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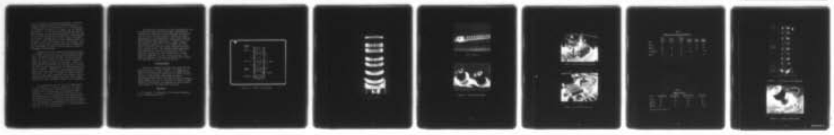

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ADIABATIC MODE OPERATION OF THYRATRONS FOR MEGAWATT AVERAGE POWER APPLICATIONS

John E. Creedon
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Electronics Technology & Devices Laboratory

February 1977

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Significant impact on the size, weight, and cost of high energy pulse systems having short on times can be obtained by designing components to operate in the adiabatic mode. Several thyratron design concepts for short term, high peak and average power switching applications have been studied. They include cavity grid designs for high voltage reliability, grid baffling designs to improve anode take over times, and plasma cathode designs to eliminate standby filament power. Using these concepts, several thyratron designs have been

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fabricated and evaluated at average powers approaching one megawatt. Evaluation of an off the shelf HY-5 operating in the adiabatic mode, was also conducted. It was found that by modifying the cathode structure the device was capable of being operated reliably at 22.5 amperes of average current at a peak voltage of 15 kilovolts.

CONTENTS

Page

Summary 1

DISCUSSION 2

Adiabatic Mode of Operation 2

High Average Power Thyratron Design 2

Megawatt Average Power Switches (MAPS) 4

ACKNOWLEDGMENT 9

REFERENCE 9

FIGURES

1. Cavity Grid Design 10
2. MAPS 70 11
3. MAPS 250 12
4. HY 5001 and HY 5002 12
5. 250 Kilovolt Blumlein Test Set-Up 13
6. AFWL and MAPS 40 Test Facility 13
7. 8 Gap Cavity Grid Thyratron 15
8. Plasma Cathode Switch 15

TABLES

1. MAPS Electrical and Mechanical Objectives 14
2. Summary of Results 14

ADIABATIC MODE OPERATION OF THYRATRONS FOR MEGAWATT AVERAGE POWER APPLICATIONS

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Summary. Significant impact on the size, weight, and cost of high energy pulse systems having short on times can be obtained by designing components to operate in the adiabatic mode. In the specific case of the thyratron switch the mass of the cathode and grid elements can be used as internal heat sinks. This allows its average current capability and thus its power handling ability to be increased several times over its normal steady state value for short operating times. Several other thyratron design concepts for short term, high peak and average power switching applications have also been studied and will be discussed. They include cavity grid designs for high voltage reliability, grid baffling designs to improve anode take over times, and plasma cathode designs to eliminate standby filament power. Effect and advantages of unbaffled grid structures on the anode take over time of the cavity grid structure was investigated. Average and peak current capabilities of several cathode sizes have been experimentally studied at a pulse width of 20 microseconds. Using these concepts several thyratron designs have fabricated and evaluated at average powers approaching one megawatt. In addition our evaluation of an off the shelf HY-5, operating in the adiabatic mode, was conducted. It was found that by modifying the cathode structure the device was capable of being operated reliably at 22.5 amperes of average current at a peak voltage of 15 kilovolts.

DISCUSSION

Adiabatic Mode of Operation

Recently, there has been interest in developing modulators that operate for short-on periods of one minute or less at peak and average powers substantially above those controllable with a single state-of-the-art switching device. Off-times, however, are relatively long and may be from several minutes to several hours. Since significant heat losses by convection,conduction,and radiation will not occur until a substantial temperature rise in the specific element occurs, the device can be considered to be operating in the adiabatic mode. For this type of an operating mode, the temperature rise of the internal elements are proportional to the total energy dissipated and the mass of the element and inversely proportional to the heat capacity. If the pulse width is long, that is, greater than a few microseconds, anode and grid heating effects associated with the P_b factor, will not be significant. For this condition, the internal dissipation of the thyratron will be directly proportional to the average current.

High Average Power Thyratron Design

Figure 1 shows a high average power switch design which differs in several ways from devices designed for radar applications. One is that high voltage hold-off capability is obtained by using a multiple cavity-grid structure rather than a stack of parallel plate grids. The problem with the latter approach is that in practice it is limited to two gaps when operation in air is desired. The limitation occurs because the external voltage stress must be less than 10 kilovolts/inch to prevent flashovers across the insulators while the internal spacing is adjusted to give a voltage stress in hydrogen or deuterium of nearly 200 kilovolts/inch. The disproportionate differences in the internal and external spacing requirements results in the use of deep cup electrodes which are not suitable for unlimited stacking of grids, the gradient grids must have the same physical configuration which permits easy construction and results in equal capacitance distribution and short paths for good electrical and heat conduction. All of the above design characteristics can be obtained by using wide spaced cavities between the high voltage grids.

