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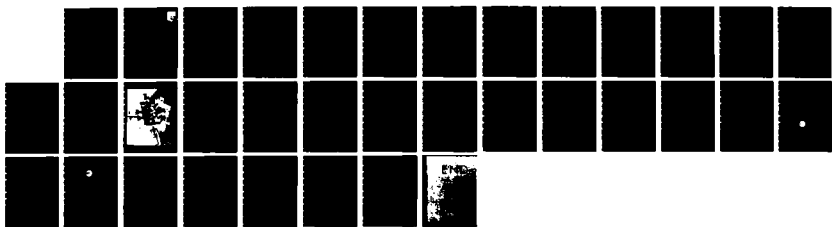
LONG-LIFE HIGH-CURRENT THYRATRONS FOR FAST DISCHARGE
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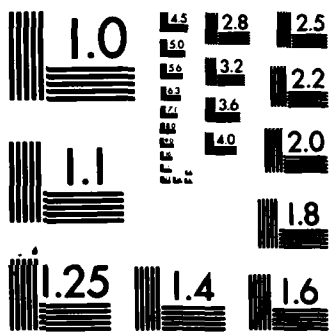
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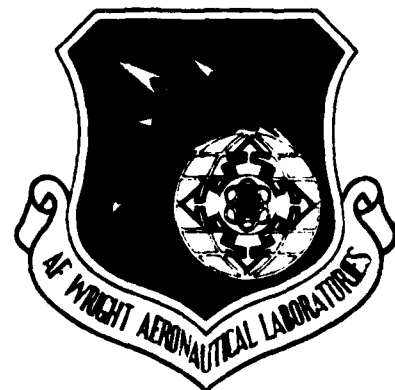
AFWAL-TR-84-2003

**LONG-LIFE, HIGH-CURRENT THYRATRONS
FOR FAST DISCHARGE LASERS**

**Mathematical Sciences Northwest, Inc.
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Bellevue, WA 98004**

and

**Impulse Electronics, Inc.
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March 1984

Final Report for Period May 1982-October 1983

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An experimental linear thyratron, 10 cm long, has been fabricated and tested as a prototype linearly-scalable, low-inductance, long-life closing switch for short pulse duration parallel plate pulse modulators. Voltage holdoff to 25 kV and peak current of 2 KA at 15 kV were demonstrated. The discharge plasma spread uniformly along the entire 10 cm length of the thyratron when operated with no external cathode heater power.		

PREFACE

This report describes the first phase of a program to develop a new class of linearly scalable, low inductance thyratrons that are matched to the geometry of high current stripline pulse modulators. A number of applications, including high-power pulsed lasers and particle beam accelerators, require this type of switch. Mathematical Sciences Northwest, Inc. (MSNW) and Impulse Electronics originated the concept and have collaborated to design, build, and test a 10 cm-long experimental linear thyatron.

A number of innovations are incorporated into the tube design. A unique grid, anode, and insulator configuration is included for high standoff voltage (up to 100 kV). Dispenser type linear cathodes are used for their high current density (up to 100 A/cm²) and their ability to operate without heater power. A tetrode configuration is used to permit uniform plasma formation and short commutation time (10 nsec). A number of diagnostic ports are incorporated in the tube walls to permit observation of the temporal and spatial behavior of the plasma produced in the tube.

During the initial tests, the experimental linear thyatron successfully held off voltage up to 25 kV, the highest that was applied, and successfully switched currents up to 2 kA at a charge voltage of 15 kV. The maximum current was limited by the gas (neon) used in the thyatron and by the inductance of the circuit used in these preliminary tests. The discharge plasma, both in the grid-anode and grid-cathode spaces, spread uniformly along the entire length of the tube during commutation. Although this spreading was sensitive to gas pressure and auxiliary grid current, the discharge plasma was uniform even when the thyatron was operated with no external cathode heater power. The thyatron performance tests were terminated prematurely by thermo-mechanical failure of the auxiliary grid supporting structure. The grid

structural problem can be overcome by using materials for the supports.

The initial tests demonstrate the feasibility of the linear thyatron concept and the soundness of the basic fabrication approach. The results confirm the possibility of developing a new class of closing switches that are linearly scalable, provide high standoff voltage (100 kV), high current (100 kA), short commutation time (10 nsec), and are capable of reliable, long lifetime (10^{10} pulses) operation. This type of switch would displace the majority of other switches used in high power military and commercial lasers and particle beams, and it could find application in many other pulsed power systems that requires a stripline geometry. Since the cathode requires no standby power, these linear switches would be suitable for space applications.

This study was performed under United States Air Force Contract F33615-82-C-2244. The contract was funded by the Defense Advanced Research Project Agency (project officer Lt Col R.P. Benedict, DARPA/DEO). The Air Force program manager was Dr Alan Garscadden, Energy Conversion Branch, Aerospace Power Division, Aero Propulsion Laboratory, Wright-Patterson AFB.

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Section 1

LINEAR THYRATRON DESIGN AND FABRICATION

1.1 DESIGN APPROACH

The conceptual design of the linear thyatron was a joint effort of Impulse Electronics and MSNW. The detailed design and fabrication described in this section were carried out by Impulse Electronics. Setting up the experimental test facilities, conditioning the thyatron, and making all experimental measurements were done by MSNW, as described in Section 2.

The design objective for the linear thyatron is to provide a fast, high-voltage, low-inductance switch for large-scale, short pulse lasers and other systems that utilize parallel plate pulse modulator geometries. Figure 2 illustrates a possible laser assembly using the linear thyatron. Commercially available thyatrons cannot supply the peak currents and fast risetimes required by these lasers and still meet lifetime specifications; present data indicates a rapid reduction in lifetime with current for these thyatrons.^(1,2) In addition, standard thyatrons require significant standby heater power, which is undesirable for many applications that demand high 'wall-plug' system efficiency.

There have been several major obstacles in previous attempts to produce low inductance, high current thyatrons. One limitation is associated with the cylindrically symmetrical tube geometry that has been used, which is inherently higher inductance than a linear (stripline) geometry. A closely related limitation is the use of permanent ceramic-to-metal seals in thyatron construction, which successfully permits high temperature bakeout of the tube to yield a long-life, sealed-off structure. However, this type of construction is subject to thermally induced stress, which restricts the maximum scale dimensions of the tube and also prevents the use of an elongated (linear) geometry. Finally, studies of large experimental thyatrons built for low inductance and very

