

E2V Technologies

Hydrogen Thyratrons Preamble

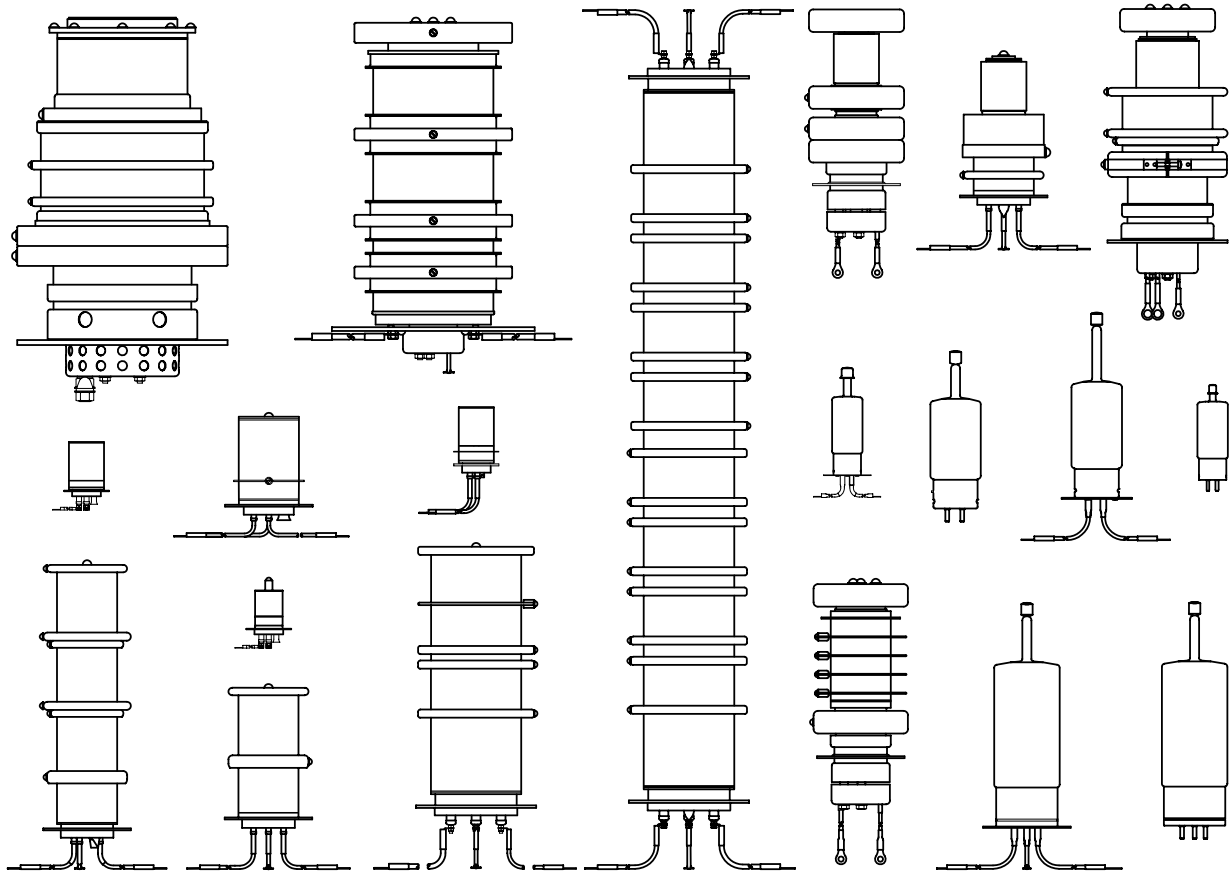


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1 INTRODUCTION

The hydrogen thyratron is a high peak power electrical switch which uses hydrogen gas as the switching medium. The switching action is achieved by a transfer from the insulating properties of neutral gas to the conducting properties of ionised gas. Exploiting the basic principles of gas discharge physics, the hydrogen thyratron is designed to withstand a high voltage in the 'off' state, to trigger at a precisely defined time, to pass high peak current pulses in the 'on' state and to recover rapidly to the 'off' state to allow high repetition rate operation.

E2V Technologies' hydrogen thyratrons have a high voltage capability which extends up to 200 kV and a peak current capability which extends up to 100 kA. Certain designs can handle partial or full reverse conduction. Pulse widths from tens of nanoseconds to hundreds of microseconds are readily achieved. Pulse repetition rate capability up to 70 kHz has been demonstrated. Thyratrons are robust and forgiving devices which can tolerate fault conditions well in excess of normal ratings. On the basis of this performance, E2V Technologies hydrogen thyratrons are ideally suited for switching energy stored in a capacitor bank or pulse-forming network into a variety of loads including magnetrons, klystrons, kicker magnets and gas discharge lasers.

E2V Technologies continues the development of hydrogen thyratrons to meet the needs of existing and future high voltage pulsed systems.

DESCRIPTION

E2V Technologies manufactures a wide variety of hydrogen thyratron designs to meet specific application requirements. The schematic of Figure 1 shows the basic structures underlying these designs.

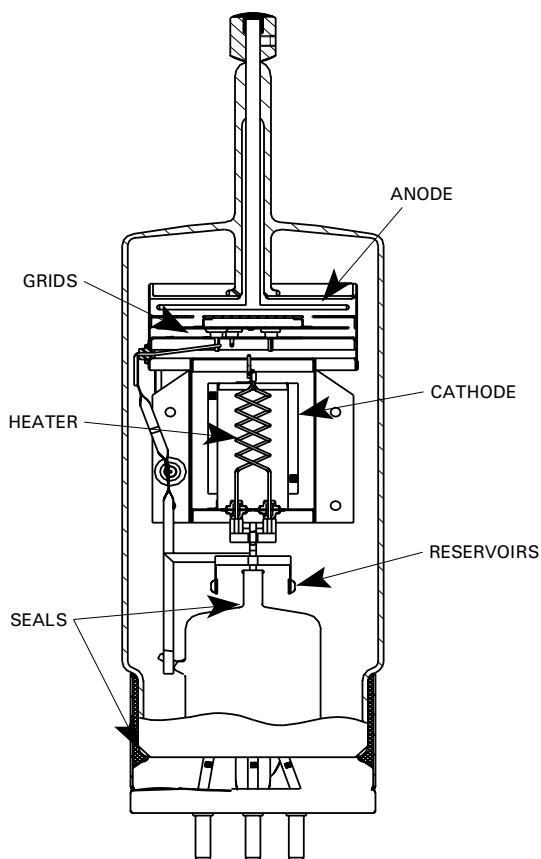


Figure 1. Basic Structure of a Thyratron

To achieve the special conditions required for thyratron operation, the cathode, grid and anode structures are contained in an insulating vacuum tight envelope of glass or ceramic sealed to the electrode and heater connections. The envelope is designed to withstand the voltages applied during operation and this leads to structures where, as a rule of thumb, the grid and anode surfaces are separated by 3 mm ($\frac{1}{8}$ inch) on the inside of the envelope and by 75 mm (3 inches) on the outside. The thermionic cathode and hydrogen reservoir system are heated by tungsten filaments to the appropriate temperatures that ensure good electron emission and optimum gas pressure respectively.

The internal electrode structures are designed to optimise high voltage hold-off, triggering, current pulse rise time and recovery characteristics. A variety of design approaches are followed to give best performance for particular applications. For example, anode designs may include hollow cavities or thermionic cathodes to enable bidirectional current conduction. Good system performance relies on the appropriate choice of thyratron type, and important parameters such as anode voltage, peak current, pulse width and repetition rate must be taken into account.

2 PRINCIPLES OF OPERATION

THE SWITCHING CYCLE

The process of switching in a hydrogen thyratron can be broken down into four phases. These are voltage hold-off, commutation, conduction and recovery (see Figure 2).

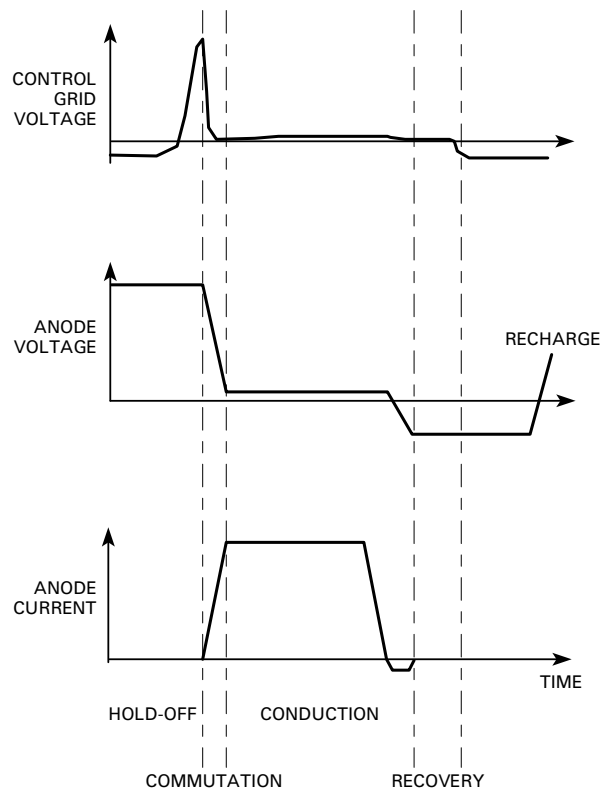


Figure 2. Thyratron Switching Cycle

i Voltage Hold-off

Thyratrons are designed to withstand a high voltage on the anode and to trigger with a low voltage on the grid. Voltage breakdown in any gas-filled gap is initiated by free charges (electrons and ions) crossing the gap under the influence of an electric field. If sufficient energy is available, gas molecules are

ionised producing more free charges. The positive ions are accelerated towards the lower potential electrode and cause the release of secondary electrons. Under the right circumstances, the processes become self-sustaining and voltage breakdown occurs. The breakdown behaviour is described by Paschen's law, where the breakdown voltage V of an electrode/gas system is a function of the product of pressure p , and electrode separation d :

$$V = f(pd).$$

The graph of this relation is of the form shown in Figure 3 and the breakdown voltage has a minimum at the pd value, designated pd_{min} . The breakdown voltage rises on either side of pd_{min} and it is thus possible to find two values of pd which give the same breakdown voltage. For example, thyratrons operate on the low pd or left-hand side of the curve. Spark gaps operate on the high pd or right-hand side of the curve.

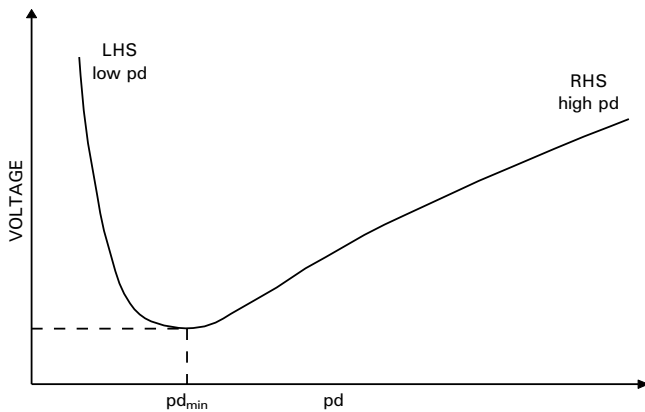


Figure 3. Paschen Curve for Hydrogen

The shape of the curve can be explained in terms of the electron mean free path between collisions. To the right-hand side of pd_{min} , the mean free path is much shorter than the electrode separation d and an electron loses energy in the many collisions it makes as it traverses the gap. In order to cause

breakdown, the applied voltage must be high enough to give an electron sufficient energy over one free path to make an ionising collision. Therefore, as pd increases, the breakdown voltage becomes higher. Once the breakdown voltage has been reached, any initial ionisation multiplies exponentially as electrons cross the gap. The ions return to the cathode where they release secondary electrons and the processes constituting breakdown are established.