In operation the cavities are made nearly field free except for a small value required to ensure complete internal breakdown and plasma propagation. One disadvantage of the wide spaced, low voltage hold-off cavities is that recovery times are long. To increase the speed of cavity deionization, which is predominantly governed by ambipolar diffusion mechanisms, inverted metal cups are placed in the cavity to increase the surface to volume ratio.

Another departure from conventional thyratron design is the incorporation of the virtual anode. This design concept offers two advantages. One is that it provides a defocusing region for high voltage electrons formed during the breakdown or commutation period prior to their collection by the annode. Substantial numbers of electrons are accelerated up to full anode potential during commutation, and in the conventional geometry the beam waist caused by the focusing action of the high field occurs at a distance approximately equal to the grid anode spacing. The high electron energy is then dissipated in a small area resulting in hole drilling and localized anode heating. The resulting sputtering of metal atoms degrades both inverse hold-off and recovery characteristics. Another advantage of the virtual anode design is that it provides a large reservoir of gas molecules behind the anode. During high peak current operation pronounced ion pumping as well as transient clean-up may take place which deplete the anode grid region of neutral gas. Gas diffusion from the upstream virtual anode cavity temporarily compensates for these losses until circulating gas flow and reservoir replenishment actions are established.

A potential problem with the multi-cavity-grid design involves the commutation time for each gap and cavity to break down and commute. If the upper gaps break down too slowly, then high voltages appear across the insulation causing external spark-over. This problem has been found to occur frequently and several ways of eliminating it are presently being evaluated.

Another departure from conventional thyratron usage is in the large peak and average current requirements that are being considered for the cathode. For example, in one high average power modulator currently of interest, switching of peak current up to 250 kiloamperes at average currents of up to 300 amperes are being considered. Cathodes designed to operate in the adiabatic mode of operation, are felt to be the most practical approach to achieve current densities of these magnitudes.

Megawatt Average Power Switches (MAPS)

Three MAPS type switches are being developed by ECOM. The electrical and mechanical objectives and characteristics are summarized in Table 1. Also shown are the characteristics for the HY 5001 and the HY 5002, which are being developed to meet a short on-time requirement for Air Force Weapons Laboratory (AFWL). The development of the MAPS 70, shown in Figure 2, has been partially supported by Wright-Patterson Air Force Base (WPAFB) who initiated and are continuing to sponsor the ECOM technology studies associated with the MAPS program. This device is a three gap two cavity deutrium filled device having a 5000 cm^2 cathode. Internal water cooling is provided to all of the grid elements.

Approximately five of the devices have been fabricated by EG&G to date. In general, leaks in the seals for the cooling channels have limited the performance of this design. One MAPS 70 operated at 700 kilowatts of average power at a peak voltage of 56 kilovolts. Operation was terminated by a seal leak.

The MAPS 250, shown in Figure 3, is being developed for use in the Blumlein Modulator. This modulator is described in a symposium paper by Wright and Schneider, entitled, "A Blumlein Modulator for a Time-Varying Load."[1] The MAPS 250 has 10 gaps and 9 cavities and a 2000 cm^2 oxide coated cathode. The cathode is mounted in a steel housing, 6 inches in diameter and the convoluted ceramic high voltage super structure is 4 inches in diameter. The cavity spacers are graduated in length and are longer at the top of the tube because of the external spark over probability during commutation. Four MAPS 250 devices have been fabricated by EG&G. One is presently being used in the MICOM modulator and the other three are being processed and evaluated at ECOM. To date the tubes have operated in the Blumlein modulator at 200 kilovolts under single shot pulsing and at 175 kilovolts at 50 hertz. In addition, the tube has been operated at a peak current of 9 kiloamperes and at an average current of 15 amperes at 40 kilovolts peak forward voltage in a line type modulator.

