THE CARE AND FEEDING OF CROWBAR THYRATRONS

Application Notes

Load faults can result in damaging internal arcs in high power RF Broadcast Transmitter Amplifier devices, such as Inductive Output Tubes (IOT), Constant Efficiency Amplifiers (CEA) and super power klystrons. The damage can range from severe to catastrophic, as a function of the amount of stored energy in the filter capacitance and the magnitude and duration of the follow-on Power Supply current.

An arc is a self-sustained discharge of energy between electrodes, limited only by the circuit impedance, which is inherently low. An incandescent cathode spot is normally created whenever an arc is formed. If the cathode spot cannot be cooled quickly, it remains a profuse source of thermal electrons. The free electrons are then accelerated by E-field in the gap, where they can re-trigger spark (field emission) breakdown.

In order to avoid RF tube performance degradation and eventual destruction, the fault currents must be removed, i.e. diverted from the IOT as quickly as possible.
Solid-state relays and circuit breakers on the input power bus operate, at best, in one cycle of the line frequency (multiple millisecond regime), sufficient time for damage to occur in the amplifier tube. Thus, a more rapid, fault clearing, switching speed is critical for successful crowbar application performance.

Thyratron commutation time is less than 500 nanoseconds, which is four(4) orders of magnitude faster than the solid-state solution; sufficiently fast to prevent arc damage. In addition to rapid switching ability, thyratrons can transfer large currents for extended periods, operate over a wide voltage range, exhibit reliable triggering with minimal triggering delay and drift, and provide long useful lifetimes in the crowbar mode. Alternate switching devices with adequate current capability, such as spark gaps and (mercury filled) ignitrons, are deficient in stability, operating voltage range and life.

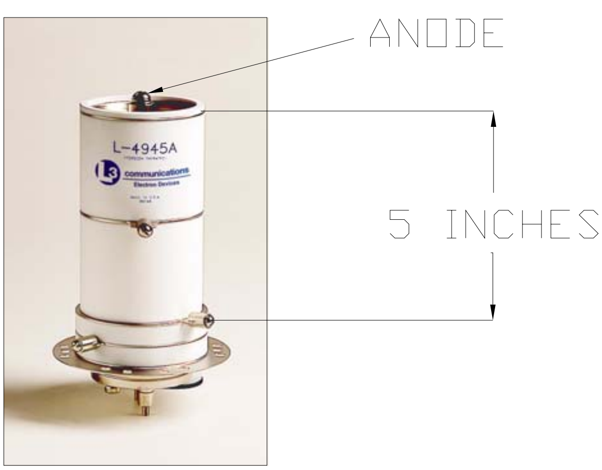
L-3 Communications Electron Devices manufactures the L-4645A thyratron for installation in crowbar protection circuitry of broadcast transmitters.
Designed specifically for this unique application, the L-4945A offers broadcasters a reliable and economic device for performing crowbar operations in IOT and high power klystron transmitters. Additionally, the L-4945A is a pin-to-pin compatible retrofit replacement for the e2v type CX-2708.

A CURSORY DESCRIPTION OF THE L-4945A CROWBAR THYRATRON

The L-4945A is a metal-ceramic envelope, deuterium gas filled tetrode, gradient grid, shielded gap, inverse current conducting switch.
The salient device features, listed below, are discussed in detail in the later sections.

• Maximum rated total conducted charge per pulse is 7 coulombs (amperes x seconds).
•The metal-ceramic envelope provides a robust construction for all environments.
• Deuterium gas fill, in lieu of hydrogen, provides increased Paschen Law pd product (pressure x distance) HV hold-off capability and long-term stability.
• Separate, adjustable cathode and reservoir heaters permit modified cathode temperature and gas pressure for non-standard operating conditions.
•Tetrode construction indicates the incorporation of an auxiliary, pre-ionizing electrode, which ensures a short, constant triggering delay and drift and provides a figure-of-merit for device switching readiness and cathode emissive condition.
•Gradient Grid construction is the utilization of two(2) internal HV series gaps. Multiple gaps reduce the voltage stress per gap and increases hold-off reliability.
• An external resistive divider equilibrates the steady state voltages across the HV gaps.
• The shields incorporated into the HV gaps provide three(3) functions,
1) Attenuation of the internally generated X-ray emission (All HV devices produce X-rays).
2) Prevention of external radiation from entering the gaps, thus causing self-triggering.
3) Prevention of metal vapor deposition, due to internal arcing, onto the ceramic walls.
• The anode is fitted with apertures and a plasma confining cavity. This structure provides the electron source for conduction of inverse current without the negative effects of anode arcing and metal vapor attachment / reduction of the fill gas.