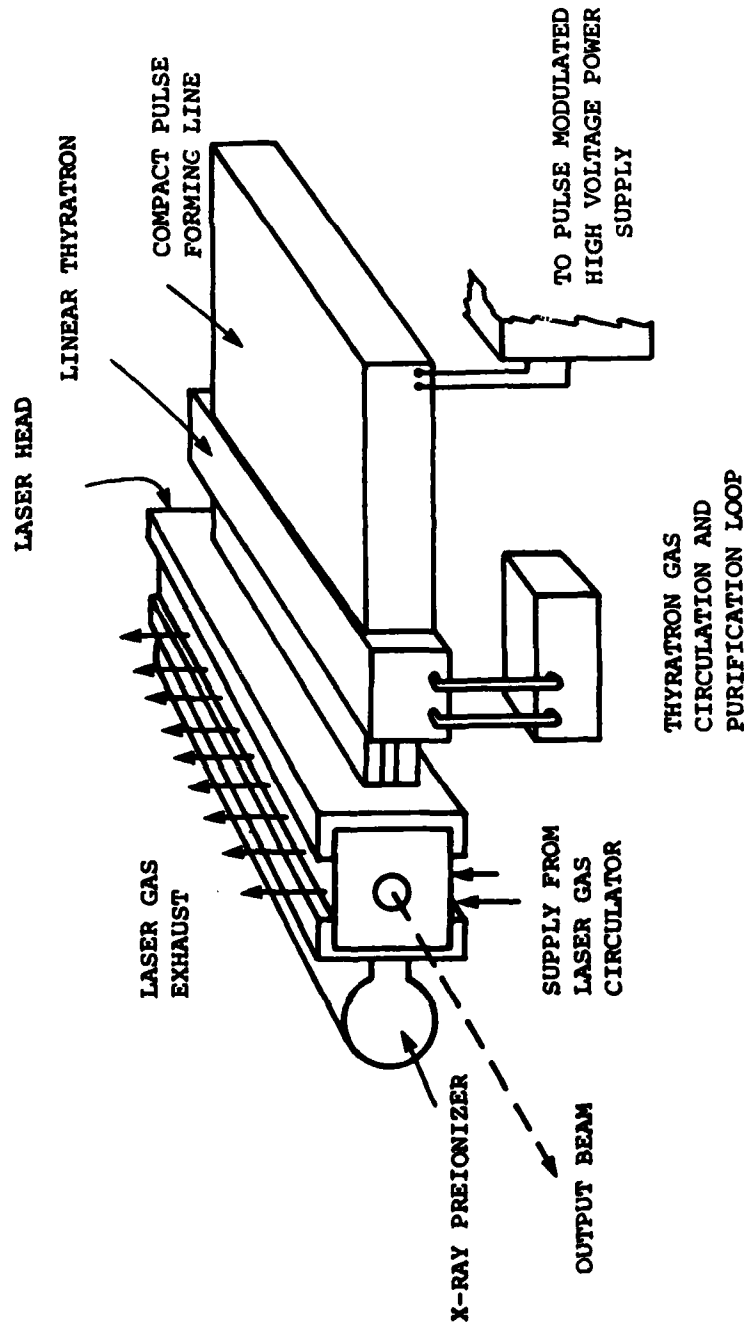


Figure 1. Schematic of Example Large-Scale Discharge Laser Assembly Using New Linear Thyatron Switch

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high dI/dt have shown that the plasma often does not form uniformly within the tube.⁽³⁾ Instead, small, high current density regions are formed, which produce cathode damage and also result in an inductance that is higher than the value calculated on the basis of a uniform plasma. Earlier studies of conventional thyratrons using oxide-coated cathodes showed that the time required for the discharge to become uniform over a 1 inch diameter area could be as long as 350 nsec.⁽⁴⁾

The design approach used here for the linear thyatron is based on a new structural concept that can be scaled linearly and does not involve oven-fired, sealed-off fabrication methods. High vacuum techniques are used in an O-ring sealed linear (or rectangular) chamber configuration that provides high gas purity. New (non-ceramic) insulator materials are incorporated that provide high voltage holdoff capability. A gas flow supply and exhaust system is used that eliminates the need for a hydrogen reservoir and permits other gases, such as helium, to be used. A high current density cathode material is used in a tetrode configuration, which aids in rapid formation of a uniform plasma.

The linear thyatron incorporates additional features to solve other major problems now encountered by commercial thyratrons in laser applications. The cathode is of the dispenser type, with documented current densities of 80 to 100 A/cm² and stable operation at room temperature, i.e., with no cathode heater power.⁽⁵⁻⁷⁾ Lifetimes of tens of thousands of hours are possible with this cathode.⁽⁸⁾ Fast switching times can be achieved by operating the linear thyatron at hydrogen or helium gas pressures approaching 1000 microns. The tube can be operated at these high pressures because the linear control grid structure allows grid slots to be tightly baffled (to insure high voltage holdoff in the grid-anode space) while keeping the current density in the grid aperture region during commutation low 1 to 2 KA/cm², the quenching limit for microsecond discharges.

In addition to the high performance design features described above, this first experimental thyatron is designed with optical ports in the tube walls that permit direct viewing of the cathode-grid space and the anode-grid space. These ports allow quantitative time-resolved spectroscopic and interferometric diagnostic techniques to be used to measure plasma properties during the formation, conduction, and recovery stages of thyatron operation.

1.2 EXPERIMENTAL LINEAR THYATRON DESIGN

The linear thyatron incorporating these advanced design features is schematically shown in Figure 2. The tube is a tetrode, with an auxiliary grid placed between the cathode and the control grid. The auxiliary grid is driven by a dc power source both to insure uniform cathode emission and to provide a grid-cathode plasma prior to commutation. This grid plays an essential role in the uniform discharge-spreading in the thyatron. The importance of the auxiliary grid will be further discussed in the section on test results. Future work will include pulsing the auxiliary grid.

The high voltage holdoff structure consists of the anode, the control grid and its electrostatic shielding baffles, and the main insulator. The anode and grid structures are derived from the most recent experimental studies of conventional thyatrons. The insulator, however, is altered significantly. In thyatrons, the alumina insulator and its surface are believed to be a major contributor to the present high voltage holdoff limits, as discussed below. With continuous gas pumping and purification, with a lower temperature cathode, and with low thermal dissipation through the walls of the switch, less perfect seals and increased outgassing rates can be tolerated. This frees us from dependence on alumina as an insulator and structural element.

Relevant literature on surface breakdown was reviewed to determine the optimum high voltage insulator material. The principal candidates were Pyrex, quartz, or glazed alumina. Good glaze candidates are chrome or

