Types of Flashlamps

Although there are many shapes and sizes of flashlamps, there are only two distinct types — linear, or wall-stabilized; and bulb, or probe-stabilized, unconfined arc lamps. This technical brief addresses the operating characteristics of the linear lamp.

The linear type is of glass or quartz tubing construction with an electrode mounted at each end (Figure 2).

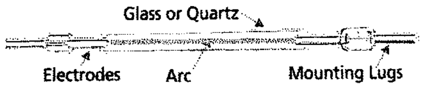


Figure 2. Linear flashlamp construction.

The bore (inside diameter of the lamp) is completely filled with plasma (ionized gas) when the lamp is flashed. Linear flashlamps can be made into a variety of shapes including helical, ring, U, and pi; electrically, however, there is no difference between two lamps that have the same bore size, arc length (distance between electrodes), and fill pressure. Linear flashlamps are well suited to applications requiring a line source and moderate to high energy levels, such as lasers, photocopiers, microfilming, video cameras, and visual beacons. Bore sizes from 1 to 19 mm and arc lengths from 1 to 48 inches are commonly available.

Electrical Characteristics

In the nonionized state, a flashlamp has high impedance (tens of megohms); therefore, all current from the power supply initially flows into the capacitor (Figure 3). As the voltage across the capacitor is increased, a point is reached, called the breakdown voltage, where xenon atoms are ionized and the impedance of the flashlamp starts to drop. In a short period of time, enough xenon atoms are ionized so that a low-impedance path is formed from anode to cathode, and current flows from the capacitor through the flashlamp. As this occurs, more xenon atoms are ionized; the arc impedance continues to drop to the milliohm region; and the arc expands outward, eventually filling the bore of the flashlamp. Most of the energy stored in the capacitor is expended in a matter of microseconds so that, eventually, the current through the flashlamp drops to such a low level that the tube deionizes and stops conducting. At this point, the capacitor starts recharging.

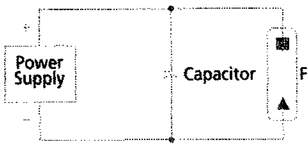


Figure 3. Basic flashlamp circuit.

Although the circuit in Figure 3 is a useful illustration of how a flashlamp works, it is not a practical circuit. The breakdown voltage of most xenon flashtubes is high, typically 10 kV or more, and not very repeatable. Therefore, most practical flashlamp circuits utilize a capacitor charging voltage which is much lower than the breakdown voltage. Conduction is then initiated by application of a brief high-voltage trigger pulse. Figure 4 shows a typical circuit with a trigger transformer connected to a trigger wire wrapped around the flashlamp. The trigger pulse is typically in the 10-20 kV range with a duration of about 1 microsecond. Other methods of triggering are discussed in detail later in this text.

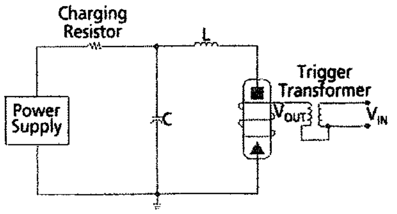
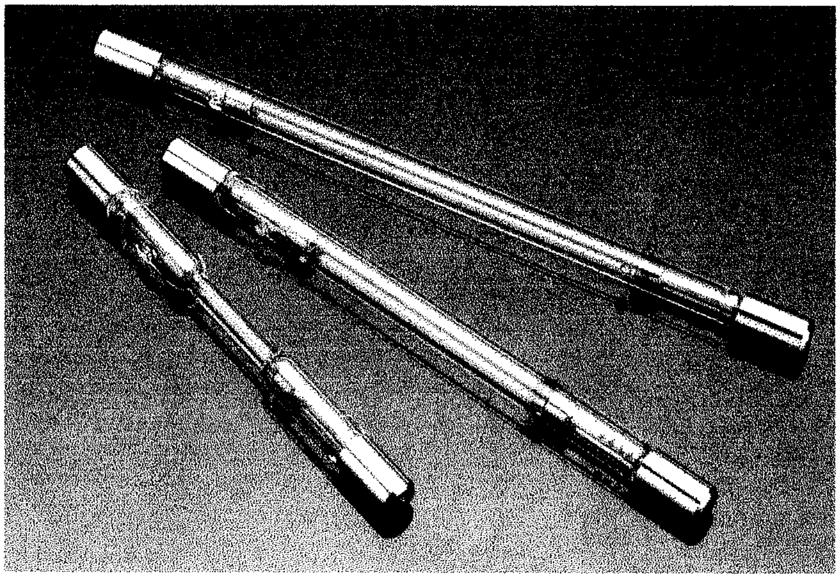


Figure 4. Flashlamp circuit utilizing trigger transformer to initiate conduction.

Critical Damping

In most practical flashlamp circuits, an inductor, L, is placed in series with the lamp and capacitor as shown in Figure 4. The values of the inductance, L, the capacitance, C, and the charging voltage, V, are chosen carefully so that the energy is transferred to the flashlamp in a critically damped pulse. Critical damping is extremely important since it results in the most efficient transfer of energy from the capacitor to the lamp. For a flashlamp, a damping factor (α) of 0.8 is considered to be optimal. For damping factors over 0.8, the circuit is considered to be overdamped, resulting in lower peak currents and power. For α less than 0.8, the circuit is considered to be underdamped, resulting in lower peak power, less efficient energy transfer and shorter lamp life. Also, the underdamped circuit produces a current reversal (or ringing) condition which is detrimental to lamp life.



Low Power Air Cooled Flashlamps

Flashlamp Impedance

The design of a critically damped flashlamp circuit would be straightforward if it could be treated as a traditional RLC circuit. However, the flashlamp cannot be treated as a linear resistor. It is in fact a dynamic impedance, designated K_o (in ohm-amperes$^{1/2}$). Goncz (1965) found the instantaneous lamp voltage and current to be related by:

(1) $V = \pm K_o |i|^{1/2}$

Based on work by Noble and Kretschmer (1972), it has been shown that K_o is a function of lamp size, fill gas, and fill pressure:

(2) $K_o = 1.28 \frac{\ell}{d} \left(\frac{p}{x}\right)^{1/5}$

where:

ℓ = arc length in mm

d = bore size in mm

p = fill pressure in torr

x = constant = $\begin{cases} 450 \text{ for xenon} \\ 805 \text{ for krypton} \end{cases}$

Circuit Design

Once the flashlamp parameter, K_o, has been determined, values of inductance L, capacitance C, and initial capacitor voltage V_o can be chosen for the single mesh circuit shown in Figure 5.