ROBUST CONSTRUCTION FOR ALL ENVIRONMENTS



The L-4945A crowbar thyratron is ruggedly constructed with metal electrodes separated by high alumina ceramics. The external anode–control grid separation is 5 inches to preclude flashover at the highest filter capacitor voltages. Handling of the ceramic surfaces during installation should be minimized. Soap and water and / or scouring cleanser can be used to remove grit and oil from the ceramic surfaces.

FIGURE 1

HYDROGEN PRESSURE AND HOLD-OFF

When not called upon to protect the IOT, the crowbar thyratron must continuously hold-off the filter capacitor voltage, which can be as high as 40 kV. The thyratron gas must remain in the neutral, non-conducting "off" state. The internal thyratron electrode spacings are specified with consideration of Paschens Law. Paschens Law states that when a gas located between two electrodes is subjected to a uniform electric field, its breakdown voltage is a function of the product of the gas pressure (p) and the spacing (d) between the electrodes. Non-monotonic Paschen curves are shown for various gases as FIGURE 2[1].

The breakdown voltage at the pd curve minimum is called the Paschen Minimum.

For hydrogen, the Paschen Minimum is approximately 300 volts at a pd product of 1.0 torr-cm. At the typical thyratron hydrogen pressure of 0.5 torr, the optimum control grid to cathode spacing would therefore be 2 cm for easiest triggering (0.5 torr X 2 cm = 1.0 torr-cm). On the other hand, the anode to gradient grid and gradient grid to control grid spacing must be on the order of 0.2 cm at 0.5 torr (left of the minimum) to allow for 20 kV hold-off.

[1]Electrode material, geometry, and surface condition also affect the functional relationship of breakdown voltage to pd product. At very low pd products, breakdown voltage can be influenced by the onset of field emission. The onset of field emission puts a practical lower limit on electrode separation.