To the left-hand side of pd_{min} , there are relatively few molecules in the gap and the mean free path for collision is much greater than the electrode separation d . Additionally, the collision cross-section or probability for electron ionisation falls rapidly as the electron energy increases above 100 eV. It is therefore extremely difficult for stray electrons to generate sufficient ionisation to enable breakdown to become self-sustaining. Thus, as pd reduces, the breakdown voltage increases rapidly. In practical cases, the limit to hold-off voltage is also constrained by field distortion at electrode corners and by field emission from electrode surfaces.

In summary, to the right of pd_{min} , gas processes dominate in determining the breakdown voltage. To the left of pd_{min} , a combination of gas and electrode surface processes are important. These considerations are incorporated in the designs of thyratrons as illustrated in Figure 4, with a high pressure spark gap shown for comparison. In the thyatron, which is filled with hydrogen to a pressure of about 0.5 torr (66 Pa), the high voltage hold-off is provided by the small inter-electrode spacing of about 3 mm, marked "low pd " in the diagram. Such a gap can hold-off a voltage of up to 40 kV. In order to minimise the trigger-voltage requirement, the cathode/trigger-grid spacing, marked " pd_{min} " in the diagram, is set at about 15 mm. This dimension is not critical since the copious supply of electrons from the thermionic cathode will ensure rapid ionisation in the grid region. The right-hand side of the Paschen curve is applied to the design of the envelope of the thyatron, which is usually in air, and the high voltage electrode must have a spacing of about 75 mm (3 inches) from other electrodes.

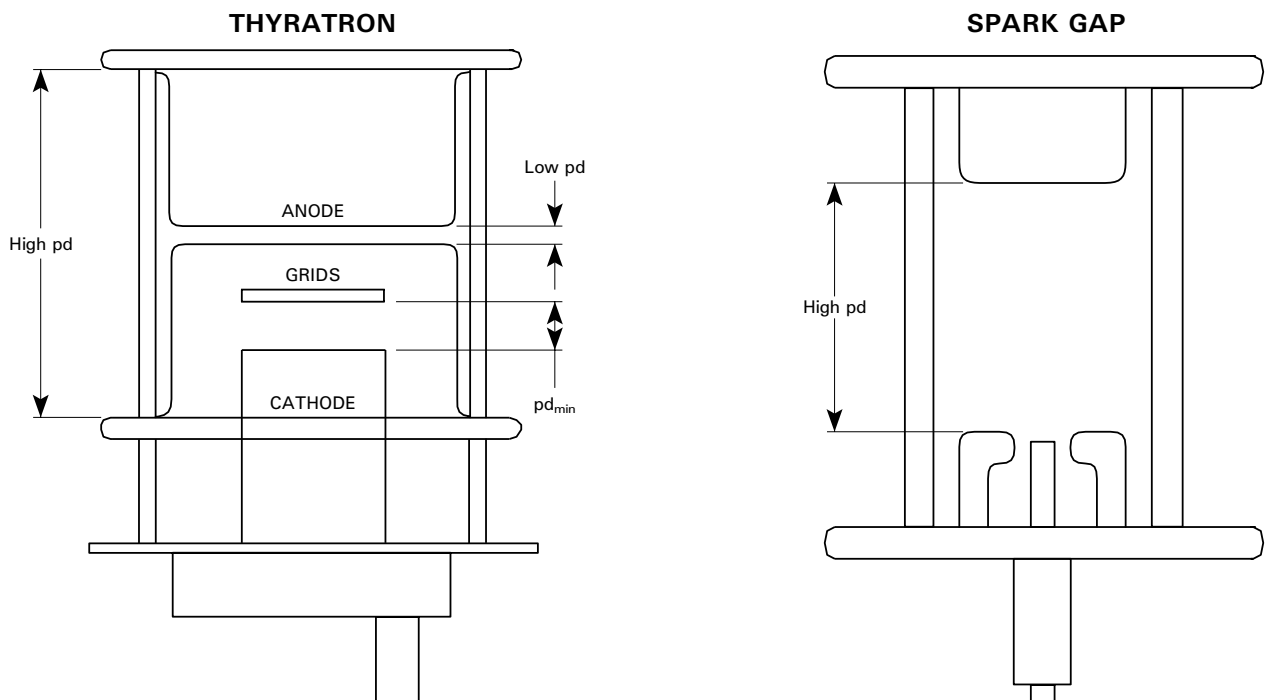


Figure 4. Comparison of Thyatron and Spark Gap Structures

ii Commutation

Thyratron commutation is achieved by introducing plasma into the grid/anode region via slots in the grid structure. The plasma is created in the cathode/grid region by a fast rising trigger pulse applied to the grid(s), which then diffuses to the grid slots where it comes under the influence of the anode field. The trigger plasma provides a copious supply of electrons so that anode breakdown proceeds until an ionised plasma connects the cathode and anode. The initial growth of ionisation in the gap is exponential in form and gives an instantaneous current I which can be described by:

$$I = I_0 e^{\alpha t}$$

There are two important points to note. The initial current I_0 is provided by the trigger pulse plasma in the cathode/grid region. The equation indicates that rapid current growth is assisted by creating a high density plasma prior to triggering with a high current pre-ionisation pulse so that I_0 is maximised. More critically, the exponent α is dominated by the effect of gas density in the grid/anode region, making gas pressure the most important factor for reducing commutation time. This is consistent with the physical processes described above in Voltage Hold-off since rapid current growth is assisted by trigger plasma electrons making collisions with gas molecules in the grid/anode gap. The second point is that grid geometry has a significant impact on I_0 and α and therefore grid design has a significant impact on thyratron commutation characteristics.

The anode voltage fall during commutation is defined by the current growth process and has a related exponential form experimentally determined as:

$$e_b = e_{py} - Ae^{t/\tau_a}$$

where e_b is the instantaneous anode voltage, e_{py} is the peak forward voltage, τ_a is the anode fall time constant and A is a constant. In the majority of radars and linear accelerators, τ_a is much smaller than the circuit time constant and the thyratron has little influence on the current rise time. In fast circuits, as used for driving kicker magnets and gas lasers, τ_a can become comparable with the circuit time constant and it becomes important to minimise τ_a to ensure best circuit performance.

Commutation loss arises from electrons crossing the gap without collision and striking the anode with energies corresponding to the instantaneous anode voltage. A small amount of the impacting electron energy is converted to X-rays with a characteristic wavelength corresponding to the rapidly dropping anode potential but the majority is converted to heat and contributes to dissipation at the anode.

In summary, it is important to ensure that the gas density in the grid/anode gap is maximised by proper adjustment of the reservoir voltage and by adequate cooling of the anode/grid region. In most cases, E2V Technologies thyratrons have a gas pressure optimised for the anticipated conditions of operation. However, when the thyratron operating conditions are fully considered, it may be possible to improve current rise time performance and reduce anode dissipation by increasing the gas pressure within the limits set by voltage hold-off and recovery time considerations.

iii. Conduction

When the commutation phase is complete, the thyratron is filled with plasma. Current is carried between cathode and anode with a potential drop of the order of 100 V when the peak current is 1000 A. This low voltage drop results from the shielding effect of the positive ions in the plasma which allows the electron current to flow without space-charge limitation. In this mode, the current passed by the thyratron is solely

dependent on the parameters of the external circuit. The high electron mobility in the plasma ensures that a sheath of positive ions develops on the grids and this sheath prevents the penetration of grid potential into the plasma. Switching off a conducting thyratron by applying a negative grid pulse is therefore impractical. The thyratron only returns to its non-conducting state after the removal of anode voltage for a time sufficient to allow the charged particles to recombine. The thyratron is closed by the application of a positive pulse to the grid, but is opened only by the removal of anode voltage.

The cathode and its related structures provide electrons for the discharge by thermionic emission, ion recombination and secondary emission. Hydrogen and deuterium are chosen for the gas filling because their ions do not bombard the thermionic cathode with sufficient energy to destroy its low work function surfaces. Generally, cathode size determines the maximum average current ratings of a particular thyratron type. At currents above the rating, ion bombardment of the cathode structure increases the temperature beyond safe limits and can cause excessive cathode evaporation. E2V Technologies thyratrons will tolerate short periods of operation up to double the average current rating and some types have been operated in burst mode at a factor of 5 - 10 times higher than the maximum.

Thyratron grid designs necessarily restrict the current flow to narrow apertures where the current density can be an order of magnitude higher than at the cathode. At very high peak currents and with long pulses, ion pumping processes in the grid region can lead to gas starvation and consequent interruption of the current flow. Current interruption is usually known as 'quenching', and the critical current for current interruption I_Q is proportional to gas density in the grid slot:

$$I_Q = kpA$$

where A is the grid slot area, p is the gas pressure at constant temperature (gas density) and k is a constant. As a result of quenching, an arc is established between grid and anode so that the discharge current flows through the grid material and not through the slots. In this case, the cathode spot on the grid can cause significant damage to the grid surface and may compromise voltage hold-off performance. Quenching is mainly of interest for crowbar protection systems where the thyratron must pass a large initial current pulse followed by a low current tail until the power supply is isolated. It is common to express the crowbar capability of a particular thyratron as a coulomb limit for a single pulse. This limit is typically hundreds of times higher than the coulombs switched under line-type modulator conditions.

iv. Recovery

At the end of the current pulse, a residual plasma exists throughout the thyratron and continues to present a short circuit to positive anode voltages. As a result, the thyratron requires a recovery period with the anode at a slight negative potential to allow the plasma to decay back to neutral gas. The plasma decay is dominated by the recombination of ions and electrons on adjacent electrode surfaces. Thyratron recovery is therefore controlled by diffusion processes in the grid/anode region. Initially, the diffusion is ambipolar, but as the ionisation density drops below $10^7/\text{cm}^3$, the ions and electrons diffuse separately to the electrodes. Since the anode/grid gap and grid slots are relatively narrow, the plasma density drops rapidly in this region with a time constant in the region of 2 - 7 μs . As a general rule, recovery time increases as gas pressure increases. However, reducing gas pressure to minimise recovery time will increase anode dissipation and may reduce thyratron lifetime.

The grid-cathode plasma decays much more slowly because of the wider gaps involved. It should be noted that complete de-ionisation is not necessary since recovery is complete when the grid-cathode plasma has shrunk away from the grid so that the grid potential can extend across the grid apertures, thereby electrically separating the anode and cathode regions. Calculation of recovery times based on diffusion coefficients gives recovery times which are longer than those measured in practice. This is because the inverse voltage which most circuits apply to the thyatron anode at the end of the current pulse assists in sweeping ions to the anode and reducing the time taken for plasma decay. Additionally, the recovery process is assisted by the use of a negative bias voltage on the appropriate control grid to sweep positive ions from the grid slot region.

It should be noted that the recovery process requires that the anode voltage remains at or below zero voltage until the anode/grid gap is substantially free of plasma and the grid has re-established control. Any positive excursions during the recovery period will create further ionisation in the thyatron and significantly enhance the risk of continuous conduction when the charging system begins to reapply voltage to the anode. In practice, it is difficult to control the effects of stray inductance and capacitance in modulator circuits and short transients may appear on the anode at the end of the current pulse. It is often possible to anticipate these effects by the use of circuit modelling software and to make appropriate design choices for best reliability. The use of command resonant charging alleviates thyatron recovery time as a modulator design consideration and may enable the thyatron to operate at higher gas pressure with lower anode dissipation and improved life. Similar benefits are also achievable with the use of switched mode power supplies since a recharge delay of 50 μ s or more is easily obtainable. Care should be taken to ensure that the switch mode supply does not pump out small bursts of current during the 'off' period. The thyatron holding current is so low that even very small currents (a few mA) will maintain the plasma and extend the recovery time.

By definition, the thyatron has recovered when re-application of a positive anode voltage does not cause further conduction. At E2V Technologies, recovery times are measured using a special test circuit which applies a positive probe pulse with a variable delay after the main current pulse. The probe pulse is distorted if the thyatron has not recovered. The recovery point can be discovered by adjusting the delay. In a typical modulator, the negative grid bias voltage gives a good diagnostic for recovery status, since the grid voltage is pulled up to cathode potential during thyatron conduction. The point at which the negative bias returns to its set value indicates recovery of the grid region and the thyatron's readiness for application of anode voltage.