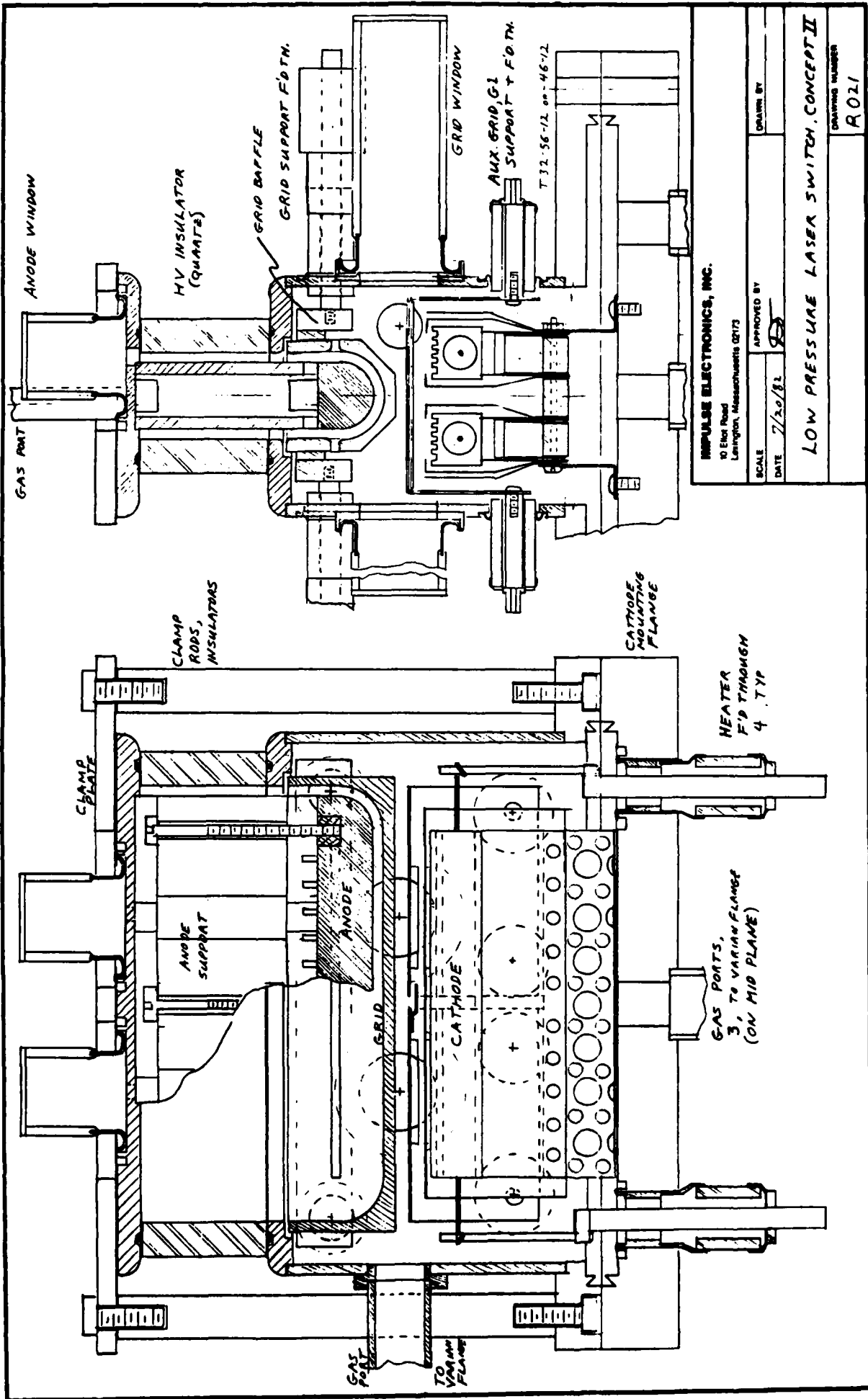


Figure 2. Longitudinal and Transverse Section Views of Experimental Linear Thyatron Design

copper oxide glazes. It seems well established that the high-alumina main insulator now being used in conventional, external-anode hydrogen thyratrons is made of a material among the worst available with respect to high voltage flashover. Its poor performance is the result of secondary electron yield and electron-bombardment-induced outgassing, both of which contribute to flashover.^(9,10) Both of these faults may be significantly enhanced by high-alumina's typical rough surface morphology.

Critical acceptance criteria considered also included timely availability, ease of sealing to the mounting flanges, dimensional stability, and ability to fabricate with the required dimensional precision. Optical transparency was not a criterion, since the tube design included a window on the anode flange to give a clear view of a portion of the grid-anode discharge. After considering all factors, a simple quartz structure was selected because it offers the best combination of mechanical stability and precision, high voltage holdoff, and ease of fabrication. This configuration and choice of materials closely duplicates the most critical elements of the earlier experimental 100 kV single stage thyratron investigated by Mancebo.⁽¹¹⁾

The cathode material is barium aluminate impregnated tungsten. This type of cathode has been used extensively in long-life electron tubes such as TWTs for satellites and high power klystrons. It was only recently,⁽³⁻⁵⁾ however, that this material was found to emit at extraordinary current densities in thyratron-type tubes: over 300 amps/cm² at a few hundred degrees centigrade, and up to 80 amps/cm² even at room temperature (i.e., with no heater power). We have used this material in a shallow, vane type cathode structure for increased emission area. In spite of its current loading, this cathode, designed specifically for high di/dt and short pulse operation, is much less prone to local thermal runaway and discharge current localization than conventional thyratron cathodes. The present generation of thyratrons, even the most recent designs, still use extended vane oxide cathodes designed for 1-10 microsecond pulses at moderate di/dt. Such cathodes are poorly utilized under high di/dt short

pulse conditions, and the gas contamination caused by the resultant overheating is still another cause of high voltage failure. These problems are avoided with the use of barium aluminate impregnated tungsten cathodes.

The cathode dimensions are 0.6 inches wide by 4 inches long. The exposed emissive surface contains 5 longitudinal grooves 0.05 inches wide by 0.06 inches deep. The total surface area of the cathode is 30 cm². Assuming a nominal room temperature emission density of 80 A/cm², the peak current capability of the cathode is 2.4 KA. This cathode should be capable of 10 KA peak current when heated to a temperature of 1000°C, based on current density versus temperature measurements.⁽¹²⁾

The cathode is directly heated, with two molybdenum end-rods bolted to a cathode feedthrough structure. The cathode itself is electrically tied to the cathode baseplate through a low-inductance Hasteloy support structure.

The control grid surrounds the anode with a single grid slot on each side of this re-entrant anode-grid structure. At 5000 A peak, the grid slot will operate at a current density approaching 1000 A/cm². The length of the control grid is 10 cm, and the dimensions of the thyratron indicate the inductance of the tube to be no more than 10 nH when mounted in a closely fitting metal housing (no viewports). The control grid, anode, and auxiliary grid are made of stainless steel.

The section drawing of the linear thyratron (Figure 2) indicates eight viewing ports for observing the discharge during tube commutation. These windows are situated two per side on opposite sides to provide a transverse view of the grid-cathode region, two on one side of the anode to view the grid-anode region, and one view port on each end of the thyratron to provide a longitudinal view of the grid-cathode region. The photograph of the thyratron in Figure 3 shows how these view ports are placed. The side and end windows provide a direct line of sight to the cathode, so