From the work of Markiewicz and Emmett (1966), it follows that (see Appendix A for complete derivation):

(3) $C = [2E_o \alpha^4 T^2 K_o^{-4}]^{1/3}$

(4) $L = \dfrac{T^2}{C}$

(5) $V_o = \sqrt{\dfrac{2E_o}{C}}$

where:

C = capacitance (Farads)
L = inductance (henries)
V_o = initial capacitor voltage
E_o = energy stored in capacitor (joules)
α = damping parameter = 0.8 for critical damping
$T = \dfrac{t_{1/3}}{3}$ = circuit time constant, an approximate relationship (see Appendix A)
$t_{1/3}$ = current pulse width (measured at 1/3 of peak)

This set of three equations (3), (4), and (5) gives explicit values for capacitance, inductance, and voltage once K_o, E_o, $t_{1/3}$ and α are specified. K_o can be calculated by solving Equation (2) or it can easily be found, since it is listed in the specifications of all EG&G flashlamp data sheets. E_o and $t_{1/3}$ are simply the desired input energy and pulse duration. α describes the pulse shape and is usually chosen to be 0.8 for critical damping. A very important axiom should be noted here:

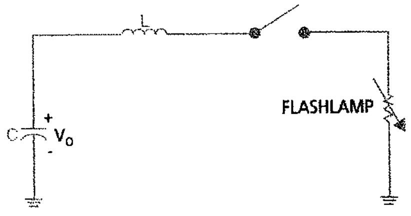


Figure 5. Single mesh flashlamp circuit

For a given flashlamp, pulse width, and energy, there is only one value for C, L, and V that will result in critical damping.

The curves in Figure 6 represent solutions of Equation [A-2] in Appendix A for various values of α. These curves illustrate why critical damping is important.

Peak Current

It is important to know the peak current through a flashlamp for several reasons. First, the spectral output is a function of the current density through the flashlamp (see page 13). Also, there are limitations on peak current which, if surpassed, result in damage to the lamp and early failure. The relationship

$V = \pm K_o |i|^{1/2}$

gives the instantaneous values for voltage and current at any point during the discharge, but does not indicate the peak values. Peak current is calculated from:

$$I_{pk} = \frac{V_o}{Z_o + R_l}$$

where

V_o = capacitor charge voltage
$Z_o = \sqrt{L/C}$ = circuit impedance
$R_l = \dfrac{\rho \ell}{A}$ = flashlamp resistance

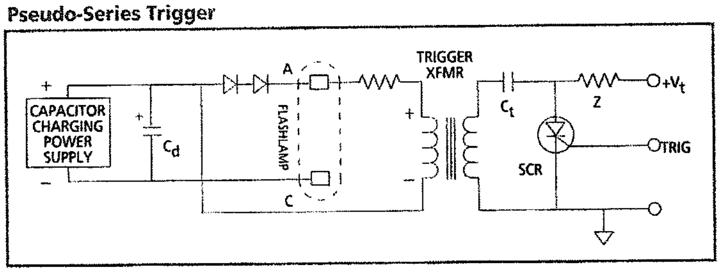
$$\rho = \text{flashlamp sensitivity} \left\{ \begin{array}{l} = 0.015 \text{ for } t_{1/3} \le 100\ \mu S \\ = 0.020 \text{ for } 100\ \mu S < t_{1/3} < 1\ mS \\ = 0.025 \text{ for } t_{1/3} > 1\ mS \end{array} \right.$$

A = cross-sectional area of flashlamp bore in cm^2
ℓ = arc length in cm

Pseudo-Series Trigger

As in the series technique, the trigger voltage is applied directly to one of the flashlamp electrodes. However, in this circuit an external trigger transformer is used but the capacitor discharge does not pass through the transformer secondary. Blocking diodes prohibit the trigger voltage from appearing across the discharge capacitor. The blocking diodes must be selected with care as they not only hold off the high voltage trigger pulse but must be capable of carrying the discharge current as well. Should critical damping be required, an inductor of appropriate value must be added in the discharge loop. |

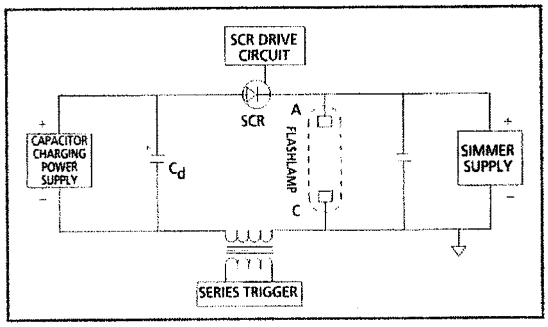
Pseudo-Series Trigger



Simmer Circuit

This simmer mode technique utilizes a separate power supply to maintain a continuous DC current through the flashlamp and keep it in the ionized state. Typical simmer currents are 100 milliamps up to several amps. Flashlamp pulsing is accomplished by closing a switch, typically an SCR, in series with the capacitor and flashlamp. An external or series trigger circuit is also required to initially start the flashlamp. |

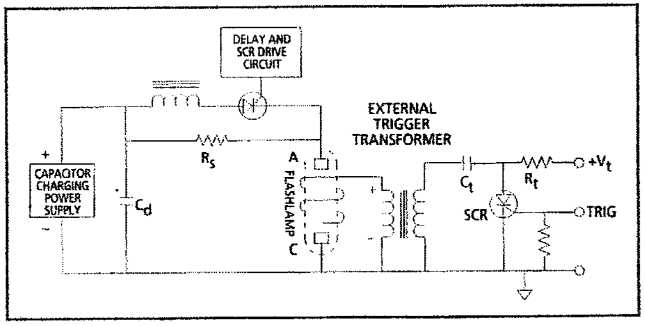
Simmer Circuit



Pseudo-Simmer Circuit

In the pseudo-simmer circuit shown, the simmer current is turned on just before the main discharge so the flashlamp is pre-ionized. |

Pseudo-Simmer Circuit



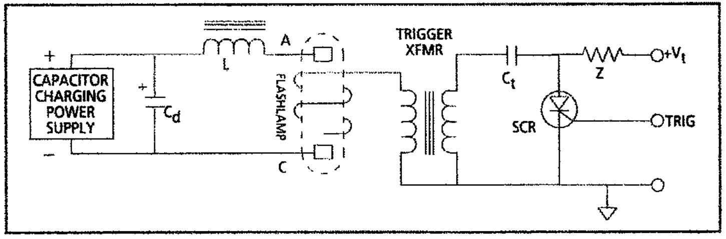
Triggering

Five types of triggering are commonly used: external, series, pseudo series, simmer, and pseudo simmer. |

External Trigger

External triggering creates a small arc streamer between the electrodes by applying a high voltage trigger pulse to a thin wire wrapped around the outside of the lamp. The pulse can also be applied to a metal bar, reflector, or cavity as long as the metal covers the entire distance between the electrodes. In these latter cases, the spacing between the lamp and metal piece should be no more than 1/4-inch and somewhat higher trigger voltages may be needed. The trigger pulse is supplied by a high-turns ratio transformer which can be compact and lightweight, since it has to produce high voltage but little current (100-300 mA). A finite amount of time is required for the trigger streamer to propagate down the bore of the flashlamp. The pulse duration for external triggering should be 200 nanoseconds per inch of arc length. Required trigger voltages depend on arc length, bore size, fill pressure, and electrode material and are listed under flashlamp specifications in EG&G data sheets. |