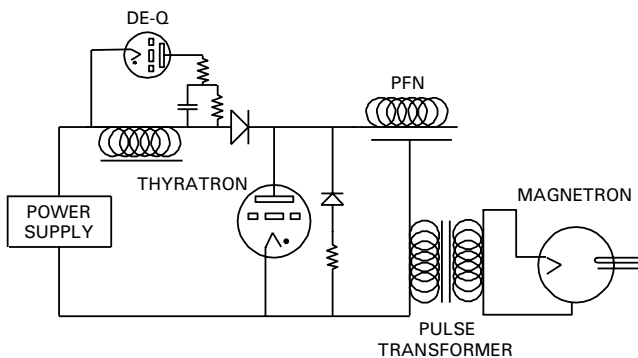


Figure 5. Typical Modulator Circuit Incorporating Thyatron

TYPICAL THYRATRON WAVEFORMS

Thytrons are often used in line-type modulators (Figure 5) to switch the energy stored in a pulse forming network (PFN) through a pulse transformer into a load. The thyatron controls the release of the pulse energy and initiates the subsequent charging cycle.

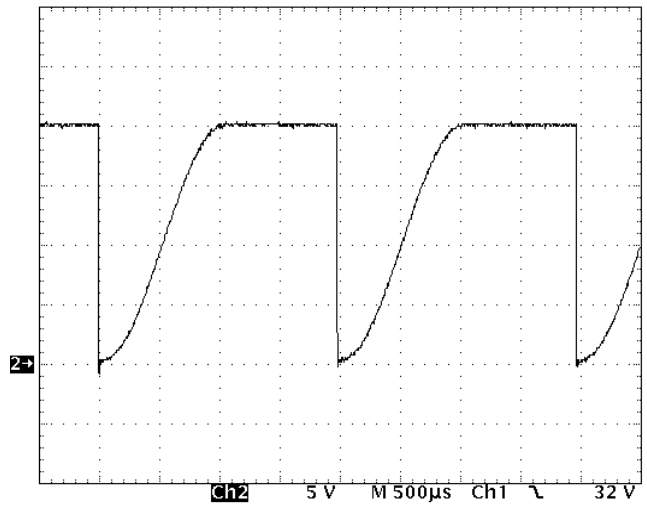


Figure 6. Anode Voltage Waveform in the Resonantly Charged Circuit of Figure 5

i. Charging Waveforms

In most modulator designs, the PFN is resonantly charged through an inductor and diode so that the PFN voltage is held at about twice the power supply voltage (Figure 6). A de-Q circuit may be used to give precise control of the PFN voltage. The circuit designer must ensure that a negative voltage is present on the thyatron anode at the end of the current pulse to allow the thyatron to recover. Alternatively, the charging system may be designed to charge on command just before the main pulse is required (Figure 7). In addition to the removal of any recovery time issues, this technique reduces duration of HV stress on the PFN and thyatron anode and can allow reliable operation at higher gas pressure in the thyatron with improved reliability and lifetime.

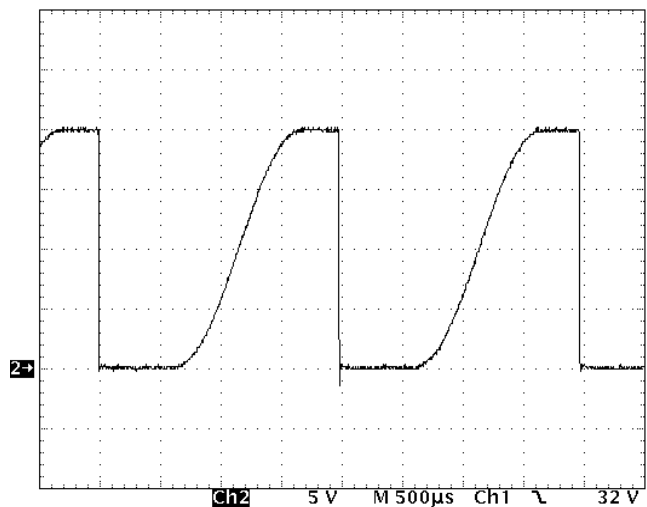


Figure 7. Anode Voltage Waveform in a Command Resonantly Charged Circuit

ii. Thyatron Anode and Grid Waveforms

When the PFN is fully charged, the thyatron holds the voltage until a trigger signal is applied to the grid. The conduction cycle and recovery phase are illustrated in Figure 8, where the upper trace shows the anode voltage, the middle trace shows the pulse current through the thyatron and the lower trace shows the grid voltage waveform. The anode voltage falls when the grid pulse is applied and the thyatron conducts pulse current. During the immediate post-pulse period, the anode voltage shows some regularly spaced negative excursions due to PFN reflections. Between these, the thyatron is conducting the positive reflections and remains in conduction for about 6 μ s after the end of the main current pulse. This is revealed by inspection of the grid pulse voltage waveform which remains at the zero voltage level whilst the thyatron is still in conduction. After remaining in conduction for 6 μ s, recovery commences when the grid voltage starts to return to the negative bias level.

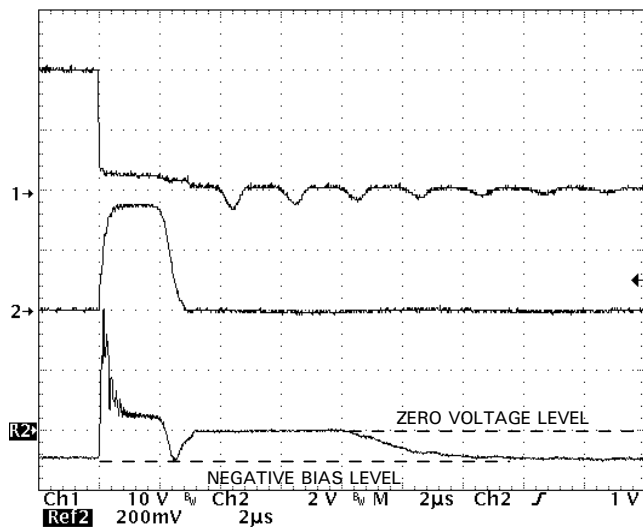


Figure 8. Typical Thyatron Anode Voltage, Pulse Current and Grid Voltage Waveforms

3 OPERATING NOTES

The following notes are intended to offer advice on the use of E2V Technologies thytrons to ensure optimum performance. They should be used with the current issue of the appropriate thyatron data sheet. E2V Technologies is pleased to advise customers on the correct choice of thyatron for specific applications. The E2V Technologies thyatron operating parameters (TOPS) form and a list of E2V Technologies technical reprints on thyatron performance and applications are included in the appendices. These are available on request.

MECHANICAL

i. Transport

E2V Technologies thytrons are delivered in packs designed to protect them from excessive shock or vibration and to ensure that excessive stresses are not imposed on the envelope or seals. As a general rule, any subsequent transportation of the device must be in the complete original packing. This also applies to the return of devices to E2V Technologies for warranty or technical investigation since transport damage may render any electrical analysis impossible.

ii. Connections

Care must be taken when making connections with the thyatron electrodes to avoid mechanical damage and poor

conductivity. Use the appropriate screws supplied with the thyatron (see data sheet) and do not over-tighten. The anode and grid connections should incorporate a degree of flexibility to allow for the effects of thermal expansion. Plug-in bases and push-on anode connectors should be checked and renewed if loose or worn. Loose base connections may cause reduced voltage to be applied to the cathode and reservoir heaters with consequent damage to thyatron performance and life. Loose anode and cathode connections may arc while passing pulse current, causing damage to the connectors and producing high levels of ozone in air or carbonisation in oil.

iii. Mounting

Thytrons with oxide cathodes may be mounted in any orientation, though with the larger tubes a base-down position is usually more convenient. Thytrons with barium aluminate cathodes (metal envelope tubes) should not be mounted with the anode downwards. Oxide cathode thytrons are insensitive to changes in orientation during operation and may be rotated (medical linacs) or moved (naval and airborne radar) without influencing the electrical performance.

iv. Storage

Thytrons should be stored in their original packing, or in suitable racks designed to protect them from excessive shock or vibration and to ensure that excessive stresses are not imposed on the envelope or seals. Orientation of unused thytrons during storage is not critical. Thytrons may be stored in ambient temperatures between $-30\text{ }^{\circ}\text{C}$ and $+50\text{ }^{\circ}\text{C}$ unless otherwise specified in the tube data sheet. Tubes must not be stored near volatile materials, acids, etc. which might have harmful effects. The external glass or ceramic envelopes of tubes stored in racks must be shielded from dust and grit. Care must be taken when cleaning to avoid scratching glass surfaces, or making permanent marks on ceramic parts. Where extended storage is unavoidable, note that there are many examples of shelf life in excess of ten years without deterioration in performance.

v. Shock and Vibration

Thytrons, including glass types, are of robust design and construction. Many types are tested to specified shock and vibration levels for the arduous conditions experienced by military radars in aircraft, missiles, vehicles and naval guns. Examples include the CX1157, 8503 and CX1535 and these thytrons have shock and vibration details included in the tube data sheet.

ENVIRONMENTAL

i. EM Radiation

Thytrons are generally resistant to the effects of intense light, X-rays and microwaves but at very high levels these may cause ionisation within the tube envelope, seriously affecting the hold-off capabilities of the thyatron and increasing the recovery time.

ii. Magnetic Fields

Magnetic fields will arise naturally from the passage of circuit current each time the thyatron switches. In cases where the pulse current exceeds several kiloamps, it is advisable to ensure symmetrical current flow in the connections around the thyatron. An asymmetrical magnetic field can impose forces on the internal plasma that prevent uniform current density at the cathode and at grid apertures with unpredictable effects on

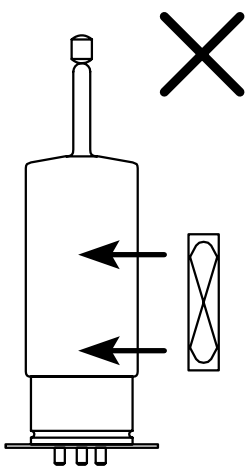


Figure 9.1

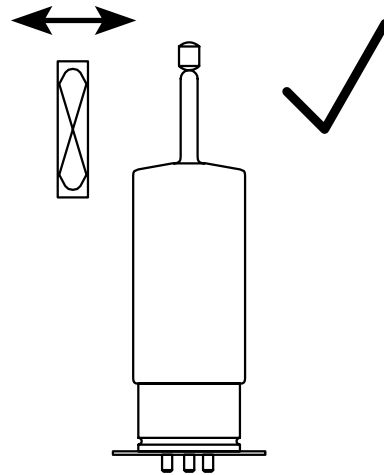


Figure 9.2

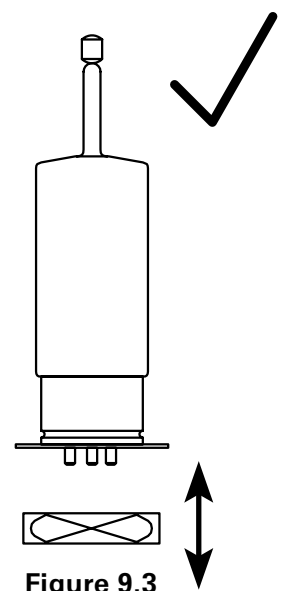


Figure 9.3

performance and lifetime. For the same reason, the thyatron should be shielded from strong magnetic fields (>0.05 T) from other sources.

iii. Atmospheric conditions

Thyatron tubes will operate satisfactorily at an elevated altitude but the reduced air pressure will require more care to prevent corona at the anode and voltage breakdown across the anode ceramic. High humidity or dusty conditions may exacerbate these problems.

iv. Helium

Helium will diffuse through the envelope of a glass thyatron if the tube is run hot in a helium-rich atmosphere. A high partial pressure of helium inside the tube makes it unserviceable. It is important that where glass thyatron tubes are used in an environment that could contain helium (e.g. a TEA CO₂ laser), they are adequately cooled. Measures should be taken to avoid helium coming into contact with hot glass thyatron tubes.

v. Cooling Glass Thyatron Tubes

E2V Technologies glass thyatron tubes operating in open equipment cabinets with some air circulation do not require any extra cooling. For glass thyatron tubes used in confined spaces, care must be taken to avoid overheating. In any cooling scheme, avoid excessive airflows directed at the cathode and reservoir regions which can reduce the envelope temperature below optimum levels (see Figure 9.1). The resulting change in radial gas density gradient is equivalent to operating the thyatron at low gas pressure and can reduce the performance and operating life. However, cooling the anode stem to below 70 °C when the tubes are being used with high forward (>30 kV) and inverse voltage is advisable. A typical arrangement is shown in Figure 9.2. As a general rule, anode and base connections should be adequately cooled to prevent oxidation of the pins and connectors. Glass thyatron tubes may be used in oil, although the silicon rubber insulation on the leads of flange mounted tubes may degrade with time.