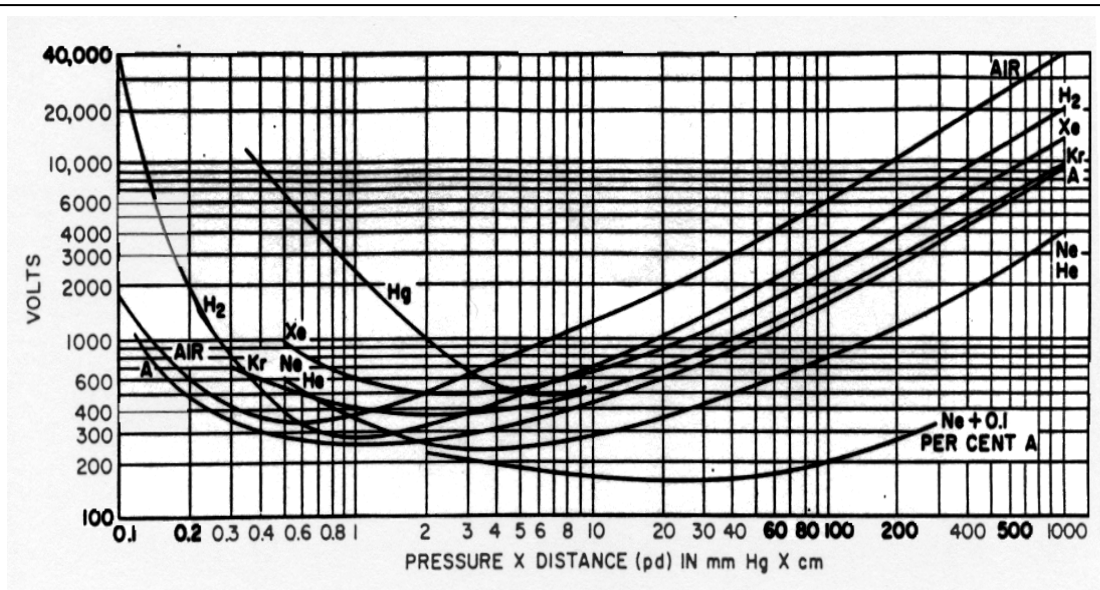


FIGURE 2
Paschen Law Curves for Various Gases

HYDROGEN PRESSURE CONTROL AND STORAGE BY MEANS OF THE RESERVOIR

The preceding discussion has explained why hold-off and triggering reliability is a function of hydrogen pressure and electrode spacings. The electrode spacings cannot be changed as they are determined by the manufacturer‘s brazing and welding processes.

We now consider how the hydrogen or deuterium gas pressure is maintained by the “reservoir”. The reservoir is a measured amount of sintered titanium powder that is heated by a tungsten heater coil. The titanium adsorbs hydrogen as it gets colder and desorbs hydrogen as it gets hotter. The voltage applied to the reservoir heater controls the temperature of the titanium and consequently the hydrogen pressure. The reservoir voltage therefore determines the breakdown voltage threshold in accordance with Paschen’s Law. As the reservoir voltage increases above the nominal level of 6.3 volts, pressure rises and the breakdown voltage threshold is lowered, thereby increasing the likelihood of false crowbars. As the reservoir voltage decreases below the nominal level of 6.3 volts, pressure drops and the breakdown voltage threshold is raised, thereby decreasing the likelihood of false crowbars. As one might expect there is a trade-off. As the pressure is lowered, the switching efficiency decreases and the likelihood of quenching increases.

QUENCHING

Quenching is an abrupt interruption, discontinuity or extinction of thyratron current flow, accompanied by a rapid rise in voltage across the tube, during the pulse period.
Current transfer through the thyratron is accomplished by the transmission of electrons in the ionized hydrogen or deuterium gas from the cathode, through the grid structures to the anode. Insufficient electron supply, due to poor cathode emission, inadequate gas pressure or excessive electrode aperture constriction, initiates this cut-off.
The primary root cause is gas pressure / density reduction.   Gas rarefication, with a consequent reduction in ionized particles, is an effect of gas heating due to the discharge.
Coulomb collisions between electrons and ions contribute predominantly to gas heating, thus electron temperature can be significantly higher than that of cold gas.
Quenching will occur at the onset of a gas temperature maximum for which the required current during the conduction phase cannot be maintained in the grid aperture region. The time necessary for the gas temperature to reach this quenching point is a function of the current density in the aperture and determines the maximum allowable pulsewidth.
Thus, the cause of current cut-off is the onset of a low gas pressure condition, i.e., the pressure at which the discharge cannot be maintained. The aperture constrictions further reduce the gas pressure, due to removal of gas in the form of ions, the effect of

the electric fields. Pressure reduction is also the result of increased heating of the gas at the tube walls, particularly in the orifice or the constriction on the cathode side.
Due to an increase in the intensity of ionization of the gas as a result of the decrease in gas pressure, further growth in electron energy is required, i.e., an increase in the potential difference at the entrance to the constriction, in order that the required ion balance in the discharge (plasma) be maintained. If the energy of the electrons passing the potential difference increases to a limiting ionization, then a further increase in the potential, accompanying an increased discharge current or a decrease in gas density in the tube, leads to current cut-off. The layer disintegrates and the current in the tube ceases spontaneously until the initial gas density is reestablished in the constriction.
It has been found, experimentally, that the critical current for which cut-off occurs (ico) is proportional to the gas density [or to the pressure (p) at constant temperature], the cross-sectional area of the constriction(S) and a constant (A): ico ~ ApS.
Figures 3 and 4 illustrate the effects of gas pressure and pulse length, respectively, on the maximum allowable current density (i_{co}) prior to cut-off (quenching).
The extent of the change in gas density in the discharge depends on the magnitude of the current, the gas pressure and the type of fill gas.
The inertia of the gas-dynamic processes in the discharge makes the critical current for cut-off a function of the pulse width of the current flow. When supplying the discharge with short rectangular pulses, the cut-off current is significantly greater than in a steady-state discharge, thus the dependence ico ~ 1/(tp).