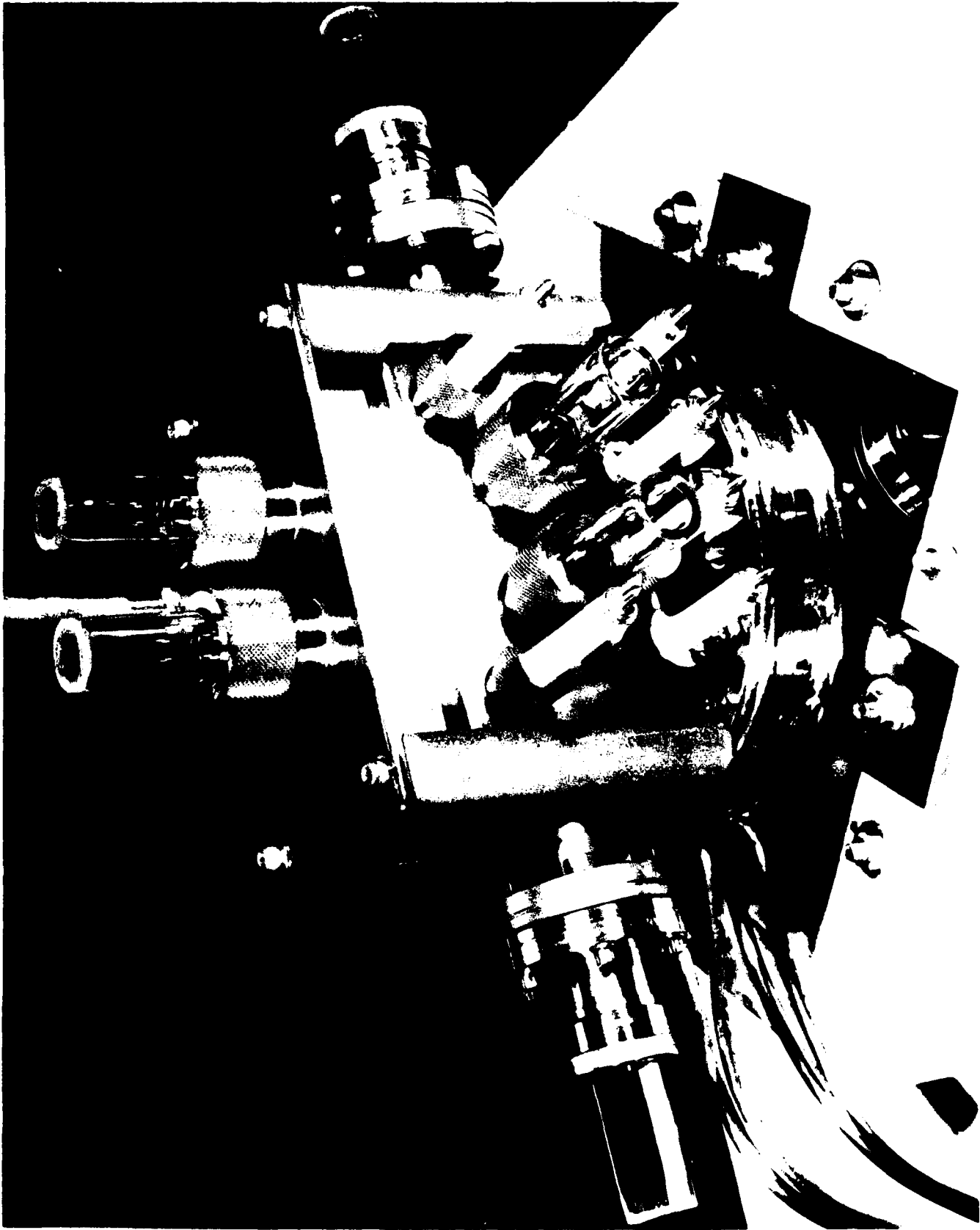


Figure 3. Photograph of the Linear Thyatron

cathode temperature can be measured with an optical pyrometer. The viewports are sealed by viton o-rings while the cathode baseplate region is sealed by copper gaskets. The entire structure is demountable.

1.3 THYRATRON FABRICATION

Following completion of detailed design of the experimental linear thyatron, the fabrication process was initiated. Suitable vendors for all components were selected and orders placed. The long-lead items included the dispenser cathodes (supplied by Spectra-Mat, Inc.), the main quartz insulator (supplied by Valley Design and by Wakefield Precision Optics), a number of high vacuum metal flanges (supplied by Varian, Inc.), and the optical window assemblies used as viewing ports (supplied by Yankee Glassblower and by Valley Design).

During fabrication of these parts, a number of difficulties were encountered which led to schedule delays and caused the fabrication process to cover the period from September 1982 to May 1983. Delivery of the cathodes was delayed by four months. Early attempts to fabricate the optical viewing ports introduced excessive distortion and required rework. The fabrication of the main quartz insulator proved to be much more difficult than expected. It was finally delivered to Impulse Electronics in January 1983. To resolve some of the difficulties, the dimensions of the insulator were altered, necessitating changes in the anode, grid, and thyatron body dimensions, which then had to be reworked. The insulator also contained several flaws which did not, however, cause any difficulties in thyatron performance. A second quartz insulator was later fabricated without flaws and is now available as a spare part.

The completed thyatron was delivered to MSNW in May 1983, and the experimental test program described in Section 2 was carried out.

Section 2

EXPERIMENTAL MEASUREMENTS

The experimental test facility for the linear thyratron assembled at MSNW included a bakeout oven, a high vacuum pumping station, a gas handling system, an electrical supply and trigger system, and the associated thermal, electrical, and gas diagnostics. In this facility, the thyratron was first evacuated and baked out, the cathodes were activated, the quiescent operation of the tube was determined, and the electrical pulse characteristics of the thyratron were measured. The experimental facility and the test results are described in this section.

2.1 EXPERIMENTAL FACILITY

To outgas the thyratron before applying heater power to the cathodes, a large, enclosed oven was used that is capable of temperatures up to 500°C. The oven temperature was kept below 200°C because of the use of Viton O-rings for some of the seals on the linear thyratron. A 30l/sec high vacuum ion pump system was connected to the thyratron during bakeout. This ion pump remained as part of the thyratron gas handling system and was used to retain high vacuum when the tube was not being tested. This procedure insured that the dispenser cathode was not poisoned between tests. Pressure measured at the ion pump was 10^{-7} Torr and thyratron pressure was estimated to be about 10^{-6} Torr.

The gas handling system is shown schematically in Figure 4. The portion of the system shown as bakeable by the dashed line in Figure 4 included parts that all could be baked out at a temperature of at least 200°C. This part of the system was sealed off by the high temperature, high vacuum valves and could be connected to the gas supply and the cold trap and pump system after bakeout.

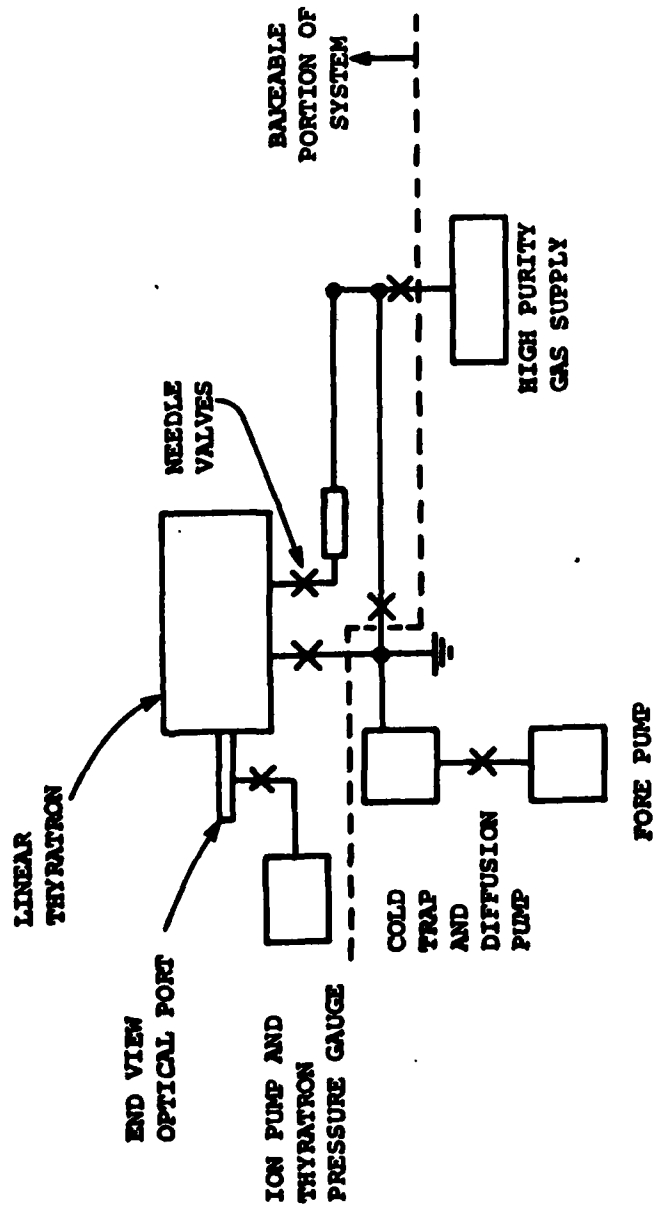


Figure 4. Schematic of Gas Handling System

During a test, the thyratron was backfilled with the operating gas to the desired pressure through a cold trap and valved off. Pressure was measured at the tube by a thermocouple gauge. The system was leak tight as determined by a helium leak detector. There was no measurable leak rate on the thermocouple gauge over an eight-hour period when the tube was operated at gas pressures of 200 to 500 μ torr. During testing, the thyratron was periodically pumped out by a roughing pump connected through a cold trap and then refilled. No tests were performed with gas flowing through the tube, although the gas system is capable of this.

The linear thyratron was tested electrically using the grid drive circuit shown in Figure 5 and the high voltage pulse circuit shown in Figure 6. The auxiliary grid was driven by a d.c. supply that delivered a current up to several hundred milliamps. In this initial test circuit, pulse charging of the anode was not used. The discharge capacitance was 12 nF and the load resistance was 2 ohms, corresponding to an RC decay time constant of 24 nsec. No attempt was made to build a low-inductance discharge circuit for these initial measurements. The waveforms obtained and described in Section 2.2 indicate that the test circuit inductance was about 200 nH, corresponding to an L/R time constant of 100 nsec.