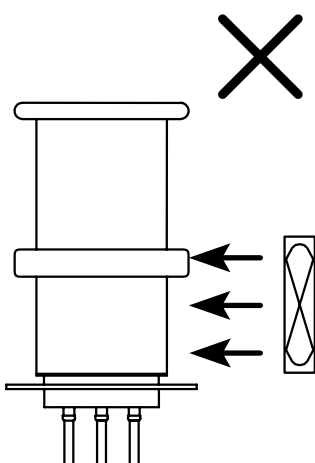


Figure 10.1

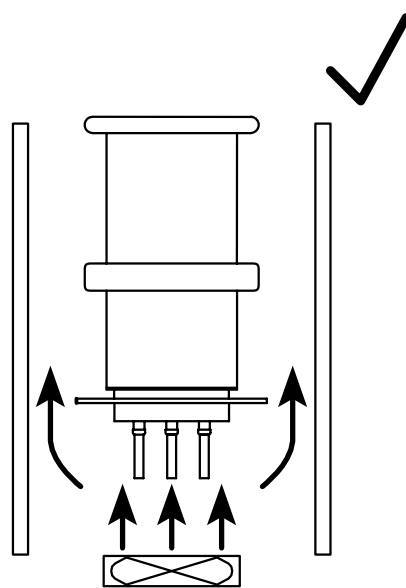


Figure 10.2

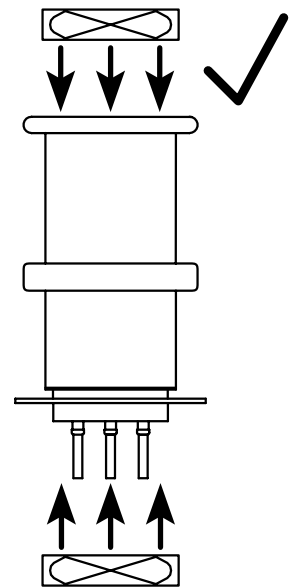


Figure 10.3

vi. Cooling Ceramic Thyratrons

Greater care must be taken to control the envelope temperature of this type of tube because of the higher ratings and greater power switching capability compared with glass tubes. This can be achieved by immersing the tube in a liquid coolant such as transformer oil or a fluorinated hydrocarbon, which is then circulated through a heat exchanger. Directing the return liquid flow at the base and anode of thyratrons operating at high power is advantageous. Multi-gap thyratrons operating as extremely fast switches are usually mounted in low inductance, coaxial housings that are liquid filled for insulating and cooling purposes. Where liquid cooling is not desirable, forced-air cooling may be used as shown in Figure 10, taking care that the maximum specified envelope temperature is not exceeded. It is important to interlock the system against fan failure using fan stop detectors. As with the glass thyatron, it is possible to overcool the thyatron which may result in a low cathode temperature and a low gas pressure. As a general guide, the ceramic envelope near the cathode must not fall below 70 °C when operating normally in air.

vii. Cooling Metal Envelope Thyratrons

Generally the same comments apply as with ceramic thyratrons, with the following exception. The base of a metal envelope tube contains a circuit that regulates the reservoir temperature against changes in applied reservoir voltage and backheating conditions. This circuit is temperature sensitive and is adjusted to its set point during manufacture to give optimum performance in the specified cooling medium. Thyratrons optimised for use in air will not operate correctly in liquid and vice-versa. Therefore it is **essential** that metal envelope thyratrons are operated in the environment for which

they were optimised. Metal envelope thyratrons with an 'A' suffix are designed for **air-cooled** operation; metal envelope thyratrons without this suffix are designed for **liquid-cooled** operation. However, a few exceptions exist and the data sheet should be consulted to ensure that the correct cooling medium is used. Metal envelope thyratrons with the suffix 'X' or 'AX' must be used with the MA942A resistor box to enable the gas pressure to be varied over a large range and to be optimised for a particular application. Recommendations for the resistor values are included with the thyatron. Optimisation of the resistor value is explained in the MA942A data sheet.

When metal envelope thyratrons are operated with air cooling, it is important that the base of the tube containing the gas pressure control circuit is adequately cooled. E2V Technologies offers two cooling modules, MA2161A/B for large tubes and MA2163A/B for medium size tubes which are specifically designed to ensure optimum thyatron performance. The module includes a large axial fan at the base, a mounting flange and air duct with a fan stop detector which may be used to provide an interlock. The outline of a cooling module is shown in Figure 11.

viii. X-Ray Warning

Thyratrons operating at high voltage may emit X-rays which can constitute a health hazard. The radiation is usually reduced to a safe level by the equipment enclosure. Equipment manufacturers and users should check the radiation level at maximum operating conditions.

All of the ceramic and metal-ceramic thyratrons except the smallest types (<57.15 mm or 2.25 inches diameter) use an internal 'immersed anode' design. The grid-anode region where X-rays are generated is shielded from the outside world by a metal enclosure. Therefore these tubes emit far lower X-ray levels than similar unshielded thyratrons. Some glass thyratrons have an internal X-ray shield. **In all cases adequate external shielding is required.**

ELECTRICAL

i. Cathode Heaters

Heater voltages must be measured with a true RMS voltmeter at the base pins or heater lead terminations.

The thyatron cathode is heated to the correct operating temperature by a tungsten filament. The cathode heater supply should be maintained within the limits defined in the data sheet to achieve best performance and life. For many applications, an AC transformer provides a simple and adequate heater supply. In cases where the voltage stabilisation needs to be improved, a constant voltage transformer may be suitable. Alternatively, a DC heater supply provides self-regulation, but electrical noise during the pulse has been known to cause interference problems, and thus care must be taken to ensure that this does not occur.

In circuits with high rates of rise of current, a substantial portion of the pulse current may pass to ground through the heater system. The effect can be reduced by installing a common mode inductive filter in series with the heater leads. Ensure that the correct voltage is applied to the thyatron connections and that the wire is adequately rated for the heater current. The common mode inductive filter will introduce an extra voltage drop and this must be taken into account.

ii. Reservoir Heaters

Thyatron reservoir systems use titanium hydride, where hydrogen or deuterium gas pressure is maintained within the thyatron via the following reversible chemical reaction:

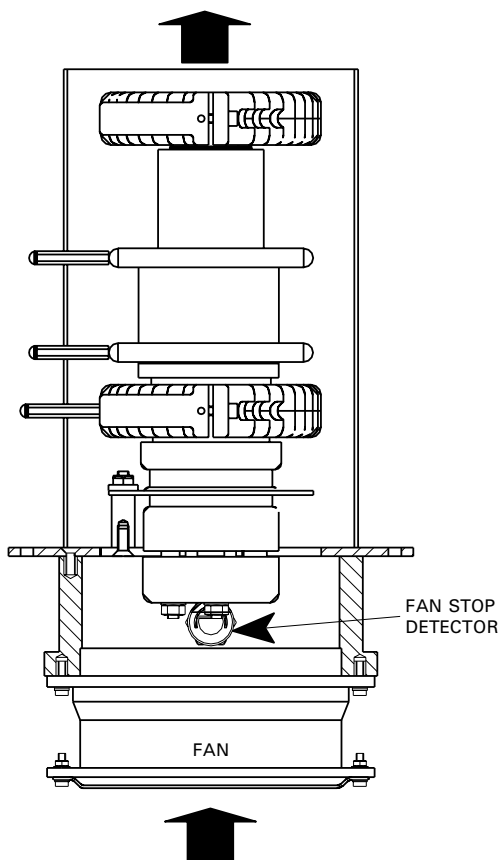
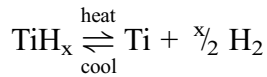


Figure 11. Metal Envelope Thyatron in Cooling Module



When the reservoir heater is not energised, there is no hydrogen present within the envelope. Therefore, the reservoir heater must be energised and the warm-up time allowed to elapse prior to thyatron operation.

The thyatron reservoir system is maintained at the correct operating temperature by a tungsten filament. Many glass thyratrons have reservoirs connected internally to the cathode heater and the gas pressure is not adjustable. Oxide cathode thyratrons with adjustable reservoir systems should be operated at the reservoir voltage recommended for the tube. Alternatively, the reservoir voltage can be maximised to a value consistent with anode voltage reliability and recovery time in the circuit to provide best performance and life. A common procedure is to increase the reservoir voltage slowly while full anode voltage is applied. The thermal time constant is about two minutes. At some point the thyatron will self-fire. Reliable operation can usually be achieved by operating the reservoir at 0.2 V lower than the self-fire voltage. **Operation with reservoir voltages much below the recommended level will result in reduced performance and lifetime and may indicate a problem in the modulator circuit.**

Thyratrons with barium aluminate cathodes have very high capacity reservoirs which do not need adjustment during life. A reservoir regulating circuit in the base of the tube keeps the gas pressure stable. As a result, varying the reservoir voltage produces only a small change in gas pressure. The best way to optimise gas pressure in these tubes (e.g. for applications with a high rate of rise of current) is to use a modified version of the tube with an 'X' or 'AX' suffix and an external, selectable resistance box MA942A. The optimisation procedure is described in the MA942A data sheet.

Circuits with rates of rise of current greater than 20 kA/μs may produce voltage spikes on the reservoir heater. Capacitors in parallel across the reservoir form an effective bypass for voltage spikes. Details are given in the tube data sheet.

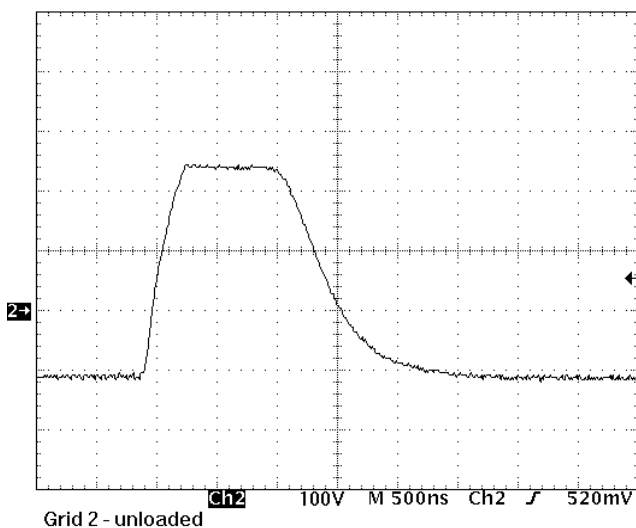


Figure 12.

iii. Tube Heating Time

The time quoted on the tube data sheet is the minimum necessary for the cathode to reach operating temperature and for the gas pressure to reach equilibrium. If trigger pulses (Figure 12) are applied before the expiry of the heating time, then grid-cathode breakdown may be observed (Figure 13), but