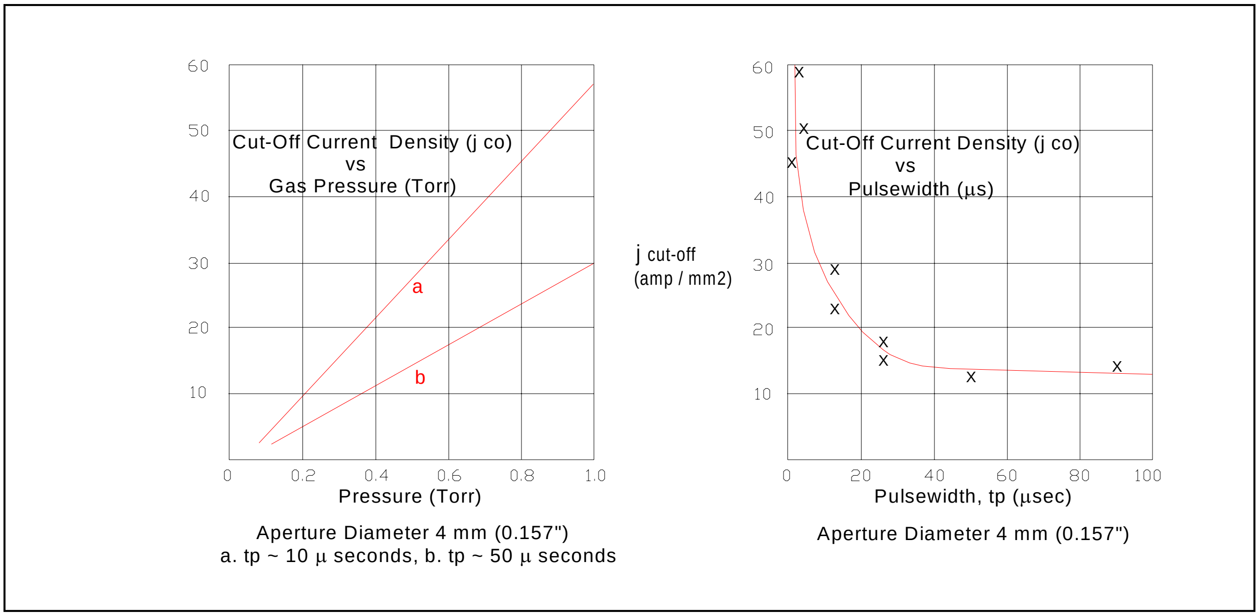


FIGURE 3
Current Density for Cut-Off in a Constriction as a Function of Hydrogen Gas Pressure

