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HOLLOTRON Switch for Megawatt Lightweight Space Inverters

R.L. Poeschel, D. Goebel, and R.W. Schumacher
Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, California 90265

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16. Abstract

Under this program our objective was to determine the feasibility of satisfying the switching requirements for a megawatt ultralight inverter system using HOLLOTRON switch technology. We modified existing experimental switch hardware to investigate a coaxial HOLLOTRON switch configuration and compared the results with those obtained for a modified linear HOLLOTRON configuration under an ongoing 1990 Hughes IR&D project entitled "Pulsed-Power Switches for Military Systems." We concluded that scaling the HOLLOTRON switch to the current and voltage specifications required for a megawatt converter system is indeed feasible using a Hughes' modified linear configuration. The experimental HOLLOTRON switch operated at parameters comparable to the scaled coaxialHOLLOTRONinvestigated under this contract. However, the linear HOLLOTRON data verified the capability for meeting all the design objectives simultaneously including current density (>2 A/cm^2), voltage (5 kV), switching frequency (20 kHz), switching time (300 ns), and forward voltage drop (≤20 V). We determined scaling relations under the IR&D project and completed a preliminary design for an engineering model linear HOLLOTRON switch to meet the megawatt converter system specifications.

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SUMMARY

Work under this program comprised one-half of the effort in the first phase of a two-phase program for developing a megawatt lightweight DC-DC converter system for space use. The Hughes Electro-optical and Data Systems Group (EDSG) performed the other half of the Phase 1 effort under a separate contract. EDSG developed a preliminary transformer design and defined the inverter system architecture.

Under this program our objective was to determine the feasibility of satisfying the switching requirements for this inverter system using HOLLOTRON switch technology. We modified existing experimental switch hardware to investigate a coaxial HOLLOTRON switch configuration and compared the results with those obtained for a modified linear HOLLOTRON configuration under an ongoing 1990 Hughes IR&D project entitled "Pulsed-Power Switches for Military Systems." We concluded that scaling the HOLLOTRON switch to the current and voltage specifications required for a megawatt converter system is indeed feasible using a Hughes' linear configuration with a diverging magnetic field.

To support this conclusion, we have included in this report representative data obtained under Hughes IR&D project with an experimental HOLLOTRON configuration operated at parameters comparable to the scaled coaxial HOLLOTRON investigated under this contract. These data verify the capability for meeting the design objectives on current density (>2 A/cm^2), voltage (5 kV), switching frequency (20 kHz), switching time (300 ns), and forward voltage drop ($\leq$20 V) with the modified linear HOLLOTRON configuration.

We determined scaling relations and completed a preliminary design for an engineering model linear HOLLOTRON switch to meet the megawatt converter system specifications. Finally, we developed a plan, in collaboration with the system design effort at EDSG, for completing the development of pre-production prototype HOLLOTRON switch hardware under the proposed Phase II program.

SECTION 1

INTRODUCTION

This report describes a significantly successful HOLLOTRON-switch development performed by Hughes Research Laboratories (HRL) under NASA Contract NAS 3-25802 and under our IR&D project entitled "Pulsed Power Switches for Military Systems." The contract portion of this work is the first phase of a two-phase program for development of HOLLOTRON switch technology to meet the requirements of advanced high-power, lightweight megawatt-level inverters/converters for future space applications (see Table 1). The first phase of the program was intended to demonstrate the capability of the HOLLOTRON approach for meeting the inverter switching requirements.

Nearly all of our performance goals were met under the contract work. In the IR&D effort, the performance goals were all met and in some cases significantly exceeded. For example, we have demonstrated 20-kHz square-wave switching at 5 kV, 12 A (2 A/cm^2 at the anode), 300-ns switching time, and 50% duty with a forward voltage drop of only 20 V. We have also interrupted up to 20 A (3.3 A/cm^2), switched on 100 A, and run dc currents up to 50 A.

TABLE 1. Switch Specifications for the Phase II Megawatt Inverter System.

Operating Voltage	5 kV
Peak Voltage	18 kV
Average Current (at 5 kV)	100 A
Peak Current	250 A
Max Fault Current	400 A
Anode Current Density	2 A/cm^2
Switching Time	300 ns
Switching Frequency	20 kHz
Duty Cycle	50%
Power Dissipation	≤4 kW
Mass	≤4.5 kg

This work has been performed in conjunction with another program conducted at Hughes Electro-Optical and Data Systems Group (EDSG) to develop a light-weight, high-voltage transformer for megawatt space inverters. Although the efforts for the HRL HOLLOTRON switch and the EDSG transformer were organized and managed separately, both programs were aimed at the same low-cost, ultralight-weight inverter system shown schematically in Figure 1, which would be driven by a high-voltage (≈5 kV), fuel-cell prime-power source.

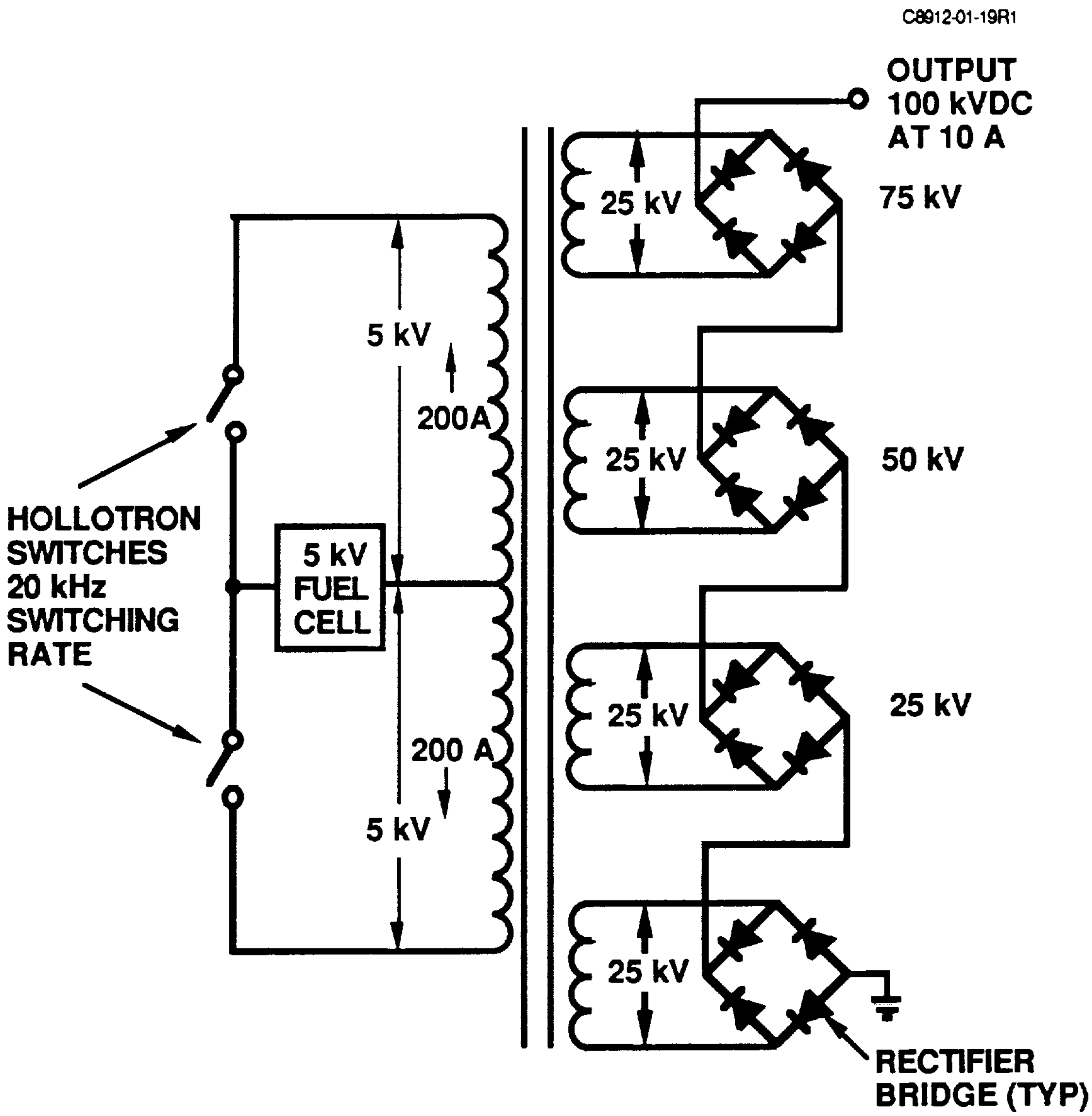

Figure 1. Hughes inverter/converter approach.

Having successfully completed the first phase of the program, the second phase of the program will be a combined effort, with Hughes EDSG as the prime contractor and system integrator and HRL assisting EDSG in the development and fabrication of pre-production prototype switches that satisfy the projected inverter/converter system specifications. Section 2 of this report describes the first phase of the HOLLOTRON switch development effort under this contract. Also described are the results of Hughes IR&D work that are relevant to the switch design proposed for conducting the next phase of the inverter development. The transformer development and the inverter system designs are discussed in detail in the final report for the Hughes EDSG program. We conclude this report (Section 3) with a discussion of the program proposed for the Phase II HOLLOTRON switch development and integration in the inverter/converter system.

A. BACKGROUND

Inverter/converter systems typically make use of series/parallel strings of solid-state switches to meet the system voltage and current requirements. Considerable improvement in specific mass, reliability, fault tolerance, parts count, and system complexity could be achieved if these solid-state networks could be replaced by a single, rugged, high-power switching module. As illustrated in Figure 1, our approach to inverter/converter development under this program makes use of a single module consisting of two switches operating with a forward voltage drop of ≤20 V, a transient voltage standoff of 18 kV, an average current of 200 A (100 A per switch), and a switching time on the order of 500 ns. The HOLLOTRONs will modulate 1 MW of average power at a 20-kHz switching frequency from a 5-kV source voltage. The HOLLOTRON switch is an extension of CROSSATRON switching technology for applications requiring a relatively low source voltage, and consequently a low forward voltage drop. At the outset of this program, the HOLLOTRON switch had been demonstrated in the laboratory at low power levels, but with the required voltage and switching the characteristics.