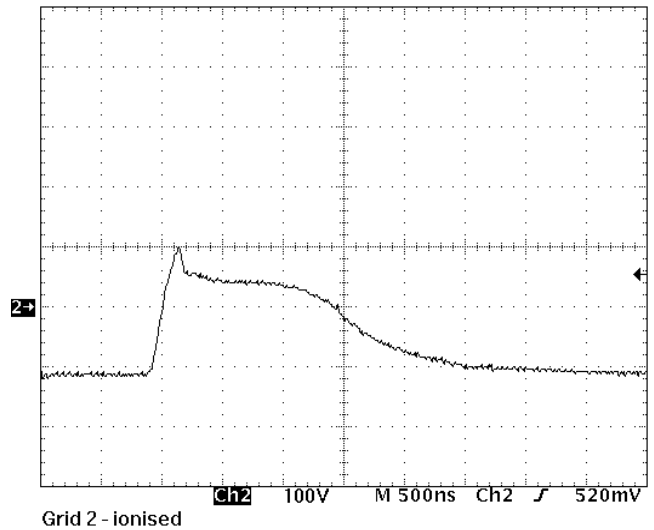


Figure 13.

this does not mean that the cathode temperature or gas pressure is high enough for full power operation. If the ambient temperature before warm-up is very low (below $-20\text{ }^{\circ}\text{C}$) then some increase in heating time may be necessary. Temporary interruptions in the heater supply have a large impact on cathode temperature, and recovery to a satisfactory operating temperature takes much longer than the off-time. Any interruption longer than 20 seconds will require the original warm-up time. Shorter interruptions will require a one minute reheat.

iv. Triggering Schemes

The choice of trigger scheme depends on the type of thyatron, the application and the required critical performance characteristics, e.g. jitter, current rise time, recovery time, operating endurance, etc. Many thyatron types require negative bias to be applied to the control grid, but there are some thyatron types that will operate with zero bias. The tube data sheet should be consulted for precise details of the grid layout and the voltages and currents required at each grid. Note that a trigger pulse duration very much greater than the minimum value specified on the tube data sheet is unnecessary and may in the extreme inhibit recovery of the thyatron after the main current pulse has been switched. The following three schemes are in common use and cover most requirements. E2V Technologies generally recommends double pulsing as the best option.

a) Double Pulsing

- Benefits: Excellent firing characteristics
- Reduced grid spike
- Significantly improved lifetime (2 - 5 times)

Double pulsing is a trigger technique used with tetrode and pentode thyratrons to achieve significantly improved performance and lifetime. The benefits arise from the pre-ionisation of the cathode grid space by the first pulse which prepares the cathode region for conducting the main current pulse. The first pulse can be relatively slow but it should provide a substantial current of about 2 A to 30 A peak depending on the thyatron. It is essential to avoid triggering the thyatron on the first pulse since this will give poor trigger characteristics and cancel any life benefit. The second pulse should be delayed by at least $0.5\text{ }\mu\text{s}$ and should provide a fast rising voltage to ensure precise triggering. E2V Technologies supplies cost-effective solid-state trigger systems which meet these requirements.

b) DC on Priming Grids

Benefits: Priming current gives "ready to fire" indication

The simplicity of driving the priming grid or grids with a low voltage (150 V) positive DC supply, resistively limited to provide a current between 20 and 300 mA (depending on the particular tube), makes this a common triggering technique. The provision of a DC priming current to the grid does not prevent operation at high prf. The priming current is particularly useful for crowbar applications since it can be used to provide a fail-safe "ready to fire" indication.

c) Split single pulse

Benefits: Simplicity

Firing delay is insensitive to anode voltage

The simplest trigger scheme is to take a single trigger pulse and split it between the thyatron grids. If negative bias is used, it should not be applied to the grid closest to the cathode. The trigger characteristics are degraded slightly with this trigger method, i.e. time jitter may extend to about 5 ns and the anode delay time drift may be as much as 100 ns. One benefit is that the anode delay time is not a strong function of anode voltage which may be an important feature for some applications.

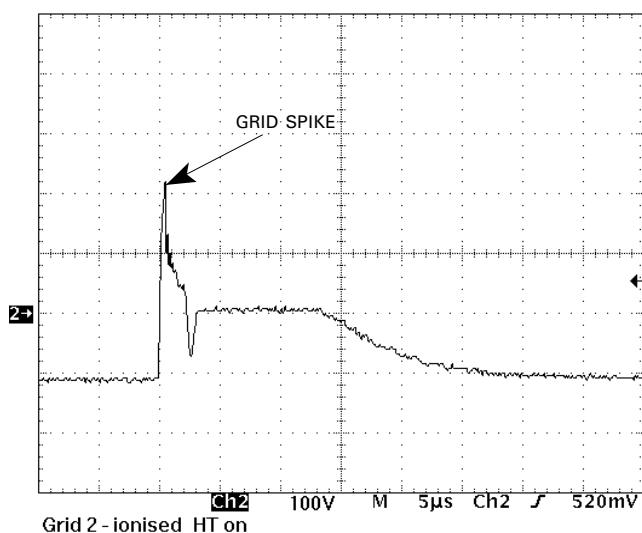


Figure 14.

v. Grid Spike

Any of these trigger circuits will need to be protected against large transient voltages (grid spikes) which may reach a substantial fraction of the anode voltage for about 20 ns at the instant of firing (see Figure 14). The amplitude of this spike increases as the rate of rise of current in the tube is increased. Typically, a grid spike is quite low (<2 kV) at the start of life, but it may increase during life and eventually may be the reason for end of life because of arcing or interference effects in surrounding circuits. The series resistor connected to the grid terminal, along with stray capacitance, will provide some filtering against it. In addition, non-linear resistors (e.g. Metrosil or Thyrite) connected close to the thyatron grid are effective in reducing the grid spike that appears on the trigger lead. However, the high capacitance of these devices degrades the grid pulse front and may increase jitter and anode delay time. In general, E2V Technologies recommends the use of a double pulse trigger system as it provides minimum grid spike. Protection will still be required, but double pulsing will provide optimum trigger characteristics and switch performance. The grid drives available from E2V Technologies incorporate grid spike protection circuitry.

vi. Trigger Characteristics

The values of jitter and anode delay time drift quoted in the tube data sheet are extreme values measured under conditions of minimum trigger amplitude, drive current and rate of rise of voltage. The minimum trigger pulse amplitude quoted in the tube data sheet is with respect to cathode potential. The value of any negative bias must be added to this figure to give the required minimum unloaded pulse amplitude from the trigger generator. This amplitude should be checked at the thyatron socket with the tube removed. In general, the trigger signal applied to the thyatron grid should have a pulse amplitude and rate of rise of voltage high enough to cause rapid ionisation of the gas in the grid-cathode space. Good performance with minimum jitter and anode delay time drift will result. Any modulation superimposed on the amplitude of the grid pulses, or on the bias supply, will show up as time jitter on the main current pulse. Additionally, it is possible for the AC magnetic field from the cathode heater to contribute to jitter. In cases where time jitter is critical, the use of a DC heater supply may be beneficial.

vii. Control Grid Negative Bias

Some thyatrons are designed to operate without a negative bias voltage applied to the control grid. However, most thyatrons require a negative bias voltage on the control grid to prevent self-firing caused by the movement of electrons to the anode/grid region. The negative bias supply can also help to reduce recovery time and it should be designed to pass a large current without an appreciable voltage drop for the duration of the recovery period. A typical circuit is shown in Figure 15. The supply must be capable of recharging the bias capacitor (about 0.1 µF depending on requirements) rapidly and should be free from ripple to avoid any contribution to time jitter on the output pulse. The control grid negative bias supply should be capable of providing up to 30 mA depending on the thyatron and the pulse repetition rate.

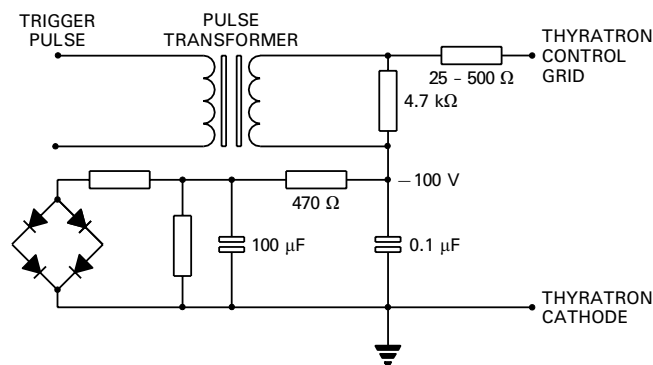


Figure 15. Typical Grid Bias Circuit

viii. Control Grid Recovery

For a thyatron with an internally connected reservoir, the tube data sheet shows recovery curves for various values of bias and recovery resistance. The published recovery times are longer than those achieved from a pulse transformer drive, since any energy stored in the pulse transformer self-inductance produces a negative voltage on the grid which helps recovery.

Recovery time varies with gas pressure and consequently curves are not published for tubes with independent reservoir voltage control. However, the reduction of reservoir voltage below recommended levels to achieve fault-free operation suggests a serious shortcoming in the modulator and should be addressed by careful investigation and correction of the

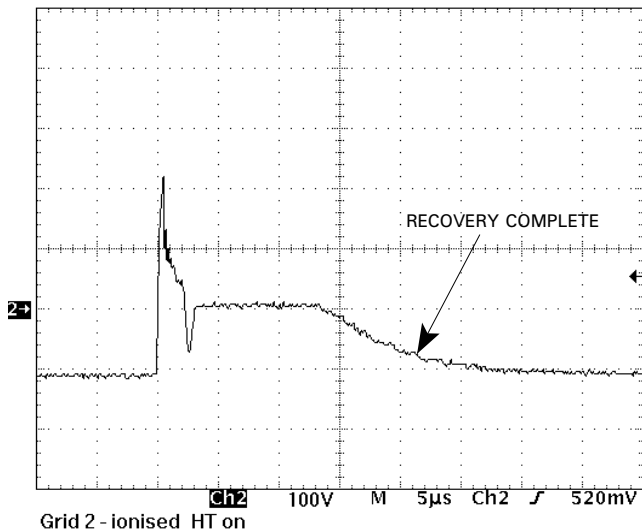


Figure 16.

anode and grid circuits of the modulator. **Setting the reservoir voltage below the recommended level will reduce thyatron lifetime.**

An indication of the recovery time of a thyatron with a negative bias supply may be obtained from an inspection of the control grid waveform. During the pulse, the dense plasma near the control grid has the effect of a short-circuit on the negative bias supply. The control grid waveform should appear as in Figure 16 and the return of the negative bias voltage to its inter-pulse value indicates that the plasma in the grid region has substantially disappeared. The thyatron has then recovered and is ready for the application of anode voltage. This measurement will require the use of a high voltage probe connected to the control grid during operation at anode voltage and should only be carried out by suitably qualified personnel in accordance with good high voltage working practice.

ix. Gradient Grids

Multi-gap thyratrons require the anode voltage to be distributed evenly between the high voltage gaps by a divider network. For circuits where the charging voltage is applied slowly (> 2 ms), a resistive network is adequate. In cases where the charging voltage is applied quickly, capacitors may also be necessary to preserve uniform voltage distribution on the gradient grids and ensure good voltage reliability. Full details are included in the relevant tube data sheets.

x. Average Current

All E2V Technologies thyratrons have an average current rating to reflect the type of service for which the tube is intended. As a guide, thyatron cathode lifetime depends on average current. When selecting a thyatron for a given circuit, it is particularly important to ensure that the effects of an impedance mismatch are considered when calculating the average current since it is possible for the thyatron to pass a higher average current than that drawn from the power supply. The full voltage swing will give the most accurate estimate:

$$I_{AV} = C \times \Delta V \times \text{prf}$$

where C is the capacitance switched, ΔV is the difference in PFN voltage before and immediately after the current pulse and prf is the repetition rate. Additionally, careful measurement of the current waveform in the actual circuit is an essential check on the theoretical estimate. Greater care is needed in cases where current reversal occurs.

xi. RMS Current

RMS current ratings are not generally quoted in E2V Technologies data sheets since the thyatron voltage drop is not a strong function of current.

xii. Anode Heating Factor

The anode heating factor is usually denoted as P_b and is defined as:

$$P_b = VI \times \text{prf}$$

where V and I are the voltage and peak current switched, and prf is the repetition rate. The anode heating factor has no weighting for commutation or reversal losses, which become the critical factor in many high prf or high di/dt circuits. As a result, the tube data sheet does not quote a figure for P_b except in the case of thyratrons for radar applications.

xiii. Inverse Voltage

Thyratrons in the non-conducting state can withstand an inverse voltage on the anode of a similar magnitude to the forward voltage rating without damage. However, transient inverse voltage applied to the thyatron anode just after the pulse, and up to the point before the residual plasma in the anode-grid region has completely decayed, can cause serious damage. Such transient voltages arise from the effects of a mismatch between the energy store and the load or from the presence of stray capacitance and inductance in the circuit. Thyratrons will tolerate transient inverse voltage up to -4 kV, and in many circuits the inverse voltage is essential to provide time for recovery before the recharge circuit takes the anode voltage positive. However, if the transient inverse voltage is between -4 kV and -7 kV, it is possible that occasional reverse arcing will occur and cause gradual loss of voltage reliability. In particularly bad cases, when the transient voltage peaks above -7 kV, the thyatron will reverse arc continually and rapidly destroy the voltage reliability.