FIGURE 4
Effect of Pulse Length on Current Quenching in Hydrogen

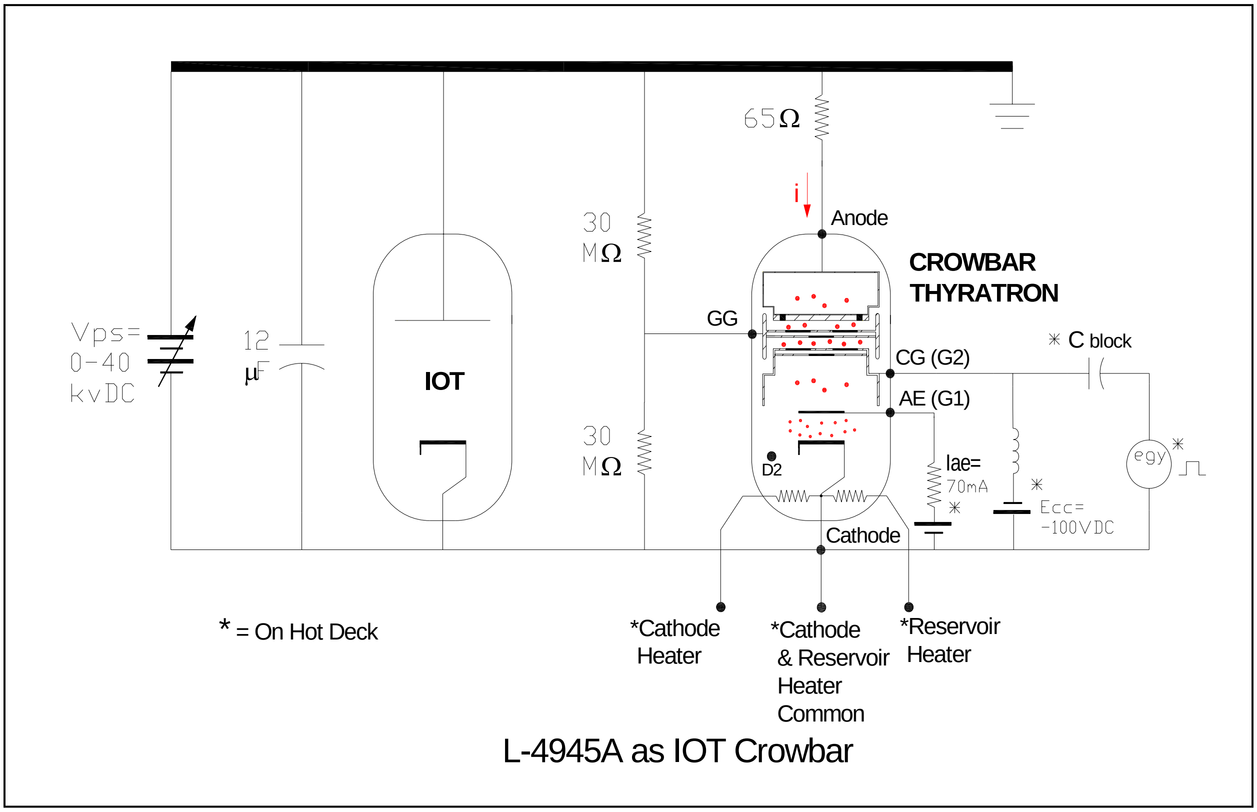


FIGURE 5

Installation / Connection Points

The following information should be read in conjunction with the L-4945A Data Sheet. Thyratron connection points and ancillary circuits are shown in Figure 5.

The L-4945A must be securely installed in the equipment by means of the mounting flange, in any orientation. Care should be taken to avoid gaps between the thyratron cathode mounting flange and the system mounting plate, which may result in arcing.

Two(2) 20 -40 Megohm resistors, in series, should be connected across the tube, from Anode to Cathode, with the mid-point tied to the Gradient Grid. These resistors divide the total steady-state voltage equally across the two(2) internal high voltage sections, preventing over voltage stress on any one gap.

RF Broadcast Transmitter Amplifier devices operate with the high voltage end of the power supply connected to the Cathode, and the Anode tied to ground.
The crowbar thyratron must also be connected with this polarity.
The Cathode and Reservoir heaters, the Auxiliary Electrode (G1) preionization circuit, the Control Grid (G2) negative bias, the Control Grid driver (egy) and any monitoring / measuring devices that are connected to the cathode, require high voltage isolation from ground.

Heater, Bias and Trigger voltages and currents should be applied in accordance with the values listed in the most current version of the L-4945A data sheet.
A ten(10) minute tube heating (warm-up) time, from a cold start, is recommended. This worse case pre-heat period provides the necessary time for the cathode to reach minimum reliable thermal emission temperature and for the reservoir to equilibrate at the design internal gas pressure. Premature thyratron starting can damage the cathode due to field emission arcs, in lieu of normal thermally emitted electrons, and may cause false fires as the result of incorrect gas pressure.