The CROSSATRON switch[1-6] is a high-power device that combines the best features of thyratrons, vacuum tubes, and power semiconductor switches. Like a thyratron, the CROSSATRON switch uses a plasma discharge to conduct high current with low forward-voltage drop, high speed, and high efficiency; but like a vacuum tube, it also maintains a grid-controlled current-interruption capability. Unlike these conventional switches, the CROSSATRON switch employs a cold-cathode, crossed-field (electric and magnetic) discharge to generate the high-density plasma required for current conduction in a localized region near the cathode, as illustrated in Figure 2. The magnetic field is produced by permanent magnets and the electric field is applied

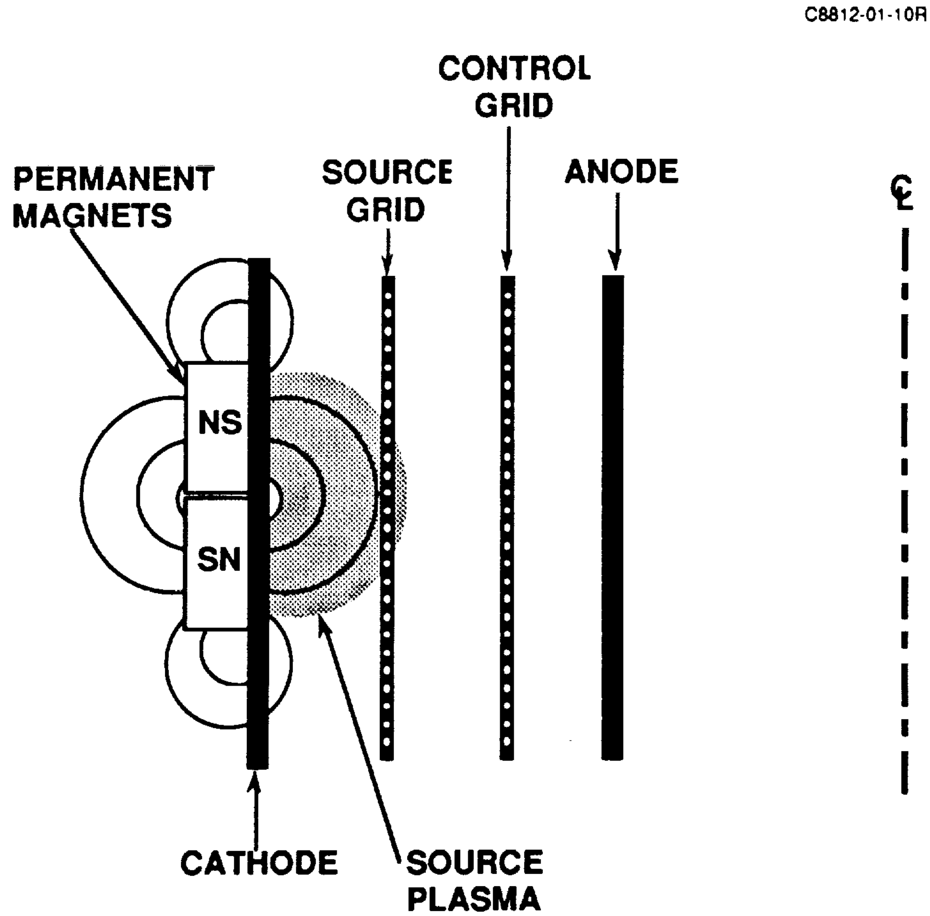

Figure 2. CROSSATRON switch configuration.

by a gridded electrode to form the plasma-generating discharge. This discharge is operated continuously, and is referred to as a keep-alive discharge.

CROSSATRON-switch electrodes (Figure 2) are arranged in a low-inductance, coaxial configuration with the cathode on the outside and the anode on the inside. The permanent magnets generate a cusp magnetic field that magnetizes only the first gap, thereby containing the keep-alive discharge within that gap. This advanced switch design provides for instant start and rugged operation (i.e., survivable to high temperatures, high radiation, electromagnetic pulse, and repeated overvoltage and overcurrent events). The use of a secondary-electron-emitter cathode rather than a thermionic cathode contributes to long-life operation, but the forward voltage drop during switch conduction must equal the voltage required for the keep-alive discharge (which is on the order of 500 V). The switch is closed by pulsing the control grid to a positive potential so that electrons from the keep-alive plasma are conducted to the control grid, and into the anode/control-grid gap, generating a plasma and providing space-charge-neutralized conduction of electrons from cathode to anode. Similarly, current interruption is accomplished by pulsing the control grid negative so that all plasma ions are collected, and electrons are reflected back into the keep-alive plasma, thereby terminating electron flow into the anode gap. The switch is opened following the diffusion of plasma remaining in the gap.

The HOLLOTRON switch combines the rugged fast-switching, high-voltage features of the CROSSATRON switch with the low-voltage plasma generation capability of xenon-gas hollow-cathode discharges for achieving low forward-voltage drop during conduction. The keep-alive discharge for xenon-gas hollow-cathode discharges are typically about 10 V and consequently a forward-voltage drop of ≤20 V is easily obtained in the HOLLOTRON switch. The HOLLOTRON switch configuration is shown schematically in Figure 3. Although xenon ions drift more slowly than hydrogen ions in the CROSSATRON switch, fast switching can still be achieved in the HOLLOTRON by employing a small grid-to-anode gap for applications requiring relatively low voltage (10 to 20 kV for this development). Because the HOLLOTRON switch is a plasma device, we consider it feasible to design a single switch module that will operate at the megawatt power level for a significant lifetime, and also operate in hostile environments (high temperature, low temperature, and/or radiation).

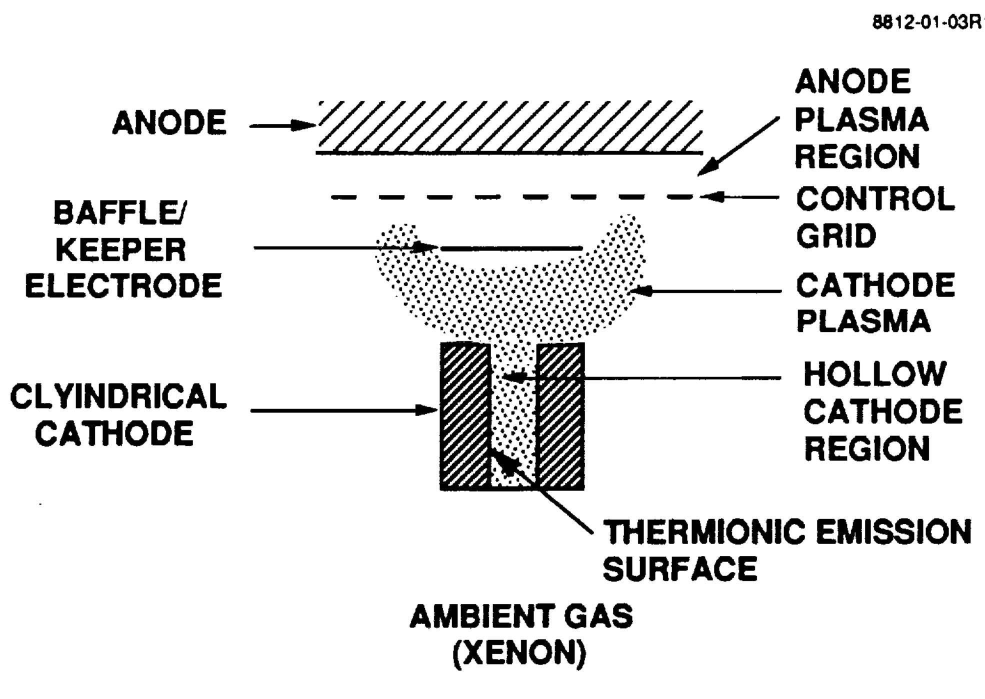

Figure 3. Schematic drawing of HOLLOTRON-switch electrodes and plasma regions.

Our objective under this program has been to formulate scaling rules and to complete a conceptual switch design for producing a pre-production prototype HOLLOTRON switch to meet the switch performance goals specified earlier. This objective required that we find a switch configuration to expand the hollow-cathode plasma so that the current density is reduced from greater than 100 A/cm^2 in the hollow-cathode interior to about 2 A/cm^2 at the surface of the control grid.

The initial HRL HOLLOTRON experiments were conducted with a configuration similar to the one shown schematically in Figure 3, where we observed a tendency for current to "pinch" into high current-density, filamentary paths that either could not be interrupted, or that damaged the control grid when interruption was attempted. Our initial approach under this contract was to explore a configuration like that shown in Figure 4, generating a cylindrical plasma column within a perforated keep-alive electrode, and conducting electron current radially through the control grid apertures to the anode. We performed experiments with a number of variations on this configuration with some success, however it was necessary to impose an axial magnetic field to prevent filamentary current paths between the cathode interior and the anode. This work is described in detail in Section 2A.

We learned that a magnetic field was probably going to be required to eliminate the formation of filamentary current paths. In our separate IR&D project we began using a diverging magnetic field in a linear configuration similar to Figure 3 to develop a low-voltage-drop switch for modulating small magnetrons in active radar seekers for missiles. By appropriately shaping the magnetic lines of force, we were able to expand the hollow-cathode plasma and distribute the current rather uniformly over the control grid surface without use of baffles. The results appear to be easily scalable to the inverter/converter specifications listed in Table 1. This IR&D work is reported in Section 2B.

The proposed design for the next phase of the program is described in Section 3A and is based on the linear HOLLOTRON approach described in Section 2B. As a consequence of the difficulties experienced with the coaxial geometry under this program, we now consider the linear configuration utilizing a magnetic field and spherically-domed electrodes to be more tractable for scaling to high-power operation.