In applications where high inverse voltages are unavoidable, resistance to reverse arcing in the thyatron can be improved by using circuit designs that reduce the peak forward current, reduce the rate of rise of inverse voltage or delay the application of inverse voltage. The use of several thyratrons in parallel to reduce the peak current combined with inductance in the anode connections to reduce the rate of rise of inverse voltage can give a significant improvement in performance. Alternatively, the use of a saturating anode inductor designed to give several hundred nanoseconds of delay before inverse voltage is applied to the anode can enable a single thyatron to withstand a transient inverse voltage of -10 kV without reverse arcing.

In some cases, the nature of the load makes it impossible to avoid excessive inverse voltage and its harmful effects. E2V Technologies recommends the use of hollow-anode or double-cathode thyratrons which allow conduction in the reverse direction and prevent destructive reverse arcing. Alternatively, a fast diode and load connected in anti-parallel will help to protect the thyatron.

xiv. Thyatron Dissipation

The average current capability of a given tube can vary by an order of magnitude from a maximum in circuits with long, slow current pulses with low reversal to a minimum in circuits with fast, short current pulses and high reversal. The reason for the wide range is that energy dissipation in a thyatron arises from three of the four phases of the switching cycle. In all cases, the loss is given by:

$$\text{Loss} = \int V(t)I(t)dt$$

a) Leading Edge Loss (Commutation)

After the thyatron is triggered, the anode voltage starts to fall. If the discharge circuit impedance is low, current starts to flow, reaching a significant level before the voltage across the thyatron has collapsed fully. The presence of simultaneous voltage and current in the tube causes a large power loss which increases with circuit di/dt and prf.

b) Conduction Loss

When the tube is fully conducting, the voltage drop is of the order of 100 V. To a first order, conduction loss is the product of this voltage and the average current conducted.

c) Trailing Edge or Clean-up Current Loss (Solid-anode Thyatrons)

As the thyatron reverts to a non-conducting state at the end of the conduction pulse, the anode is subject to positive ion bombardment which causes heating. The size of the clean-up current depends on the preceding forward current pulse, the falling edge di/dt and the magnitude of the applied inverse voltage.

d) Reverse Conduction Loss (Hollow-anode Thyatrons)

Since the reverse arc drop of a hollow anode thyatron is about five times its forward conduction value, the reverse conduction heating is five times as high. This effect is most severe in high prf circuits with large current reversal.

Dissipation arising from the commutation and trailing edge or reverse conduction loss causes heating of the anode. It is important to avoid a situation where the anode becomes hot enough to reduce the local gas density to the point where the losses increase and thermal runaway occurs. It should be noted that thermal runaway can develop over a period of several hours and can destroy the thyatron by melting the anode and its support structures. An early indicator of thermal runaway is a distortion in the shape of the leading edge of the current pulse as indicated in Figures 17 to 19. Therefore the current pulse shape can be used as a diagnostic to determine a safe range of operating conditions for the system. The current pulse shape observed in Figure 17 is obtained with optimum gas pressure in the thyatron. The current rises cleanly and sharply at the start of the pulse and anode dissipation is low.

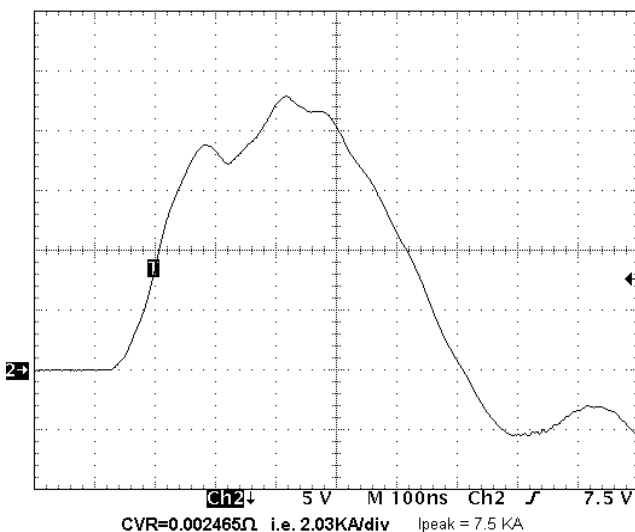


Figure 17.

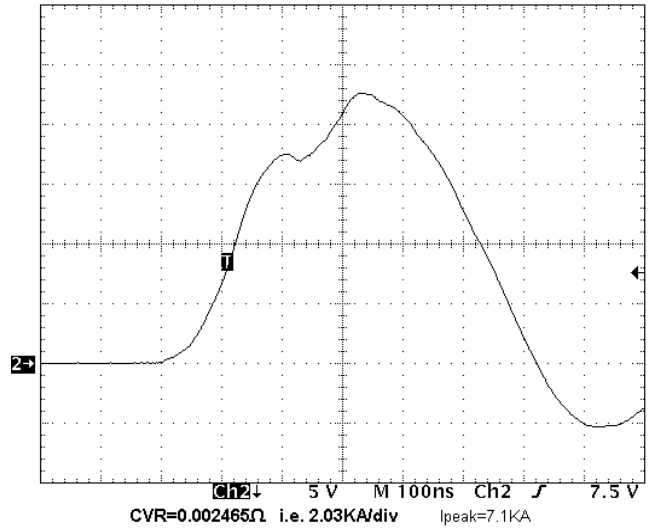


Figure 18.

The current pulse shape observed in Figure 18 is obtained with lower gas pressure in the thyatron. The current rises slowly at the start of the pulse and anode dissipation is significant and may lead to reduced gas density in the anode region with the possibility of thermal runaway.

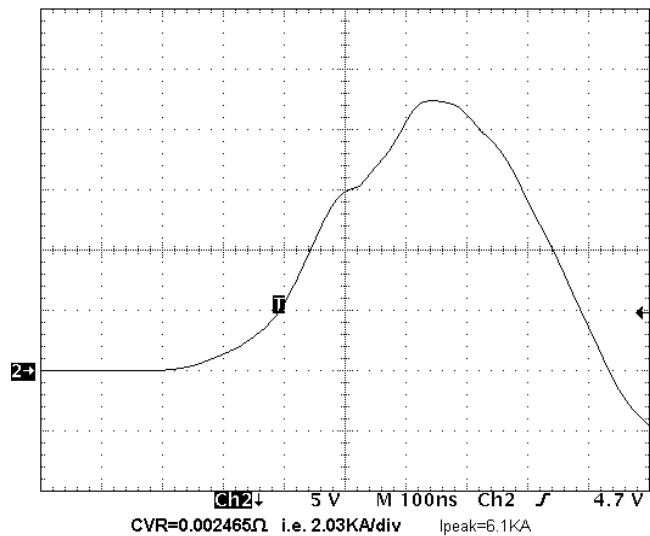


Figure 19.

The current pulse shape observed in Figure 19 is obtained with very low gas pressure in the thyatron. The current rises very slowly at the start of the pulse and anode dissipation is high with an inevitable progression to thermal runaway and catastrophic anode melting.

xv. Minimising Thyatron Dissipation

The thyatron discharge circuit should be designed to reduce dissipation in the tube. This allows the circuit to operate efficiently, reduces the amount of tube cooling needed and provides the best tube life under a given set of conditions.

Leading edge loss can be minimised by limiting the discharge circuit di/dt, by reducing stray capacitance on the anode and by operating the thyatron at a high gas pressure to reduce voltage fall time. The use of a double pulse trigger system can also reduce dissipation and is essential for successful operation of high di/dt circuits at high repetition rates. An effective method for reducing switching loss is to use a saturating anode

inductor to provide a delay of 30 to 50 ns between the anode voltage fall and the growth of circuit current.

Trailing edge or clean-up current loss is reduced by reducing circuit di/dt and, more importantly, the amplitude of the inverse voltage. The clean-up current flows for a period of the order of 100 ns. A saturating anode inductor is also effective at reducing clean-up losses since it delays the inverse voltage being applied to the tube until the clean-up current pulse has finished. By limiting the reverse voltage until the residual plasma density is much reduced, it also reduces the probability of an inverse arc-back.

Reverse conduction dissipation in hollow-anode thyratrons may be reduced by diverting some reverse current into a fast inverse diode circuit.

4 GLOSSARY

Absolute Ratings

All the maximum ratings given in the tube data sheet are absolute, non-simultaneous ratings. The equipment designer is responsible for seeing that they are not exceeded, even momentarily, under any conditions of mains fluctuation, surges, faults or component tolerances.

Ambient Temperature

The temperature of the cooling medium immediately surrounding the tube, with the tube operating.

Anode Delay Time (t_{ad})

The time interval between the point on the rising portion of the control grid voltage pulse which is 25% of the maximum unloaded pulse amplitude and the point where anode conduction takes place. For tubes having negative bias on the control grid, the anode delay time is the time interval between the instant when the unloaded control grid voltage passes cathode potential and the instant when anode conduction takes place.

Anode Delay Time Drift (Δt_{ad})

The change in anode delay time during a specified period of operation of the tube, typically 8 minutes. Pulse-to-pulse variation in t_{ad} is known as jitter.

Anode Heating Factor (P_b)

The product of peak forward anode voltage (V), peak anode current (I) and pulse repetition rate (prf).

Anode Pulse Current (i_b)

The amplitude of the anode current pulse at the 100% point.

Arc Drop

The voltage drop between an electrode and the cathode.

Average Anode Current (I_b)

The average value of anode current (usually averaged over one second).

Cathode and Reservoir Heater Voltage

The true rms voltage at the tube heater and reservoir pins or terminals.

Critical DC Anode Voltage for Conduction

The minimum voltage at the anode which causes conduction under specified conditions.

Crowbar

The term given to energy diverter service where the thyatron discharges a filter or reservoir capacitor and the power supply follow-on current into a resistive impedance to protect a load which is drawing too much current, e.g. an arcing klystron.

Dark Current

Low-level anode current (1 – 100 μ A) which flows when voltage is applied to the tube anode, but the tube remains untriggered. The amplitude depends on the type of thyatron, anode voltage and grid circuit used.

Forward Grid Drive Circuit Impedance

The output impedance of the grid drive and bias circuit.

Grid 1 DC Priming Current

A current flowing between grid 1 and cathode to maintain a continuous discharge.

Grid 2 Pulse Delay

The time interval between the leading edges of the grid 1 and grid 2 unloaded drive pulses measured at the 75% levels.

Grid Spike

A voltage transient of duration less than 10% of the pulse duration during which the amplitude appreciably exceeds the pulse amplitude.

Holding Current

The minimum current at which the thyatron will remain in conduction. Typical values lie in the range 10 – 100 mA. Holding current is an unspecified parameter.

Instantaneous Start Voltage

The maximum anode voltage for instantaneous starting. Higher start voltages may require a two-step start.

Jitter (t_{pi})

The pulse-to-pulse variation of the instant when anode conduction occurs with reference to any constant level on the unloaded control grid pulse.

Keep Alive Current

See Grid 1 DC Priming Current.

Loaded Grid Bias Voltage (E_c)

The interpulse negative DC voltage at the grid with respect to cathode when the tube is operating.

Metal Envelope Thyatron

Thyatron having a dispenser cathode and an electrode design optimised for cooling under very high power operating conditions.