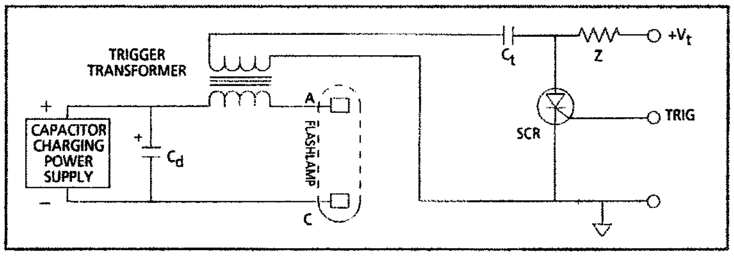
External Trigger



Series Trigger

In the series technique, the trigger voltage is applied directly to one of the flashlamp electrodes from the secondary of a transformer which is placed in series with the flashlamp. Again, the purpose is to create a small arc streamer between the electrodes. Although it is not required, the trigger wire, used for external triggering, may be left wrapped around the lamp and grounded. This facilitates triggering by lowering the voltage requirement. The series trigger transformer is larger and heavier than the parallel transformer since the secondary must carry the full flashlamp current. Also, the secondary adds impedance to the circuit, and this must be considered in the circuit design. In fact, by choosing a trigger transformer having the proper value of saturated inductance, no other choke should be necessary to achieve critical damping. The trigger pulse duration for a series trigger is 150 nanoseconds per inch of arc length, and the required voltages are listed under flashlamp specifications in EG&G data sheets. |

Series Trigger



Efficiency

The maximum efficiency for a xenon flashlamp is about 60%; i.e., 60% of the input electrical energy can be converted to optical energy in the 200-1100 nm region. Actual efficiency for a particular flashlamp depends on several factors, including fill gas, fill pressure, current density, and circuit design. Generally, as the current density is increased, the overall efficiency increases as shown in Figure 10, although there are limits on maximum peak current. Also, as Figure 13 shows, efficiency increases as fill pressure increases until a saturation point is reached. The saturation point is approximately 650 torr for xenon and 1100 torr for krypton.

Photometric efficiency is much higher for xenon than krypton, since more of the output from xenon is in the visible region. The maximum photometric efficiency for xenon is about 40 lumens per watt. |

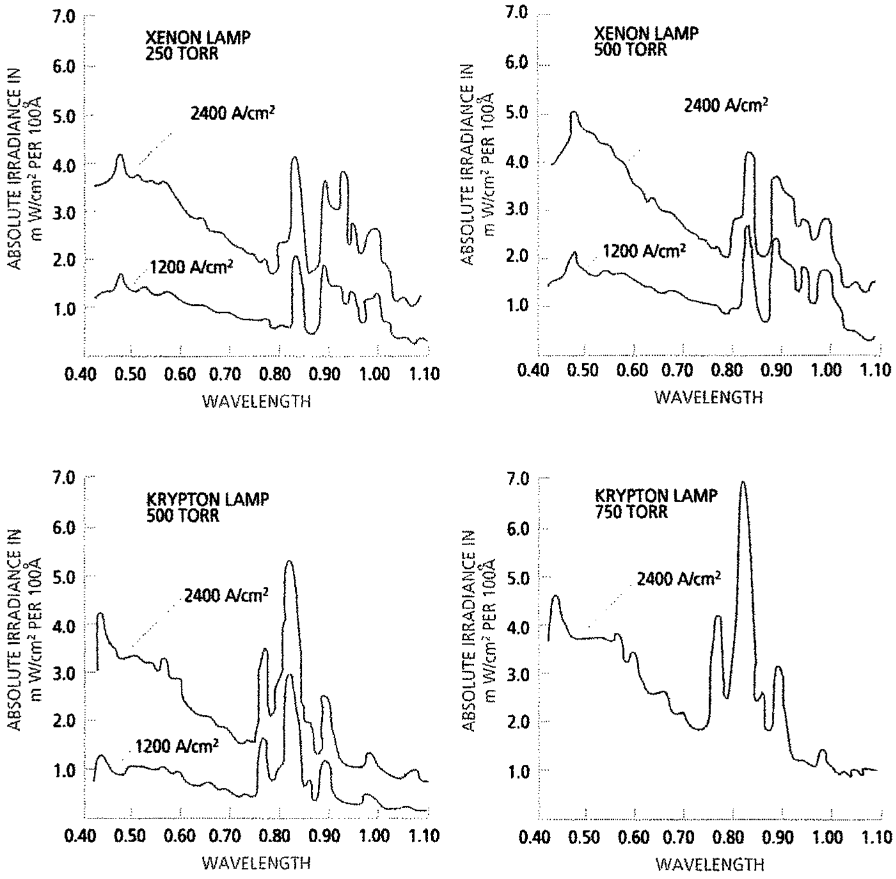


Figure 13. Effect of fill pressure on lamp

Capacitor Selection

The overall efficiency of the circuit is determined to a great extent by the quality of the capacitor. If the ratio of circuit impedance to arc impedance is large, a high percentage for the stored energy can be wasted in heating up the capacitor itself. Most manufacturers publish a dissipation factor for their capacitors, which is used to determine the equivalent series resistance (ESR). ESR combines all losses, both series and parallel, in a capacitor at a given frequency so that the equivalent circuit is reduced to a simple R-C series connection.

$ESR = DF \times X_c$

where:

DF = Dissipation Factor

$X_c = \frac{1}{2\pi fC}$ = capacitive reactance

$f = \frac{1}{t_{1/3}}$ = equivalent frequency

$t_{1/3}$ = current pulse width

C = capacitance

Other important parameters which must be considered when selecting a capacitor include:

- voltage rating
- capacitance rating
- life rating
- duty cycle
- storage density

A number of capacitor technologies are available, including electrolytic, oil filled paper, and polypropylene film. The choice usually depends on a trade off between price and performance. The electrolytics are capable of storing the most energy per pound; however, they also exhibit exceedingly high ESR values, and are recommended only for applications where size and weight are the most important factors. The oil-filled paper types represent the best price/performance ratio and are a good choice for many applications.

Average Power and Cooling

Average power refers to the electrical input power to the lamp and is calculated as:

$P_{AVG} = E \times f$

where:

$E = 1/2\ CV^2$ = input energy in joules

f = flash repetition rates in pulses per second (pps)

All linear flashlamps have average power limitations based on the types of glass-to-metal seal used and the method of cooling. The ratings in Table 1 are in terms of the maximum loading of the inside wall area between the electrodes, given in watts/cm². Wall area of the flashlamp is π LD where:

L = Arc Length in cm

D = Bore size in cm

Type of Seal	Method of Cooling	Maximum Wall Loading (watts/cm2)
End-Cap	Convection	4
End-Cap	Forced Air	30
End-Cap	Water	300
Graded	Convection (low power)	15
Graded	Forced air (low power)	30
Graded	Water (high power)	200

Table 1. Power limitations of flashlamps with various seals and cooling methods.

