentially with distance in an absorbing medium. This decay is in addition to the angular dilution effect (inverse square law) which applies in a non-absorbing medium. Note also that the extinction coefficient ε varies with wavelength, and in water, the attenuation is much greater at the red end of the spectrum than at the blue end. The upshot is that flash illumination only works for a very short range underwater; and the range which permits red to be recorded effectively is much shorter than the range which permits blue or monochrome photography.

As a rough starting approximation, light absorption by water reduces the effective guide number of a flash by a factor of 3. (e.g., a strobe with a guide number of 24 in air becomes a strobe with a guide number of about 8). The water also acts as a filter with a density of about 0.12 red per metre of light path; which means that you lose a whole stop of red for every 2.5m, and since the light must travel from flash to subject, and then from subject to camera, you lose 1 stop of red when you are only 1.25m away from the subject.

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