Pant Leg or Anode Stem

The glass stem below the anode connection on a glass thyatron.

Peak Forward Anode Voltage (e_{py})

The maximum positive voltage applied to the anode with respect to cathode.

Peak Forward Grid Voltage

The algebraic sum of the total drive and the bias voltage, if any.

Peak Inverse Anode Voltage (e_{px})

The maximum negative voltage at the anode with respect to cathode.

Peak Inverse Grid Voltage (e_{gx})

The maximum negative voltage appearing at the grid with respect to cathode.

Pulse Amplitude

The maximum value of a smooth curve through the average of the fluctuations of the top portion of the pulse, exclusive of spike.

Pulse Duration (t_p)

The time interval between the instants at which the value of the parameter equals 75% of the pulse amplitude, unless otherwise stated.

Pulse Fall Time (t_{pf})

The time required for the pulse to fall from 75% to 25% of the pulse amplitude.

Pulse Repetition Frequency (prf)

The pulse repetition rate when this is independent of the interval of time over which it is measured.

Pulse Repetition Rate (pr)

The average number of pulses in unit time. Unless otherwise stated in the tube data sheet, the average shall be taken over an interval of one second.

Pulse Rise Time (t_{pr})

The time required for a pulse to rise from 25% to 75% of the pulse amplitude.

Quenching

The abrupt cessation of conduction through the thyratron resulting from gas starvation during a long or high current pulse. The circuit inductance then causes a build-up of voltage across the tube which may initiate arcing and subsequent electrode damage.

Rate of Rise of Anode Current (di/dt)

The ratio of the current change to the rise time for that portion of the pulse between the 25% and 75% levels of the pulse amplitude.

Recovery Impedance (Z_R)

The impedance through which the decaying ion recombination current flows during the recovery period.

Recovery Time (t_R)

The time required after cessation of forward anode current for the grid to regain control.

Reservoir

A device inside the tube for maintaining the correct gas pressure.

Resonant Charging Conditions

Conditions of resonant charging occur when the pulse repetition rate is twice the resonant frequency of the charging inductance in combination with the pulse forming network (pfn) capacitance.

Tube Heating Time

The time required for all essential parts of the tube to reach temperatures which enable it to operate satisfactorily.

Unloaded Grid Bias Voltage (E_{CC})

The open circuit negative DC voltage available from the source of grid bias.

Unloaded Grid Drive Pulse Voltage

The open circuit pulse amplitude available from the source of grid pulse voltage.

Unloaded Grid Priming Voltage

The open circuit DC voltage available from the priming source.

5 APPENDICES

i. TECHNICAL REPRINTS

A number of technical reprints are available from E2V Technologies covering aspects of thyatron circuit design and thyatron performance in special applications as listed below.

Reprint Number	Title/Author(s)
72	Gapped-core Current Transformers for Measuring Pulse Currents G J Scoles, B P Newton
75	A Multigap, Double-ended Hydrogen Thyatron H Menown, B P Newton
79	The Development of Deuterium Thyatrons for Operation at High Duty Ratios and High Average Currents R J Wheldon, N S Nicholls
80	High Voltage Pulse Generators for Kicker Magnet Excitation D C Fiander, D Grier, K D Metzmacher, P Pearce
81	Generation of High Current, Long Duration Rectangular Pulses P E Faugeras, H Kuhn, J P Zanasco
91	The Reduction of Excessive Forward and Inverse Voltages in Line-type Pulse Generating Circuits G J Scoles
93	The use of a Double-ended Hydrogen Thyatron for Crowbar Applications W E Hannant, C Rowe, H Menown
94	The Reduction of Unwanted Oscillations (ringing) in Charging Inductors and Power Transformers G J Scoles
96	A Triple Grid Thyatron L J Kettle, R J Wheldon
101	Symmetrical Double-ended Thyatrons in Pulse Modulators R B Molyneux-Berry
102	The SPS Fast Pulsed Magnet Systems P E Faugeras, E Frick, C G Harrison, H Kuhn, V Rödel, G H Schröder, J P Zanasco
121	Operating Hydrogen Thyatrons in Parallel G J Scoles, R L Snelling
122	Double-ended Hydrogen Thyatrons for Crowbar Protection of High Power TWT Systems N S Nicholls, H Menown, R J Wheldon
124	Flange Mounting Glass Envelope Hydrogen Thyatrons L J Kettle, C V Neale, B P Newton
125	Power System for a High Power Burst Mode Pulsed Load T H Robinson
126	Double-ended Thyatrons in High Power Burst Mode Pulse Modulator Applications R B Molyneux-Berry
130	High Power Pulse Generators for Fast Pulsed Magnets; Developments and Operational Experience H Kuhn, G H Schröder
132	An Economical High Current Fast Recovery Thyatron System T P Donaldson, L J Kettle, H Menown, C V Neale, B P Newton, R Sheldrake
133	A Thyatron Inverter Circuit to Drive a Capacitive Load for the Production of Ozone H Menown, B P Newton, R Sheldrake, R L Snelling
134	Rapid Cycling Synchrotron (RCS) Single Stage Kicker Magnet D E Suddeth, G J Volk
136	A Two-step High Voltage Pulse Generator D C Fiander, D Grier, K D Metzmacher, P Pearce
144	Thyatron Switch Generation of Multi-Kilovolt Pulses in the Nanoseconds Region for Linac Electron Gun Drive H D Kitchin, J M Salome
147	Evaluation of Bidirectionally Conducting Thyatrons for Pulsed Excimer Lasers G McDuff, K Rust, H Menown, C V Neale
151	A Pulse Generator for Short-circuited Delay Line Magnet Excitation D C Fiander, A Fowler, D Grier, K D Metzmacher, H Menown, R Sheldrake

- 152 Operational Experience with the Fermilab 150 GeV Injection Kicker
R C Trendler
- 154 Kickers and Power Supplies for the Fermilab Tevatron 1 Antiproton Source
T Castellano, L Bartoszek, E Tilles, J Petter, J McCarthy
- 155 A Low Jitter, Hydrogen Thyatron Pockels Cell Driver
J A Oicles, H D Kitchin
- 159 A Short Note on Hollow Anode Metal Envelope Thyatrons for High-Power, High-Repetition Rate Lasers
G McDuff, K Rust
- 161 A Multi-Paralleled Thyatron, Repetitively Pulsed, Power Supply for High Power Gas Lasers
A J W Brown, P W Smith
- 163 Fault Protection in High Power Pulse Modulators
L J Kettle, B P Newton
- 164 Advanced Thyatrons as Switches for the Nineties
H Menown, C A Pirrie, N S Nicholls
- 169 A Fast Rise Time, High P.R.F. Pulse Generator Using a Hydrogen Thyatron
H D Kitchin, D M Parkes
- 170 The 3.6 MW High Voltage Interface for the LEP Main Ring Klystrons
H O'Hanlon, G Pecheur
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ii. THYRATRON ABRIDGED DATA AND ACCESSORIES

The abridged data below provides a representative sample from E2V Technologies' complete range of thyatron products.

a. Glass Thyratrons

Type Number	Description	Anode			Reverse Current Capability	Heater Currents		Glass Diameter (inch)	Weight (kg)	Base
		Voltage (kV)	Peak Current (A)	Average Current (A)		I _h (A)	I _r (A)			
8503	Triode	16	325	0.25	No	11.6	NA	2.5	0.4	Pins
8503AF	Triode	20	325	0.50	No	11.6	NA	2.5	0.3	Leads
8503B	Triode	20	325	0.50	No	11.6	NA	2.5	0.4	Pins
CX1140	Tetrode	25	1000	1.25	No	25.0	NA	3.2	0.7	Pins
CX1159	Tetrode	33	1000	1.25	No	25.0	NA	3.2	0.7	Pins
CX1191	Tetrode	16	400	0.40	No	13.0	NA	2.5	0.3	Pins
CX1550	Tetrode	16	200	0.20	No	6.7	NA	1.5	0.1	Pins
CX1551	Tetrode	33	1000	1.25	No	25.0	NA	3.2	0.7	Leads
CX1559	Tetrode	35	1500	1.50	No	25.0	9.5	3.2	0.8	Leads
CX1585	Tetrode	35	5000	0.60	No	14.5	NA	2.5	0.5	Leads
CX1585A	Tetrode	40	5000	0.60	No	14.5	NA	2.5	0.5	Leads
CX1622	Pentode	35	5000	0.50	No	25.0	NA	3.2	0.7	Leads
CX1666	Pentode	35	5000	0.50	No	28.0	3.3	3.2	0.7	Leads
CX1685	Pentode	35	5000	0.60	No	12.5	2.5	2.5	0.5	Leads
CX1722	Pentode	35	5000	0.50	Yes	25.0	NA	3.2	0.7	Leads
CX1766	Tetrode	35	5000	0.50	Yes	28.0	3.3	3.2	0.7	Leads
CX1785	Pentode	35	5000	0.20	Yes	12.5	2.5	2.5	0.5	Leads
FX2505	Triode	10	100	0.13	No	6.7	NA	2.5	0.26	Pins
FX2519A	Triode	25	500	0.50	No	22.0	3.3	3.2	0.70	Pins
FX2524	Triode	16	325	0.25	No	11.6	NA	2.5	0.35	Pins
FX2525	Triode	16	200	0.20	No	6.7	NA	1.5	0.11	Pins
FX2530	Triode	8	85	0.10	No	3.5	NA	1.5	0.06	Pins
FX2535	Triode	10	100	0.10	No	6.7	NA	1.5	0.11	Pins
FX2572A	Triode	20	200	0.20	No	6.7	NA	1.5	0.11	Leads
FX2613	Triode	16	325	0.25	No	13.6	NA	2.5	0.35	Pins

b. Ceramic Thyratrons

Type Number	Description	HV Gaps	Anode			Reverse Current Capability	Heater Currents		Ceramic Diameter (inch)	Weight (kg)
			Voltage (kV)	Peak Current (A)	Average Current (A)		I _h (A)	I _r (A)		
7665A	Triode	1	16	350	0.50	No	6.0	NA	1.4	0.2
CX1135	Tetrode	1	25	1500	1.25	No	25.0	2.5	2.5	1.5
CX1154	Tetrode	1	40	3000	2.00	No	25.0	8.0	3.0	1.8
CX1154B	Tetrode	1	35	3000	2.00	Yes	26.0	9.0	3.0	2.5
CX1157	Tetrode	1	20	350	0.50	No	10.5	NA	1.8	0.3
CX1168	Tetrode	2	70	3000	2.00	No	25.0	8.0	3.0	3.0
CX1168B	Tetrode	2	70	3000	3.00	Yes	25.0	9.0	3.0	3.5
CX1168C	Pentode	2	70	4000	2.00	No	30.0	9.0	3.0	3.0
CX1171	Tetrode	3	105	3000	2.00	No	25.0	8.0	3.0	4.0
CX1171B	Tetrode	3	100	3000	3.00	Yes	25.0	9.0	3.0	4.7
CX1174	Tetrode	1	40	6000	4.00	No	45.0	12.0	4.5	3.5
CX1174B	Tetrode	1	35	6000	4.00	Yes	45.0	12.0	4.5	4.7