Figure 4 shows the HY 5001 on the right and HY 5002 on the left. These tubes are modifications of the standard EG&G HY 5. The HY 5 was evaluated at 22.5 amperes average current with a 30 second on-time and a 4 1/2 minute off-time. After approximately 50 on-off cycles, the devices exhibited a missing pulse characteristic which was found to be due to severe distortion of the cathode baffle. An 0.060 mils molybdenum baffle was substituted for the 0.040 mils copper. Over 1000 fault free cycles at 22.5 amperes have been demonstrated for the 5002. The 5001 had 3 pre-firings in a similar number of on-off cycles.

The MAPS 40 is to be developed on an external contract. Several preliminary devices, dependent of the contract effort, have been designed and are being fabricated by EG&G. These pre-MAPS 40 devices will be tested and evaluated at ECOM and the results will be used to implement the contractual development particularly with respect to cathode and grid current characteristics near full power. The MAPS 40 work is being sponsored by MICOM.

The test facilities being used to evaluate devices are shown in Figures 5 and 6. Figure 5 shows the 250 kilovolt - 2.5 microsecond Blumlein modulator which is described in detail in the paper of Wright, Schneider and Buffa.[1] An essential element of the modulator, from the viewpoint of the MAPS 250 thyratron is the front end clipper diode which in the photograph is in front of and partially blocks the thyratron from view. The clipper diode shunts the thyratron during the time that inverse voltage is present. At the peak current of interest the thyratron conducts easily in the reverse direction and this limits recovery characteristics. The modulator is charged by a 250 kilovolt 4 ampere dc power supply. Figure 6 shows the facility being set up for testing either the HY 5001/5002 or the MAPS 40 devices. Each PFN is 2 ohm in impedance and has a pulse width of 20 microseconds. One line is used for the AFWL tests at 15 kilovolts, 281 hertz. For the MAPS 40 testing all four networks are connected in parallel but with the number of sections reduced to give a 10 microsecond pulse width. The large box in front of the PFNS houses 4 banks of ohmweave resistors which can be arranged to give a load impedance of 0.25, 0.5, 1.0, and 2.0 ohms with a continuous dissipation of 500 kilowatts. For short term operation it is anticipated that the load will be capable of dissipating nearly one megawatt.

The modulator is charged from a 40 kilovolt - 30 ampere dc power supply which can be run at 40 amperes at somewhat reduced voltage. Two charging inductors of 0.75 henries each are available and they can be connected in either series, parallel or used individually to give the resonance frequencies of interest. Two 40 kilovolt - 20 amperes charging diodes are also in the facility and they allow the modulator to be run at frequencies lower than resonance.

Table 2 summarizes the maximum operating levels obtained to date. Both the HY 5001 and the HY 5002 meet the original objectives of AFWL. The 5002 has demonstrated a peak current capability of 75 percent higher than originally needed. The 5002 also operated for over 50 cycles at a 30 ampere average current level with a 10 second on-time. It has also demonstrated a capability to run at 35 amperes provided the current did not exceed 8 kiloamperes. There was not difficulty experienced with a 3 second on, 3 second off, operating cycle, obtained by snapping the grid on and off at full peak and average powers. Both types were capable of being snapped on after a 15 minute warm up and during stand-by.

The MAPS 70 has demonstrated operation at 80 percent of the voltage and at 87 percent of the average current objectives. The MAPS 250 has operated at 80 percent of the objective voltage level on single shot and70 percent of the objective at 50 hertz.

Figure 7 shows an earlier 8 gap version of the MAPS 250 with the gap-cavity geometry outlined on the photograph. Nominally, a series resistance divider is used to assure equal voltage division across the gaps. The value of resistance per gap depends on the distributed capacitance and anode recharging time. Generally, values between 10 and 40 megohms are used. A smaller resistor, usually 100-200 kilohms, is used across the cavity. The cavity can be negatively biased by placing the gap resistor from gradient anode to gradient anode and this has been found in some instances to give higher peak voltage operation. At the high values of peak and average current of interest for the adiabatic thyratron development, the peak forward voltage hold-off obtainable per gap is reduced from 30 -40 kilovolts to 15 - 20 kilovolts. The reduction in hold-off is mainly due to recovery limitations. It has been observed that the thyratron conducts in the inverse direction when the peak forward current exceeds approximately 3 kiloamperes. As a result, matched end of line clipper circuits and front and clippers have been found necessary to prevent or limit the inverse arc from forming. Use of the virtual anode has been observed to minimize glow discharges in the grid anode region during recharging of the network.