Diagnostics included standard thermocouples in the bakeout oven and at a number of locations on the thyratron body to assure the integrity of the Viton O-ring seals. The cathode temperature was measured by an optical pyrometer through one end port window. Cathode heater d.c. current and voltage and auxiliary grid d.c. current and voltage were measured by conventional methods. The pulsed voltage across the thyratron during commutation was measured with a Tektronix P-6015 probe (10 nsec risetime) and the current conducted by the tube was measured with a Pearson current transformer (10 nsec risetime). A Tektronix 7844 dual-beam oscilloscope was used to record voltage and current waveforms.

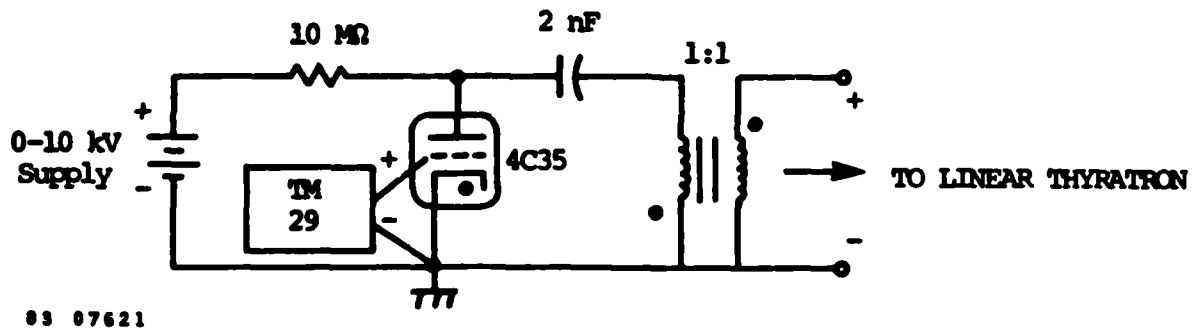


Figure 5. Control Grid Drive Circuit for the Linear Thyatron

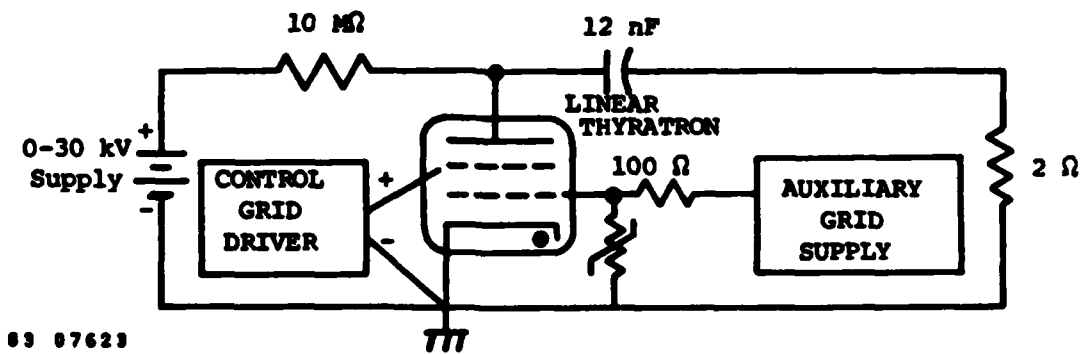


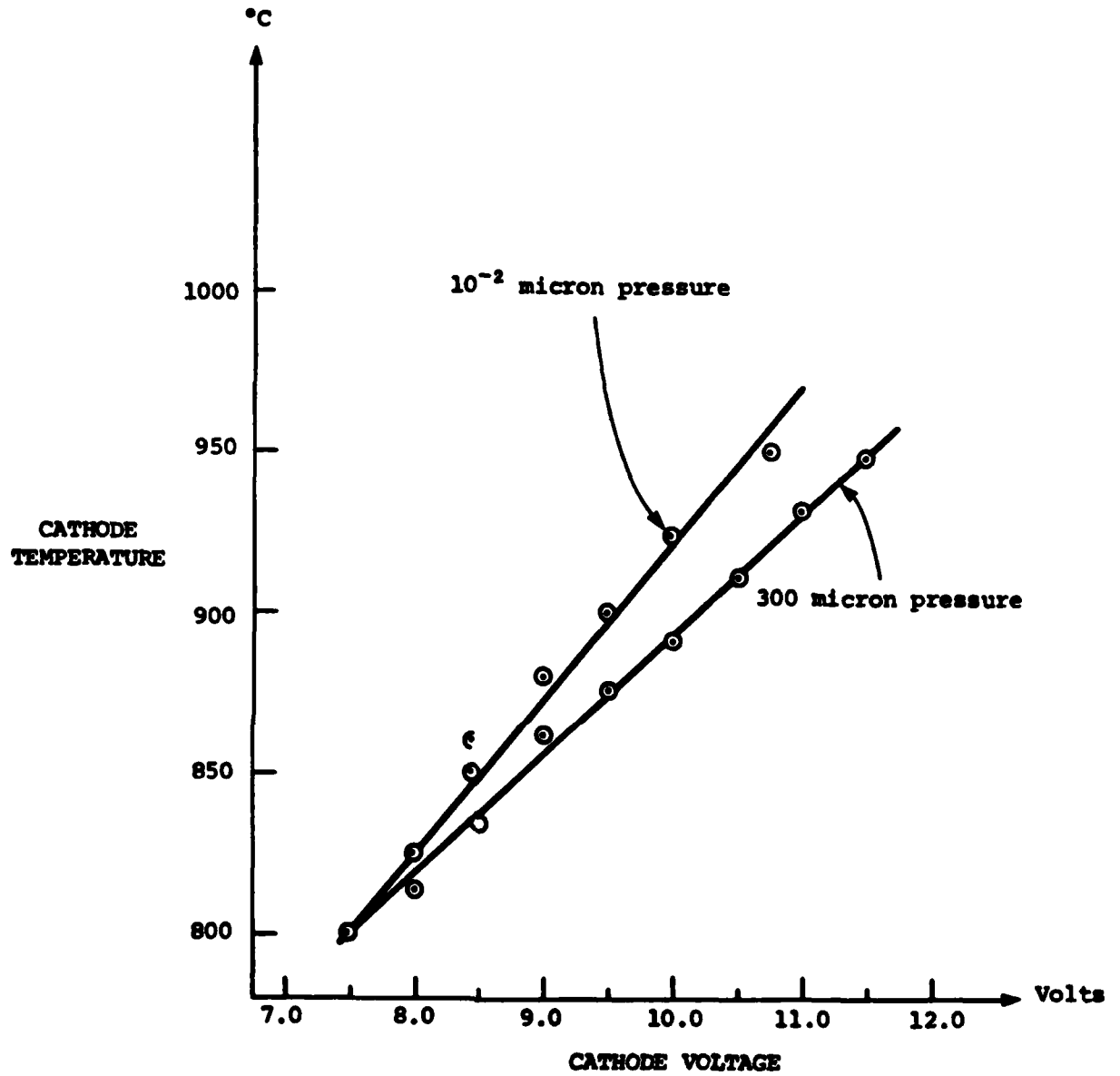
Figure 6. Linear Thyatron Test Circuit

2.2 TEST RESULTS

Initially, the thyratron was outgassed using the ion pump and the bake-out oven. Over a period of about one week, the oven temperature was gradually increased as the tube pressure decreased until a stable pressure of less than 10^{-7} Torr at the ion pump was achieved with the oven temperature at about 180°C . The cathodes were then activated by gradually increasing the cathode current while maintaining a high vacuum in the thyratron using the ion pump.