Cooling of the thyratron may be required. This can be accomplished by directing forced air at the base of the tube at a flow rate sufficient to maintain the thyratron surface temperatures below 200^{o}C.

Trouble Shooting

Thyratron malfunction can be classified in three(3) major categories.

1) False Crowbar Event: The switch closes (fires) spontaneously without application of a Control Grid (G2) signal; also commonly referred to as self-fire, pre-fire or false fire.

Extraneous trigger signals or excessive gas pressure are the usual root causes. Coupling of pulse power or supply line radiation into the Control Grid driver circuit; or, RF or UV irradiation of the thyratron HV gap can trigger the device. Care should be taken to ensure proper wiring routing and that tube shielding remains properly in place.

Thyratron breakdown for tube conduction is inversely proportional to gas pressure. Gas pressure is controlled by the reservoir input power (voltage) set level. Verification of the reservoir heater voltage (6.3 volts) is the first step in the resolution of an excessive false fire problem. Measurement should always be performed at the lead connections lugs with an RMS reading voltmeter. Although data sheet set point tolerance is +/- 2%, precise setting is preferred to allow for line voltage variation / excursion. The L-3 manufacturing process includes an acceptance test to confirm that no false crowbars occur at 6.5V/40 kV and 6.8V/37.5kV.
In rare instances, system voltage supply line deviations periodically exceed acceptable thyratron maximum tolerance, resulting in a Paschen breakdown false crowbar event. Reduction of the reservoir voltage set point by 0.1 – 0.2 volts resolves this issue. Although an operational nuisance, this failure mode is preferential to the potentially catastrophic “failure to fire” condition.

Immediate crowbar of the Power Supply upon application of high voltage to the RF Amplifier indicates a system short circuit. An unlikely, but possible, root cause is loss of vacuum integrity in the thyratron envelope, resulting in an “air tube”. This condition can be investigated by comparing the cathode heater current to the value at tube installation. Increased heater current (typically 10%), indicates a tube seal braze failure.

2) No Fire: Switch remains open / failure of the crowbar to operate.
This is the worse case scenario, where the total arc fault current can pass through the RF Amplifier, resulting in damage ranging from severe to catastrophic.

Missing or inadequate trigger signal or insufficient gas pressure, the converse to the self fire case, above, are the probable root causes. Verification of conformance of the trigger signal amplitude and duration to thyratron trigger minimum requirements, and presence of the nominal reservoir heater voltage (6.3 volts) are initial actions.

The loaded voltage drop across the Auxiliary Electrode(G1) is a convenient Figure-of-Merit for thyratron performance capability and switching reliability. A newly installed L-4945A will exhibit a voltage drop of 19 +/- 1 VDC at 70 mADC. As the tube ages and the cathode coating and gas pressure are depleted, the voltage drop increases. A voltage drop of 25 volts indicates a condition for tube replacement. If a replacement thyratron is not immediately available, a 0.1 - 0.2 volt increase in reservoir voltage may temporarily offset a low gas pressure condition.

3) Quenching: Incomplete discharge of the filter capacitor and / or the Power Supply follow-on current, resulting in some internal arcs in high power RF Broadcast Transmitter Amplifier device.

This is a partial “No Fire “condition that occurs during the crowbar event period.
The thyratron is triggered normally, conducts the initial portion of the pulse, but then abruptly turns off at some point during mid-pulse, reapplying the remaining portion of the fault current to the RF Amplifier tube.
Determination / verification of a quenching fault can be made by viewing the Anode to Cathode voltage across the thyratron. This voltage should remain at ground potential for the entire crowbar period.
The root cause of this anomaly is gas pressure related and resolution is similar to the “No Fire “rectification process, above. The L-3 manufacturing process includes an acceptance test to confirm that each thyratron fires properly with no quenching at 40kV/12uF with the reservoir and cathode heater voltages set at 5.8 volts.
Conformance is verified by viewing oscilloscope waveforms while performing “38 gauge wire protection” tests.