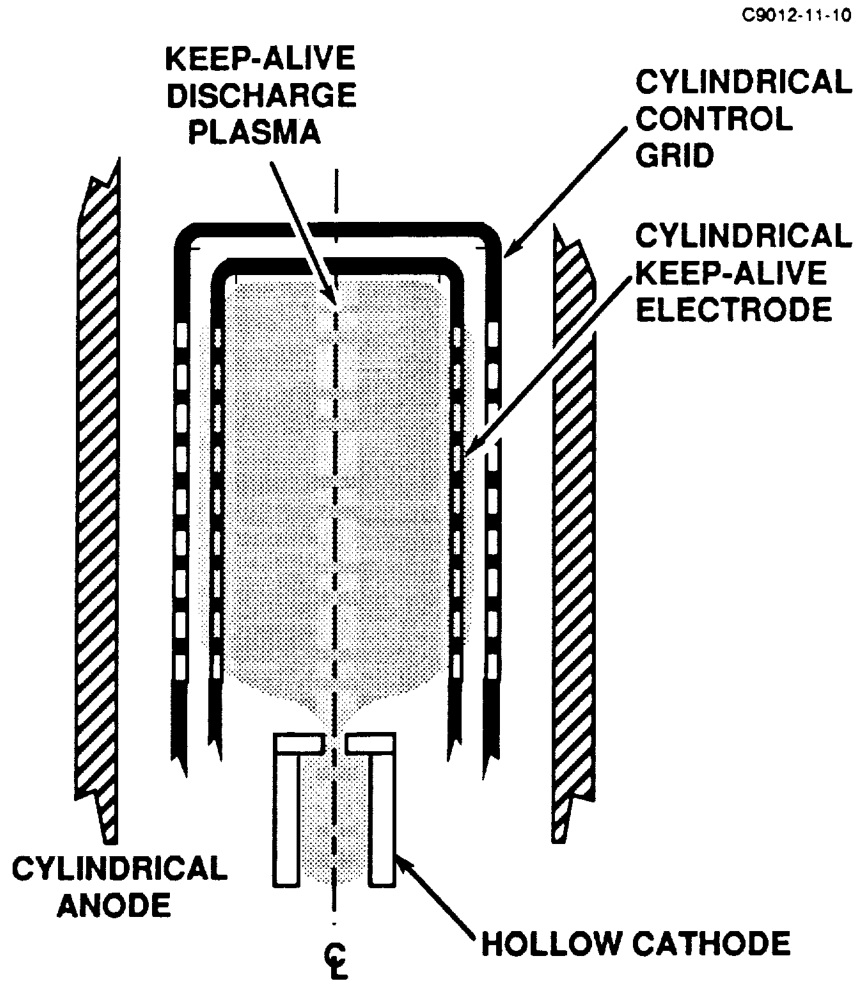

Figure 4. Radial HOLLOTRON concept.

SECTION 2

PHASE I HOLLOTRON SWITCH DEVELOPMENT

The long-range objective of our program is to develop a 0.5-MW HOLLOTRON switch for space-power inverters to meet the specifications shown in Table 1. Figure 5 shows the coaxial HOLLOTRON switch configuration as envisioned at the outset of this program. Our work under this contract was planned to utilize the experimental hardware already existing at HRL in order to verify the design concepts illustrated in Figure 5.

Under a separate IR&D project entitled "Pulsed-Power Switches for Military Systems," we continued our investigation of the original linear switch configuration for low-voltage magnetron modulators in active missile seekers. In this Section, we present the results of these investigations, and our rationale for selecting the Phase II, high-power switch design.

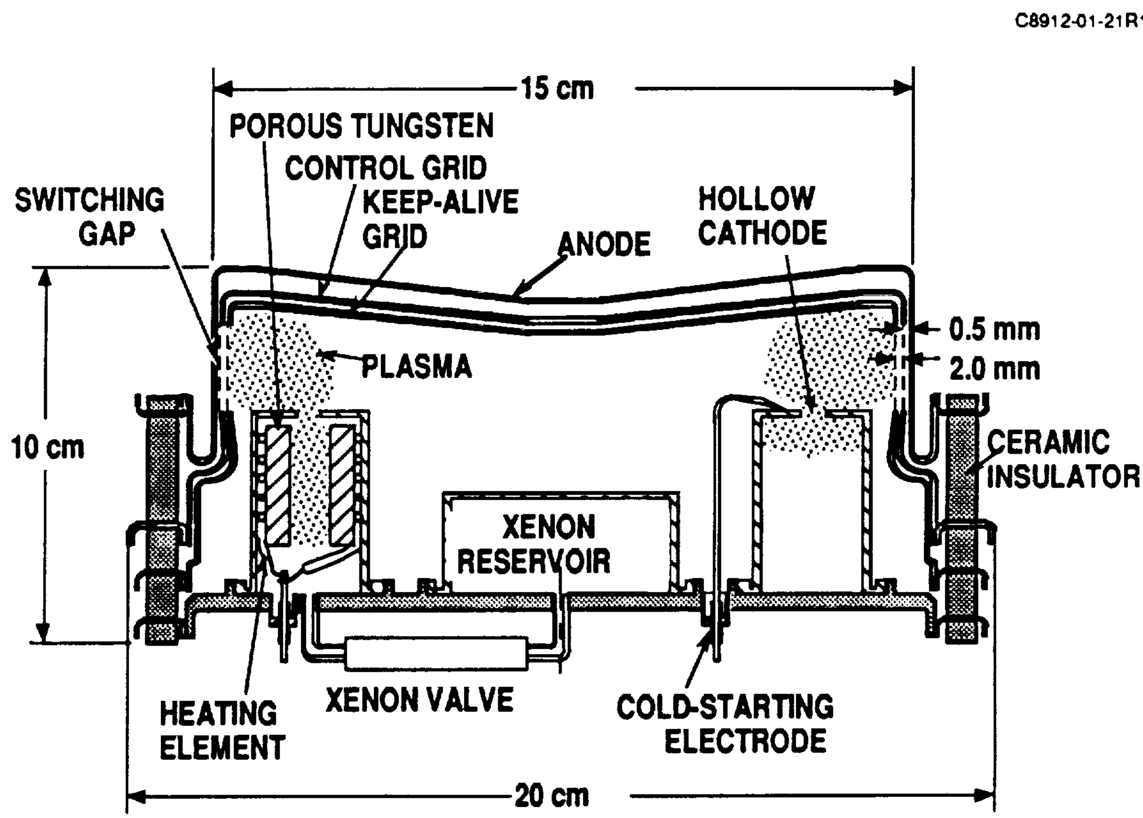

Figure 5. Initial design configuration for the engineering model HOLLOTRON switch.

A. COAXIAL HOLLOTRON SWITCH DEVELOPMENT

Demonstrating the feasibility of the HOLLOTRON approach for satisfying the projected inverter/converter specifications required experimental verification of the following:

(1) Operation of a hollow cathode in a low-voltage mode, without a magnetic field, and in a non-flowing ambient gas fill.

(2) Maintenance of the low-voltage discharge mode with current density in the hollow-cathode plasma on the order of 100 A/cm^2.

(3) Maintenance of the low-voltage discharge mode at ambient pressure less than 133 Pa (1 Torr); which is necessary for achieving the voltage standoff requirement.

(4) Permissible cathode and envelope operating temperature range for maintaining low forward-voltage drop without loss of voltage standoff.

(5) Forced current interruption by the control grid at the required switching speed and under the conditions satisfying (1) through (4).

The unmagnetized configuration was thought to be desirable because of mass constraints, but as shown in Section 3, the simplified linear configuration meets the mass requirement even with a magnetic field.

To demonstrate the conditions listed above, we modified the Hughes laboratory prototype HOLLOTRON switch to a coaxial configuration (shown in Figure 6) that was considered scalable for operation at the required 250-A peak current level. Our design objective was to have the switch operate at an anode current density of 2 A/cm^2, and the components available were suitable for a 6-cm^2 anode current collection area. Consequently, the laboratory prototype coaxial HOLLOTRON switch was designed to meet all of the switching requirements at 12-A peak current. The switch was constructed to be demountable, so the switch could be readily disassembled, modified, and re-processed to evaluate changes in electrode configuration, or to replace failed components. The component parts and assembled switch are shown in Figures 7 and 8, respectively.

AI. Description of the Hardware and Experimental Procedures

The HOLLOTRON switch configuration shown in Figure 6 closely resembles the coaxial geometry of the Hughes CROSSATRON switch with concentric electrodes for generating and controlling the plasma that acts as the switch cathode. The major difference is that in the HOLLOTRON we employ a low-voltage hollow-cathode discharge to generate this plasma. For

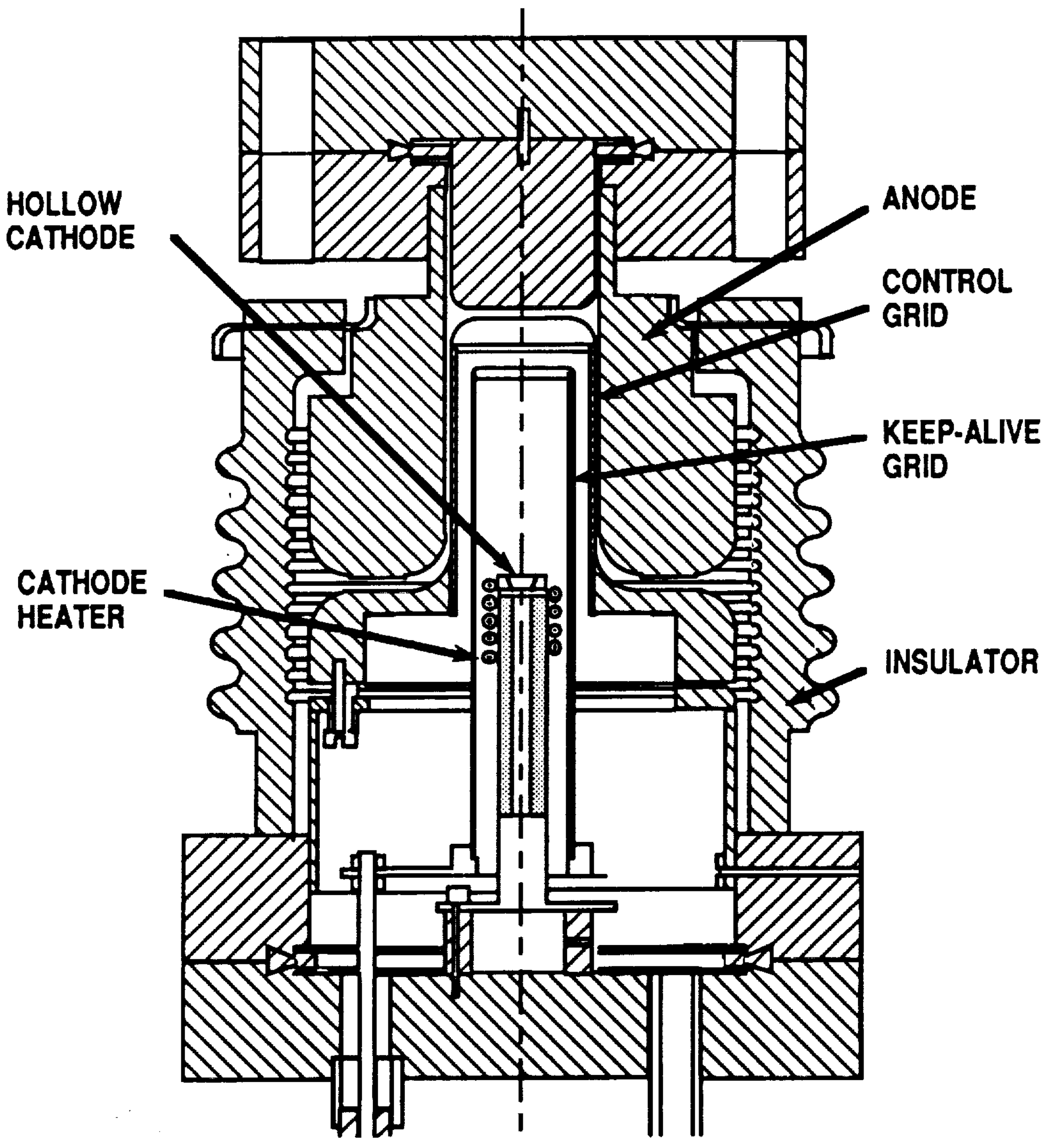

Figure 6. Prototype HOLLOTRON switch configuration for Phase I.