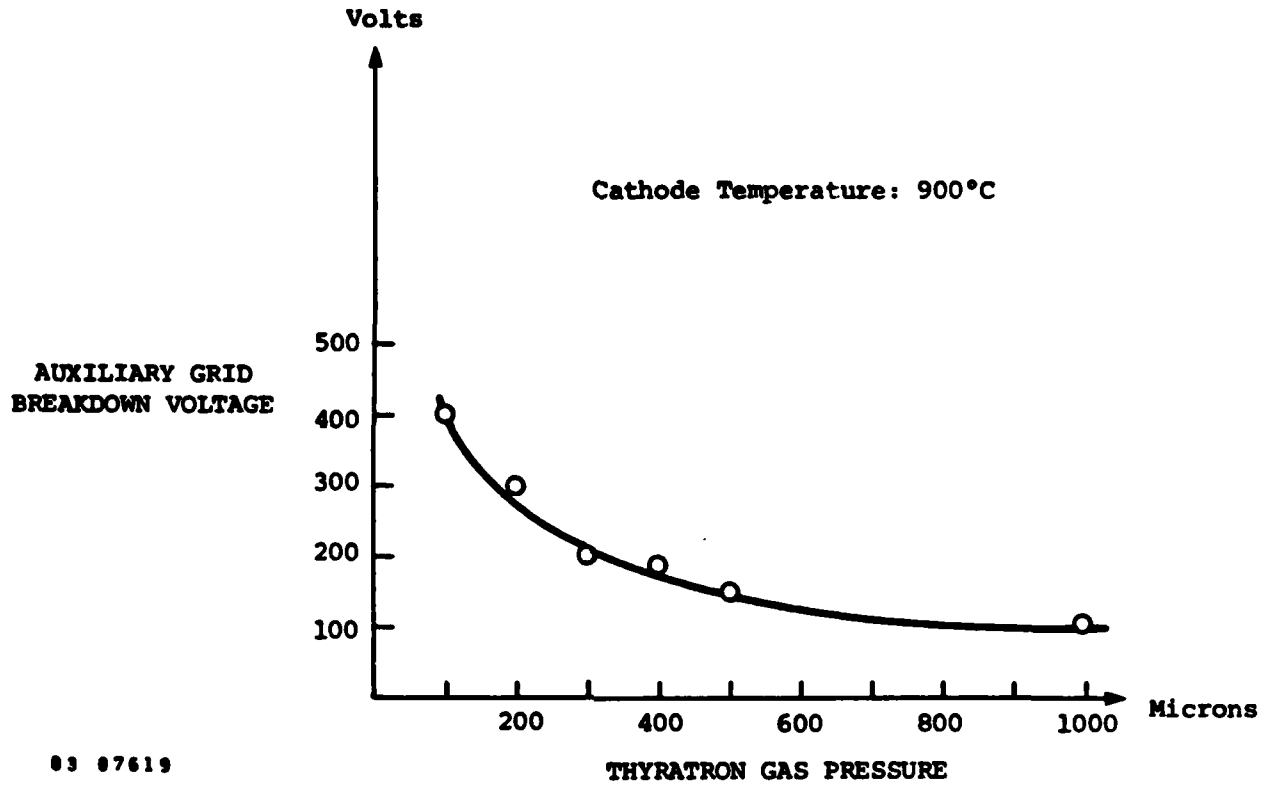
The first step in evaluating the linear thyratron involved documenting the quiescent operation of the tube with no applied anode voltage. Figure 7 shows the cathode temperature versus cathode voltage for two different tube pressures. In the initial tests, neon rather than helium was used because neon is readily pumped out by the ion pump. Subsequent tests using hydrogen were planned but were not carried out because of a thyratron structural failure that is described later. At a pressure of 300 microns neon, the cathode reached 950°C at a cathode voltage of 11.5 V and a cathode current of 35 A.

Figure 8 illustrates auxiliary grid breakdown voltage versus tube pressure at a cathode temperature of 900°C . The plasma formed by this discharge could be seen through any of the grid-cathode windows. After operating the tube with a heated cathode, it was noticed that the auxiliary grid was not parallel to the cathode; one end seemed to be sagging, as shown by Figure 9. (This sagging became more pronounced during thyratron evaluation until the grid finally touched the cathode. Thyratron testing was stopped prematurely once this grid shorted out to the cathode. Thermal fatigue at the auxiliary grid support structure caused this unfortunate failure.) The cathode and auxiliary grid behaved as expected before grid failure.



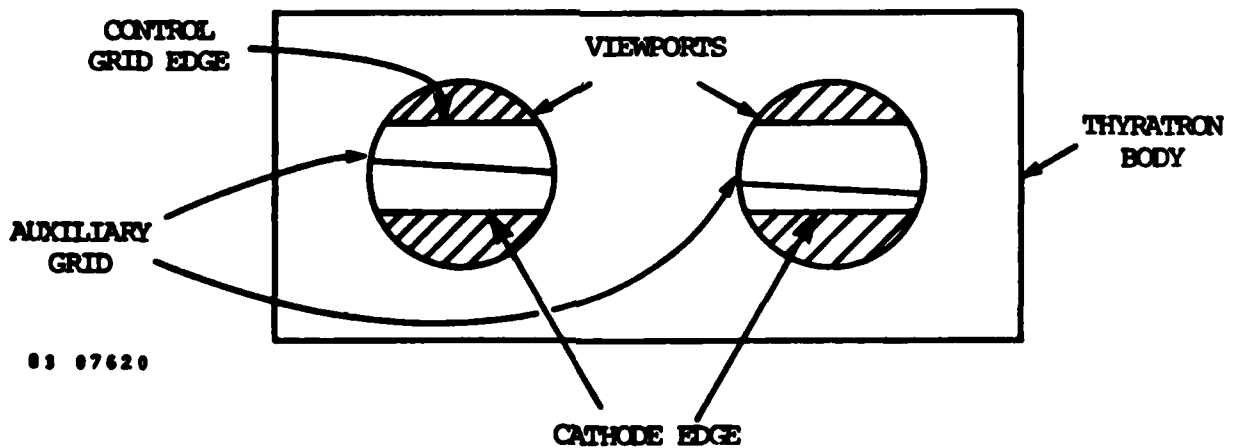
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Figure 7. Cathode Temperature vs. Cathode Voltage



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Figure 8. Auxiliary Grid Breakdown Voltage vs. Tube Pressure



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Figure 9. Auxiliary Grid Alignment With Respect To Cathode

Figure 10 illustrates the control grid breakdown voltage versus tube pressure for different settings of auxiliary grid current. Figure 11 shows a typical oscillogram of voltage and current at the control grid.