For example, a 5-mm bore size graded seal flashlamp with a 3-inch arc length has an inside wall area of 12 cm². Therefore, it could safely operate up to 180 watts for convection cooling, 360 watts for forced air, and 2400 watts for water cooling. Thus, the 4-mm, 3-inch flashlamp used as an example previous-

Appendix A

Starting with the Goncz relationship

$V = \pm K_o |i|^{1/2}$,

the differential equation for the single mesh flashlamp circuit of Figure 6 is:

(A-1)

$$L\frac{di}{dt} \pm K_o |i|^{1/2} + \frac{1}{C}\int_0^t i dt' = V_o,$$

where the sign of K_o is chosen to be the same as the sign of current, i. The symbols are:

C = capacitance (farads)
L = inductance (henries)
i = current (amperes)
t = time (seconds)

It should be noted that only losses in the flashlamp are considered. The driving circuit is assumed lossless.

With the following substitutions and normalizations, one can rewrite Equation (A-1).

$Z_o = \sqrt{\frac{L}{C}}$ = driving circuit impedance (ohms)

$i = I\frac{V_o}{Z_o}$, where I is normalized current

$T = \sqrt{LC}$ = circuit time constant (seconds)

$\tau = \frac{t}{T}$ = normalized time

$\alpha = \frac{K_o}{\sqrt{V_o Z_o}}$

Equation (A-1) becomes

(A-2)

$$\frac{dI}{d\tau} \pm \alpha |I|^{1/2} + \int_0^\tau I d\tau' = 1$$

Note that Equation (A-2) relating the development of normalized current with respect to normalized time has only one parameter, α. Thus the solutions of Equation (A-2) can be presented compactly as in Figure 6a. Wide combinations of actual situations are represented.

The energy stored in the capacitor is:

$E_o = \frac{1}{2} CV_o^2$.

The relation can be rewritten as

$V_o = \sqrt{2 E_o/C}$

Substituting V_o into the expression for $\propto$, one obtains:

$$C = \left(\frac{2 E_o \alpha^4 T^2}{k_o^4}\right)^{1/3}$$

From the driving circuit time constant, one obtains

$$L = T^2/C.$$

Normalized power, P_N, can be defined:

$$P_N = \frac{P}{V_o^2 / Z_o} = a \mid I \mid^{3/2}$$

where

P = power $Vi = K^o \mid i \mid^{3/2}$
V = voltage across the flashlamp.

Normalized energy, E_N, dissipated in the lamp:

$$E_N = \frac{\int_0^t P dt'}{\frac{1}{2} C V_o^2} = 2 \alpha \int_0^\tau \mid I \mid^{3/2} d \tau$$

E_N is the fraction of the initial energy stored in the capacitor dissipated by the lamp up to time, τ.

Since the unit of normalized time is the driving circuit time constant

$$T = \sqrt{LC}$$

one can relate the current pulse width at one-third peak current, $t_{1/3}$, to the time constant at various values of α by examining figure 6a, which is a plot of the solutions of Equation (A-2). One can see that:

$t_{1/3} = 2.5\ T$ for $\alpha = 0.6$ and 0.8
$t_{1/3} = 2.7\ T$ for $\alpha = 1.2$
$t_{1/3} = 3.2\ T$ for $\alpha = 1.6$

Hence our approximation of

$$T = \frac{t_{1/3}}{3}$$

In the same way one can use Figure 6a to estimate peak current. For example, we have at $\alpha = 0.8$, peak current equals $\frac{1}{2}\frac{V_o}{Z_o}$. In a practical case this will overestimate peak current by as much as 10 percent due to other sources of impedance not considered here.

Design Considerations for Triggering of Flashlamps

Introduction

Xenon flashlamps (bulbs or tubes) are devices that emit large amounts of spectral energy in short duration pulses. Power supply energy accumulates in a storage capacitor. When this energy is released and dissipated it forms a highly excited xenon plasma within the flashlamp. The energy released covers a wide spectral range from ultraviolet (UV) to infrared (IR), closely resembling sunlight.

This intense pulse of radiant energy is used in many applications including applications which; stop motion, pump lasers, provide a stable spectral source for absorption or fluorescence measurements, cure polymers with UV, strip paint, or simply provide a visible beacon.

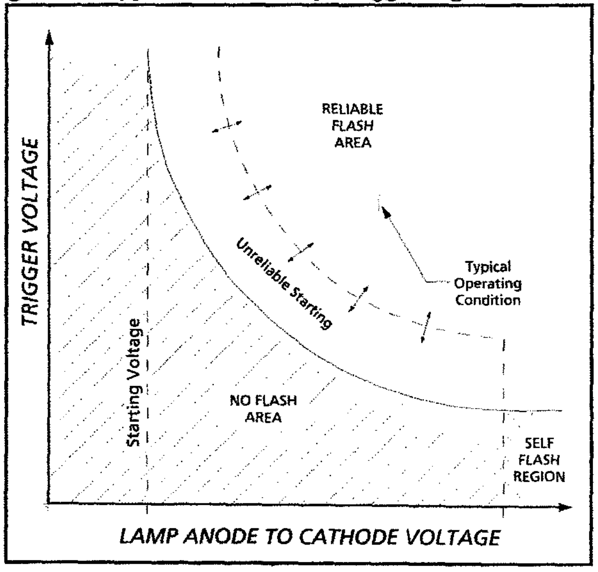
Theory of Operation

The charged energy-storage-capacitor is normally connected across the two main electrodes (commonly called "ANODE" and "CATHODE") of the flashlamp. The voltage to which this capacitor is charged is usually lower than that which would cause the xenon to ionize. The process which effects the initial ionization is known as "TRIGGERING".

Triggering creates a voltage gradient (Volts/Inch) in the gas of sufficient magnitude to cause ionization.

Figure 1 shows typical flashlamp triggering characteristics. It should be noted that the curves are somewhat dependent on the triggering method and other factors external to the flashlamp itself. For instance, the arrows on the curve limiting the "reliable flash" area indicate how the curve typically migrates back and forth over the life of the flashlamp.

Figure 1. Typical Flashlamp Triggering Conditions



Most triggering schemes use a trigger transformer to produce high voltage pulses of short duration. Several different circuits have been developed which introduce this voltage to achieve ionization. Once this has occurred as evidenced by a thin streamer between the main electrodes, a conductive path exists through which the energy-storage-capacitor can discharge. As the level of ionization increases, the streamer increases in cross section and produces an intense flash.

Methods of Triggering

Most of the triggering schemes can be grouped into three categories;

1. External
2. Series Injection
3. Pseudo-Series Injection

Two other commonly used circuits which are initiated using one of the above three triggering methods are;

4. Simmer Mode
5. Pseudo-Simmer Mode

Another variation on the these circuits which indirectly uses a trigger transformer is;

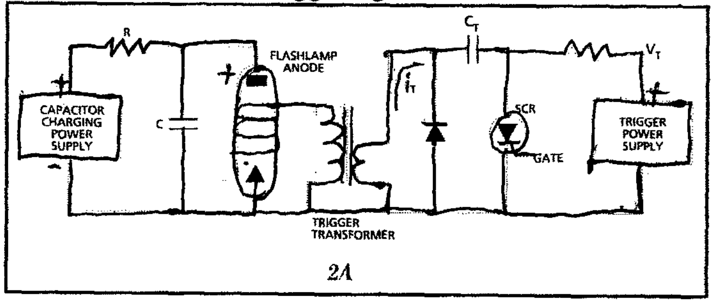
6. Overvoltage Triggering

1. External Triggering

External triggering uses a high voltage trigger pulse to create a thin ionized streamer between the anode and cathode within the lamp. Ionization starts when gas adjacent to the tube wall is excited by the voltage gradient induced by this high voltage pulse from the trigger transformer. The coupling of this voltage to the lamp can be accomplished in any one of several ways. *(See Figure 2A - 2E.)*

A thin nickel wire can be wrapped around the surface of the glass (or quartz) envelope (tube) as shown in *Figure 2A*. The wire must touch the glass over as much as possible of the length of the envelope for the most reliable operation, although even a minimum of contact can be satisfactory if a higher peak trigger voltage is applied. The trigger transformer high voltage output (secondary winding) is connected to one end of this wire.