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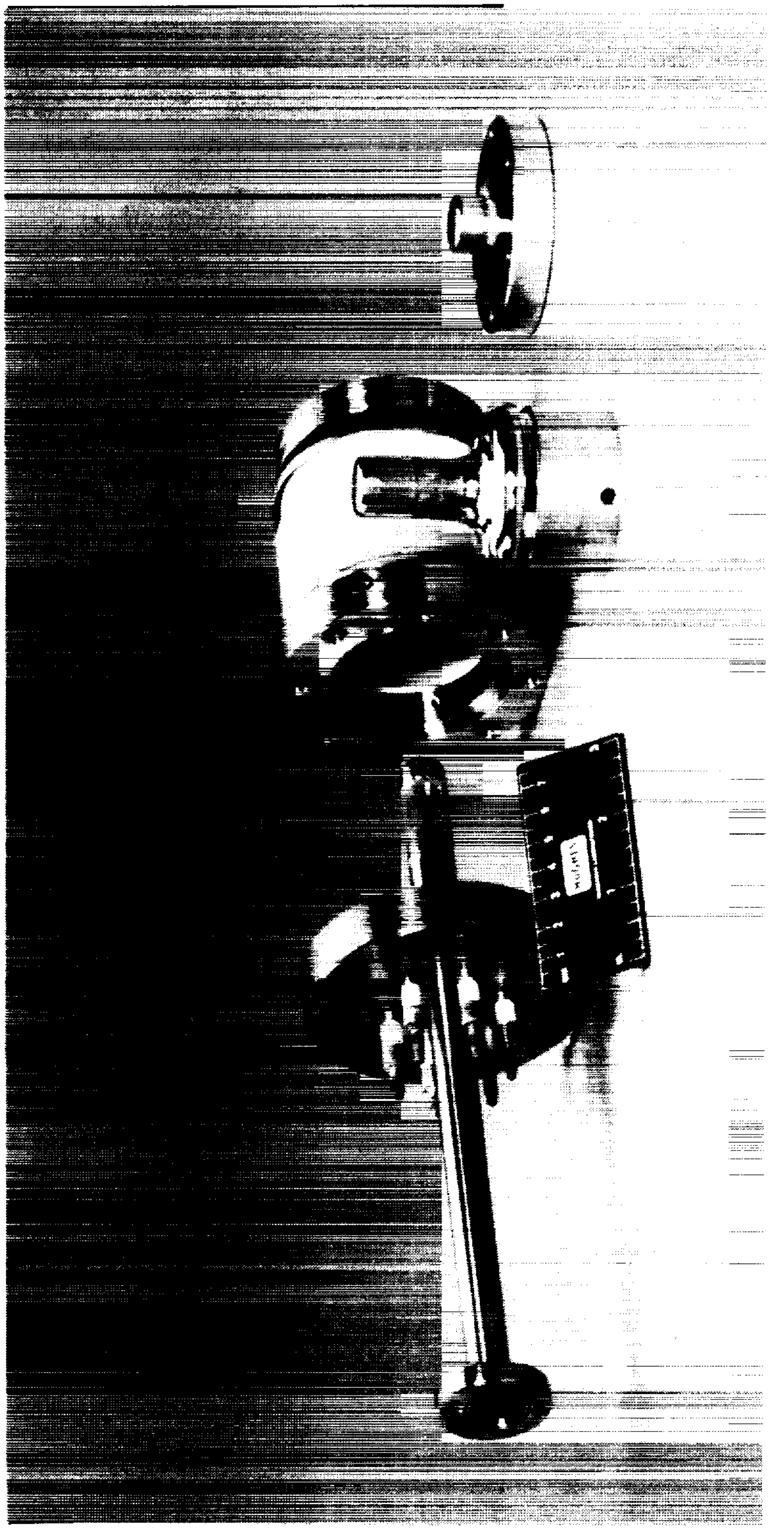

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Figure 7. Photograph of Phase I coaxial HOLLOTRON subassemblies.

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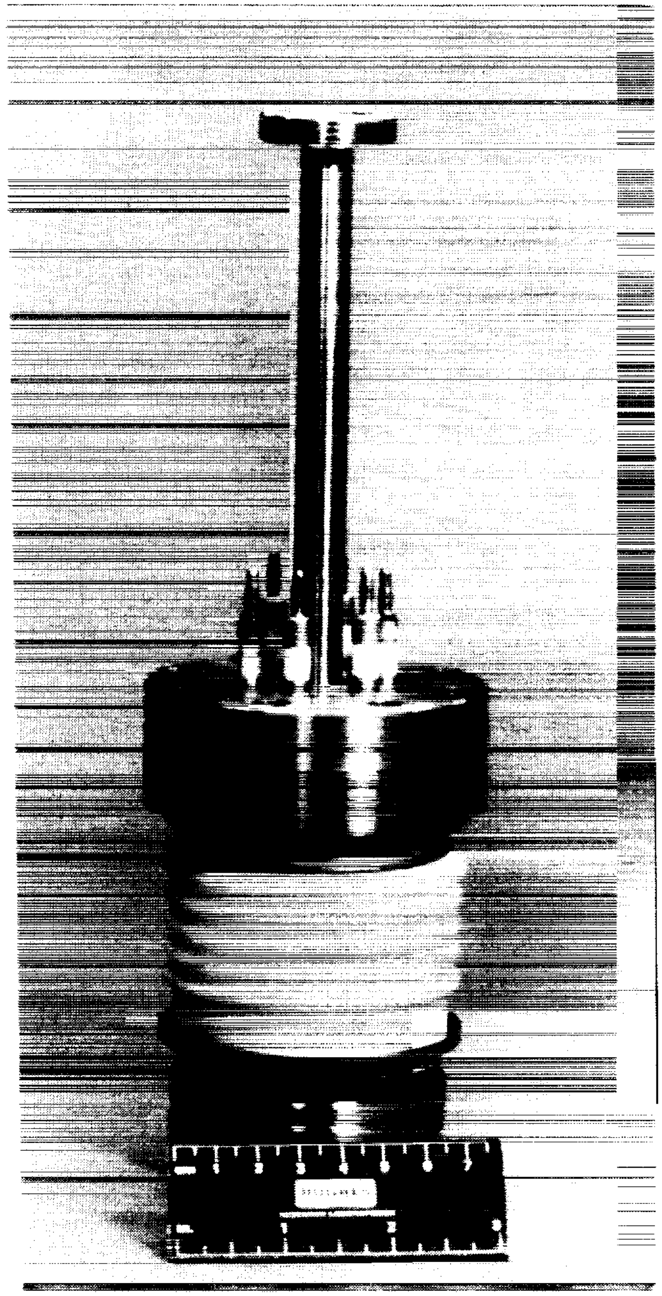

Figure 8. Photograph of Phase I coaxial HOLLOTRON (assembled).

the laboratory prototype, the hollow cathode was located on the switch axis. The cathode design is identical to the cathodes used in Hughes inert gas ion thrusters. The cylindrical cathode has a barium-aluminate-impregnated-porous-tungsten insert, and is heated to thermionic emission temperature to initiate a keep-alive discharge to the cylindrical keep-alive electrode. The keep-alive electrode has an open structure, covered with a perforated material, as can be seen in the photograph shown earlier as Figure 7. The cylindrical control grid has a similar structure, except the perforated material has much smaller apertures. The control grid aperture size determines the current interruption characteristics of the switch. We had previously determined that for interruption of 2 A/cm^2, with a control-grid voltage of 50 V (negative), the aperture required was about 0.08 mm. We planned to vary this aperture size as a design parameter, but problems with vendor deliveries limited the investigation to only 3 iterations on control-grid material specifications.

For maintaining the switch in an open circuit condition, the control electrode is operated at cathode potential (or slightly negative relative to cathode potential) to prevent the keep-alive plasma from entering the space between the control electrode and the anode. The dimensions of this annular gap are designed to prevent Paschen breakdown, and we maintained this gap in the range of 0.5 to 0.8 mm for the experiments conducted during this investigation. This dimension permits operation at ambient pressure up to 133 Pa (1 Torr) without Paschen breakdown in the anode/control-grid gap. To close the switch, we apply a positive pulse to the control grid, so that it becomes positive with respect to the cathode. Under this condition, the keep-alive-discharge plasma will expand into the anode/control-grid gap and current will be conducted to the anode. Typically, as the cathode-to-anode current is increased from zero, the forward voltage drop decreases at first until a minimum value is reached and then increases with increasing current. We observe that the current carrying capacity of the switch for a given forward voltage drop depends on the pressure of the ambient gas, the emission capability (temperature) of the thermionic emission surface, and the keep-alive electrode geometry.