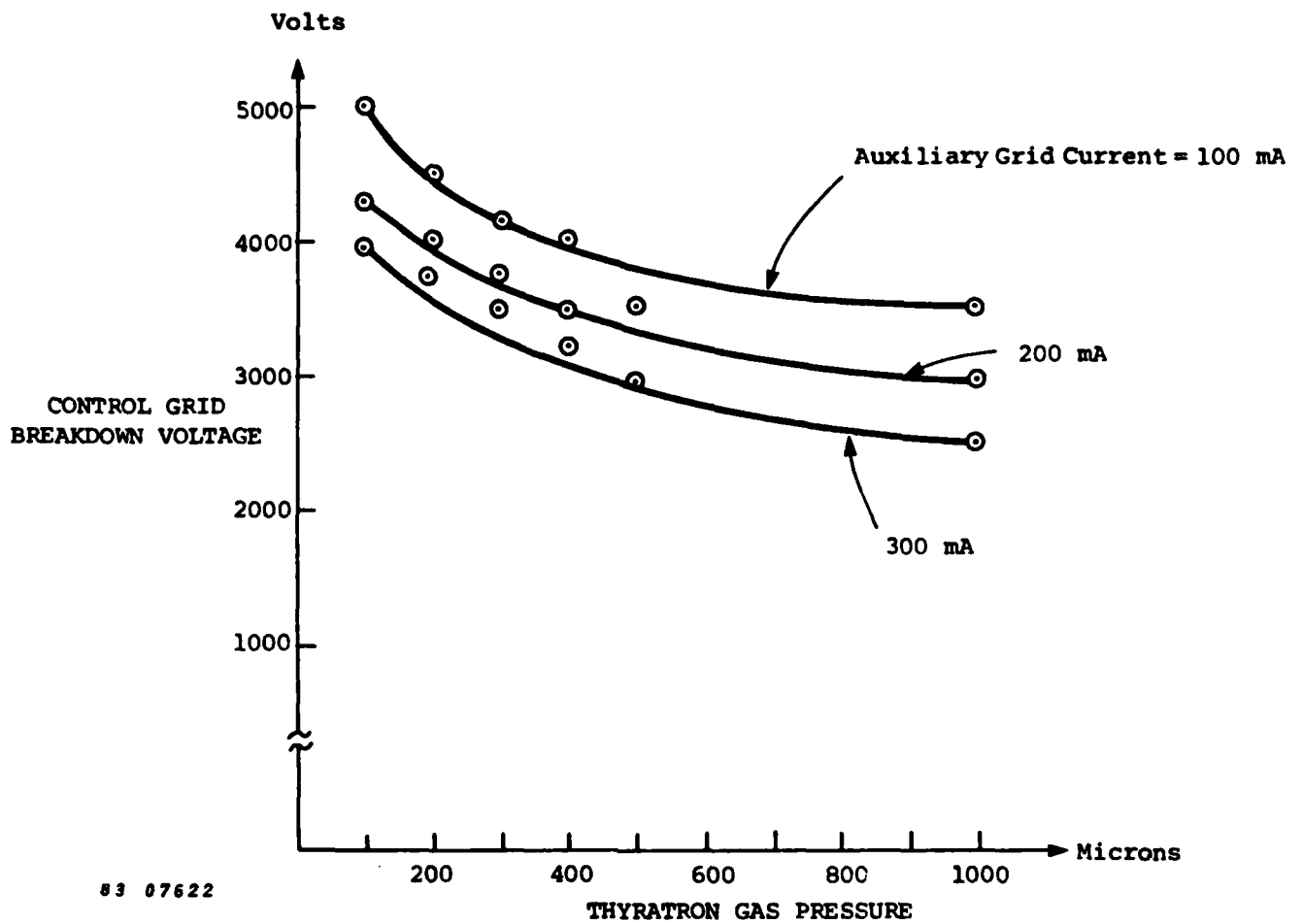
Figure 12 shows a typical oscillogram of tube commutation with a hot cathode (900°C). The duration of the discharge current pulse was approximately 120 nsec FWHM. Table 1 summarizes the switching characteristics of the thyatron with a hot cathode.

Table 1

Peak Anode Voltage	15 KV
Peak Discharge Current	2 KA
Discharge Current Duration	120 nsec FWHM
Anode Fall Time (500 microns neon)	100 nsec
Auxiliary Grid Current	100 mA
Cathode Temperature	900°C

The discharge plasma did not spread uniformly across the thyatron when operated with a hot cathode. First, the auxiliary grid-to-cathode plasma was not uniform along the length of the grid. Most of this grid-cathode ionization appeared at the end of the auxiliary grid furthest away from the cathode. (Recall that the auxiliary grid was not parallel to the cathode because of a failure in the grid support.) The main discharge from the 12 nF capacitor bank was seen to form in the same area as the auxiliary grid-cathode plasma. Figure 13 illustrates how the plasmas appeared in the thyatron view ports during commutation. The auxiliary grid discharge and the main anode-grid discharge were seen only in the window ports on the left. No discharge was seen on the right. This plasma distribution was independent of auxiliary grid current, gas pressure, and discharge current.

After making initial measurements with a hot cathode, the thyatron was operated cold. The cathode heater was turned off, tube pressure was



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Figure 10. Control Grid Breakdown Voltage vs. Tube Pressure for Different Auxiliary Grid Current Settings. No applied anode voltage.

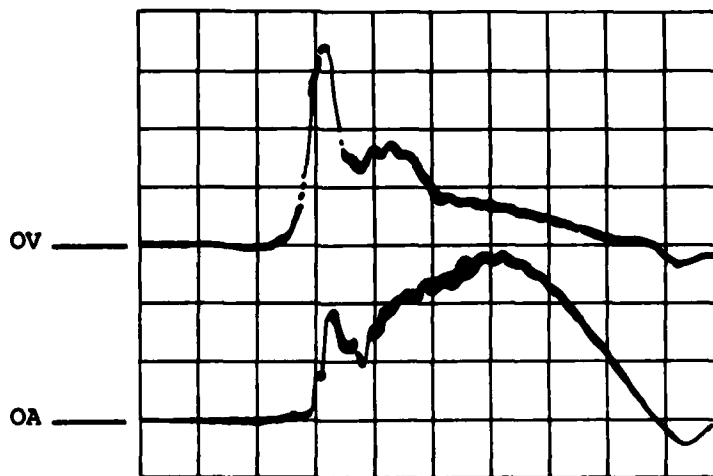


Figure 11. Typical Control Grid Voltage and Current

Top: Grid voltage 1 kV/div
 Bottom: Grid current 10 A/div
 Horizontal: 100 nsec/div
 No applied anode voltage.



Figure 12. Typical Thyatron Commutation Waveforms With a Hot Cathode

Top: Anode voltage 2 kV/div
 Bottom: Anode current 200 A/div
 Horizontal: 100 nsec/div
 Gas pressure: 100 microns neon
 Cathode temperature: 900°C
 Auxiliary grid current: 100 mA