Type Number	Description	HV Gaps	Anode			Reverse Current Capability	Heater Currents		Ceramic Diameter (inch)	Weight (kg)
			Voltage (kV)	Peak Current (A)	Average Current (A)		I _h (A)	I _r (A)		
CX1174C	Pentode	1	35	6000	4.00	No	45.0	12.0	4.5	3.5
CX1175	Tetrode	2	70	6000	4.00	No	45.0	12.0	4.5	5.9
CX1175B	Tetrode	2	70	6000	4.00	Yes	45.0	12.0	4.5	8.0
CX1180	Tetrode	1	25	1000	1.25	No	16.0	5.0	2.5	1.0
CX1192	Tetrode	3	105	6000	4.00	No	45.0	12.0	4.5	8.4
CX1192B	Tetrode	3	100	6000	4.00	Yes	45.0	12.0	4.5	9.5
CX1193	Tetrode	4	130	6000	4.00	No	45.0	12.0	4.5	10.8
CX1193B	Tetrode	4	130	6000	4.00	Yes	45.0	12.0	4.5	11.6
CX1194	Tetrode	5	155	6000	4.00	No	45.0	12.0	4.5	12.8
CX1194B	Tetrode	5	155	6000	4.00	Yes	45.0	12.0	4.5	13.6
CX1199	Tetrode	4	130	3000	2.00	No	25.0	8.0	3.0	5.0
CX1199B	Tetrode	4	130	3000	3.00	Yes	25.0	8.0	3.0	6.0
CX1570	Tetrode	1	16	1500	0.30	Yes	10.5	NA	1.8	0.3
CX1572C	Pentode	1	25	5000	0.50	Yes	16.5	5.0	2.5	1.0
CX1573C	Pentode	1	35	10000	1.00	Yes	28.0	9.0	3.0	1.8
CX1574C	Pentode	1	35	15000	2.00	Yes	45.0	12.0	4.5	3.5
CX1575	Tetrode	2	60	10000	3.00	Yes	45.0	12.0	4.5	5.9
CX1575C	Pentode	2	60	10000	3.00	Yes	45.0	12.0	4.5	5.9
CX1588	Tetrode	1	25	1000	NA	No	8.5	2.5	1.8	0.3
CX1592	Tetrode	3	100	10000	3.00	Yes	45.0	12.0	4.5	8.6
CX1593	Tetrode	4	130	6000	4.00	Yes	45.0	12.0	4.5	10.8
CX1599	Tetrode	1	12.5	1000	0.13	No	8.5	2.5	1.8	0.3
CX1640	Tetrode	1	25	2500	0.25	Yes	5.0	2.5	1.4	0.2
CX1671D	Pentode	3	105	3000	1.00	Yes	25.0	8.0	3.0	4.0
CX1688	Tetrode	1	25	1000	1.00	Yes	8.5	2.5	1.8	0.3
CX1699	Tetrode	4	130	3000	1.00	Yes	25.0	8.0	3.0	5.0
CX2098B	Tetrode	8	240	6000	4.00	Yes	45.0	12.0	4.5	21.5
CX2282	Tetrode	2	40	1000	1.25	Yes	15.0	4.5	2.5	2.0
CX2284	Tetrode	4	80	1000	0.50	Yes	15.0	4.5	2.5	3.4
CX2410	Tetrode	2	60	10000	10.00	No	85.0	21.0	6.0	18.8
CX2540	Tetrode	5	120	40000	NA	Yes	85.0	20.0	6.0	13.6
CX2608	Tetrode	2	40	10000	0.50	Yes	24.0	8.0	3.0	2.2
CX2708	Tetrode	2	40	1500	NA	Yes	25.0	2.0	3.0	2.2
CX2801	Tetrode	1	35	5000	0.50	No	20.0	NA	3.0	1.2
CX2804	Tetrode	1	35	5000	0.50	No	14.5	7.0	3.0	1.2
FX2522	Triode	1	16	500	0.50	No	11.6	NA	1.8	0.45
FX2533	Triode	1	16	350	0.50	No	8.0	NA	1.4	0.12
FX2534	Triode	1	12	350	0.20	No	8.0	NA	1.2	0.12
FX2536	Triode	1	16	350	0.50	No	6.0	4.0	1.8	0.25
FX2600	Triode	1	35	10000	0.50	No	14.5	6.0	3.0	1.20
FX2802	Triode	1	35	5000	0.50	No	13.0	6.0	3.0	1.2
FX2803	Triode	2	40	5000	0.50	No	13.0	6.0	3.0	1.8

c. Metal Envelope Thyratrons

Type Number	Description	HV Gaps	Anode			Reverse Current Capability	Heater Currents		Ceramic Diameter (inch)	Weight (kg)
			Voltage (kV)	Peak Current (A)	Average Current (A)		I _h (A)	I _r (A)		
CX1525	Tetrode	2	70	5000	5.00	No	45.0	8.0	3.0	3.6
CX1525A	Tetrode	2	50	5000	5.00	No	45.0	8.0	3.0	3.6
CX1528	Tetrode	1	35	5000	5.00	No	45.0	8.0	3.0	3.6
CX1535S	Pentode	1	20	1000	1.00	No	18.0	7.0	2.5	1.7
CX1535X	Pentode	1	25	1000	1.00	No	18.0	7.0	2.5	1.5
CX1536	Tetrode	2	70	10000	10.00	No	100.0	8.0	4.5	10.6
CX1536A	Tetrode	2	50	10000	8.00	No	100.0	8.0	4.5	10.6
CX1547	Tetrode	1	35	10000	15.00	No	100.0	8.0	4.5	10.2
CX1549	Tetrode	1	35	10000	15.00	No	100.0	8.0	4.5	10.2
CX1625	Pentode	1	35	15000	5.00	Yes	45.0	8.0	3.0	3.6
CX1625A	Pentode	1	35	15000	5.00	Yes	45.0	8.0	3.0	3.6
CX1720	Pentode	2	50	50000	25.00	No	280.0	8.0	8.0	31.8
CX1720X	Pentode	2	50	50000	25.00	No	280.0	8.0	8.0	31.8
CX1725	Tetrode	2	70	15000	5.00	Yes	45.0	8.0	3.0	3.6
CX1725A	Tetrode	2	70	15000	5.00	Yes	45.0	8.0	3.0	3.6
CX1735A	Pentode	1	20	1000	0.75	Yes	18.0	7.0	2.5	1.6
CX1736	Tetrode	2	70	10000	10.00	Yes	100.0	8.0	4.5	6.6
CX1736A	Tetrode	2	50	10000	10.00	Yes	100.0	8.0	4.5	6.6
CX1747	Tetrode	1	35	10000	15.00	Yes	100.0	8.0	4.5	10.2
CX1747X	Tetrode	1	35	10000	15.00	Yes	100.0	8.0	4.5	10.2
CX1826	Pentode	1	35	5000	5.00	No	45.0	8.0	3.0	3.6
CX1826A	Pentode	1	35	5000	5.00	No	45.0	8.0	3.0	3.6
CX1835	Pentode	1	25	1000	1.00	No	18.0	7.0	2.5	1.8
CX1835A	Pentode	1	20	1000	1.00	No	18.0	7.0	2.5	1.8
CX1836	Pentode	2	70	10000	10.00	No	100.0	8.0	4.5	11.4
CX1836A	Pentode	2	50	10000	10.00	No	100.0	8.0	4.5	11.4
CX1925	Tetrode	3	80	15000	5.00	Yes	45.0	8.0	3.0	4.2
CX1925X	Tetrode	3	80	15000	5.00	Yes	45.0	8.0	3.0	4.2
CX1936	Tetrode	3	80	10000	10.00	Yes	100.0	8.0	4.5	12.5
CX1936A	Tetrode	3	80	10000	10.00	Yes	100.0	8.0	4.5	12.5
CX1937	Tetrode	3	80	10000	10.00	No	100.0	8.0	4.5	12.5
CX1937A	Tetrode	3	80	10000	10.00	No	100.0	8.0	4.5	12.5
CX2025X	Tetrode	4	100	15000	3.50	Yes	45.0	8.0	3.0	5.6
CX2168	Tetrode	2	70	10000	4.00	No	45.0	8.0	3.0	4.7
CX2168A	Tetrode	2	70	10000	4.00	No	45.0	8.0	3.0	4.7
CX2171	Tetrode	3	90	10000	4.00	No	45.0	8.0	3.0	4.7
CX2171A	Tetrode	3	80	10000	4.00	No	45.0	8.0	3.0	4.7
CX2193	Tetrode	4	100	20000	10.00	No	100.0	8.0	4.5	14.4
CX2199	Tetrode	4	130	10000	4.00	No	45.0	8.0	3.0	12.5
CX2199A	Tetrode	4	100	10000	4.00	No	45.0	8.0	3.0	12.5
CX2412A	Tetrode	2	60	15000	15.00	No	150.0	10.0	6.0	24.0
CX2593	Tetrode	4	100	20000	10.00	Yes	100.0	8.0	4.5	14.4
CX2593X	Tetrode	4	100	20000	10.00	Yes	100.0	8.0	4.5	14.4
CX2668	Tetrode	2	70	10000	4.00	Yes	45.0	8.0	3.0	4.7

Type Number	Description	HV Gaps	Anode			Reverse Current Capability	Heater Currents		Ceramic Diameter (inch)	Weight (kg)
			Voltage (kV)	Peak Current (A)	Average Current (A)		I _h (A)	I _r (A)		
CX2668A	Tetrode	2	70	10000	4.00	Yes	45.0	8.0	3.0	4.7
CX2671	Tetrode	3	90	10000	4.00	Yes	45.0	8.0	3.0	5.7
CX2671A	Tetrode	3	80	10000	4.00	Yes	45.0	8.0	3.0	5.7
CX2699	Tetrode	4	130	10000	4.00	Yes	45.0	8.0	3.0	12.5
CX2699A	Tetrode	4	100	10000	4.00	Yes	45.0	8.0	3.0	12.5

d. Thyatron Accessories

In addition to the comprehensive range of thyatrons, E2V Technologies also manufactures a range of thyatron accessories and auxiliary equipment. The abridged data below lists some of the more common items available. Detailed product data sheets and further details are available on request.

Top Cap Connectors and Sockets

MA358	Top cap connector for 9.1 mm (0.359 inch) diameter glass thyatron anodes.
MA359	Top cap connector for 14.4 mm (0.566 inch) diameter glass thyatron anodes.
MA360A	As MA359, but with improved heat dissipation and good anti-corona characteristics.
MA91	Five-contact BF5 socket with flying leads on an insulating base.
MA92	As MA91, but incorporating an R-C network so that tetrode plug-in thyatrons can be driven with a single pulse.
MA153	Five-contact B5F socket with a base clamp.
MA94	Five-contact B5F socket with 95.25 mm (3.750 inch) diameter flange.
MA356A	Four-contact porcelain UX4 socket.
MA357	Four-contact B4D socket with Tufnol mounting plate.
MA357A	As MA357, but with base clamp.

Current Pulse Measurement Transformers

MA391 Series	Sensitivity range from 20 to 500 A/V, peak current range from 6 to 150 kA and rms currents range from 80 to 300 A. The central aperture is 114.3 x 114.3 mm (4.5 x 4.5 inches) square.
MA459 Series	Similar to MA391 Series, but with a central aperture 155.6 x 155.6 mm (6.125 x 6.125 inches) square. Sensitivities and peak current ratings are the same as for MA391, but rms current ratings are 100 to 360 A.

Voltage Dividers

MA2160A	A precision, rugged, compact voltage divider with a 2000:1 ratio, rated to 40 kV dc. The divider impedance is 1 GΩ and the accuracy is ±0.25 °C.
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Thyatron Grid Drivers

MA2437 Series	A range of single-pulse grid drivers offering options for output voltage amplitude (500 or 1000 V) and for means of triggering (electronically via a BNC input socket or optically via a fibre-optic FSMA connector). Suitable for most low to medium power glass and ceramic thyatrons at up to 1000 pps. Higher repetition rates are available upon request.
MA2709A	A dual-pulse grid driver which provides the pulse voltages and impedances suitable for driving all medium to high power thyatrons at up to 1000 pps. The MA2709A is electrically rugged and has in-built grid spike protection. Repetition rates above 1000 pps are available upon request.

Auxiliary Equipment

MA2447A	Crowbar protection system designed around the CX2708 crowbar thyatron. Rated to -40 kV dc, the MA2447A offers in-built fault detection and direct triggering, or external triggering via an integral optical fibre link. The MA2447A is designed to protect high power microwave tubes from filter capacitor discharge and power supply follow-on current in the event of an arc occurring.
MA2619A	A -100 kV crowbar protection system in an integral oil tank designed to incorporate a five-gap double-ended thyatron such as CX1194B. The MA2619A incorporates all of the detection and firing circuitry necessary to protect high power microwave tubes at operating voltages up to -100 kV dc.