The HOLLOTRON switch is essentially a vacuum device, and had to be "processed" before testing, both initially, and after each modification of electrode geometry. Figure 9 shows a schematic of the pumping and gas-filling apparatus used for processing the switch tube. The switch tube and gas-filling manifold are initially pumped out and heated to outgas the internal surfaces. Typically, the switch was baked out at 100°C to 150°C for 8 hours. The base pressure after bakeout and cooling to room temperature was 10^{-8} kPa ($8x10^{-8}$ Torr). After achieving this vacuum condition, the cathode heater was used to activate the bariated insert, and current was extracted from the cathode under high-vacuum conditions. The pumpout valve was then closed, and xenon was admitted to the tube and manifold through the controlled leak valve. Gas-fill

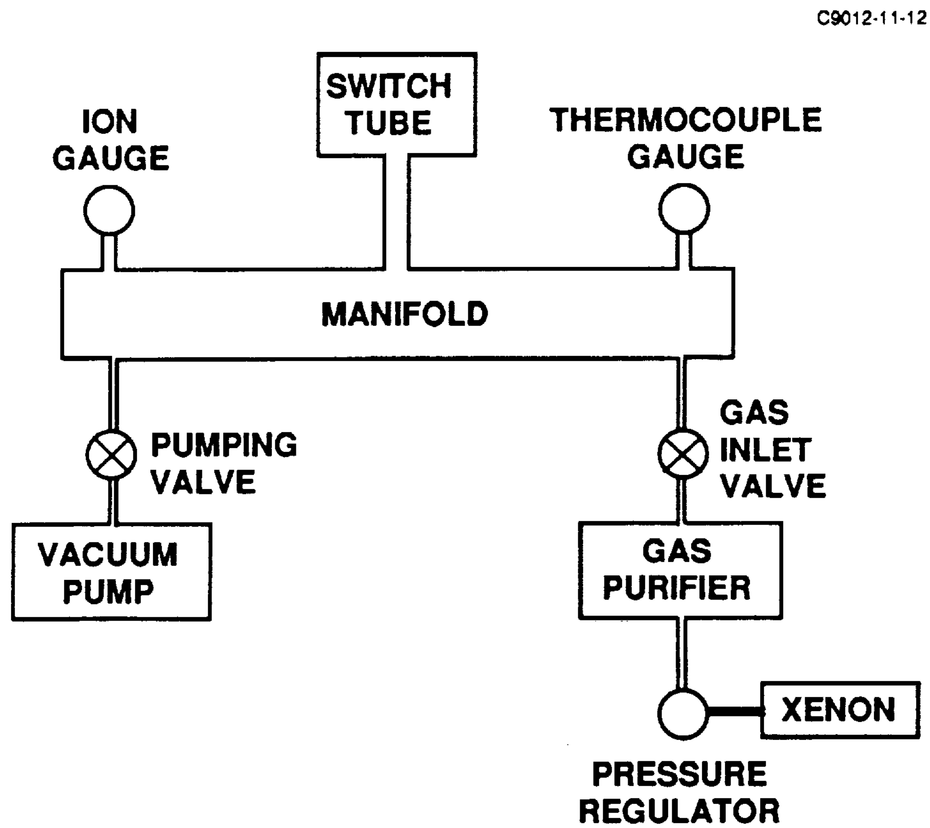

Figure 9. Schematic diagram of pumping and gas-filling system for testing switch tubes.

pressure is measured with a Hastings-Raydist DV-6M thermocouple gauge. Gauge-pressure readings are converted to xenon-pressure using the manufacturer's calibration nomograph; xenon pressure is 133 Pa (1 Torr) for a gauge reading of 27 Pa (200 mTorr). For initial processing, the tube was filled to a xenon pressure of several hundred Pascal (several Torr) and the keep-alive discharge was operated at currents of 1 to 2 A for several hours to further clean the electrode surfaces of adsorbed gases. If there was a notable rise in gas pressure during this procedure, the discharge was shut off, the gas was pumped out and refilled, and the discharge started over again. Following this procedure, the tube was filled to a xenon pressure of about 27 Pa, and high voltage was applied to the anode through a 20,000-Ω current-limiting resistor, and with the control grid, keep-alive electrode, and cathode all connected to ground. This was a "high-pot" test, intended to burn off any protrusions on the internal electrodes that could form arcs during normal switch operation. The maximum voltage applied was 10 kV. When we had completed these procedures, the tube was ready for evaluation as a switch. It should be noted, that having completed these processing procedures, and with the tube filled to the desired ambient gas pressure, the switch could be valved off from the manifold and we were able to operate the switch essentially as a sealed tube, until we wanted to change an internal part.

Testing of the laboratory prototype switch was performed using the grid and anode drive circuits shown in Figure 10. The anode source voltage, source capacitor, C_S, and current-limiting resistor, R_L, were adjusted to demonstrate current capability, voltage capability, or repetition rate as required. Most of the testing was performed using this circuit (or this circuit with minor modifications).

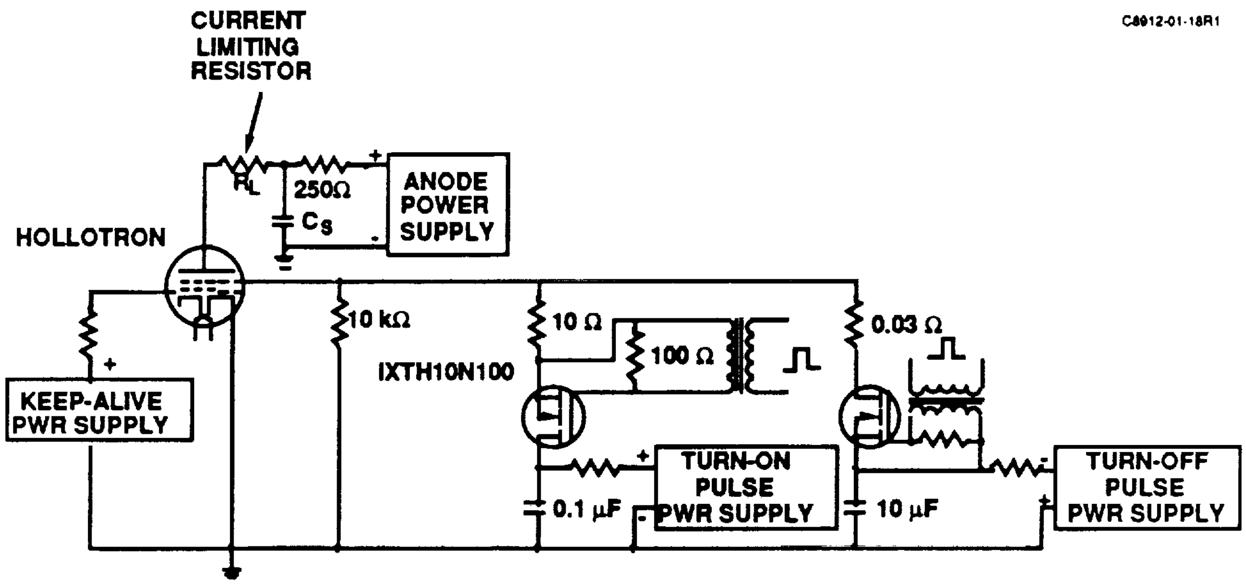

Figure 10. Circuit diagram for initial testing of the Phase I HOLLOTRON switch.

A2. Experiments and Results

A primary objective under this contract was to demonstrate that the switch would operate with 12-A peak current, 50% duty cycle, and azimuthally uniform anode current distribution. Before the control grid structure was installed, as shown in the Figure 11, we operated the switch as a diode using the keep-alive discharge with its dc power supply, and applying a full-wave rectified, 60 Hz voltage from cathode to anode, using a resistor as ballast (see Figure 12 circuit diagram). The anode voltage and resistor value were adjusted to obtain the rated peak current (12 A) at approximately 50% duty cycle. Typical waveforms for anode voltage and current are shown in Figure 13. It is apparent, that the tube switch was capable of conducting the required current with low forward voltage drop. As stated earlier, forward voltage drop varies with the

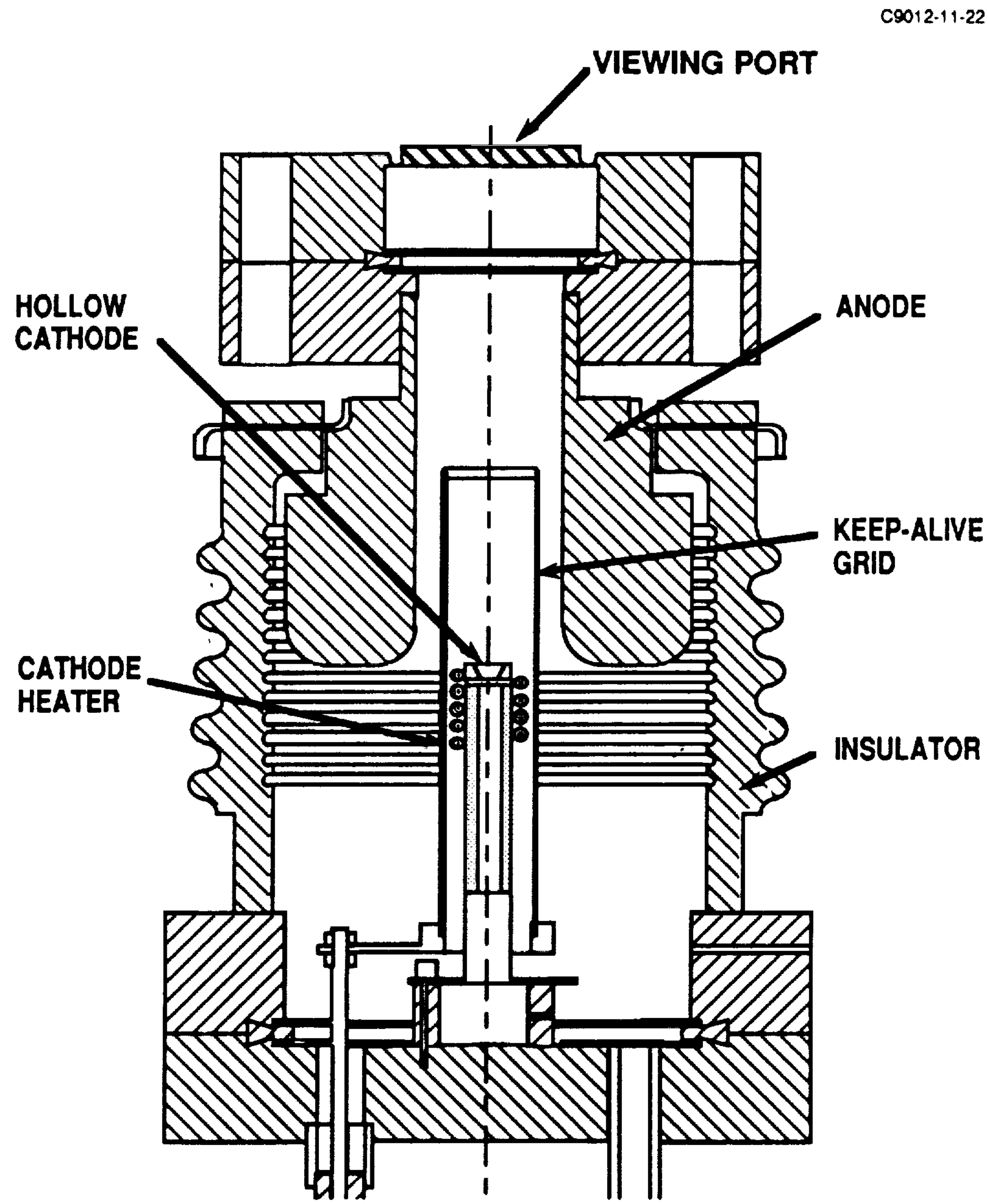

Figure 11. Prototype HOLLOTRON switch configuration for evaluating current distribution in diode-mode operation.