Commutation of the multiple cavity-grid structure takes time and this has caused external spark-over. Ordinarily the breakdown proceeds from the bottom of the structure up and on each gap breakdown, the anode voltage is capacitively divided among the remaining caps and cavities. Since the distributive capacitances of the gaps and cavities are about equal, high voltage can appear across the upper ceramics. Probability of an external breakdown in air thus assumes a non-vanishing value and spark-over can occur. Although the device subsequently breaks down internally and commutes the deionization of the external discharge, thus limits the rate at which recharge voltage can be applied.

The problem can be effectively eliminated by (a) increasing the internal spacing of the upper elements; (b) using a high dielectric strength medium; and (c) decreasing the breakdown time of the gaps. All three approaches have been tried with some success. Decreasing the breakdown time was achieved by eliminating the grid baffling in the upper structure. Although the hold-off capability was reduced to approximately 13 kilovolts per gap, the firing time (TAD) was for a 3 gap structure from 0.75 to 0.3 microseconds.

Considerable interest has been expressed by the Air Force in reducing heater power requirements. Towards this end we are investigating the feasibility of using a plasma cathode. Figure 8 shows a photograph of an experimental device fabricated by IT&T in which peak currents of 70 amperes at 8-10 kilovolts were switched using a plasma cathode. The electron source was a cold cathode arc from which electroncs were extracted through apertures in a cathode plate. The anode-cathode separation and pressure are similar to those used in conventional thyratrons. This cathode arc current must be comparable to the circuit current. The approach appears to be quite promising with respect to achieving an instant turn-on device.

ACKNOWLEDGMENT

The work reported here has been supported and encouraged by R. Verga of WPAFB. D. Turnquist of EG&G contributed to the design of the MAPS and his efforts are gratefully appreciated. IT&T's contribution on fabricating the plasma cathode is acknowledged and finally the authors wish to express their appreciation to S. Schneider of ECOM for many technical discussions and suggestions particularly with respect to the unbaffled structure.