Figure 2A. External Triggering Methods



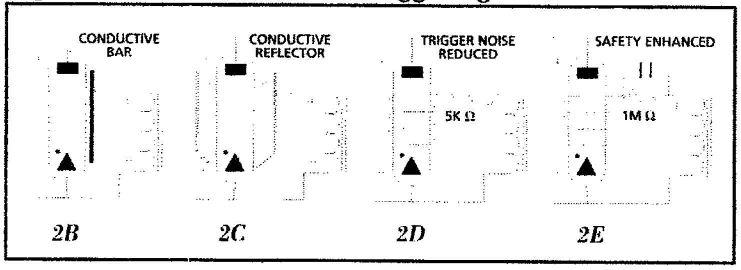
The trigger voltage required to reliably trigger a particular flashlamp depends on the arc length, bore diameter, fill pressure, and electrode material, and is normally given in the flashlamp Characteristic Data. *(See EG&G Flashlamp Data Sheets)*

Other factors such as ambient radiant energy and aging characteristics of the lamp also affect triggering requirements.

The trigger pulse width is important using this method because a finite amount of time is required for the ionized streamer to propagate down the bore of the flashlamp. Triggering has been found to be most reliable when the pulse width is at least 200 nanoseconds per inch of arc length.

If a wrapped trigger wire is for some reason inconvenient, then the trigger pulse may be applied to a conductive bar ***(See Figure 2B)*** or a conductive reflector or cavity ***(See Figure 2C)***. In these cases the conductive component should be as close to the lamp as possible and no more than 1/4" away, and a somewhat higher trigger voltage should be employed.

Figure 2B thru 2E. External Triggering Methods



Since the trigger transformer has to supply a high voltage pulse but very little current (only about 100 to 300 mA), it can be made small and lightweight. The turns ratio is usually high to accommodate lower voltage components in the primary circuit. The trigger pulse is produced by discharging a capacitor into the primary winding of the trigger transformer using either a mechanical switch or a semiconductor device such as an SCR or a gas filled switch such as a triggered spark gap. Care must be taken in the selection of the switch to ensure that the rate of rise of current can be accommodated without device failures. This is especially critical when an SCR is used. Also, camera shutter switches which are sometimes used to trigger a flash often have fragile, sensitive contacts and an intermediary switch is usually required to prevent the trigger transformer primary current from causing contact damage.

Generally speaking, the polarities of the anode-to-cathode voltage should be arranged so that the voltage stress or gradient (Volts/Inch) is maximized in the vicinity of the anode (or cathode) of the flashlamp. Voltage from the energy-storage-capacitor should always be arranged so that the anode is more positive than the cathode. Since any node in the circuit can be chosen to be grounded, this leads to a variety of possible circuits. Some possibilities can be eliminated by ensuring that the trigger transformer secondary winding's start-to-primary insulation is not stressed any greater than as specified in the data. Careful examination of potentials in the circuit will show the best circuit for the application.

EMI and Noise

Flashlamp triggering using fast rising, high voltage pulses is an inherently noisy (EMI) procedure. The trigger current, upon ionization of the gas (xenon), contains discontinuities and irregular pulse-to-pulse anomalies. The harmonics generated can be measured into the gigahertz region, with various peaks being exaggerated by wire lengths and ground planes.

Relief can usually be obtained by good shielding, enclosure design, and ground layout. The noise from the trigger discharge can also be lessened by including a resistor in series with the high voltage secondary lead (see Figure 2D). This slows down the discharge of the parasitic secondary winding capacitance. A 2 Watt carbon composition resistor of about 1 to 5 K Ohms is usually effective. Metal-film resistors with helical paths usually fail due to delays of voltage wavefronts and subsequent turn-to-turn breakdown at the transformer end of the resistor and are therefore not recommended.

Safety is another consideration that may lead to the selection of one circuit over another. For instance, one should consider the consequences of arcing between the high-potential end of the trigger transformer and the high-potential end of the energy-storage-capacitor. If this occurred, the capacitor would discharge into the winding and perhaps destroy it. One possible solution would be to include a capacitor/resistor network in the discharge path ***(see Figure 2E)*** which would pass the trigger pulse without attenuation but prevent the discharge of the energy-storage-capacitor into the winding. About 500 picofarads in parallel with 1 megohm would suffice in most cases, the capacitor being a disc-ceramic type able to withstand the about 6 K Volts.

2. Series Injection Triggering

Series injection triggering passes the discharge current from the energy-storage-capacitor through the secondary winding of the trigger transformer. The secondary winding of the trigger transformer must therefore be designed to carry the total current of the discharge within the ambient temperature design limits. This type of trigger transformer is consequently larger, heavier and more expensive than the external type. There are, however, certain important advantages.

The inductance of the secondary winding (of the trigger transformer) is now part of the discharge circuit and may be utilized to control the energy-storage-capacitor's current pulse waveshape. Since flashlamp life is inversely proportional to peak current, it is desirable to optimize this inductance for damping and design a critically damped circuit. This will produce minimum peak current and prevent current reversal which may damage the flashlamp. The life of the flashlamp is now maximized for the particular energy required and the power requirement now dictates the size of the trigger transformer.

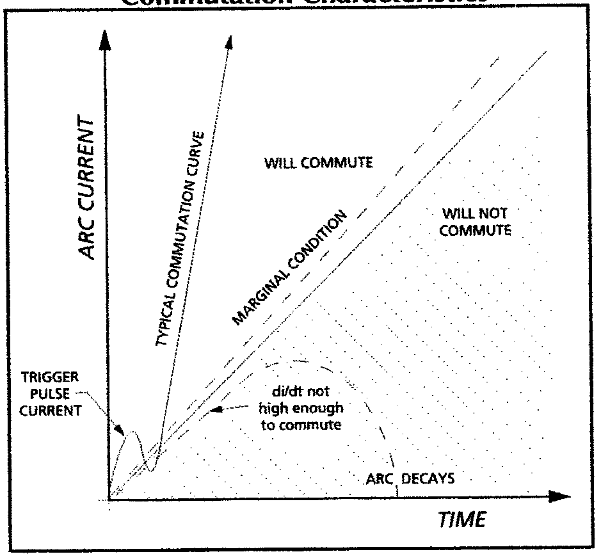
Skin Effect

A certain amount of energy will be dissipated in the resistance of the secondary winding which will be dependent on the arc-resistance of the flashlamp. (A non-linear function) Since current risetimes could be in the order of microseconds, skin effect should be taken into account.