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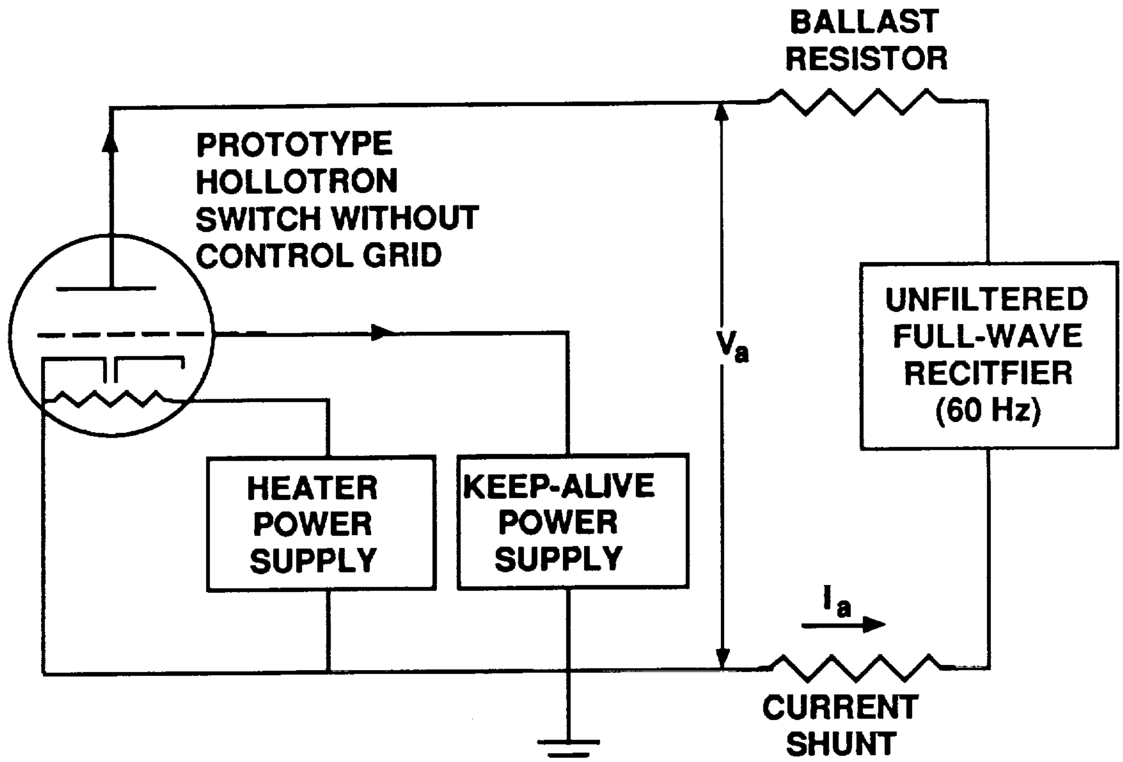

Figure 12. Circuit diagram for diode-mode testing the prototype HOLLOTRON tube (before installation of the control grid).

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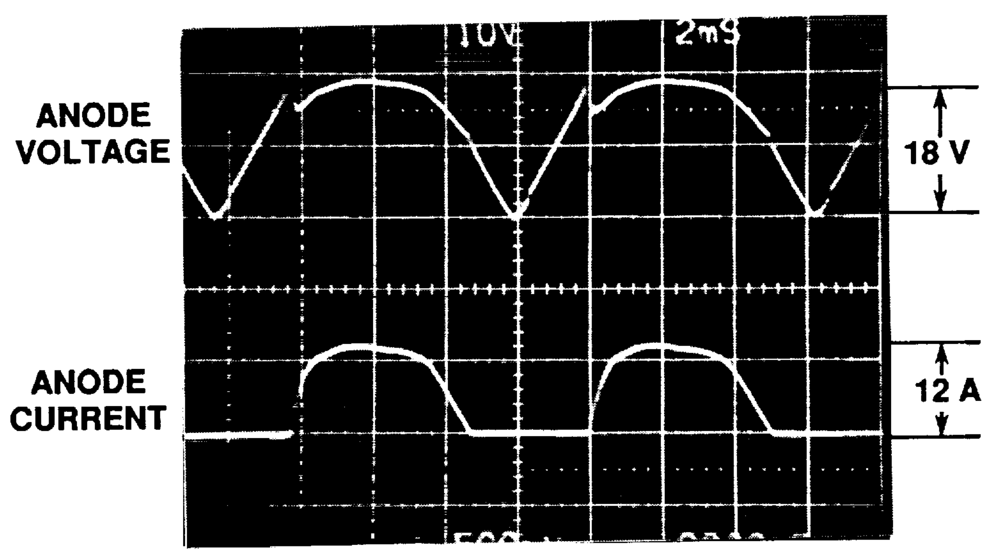

Figure 13. Voltage and current waveforms for diode-mode operation of the prototype HOLLOTRON tube (before installation of the control grid).

anode current, the gas-fill pressure, and the cathode conditioning (temperature dependent). Over the range of parameters varied during the investigation, we observed forward voltage drop in the range 14 to 20 V. With the cathode current at 12-A peak, 50% duty cycle, stable operation was sustained without application of cathode heater power under static xenon gas-flow conditions [with the tube sealed at an ambient xenon pressure in the 0.5- to 1-Torr (67 to 133 Pa) range]. The cathode-to-anode current distribution was initially judged to be relatively uniform on the basis of the light distribution in the anode/keep-alive-electrode gap as observed through the anode viewing port. In these initial diode experiments for evaluating anode current uniformity, we detected no formation of concentrated current paths, the grid supports were clearly visible, and it was apparent that current was flowing through all of the windows.

In our first successful operation of the switch using the control grid to achieve current interruption, we obtained the ≥12 A switching performance that meets the contract objectives. Figure 14 shows the current and voltage waveforms for operation at the required peak current and pulsewidth, obtained by operating the test circuit power supplies to obtain 1-kV open circuit anode voltage, and the timing circuit for 100-Hz repetition rate. The ambient xenon pressure for this operating condition was 25 Pa (180 mTorr). The standard practice for initial testing of switch tubes at HRL is to start testing newly processed switches at low duty cycle and reduced voltage, slowly increasing these parameters until the rated values are achieved. Because of an interruption in contract funding, we stopped testing at the performance level shown in Figure 14, and when the new funding increment was received, we were unable to achieve equivalent performance. The remainder of this section describes our subsequent experiments and assessment of the feasibility for scaling the coaxial HOLLOTRON geometry to high-power operating levels.

When testing of the laboratory prototype resumed, we determined that the valved off switch tube was at significantly higher ambient pressure than it had been operated at previously. Accordingly, we baked-out and re-processed the tube. Although we were able to reproduce the properties of the keep-alive discharge that were measured to obtain the results of Figure 14, under the same conditions we were unable to interrupt anode currents greater than about 2 A. In an effort to increase the interruptible amount, we varied the switch operating parameters as follows:

Ambient pressure	10 Pa (75 mTorr) to 54 Pa (400 mTorr)
Keep-alive current	10 mA to 2.5 A
Anode voltage	200 V to 5000 V
Cathode heater power	10 W to 40 W

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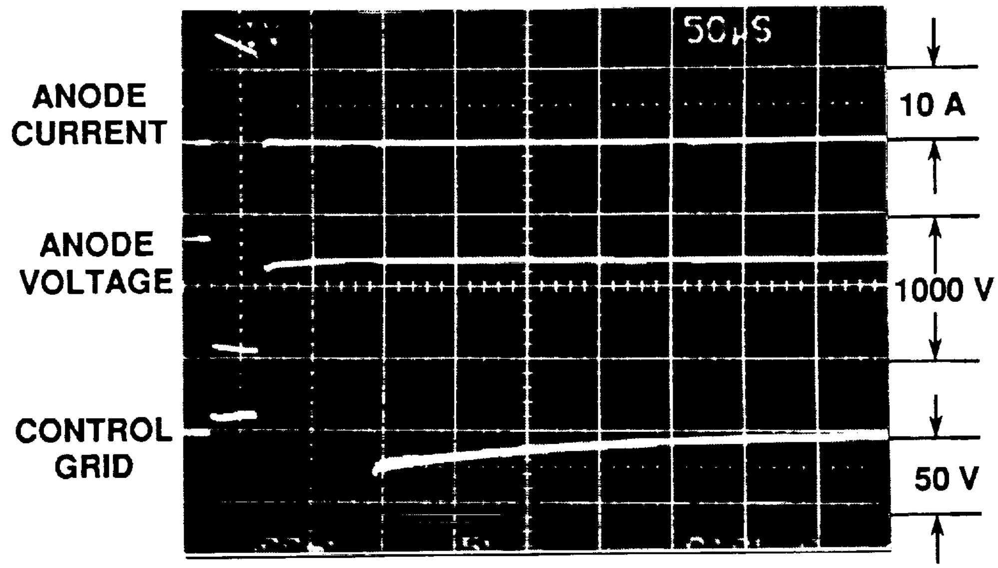

Figure 14. Oscilloscope waveform showing control-grid voltage, anode voltage, and anode current.

We changed the anode-current-limiting resistor to an inductor to limit the current rate of rise, and operated the switch for extended periods at low anode currents that could be interrupted. Eventually grid control was lost, and the switch was carefully disassembled. We could not measure any change in the electrode and cathode concentricity, however several webs of the control grid mesh had been destroyed, leaving a relatively large aperture in the control grid. Figure 15 shows a photograph of the hole in the control grid mesh. This control grid material is 0.0254-mm-thick (0.001 in.) tungsten with square apertures formed by chemically milling. The apertures are 0.076-mm (0.003 in.) squares spaced on 0.114 mm (0.0045 in.) centers.