REFERENCE

1. W. Wright, S. Schneider, "A Blumlein Modulator for a Time Varying Load."

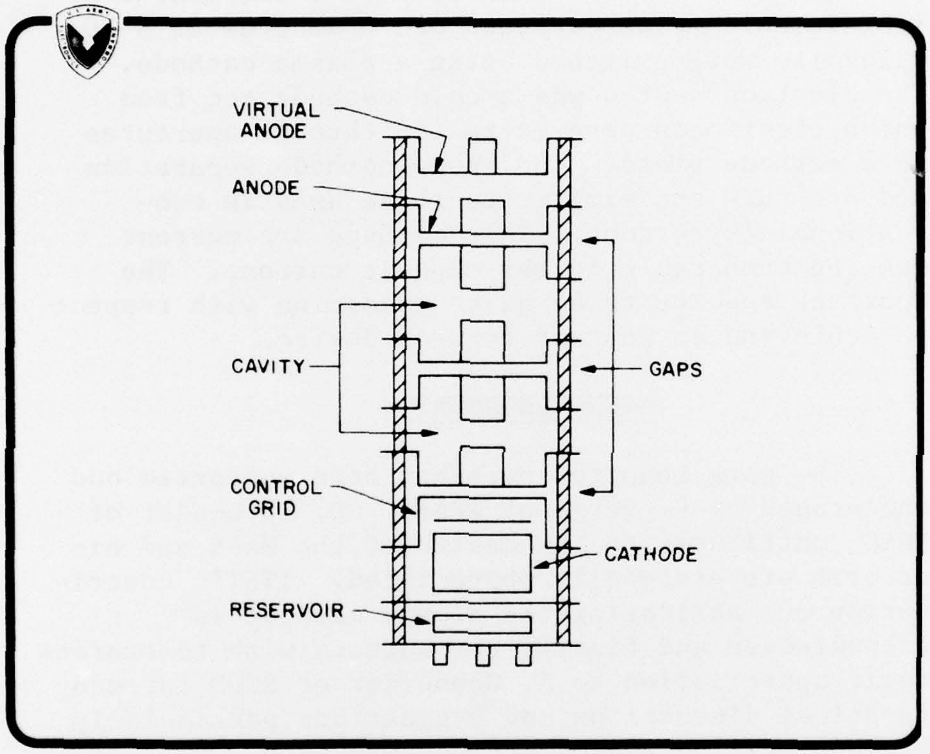

Figure 1. Cavity Grid Design

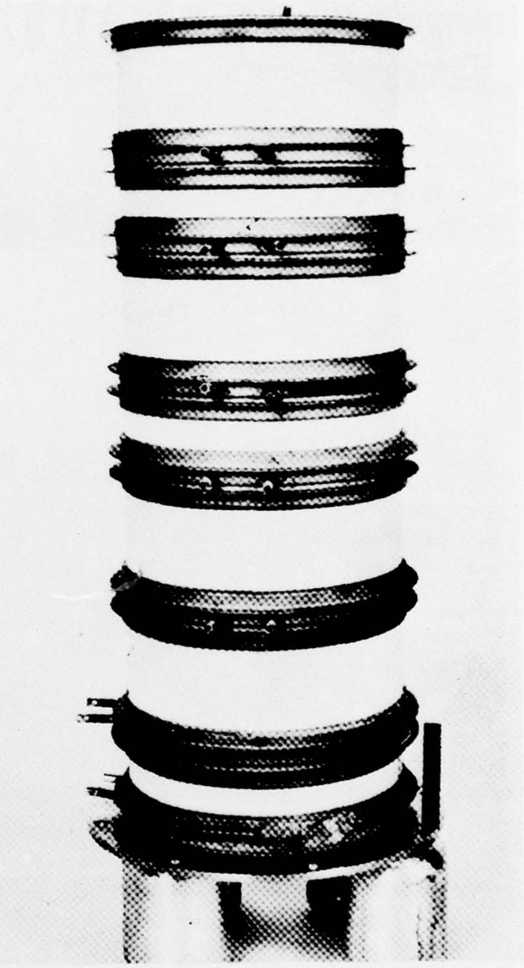

Figure 2. MAPS 70

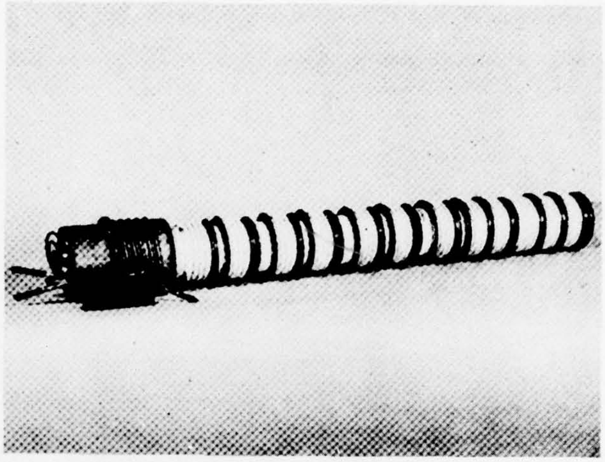

Figure 3. MAPS 250

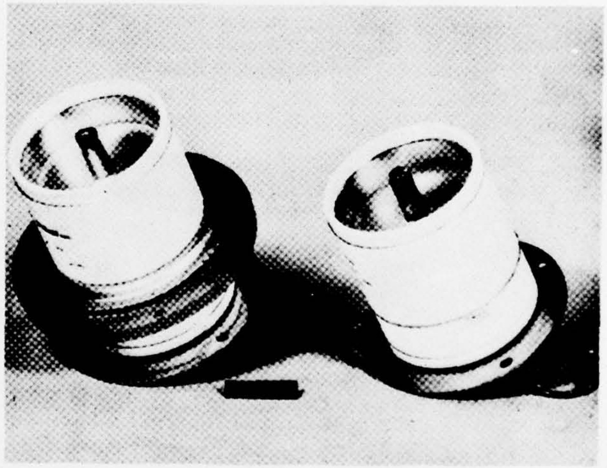

Figure 4. HY 5002 and HY 5001

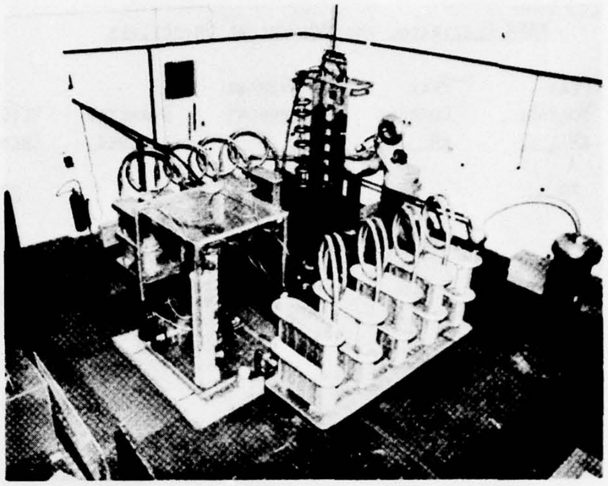

Figure 5. 250 kilovolt Blumlein Test Set-Up

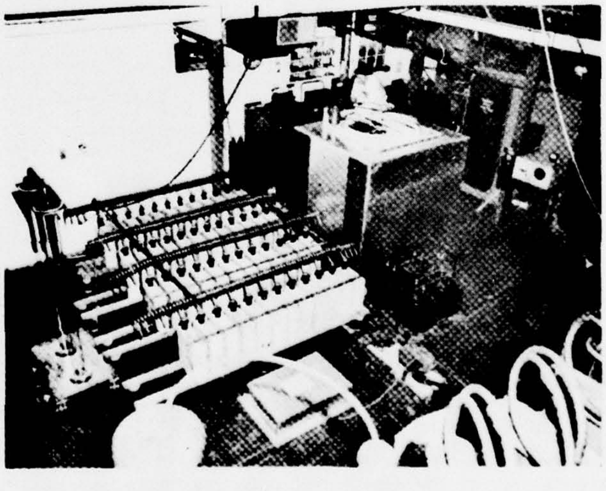

Figure 6. AFWL and MAPS 40 Test Facility

TABLE I

MAPS Electrical and Mechanical Objectives