In the design of some transformers an attempt has been made to reduce skin effect by winding them with copper strip or doubled wires. It is difficult to predict with precision the exact circuit performance since typically only the DC resistance of the secondary windings are provided in transformer data. If more data are required, it becomes necessary to take measurements using the intended circuit configuration.

The trigger transformer peak secondary output voltage is applied across the anode/cathode of the flashlamp, and is usually somewhat lower than that required for external triggering. Also, the anode to cathode starting voltage is usually much lower. Triggering will be enhanced by any ground planes brought into close proximity of the flashlamp envelope. If desired, a trigger wire (as used with external triggering) may be wrapped around the envelope and brought to ground. A sharp grounded point close to the triggered electrode also enhances triggering by increasing the electric field gradient in that area.

Figure 3. Typical Idealized Arc Commutation Characteristics

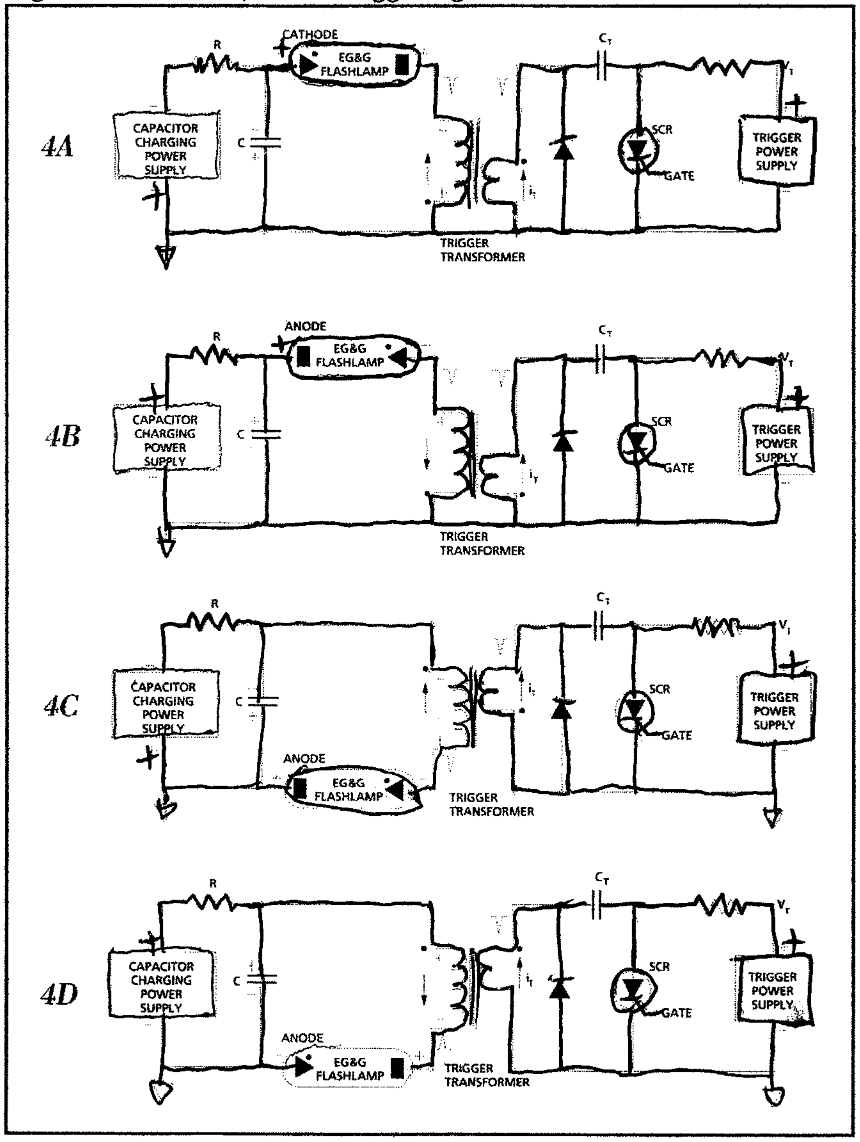


Previously, the inductance of the secondary winding was mentioned as being useful in shaping the discharge current pulse. The inductance referred to is the "saturated inductance" (Lsat) as given in the transformer data tables. Series ignition trigger transformers are usually wound on magnetic cores, either ferrite or silicon steel. This is necessary in order to keep the primary conditions within reasonable limits. The presence of this core may cause problems when considering the rate of change of current(di/dt) in the secondary winding of the trigger transformer. ***(See Figure 3)*** The problem is that when unsaturated, this core may inhibit the discharge pulse current rise so much that the lamp won't flash.

Figure 3 illustrates the current/time commutation characteristics of flashlamps. The low excitation inductance of the secondary winding will be considerably greater (say - 50 times more) than the inductance after the core has saturated and the volt-second product of the core must be taken into account. The commutation characteristics of a particular flashlamp, the series injection trigger transformer, and the energy discharge circuit constants may combine to produce a condition where the trigger ionization streamer is quite evident but no energy discharge occurs. Since the interdependence of all of these parameters (some of which are unknown) determine the triggerability, it is usually necessary to conduct experiments to ensure reliable operation.

As with external triggering, safety is enhanced using circuit configurations where one end of the trigger transformer secondary is at ground potential. ***Figure 4*** shows the four possible circuit configurations for series injection triggering. Note that the dots adjacent to the trigger transformer indicate the starts of windings. The dot may also indicate the finish of windings should some specific reason exist such as restraints due to insulation. The arrows indicate current flow from positive to negative voltage (i.e. conventional current flow). The arrow at the primary indicates current flow due to the pri-