This finding prompted a series of experiments to determine the cause of grid destruction and to seek a means of preventing it. The switch was modified for operation with an anode viewing port as shown in Figure 16. With this port in place, we soon determined that when anode currents greater than 2 A could not be interrupted, the anode current was flowing through only one section of the control grid. Some success was achieved in "tuning" the keep-alive current, the ambient gas pressure, the cathode temperature and the pulse repetition rate in order to obtain anode current conduction over a larger portion of the anode surface, and thereby obtain current interruption for larger anode currents. These conditions were very transient, however, and required nearly continuous adjustment of the aforementioned parameters. By operating at

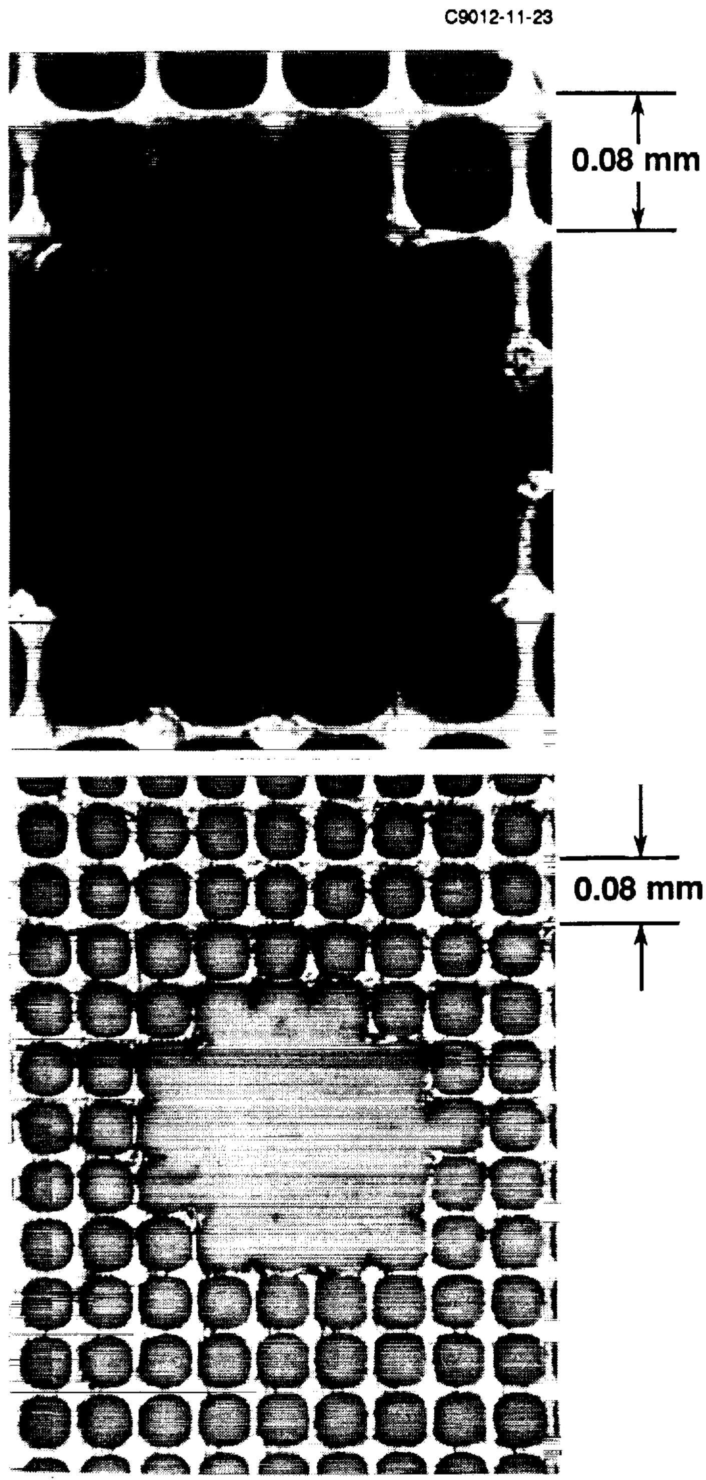

Figure 15. Hole in control grid structure from a concentrated current channel.

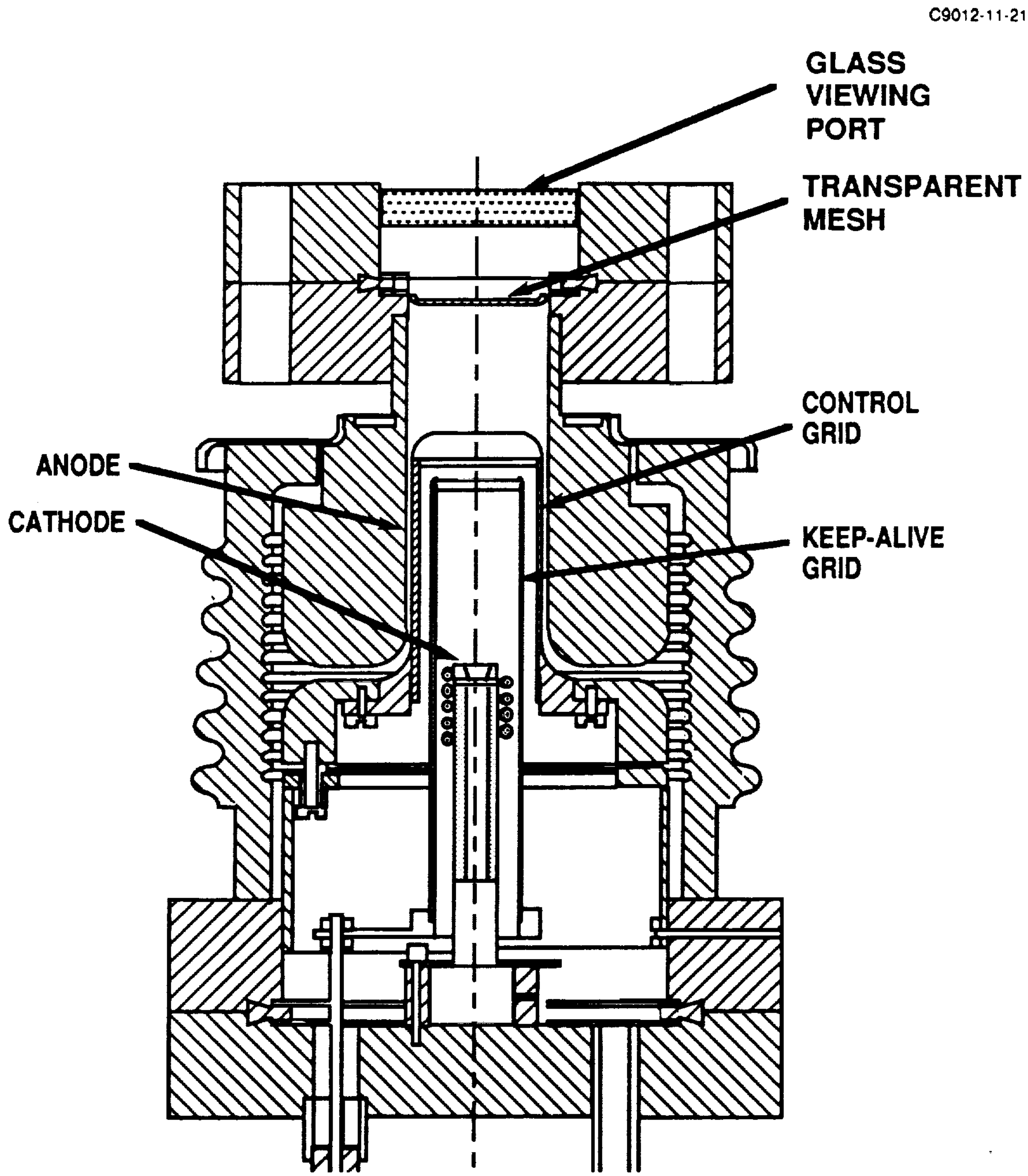

Figure 16. Cross-section of laboratory prototype HOLLOTRON with viewing window installed.

very low repetition rates, we eventually discovered that the current conduction path varies for each pulse, sometimes being distributed more or less uniformly over the anode surface, but more frequently forming a path constricted to one or two sections of the control grid. We consider this condition to be caused by unstable plasma conditions in the keep-alive plasma, which could probably be stabilized by modifying the keep-alive and/or control-grid electrodes to achieve appropriate boundary conditions or by imposition of an appropriately shaped magnetic field.

Although this unexpected circumstance required work beyond the resources allocated for switch optimization under the original work plan, we were able to explore some electrode modifications, and to determine the effects of applying an axial magnetic field. Some of the modifications we tested improved switch operation, but the results imply that the keep-alive plasma volume should be larger and that the hollow cathode should be farther away from the control grid. The laboratory prototype switch configuration is too compact for implementation of any significant design modifications of this nature. The minor changes in design that were evaluated are listed in Table 2 and summarized below:

- Cathode-potential grid in keep-alive plasma (Figure 17)
- Side-extraction of electrons from the hollow cathode (Figure 18)
- Thicker control-grid material (0.058- and 0.076-mm-thick molybdenum)
- Open mesh support for thin tungsten grid material
- Closure of keep-alive electrode apertures nearest cathode to obtain effective increase in distance of hollow cathode to the control grid
- Imposition of uniform axial magnetic field of up to 0.04 Tesla (400 Gauss)

Whereas the results of the experiments described above could probably be extended to achieve a stable coaxial configuration that would meet the inverter objectives, the results obtained under Hughes IR&D Project entitled "Pulsed-Power Switches for Military Systems" using our original linear HOLLOTRON configuration offered a more straightforward and promising path for scaling to high-power operation. Consequently, the full-scale engineering design effort under this contract does not make use of the coaxial switch development described in this section, but is based on the results obtained with the linear HOLLOTRON switch that is summarized in the next section.

TABLE 2. Summary of Coaxial HOLLOTRON Switch Test Configurations.