Type	Peak Voltage kV	Peak Current kA	Average Current A	Diameter Inches	Height Inches	Weight Pounds
MAPS 70	70	5	30	8	27	85
MAPS 250	250	20	4	4	54	45
HY 5001/5002	15	5	22.5	4.5	5	7/12
MAPS 40	40	40	50	--	--	25

TABLE II

SUMMARY OF RESULTS

Type	Peak Voltage kV	Peak Current kA	Average Current A	Pulse Width μs
HY 5001	15	4	22.5	20
HY 5002	15	8.4	30	20
MAPS 70	56	4	26	20
MAPS 250	200	13	15*	2.5-5

*Obtained at 40 kV and 10 μs

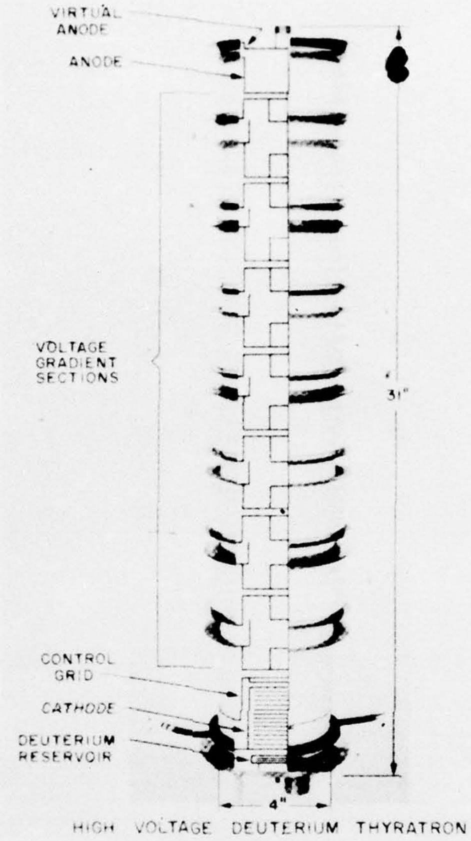

Figure 7. 8 Gap Cavity Grid Thyratron

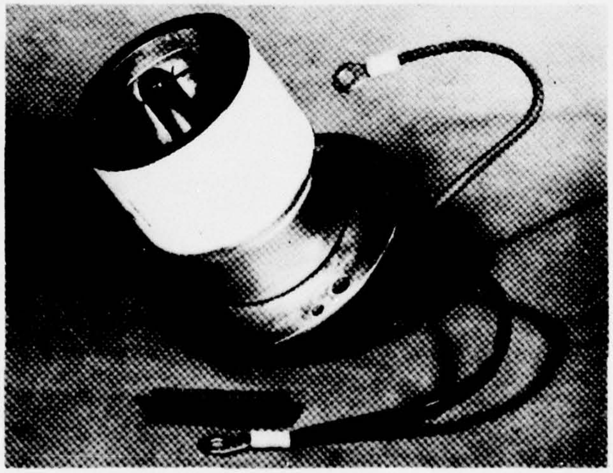

Figure 8. Plasma Cathode Switch