Figure 4. Series Injection Triggering



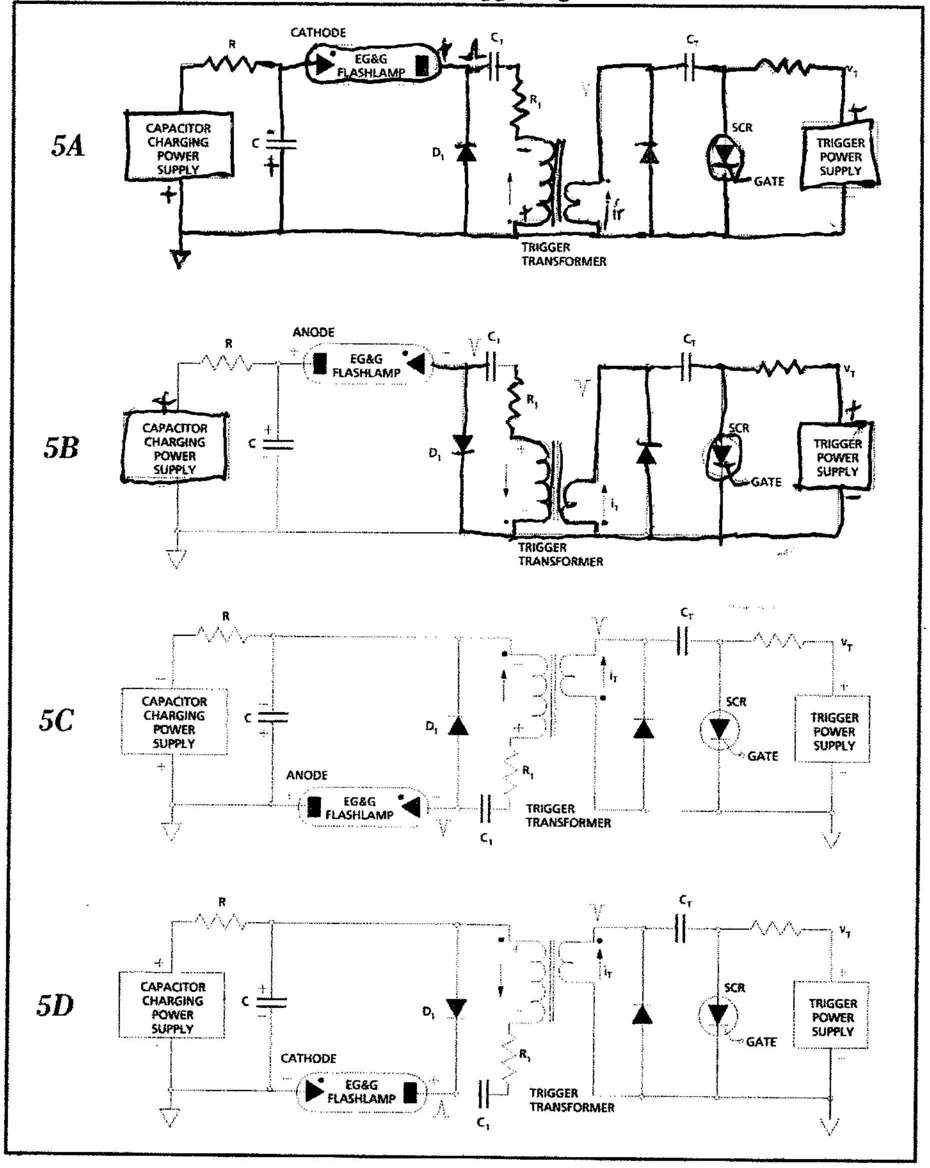
mary trigger discharge and the arrow at the secondary indicates the current flow due to the main discharge. Note that in all of the circuits shown, both arrows point opposite with respect to the polarity dot on the primary to the secondary indicating the remanence after a flash is in the opposite quadrant of the core B-H curve to that in which core saturation occurred. This suggests that, if triggering starts when on the first pulse zero remanence exist in the core, the second and subsequent trigger pulses will be higher due to the greater total change in flux. This should be taken into account when considering triggering reliability margins.

Furthermore, there are other possible circuit configurations where both arrows may point in the same direction with respect to the polarity dots. In these cases the opposite is true and the pulses after the first pulse will be lower in peak amplitude.

3. Pseudo Series Injection Triggering

Pseudo series injection triggering retains some of the advantages of series injection triggering without some of the penalties, especially those of size, weight, and cost. ***Figure 5*** shows four versions of this circuit in various possible configurations of polarities and grounded nodes. The trigger voltage is

Figure 5. Pseudo-Series Injection Triggering

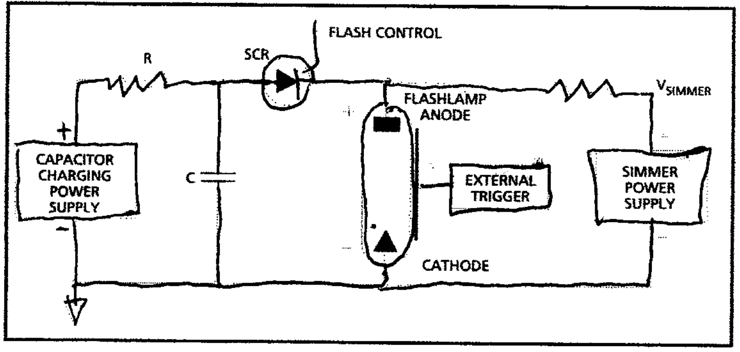


applied to the flashlamp in the same manner as with series injection, however in this case the main energy discharge does not flow through the trigger transformer secondary winding. Instead, a path is provided through D1.

D1 is constructed of several diode junctions in series and is chosen to be able to carry the main discharge current. It could therefore be a substantial diode string depending on the current requirement. The trigger voltage is applied to this diode assembly in it's reverse direction, so that the peak voltage applied across the flashlamp is limited by the reverse breakdown voltage of the diode string. Individual diodes with nominal reverse breakdown of 1000 volts are normally used. This means that the basic silicon material is of high resistivity (100 ohm/cm or higher). Significant loss of discharge energy can therefore be expected. Careful choice of junction profile limits this loss.

Diode assemblies are available from EG&G with these characteristics and reverse breakdown of 10 Kv minimum. The resistor R1 shown in the schematics ***(Figure 5)*** is useful in the reduction of EMI and is about 5 K ohm, 2 Watt, Carbon composition. The capacitor is included for safety reasons as in other triggering schemes. Judicious placement of grounded features close to the lamp envelope, especially near the triggered end of the flashlamp, will enhance voltage field gradients and produce more reliable triggering.

Figure 6. Simmer Mode Circuit

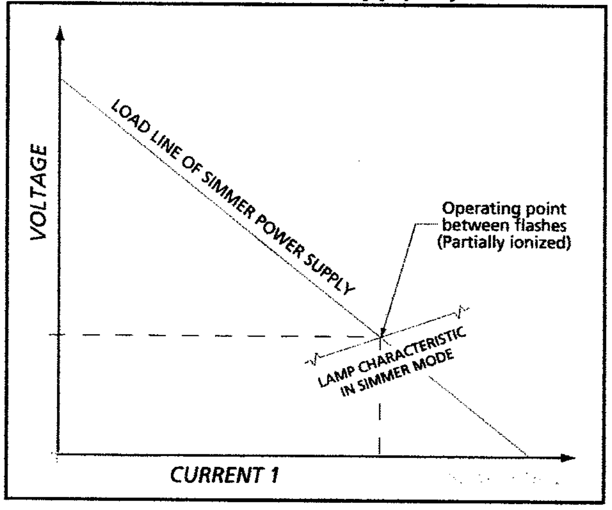


4. Simmer Mode

The simmer mode technique requires that the flashlamp be triggered only once in a sequence of flashes. A separate power supply with a specially designed load characteristic is used to force the current to continue flowing in the lamp in a low but stable state of ionization. ***(See Figure 6)***

Depending on the flashlamp type, typical simmer current may be from 100 milliamps up to several amperes. The voltage across the lamp will be 100 to 150 volts. ***(See Figure 7)*** The main discharge energy, obtained from a capacitor charged by a separate power supply, may now be switched into the lamp. A semiconductor switch, such as an SCR (shown) or a gas or vacuum gap may also be used. The gas in the lamp will become more highly ionized, producing a flash as the energy is dissipated. The gas will then be forced to return to the simmer state.Care must be taken in circuit design and layout, that transients due to parasitic elements do not cause deionization to occur, or that semiconductors or insulation do not become over stressed.