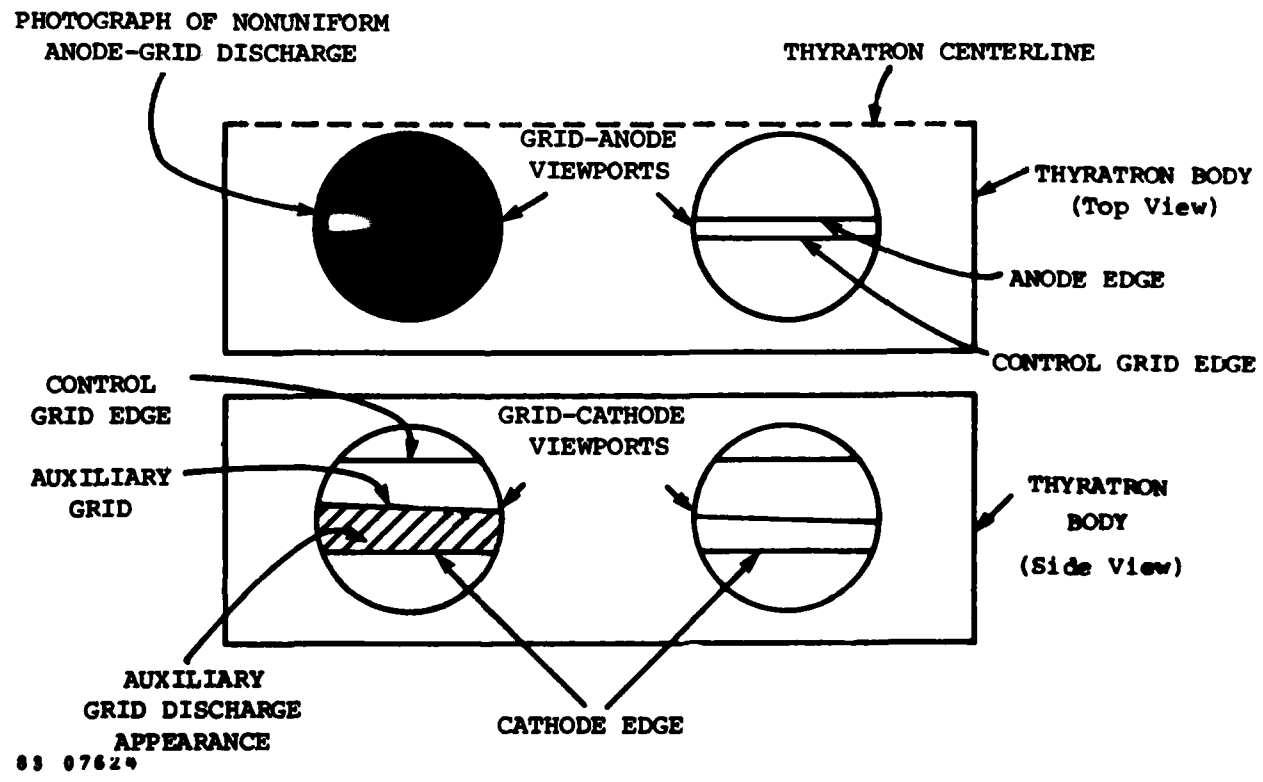
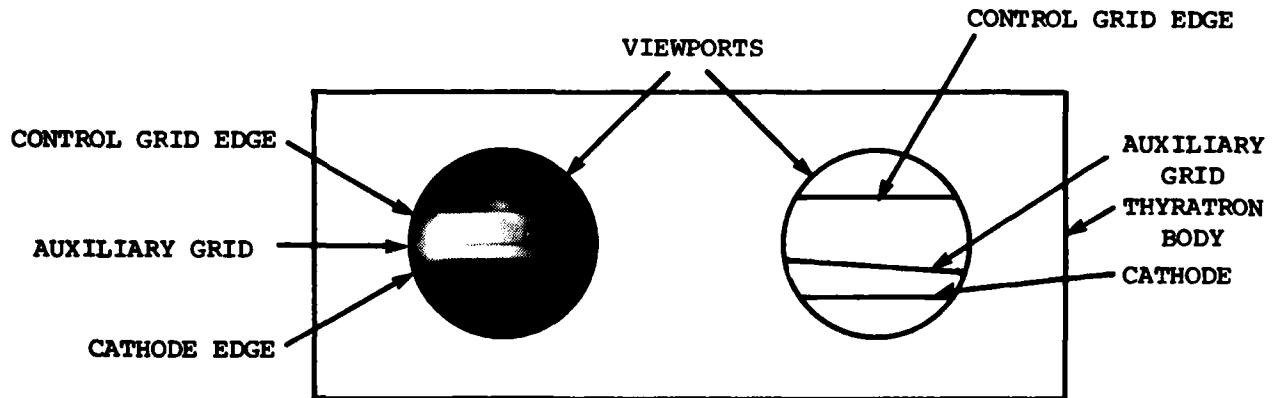


Figure 13. Location of Discharge With a Hot Cathode

set to 500 microns neon, and the auxiliary grid was turned on. The voltage across the conducting auxiliary grid was approximately 100 V higher than for corresponding grid settings with a hot cathode, but the entire auxiliary grid-to-cathode space appeared to be uniformly ionized for currents below 100 mA. Higher auxiliary grid d.c. currents led to multiple arcs distributed in the auxiliary grid-cathode region. The temperature of the thyatron during this cold-start procedure was 20°C.

Anode voltage was applied and the discharge was seen to spread the entire length of the tube. Figure 14 shows a photograph of the plasma discharge taken through a grid-cathode viewport. The plasma appeared the same in both the left and the right viewports. As described previously, the top edge of the picture is the control grid, the bottom edge is the cathode, and the thin line in the middle is the side view of the auxiliary grid. This exposure is for a single discharge only. We were attempting to photograph the discharge in the grid-anode window when the auxiliary grid fell on the cathode, shorting the grid and ending the experiment. However, an oscillogram of the thyatron switching with a cold cathode was obtained and this waveform is presented in Figure 15. It is seen in Figure 15 that the commutation time is much shorter than in Figure 12, due largely to the higher pressure of neon used for the case shown in Figure 15. Also, the commutation in Figure 15 indicates two stages, with a steep initial drop to 1/2 voltage in about 20 nsec, followed by a slower voltage collapse curve (~50 nsec).

Maximum anode voltage and discharge current switched with the cold cathode before grid failure were 5 KV and 700 A, respectively. Table 2 summarizes the switching characteristics of the thyatron with a cold cathode.



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Figure 14. Photograph of Discharge Taken Through Grid-Cathode Viewport

Gas pressure: 500 microns neon
 Auxiliary grid current: 100 mA
 Anode current: 700 A
 No cathode heater power

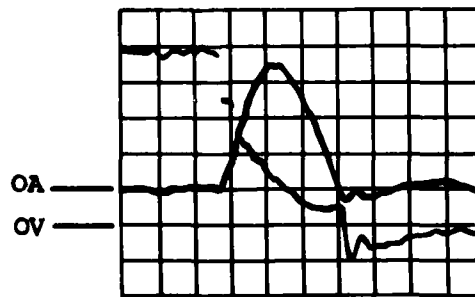


Figure 15. Thyatron Commutation Waveforms with a Cold Cathode

Left: Anode voltage 1 kV/div
 Right: Anode current 200 A/div
 Horizontal: 50 nsec/div

Gas pressure: 500 microns neon
 Cathode temperature: 20°C
 Auxiliary grid current: 100 mA

Table 2

Peak Anode Voltage	5 KV
Peak Discharge Current	700 A
Discharge Current Duration	120 nsec FWHM
Anode Fall Time (500 microns neon)	<50 nsec
Auxiliary Grid Current	100 mA
Cathode Temperature	20°C

The slow anode fall times reported in Tables 1 and 2 are due at least in part to the use of neon gas. Anode fall times approaching 10 nsec can be expected by using hydrogen or helium gas at high pressure, by operating at high voltage, and by pulsing the auxiliary grid.

Section 3

CONCLUSIONS AND RECOMMENDATIONS

The shortcomings of conventional thyratrons dictate that new switches must be developed to meet the lifetime, current, and risetime requirements of present day high power laser systems. The thyatron remains the most attractive type of switch because of its commutation speed, triggering and conduction stability, and long life under favorable applications. The linear thyatron is an effort to upgrade thyatron technology to be compatible with these multi-Joule, short pulse laser systems.

The initial testing of the linear thyatron has demonstrated several advanced design features, these being:

1. A thyatron can be fabricated with a linear, low-inductance stripline geometry.
2. The discharge spreads along the entire length of the thyatron. This implies that tube inductance can be determined by housing geometry rather than by conducting plasma.
3. The linear thyatron can be operated with a cold cathode and achieve uniform discharge spreading.

These results indicate the possibility of developing a long, low-inductance thyatron requiring little or no standby power. This device would serve as an efficient, high repetition rate switch that is suitable for both lasers and other long-life rail switch applications.

There is considerably more information to be collected from the linear thyatron described here. Following repair of the grid support, the studies of operating parameters can be completed. In addition, plasma diagnostics should be applied to this device to learn how this thyatron

really works. The linear thyatron was designed with this purpose in mind; the optical viewports give clear access to both the grid-anode and grid-cathode regions. Since the tube is equipped with a dispenser cathode, fundamental cathode studies can be performed. Finally, the gas system is flexible, so that switching properties using different gases can be easily investigated. The linear thyatron offers a unique opportunity to study fundamental properties of low pressure gas discharges and to develop scaling laws for advanced high-power thyatrons.

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