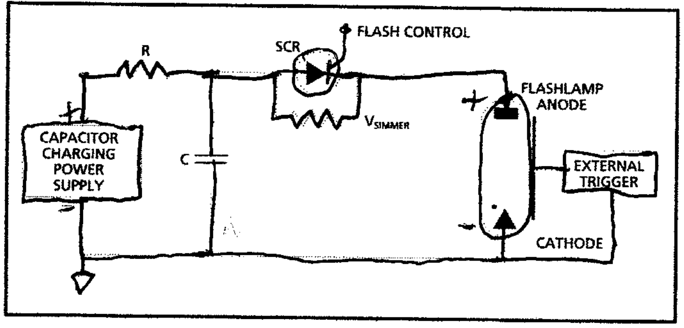
Figure 7. Simmer Power Supply Operation



5. Pseudo Simmer Mode

Pseudo simmer mode is a variation on the simmer mode circuit which combines the simmer power supply with the capacitor charging supply. *(See Figure 8)* Operating conditions are limited by lamp and power supply load line considerations.

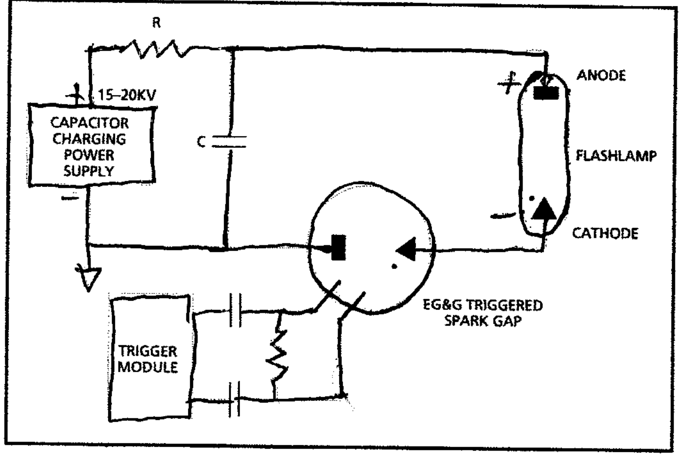
Figure 8. Pseudo-Simmer Mode Circuit



6. Overvoltage Triggering

Overvoltage triggering is a method of flashing a flashlamp without using a trigger transformer and is mentioned here only for completeness. *(See Figure 9)* The energy-storage-capacitor is charged to a voltage which exceeds the self-breakdown voltage of the flashlamp. (Typically 10 to 20 Kv) The energy is switched into the flashlamp using a high-voltage/high-current switch. This is typically a triggered spark gap or thyratron. When the switch is activated the flashlamp gas breaks down and a flash is produced.

Figure 9. Overvoltage Trigger



RUGGED SOLDER SEAL LAMPS FOR CONVECTION, FORCED AIR AND LIQUID COOLED APPLICATIONS

FLASHLAMP TYPE	BORE SIZE (mm)	ARC LENGTH (A) (in/mm)	QUARTZ LENGTH (B) (in/mm)	OVERALL LENGTH (C) (in/mm)	ENDCAP DIA. (D) (in/mm)	ENDCAP LENGTH (E) (in/mm)	KO IMPEDANCE PARAMETER (OHM-AMP$^{1/2}$)
FXC-1312-2	4	2/51	3.06/77.7	4.56/115.8	0.282/7	0.25/6	16.3
FXC-1312-3	4	3/76	4.06/103.1	5.56/141.2	0.282/7	0.25/6	24.4
FXC-1312-4	4	4/102	5.06/128.5	6.56/166.6	0.282/7	0.25/6	32.5
FXC-1313-3	5	3/76	4.06/103.1	5.56/141.2	0.320/8	0.25/6	19.5
FXC-1313-4	5	4/102	5.06/128.5	6.56/166.6	0.320/8	0.25/6	26.0
FXC-1313-6	5	6/152	7.06/179.3	8.56/217.4	0.320/8	0.25/6	39.0
FXC-1314-3	6	3/76	4.06/103.1	5.56/141.2	0.354/9	0.25/6	16.3
FXC-1314-4	6	4/102	5.06/128.5	6.56/166.6	0.354/9	0.25/6	21.7
FXC-1314-6	6	6/152	7.06/179.3	8.56/217.4	0.354/9	0.25/6	32.5
FXC-1315-3	7	3/76	4.06/103.1	5.56/141.2	0.394/10	0.25/6	13.9
FXC-1315-6	7	6/152	7.06/179.3	8.56/217.4	0.394/10	0.25/6	27.9
FXC-1315-8	7	8/203	9.06/230.1	10.56/268.2	0.394/10	0.25/6	37.2
FXC-1316-4	8	4/102	5.06/128.5	6.56/166.6	0.433/11	0.25/6	16.3
FXC-1316-6	8	6/152	7.06/179.3	8.56/217.4	0.433/11	0.25/6	24.4
FXC-1316-8	8	8/203	9.06/230.1	10.56/268.2	0.433/11	0.25/6	32.5
FXC-1317-6	10	6/152	7.06/179.3	8.56/217.4	0.507/13	0.25/6	19.5
FXC-1317-8	10	8/203	9.06/230.1	10.56/268.2	0.507/13	0.25/6	26.0
FXC-1317-10	10	10/254	11.06/280.9	12.56/319.0	0.507/13	0.25/6	32.5

Notes:

1) Minimum flashing voltage data predicated on an unloaded trigger pulse as specified.
2) Based on minimum coolant flow of 4GPM, with reservoir temperature controlled to 80°C.
3) All lamps listed are filled with xenon to a pressure of 450 Torr. Other fill pressures and gases are available. Consult the factory for assistance.
4) All lamps listed are processed to operate in either trigger mode and are supplied with a trigger wire.
5) Lamps can be customized to meet your specific mechanical and electrical requirements. Please consult the factory for assistance.

MINIMUM FLASHING VOLTAGE (1) (VOLTS)	MAXIMUM AVERAGE POWER (WATTS)			MINIMUM TRIGGER VOLTAGE (kV)		EXPLOSION ENERGY (JOULES)	
	CONVECTION	FORCED AIR	LIQUID(2)	SERIES	EXTERNAL	@t=100μSEC	@t=100mSEC
500	25	190	1900	12	15	225	720
600	35	280	2800	12	15	340	1080
700	50	380	3800	12	15	455	1440
600	45	355	3550	15	20	425	1350
700	60	480	4800	15	20	565	1800
900	95	710	7100	15	20	850	2700
600	55	425	4250	15	20	510	1620
700	75	575	5750	15	20	680	2160
900	110	855	8550	15	20	1020	3240
600	65	500	5000	20	25	595	1890
900	130	1000	10000	20	25	1195	3780
1100	175	1335	13350	20	25	1590	5040
700	100	765	7650	20	25	910	2880
900	150	1145	11450	20	25	1365	4320
1100	200	1530	15300	20	30	1820	5760
900	190	1430	14300	25	30	1700	5400
1100	255	1910	19100	25	30	2275	7200
1300	400	3000	30000	25	30	2845	9000

Rugged Solder Seal Series