C9012-11-51

CONFIGURATION	CONTROL GRID REF.	MAGNETIC FIELD (gauss)	INTERRUPTION CURRENT LIMIT	OPERATION STABILITY	COMMENTS
DIODE	NONE	NONE	N/A	YES	• ACHIEVED 12 A MAX 6 A AVERAGE • NO HEATER POWER
PROTOTYPE	1	NO	12 A	NO	LOW DUTY (100 Hz)
PROTOTYPE	1	50-150	2 A - 5 A	NO	NO OPTIMUM-MAGNETIC FIELD — "BETTER" VALUES
PROTOTYPE	3	0-300	N/A	NO	CANNOT INTERRUPT CURRENT AT PRESSURE REQUIRED FOR TURN-ON
PROTOTYPE	2	50 - 150	5 A - 8 A	NO	DEFECTS IN GRID MATERIAL AFFECT CURRENT DISTRIBUTION SEVERAL ITERATIONS
PROTOTYPE	1*	200 (VARIED 0 - 400)	10 A	NO	COULD NOT MAINTAIN OPERATING POINT WITHOUT FREQUENT PARAMETER ADJUSTMENT. SHORT GRID LIFETIME
PROTOTYPE	1*	NO	2 A	NO	HARD TURN-ON, FORWARD VOLTAGE ~30 V
CATHODE GRID	1*	<100 g	2 A	NO	IMPROVES TURN-ON, LOWERS FORWARD V
RADIAL HOLLOW CATHODE	1*	NO	2 A	NO	NO CHANGE IN CURRENT UNIFORMITY
RADIAL	1*	30 - 150	N/A	NO	KEEP-ALIVE UNSTABLE

* REINFORCED WITH OPEN MESH

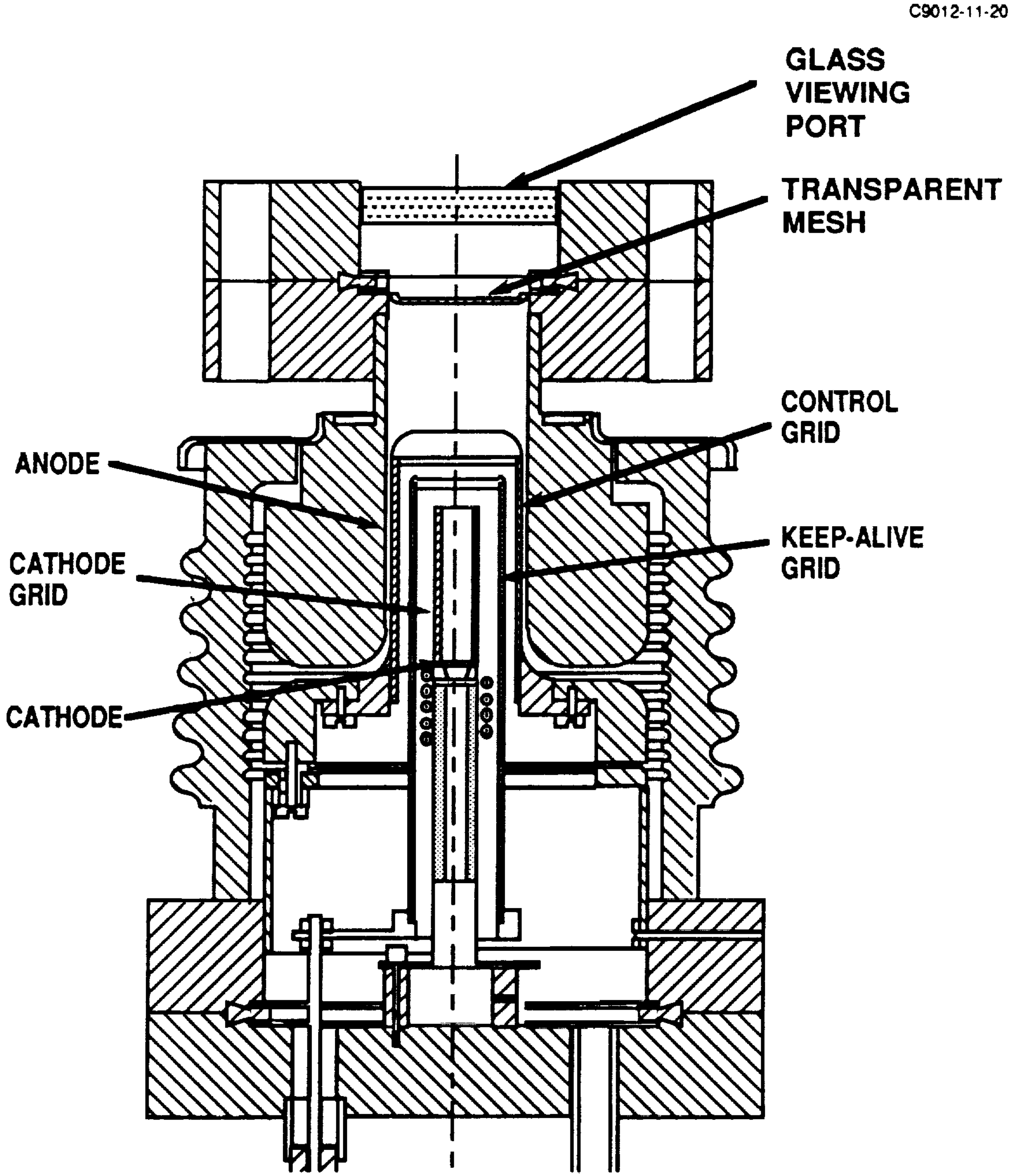

Figure 17. Cross-section of laboratory prototype HOLLOTRON with cathode potential grid installed to prevent formation of current channels.

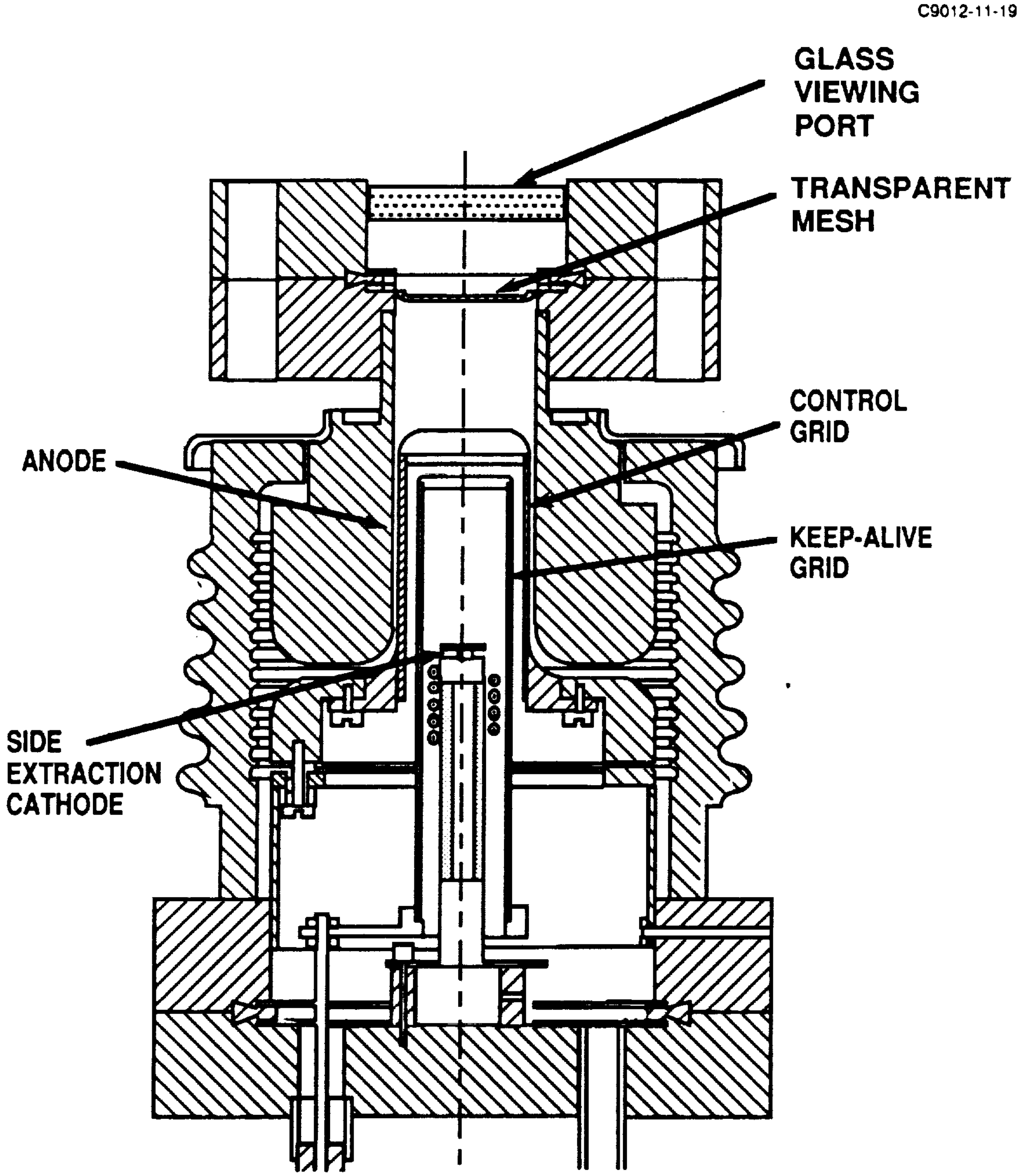

Figure 18. Cross-section of laboratory prototype HOLLOTRON with hollow cathode modified for radial electron extraction.

B. LINEAR HOLLOTRON SWITCH DEVELOPMENT

At the onset of this program Hughes considered the scaling of the linear HOLLOTRON switch to high-current operation to be impractical because of the tendency for the current to pinch into high current-density filamentary paths. By imposing a magnetic field with appropriately diverging lines of force, we demonstrated a switch configuration that will satisfy the inverter/converter requirements listed earlier in Table 1. A laboratory model of this switch was tested at the same power level as the laboratory model coaxial HOLLOTRON switch described in the preceding section. This linear HOLLOTRON switch is being developed under our IR&D project entitled "Pulsed-Power Switches for Military System" for a magentron modulator circuit in advanced missile seekers.

The linear HOLLOTRON switch originally invented at Hughes Research Laboratories in 1989 was capable of switching 2 A of peak current at a current density of approximately 2 A/cm^2. As the current was increased above this level, the higher plasma density generated in the switch and the filamentation of the current channel prevented interruption of the current by Debye shielding the interruption potential applied to the control grid. To limit the plasma density at higher currents and restrict the current density to acceptable levels, the plasma must be expanded to large areas and the current must remain diffuse. Simply building larger hollow cathodes or moving the control grid and anode further from the hollow cathode does not necessarily result in larger plasma areas. The plasma channel carrying the current from a hollow cathode tends to self-pinch to a small cross section. This is because the plasma channel exhibits a negative resistance, and because there is a finite inward JxB force from the neutralized electron current flowing in a plasma that pinches the current channel.

The plasma must be forced to expand uniformly to larger areas. This is best accomplished in the HOLLOTRON-switch configuration by imposing a diverging magnetic field on the plasma column. Under Hughes IR&D, the linear HOLLOTRON was rebuilt for this purpose in the configuration shown schematically in Figure 19. A 0.64-cm-inner diameter, Ba-oxide impregnated hollow cathode, which is heated by a sheathed tantalum heater, was mounted to a base flange connected to a turbomolecular pump. A cone-shaped keep-alive electrode was placed just outside the hollow-cathode exit. This geometry provides the keeper current required to reduce the switch jitter without imposing a restriction on the plasma column by placing a grid or solid disk directly in the plasma. Around the keeper support tube, a 7-turn coil was installed to provide a diverging magnetic field. The coil produces 2.8 gauss/A, as measured at the keeper cone location.

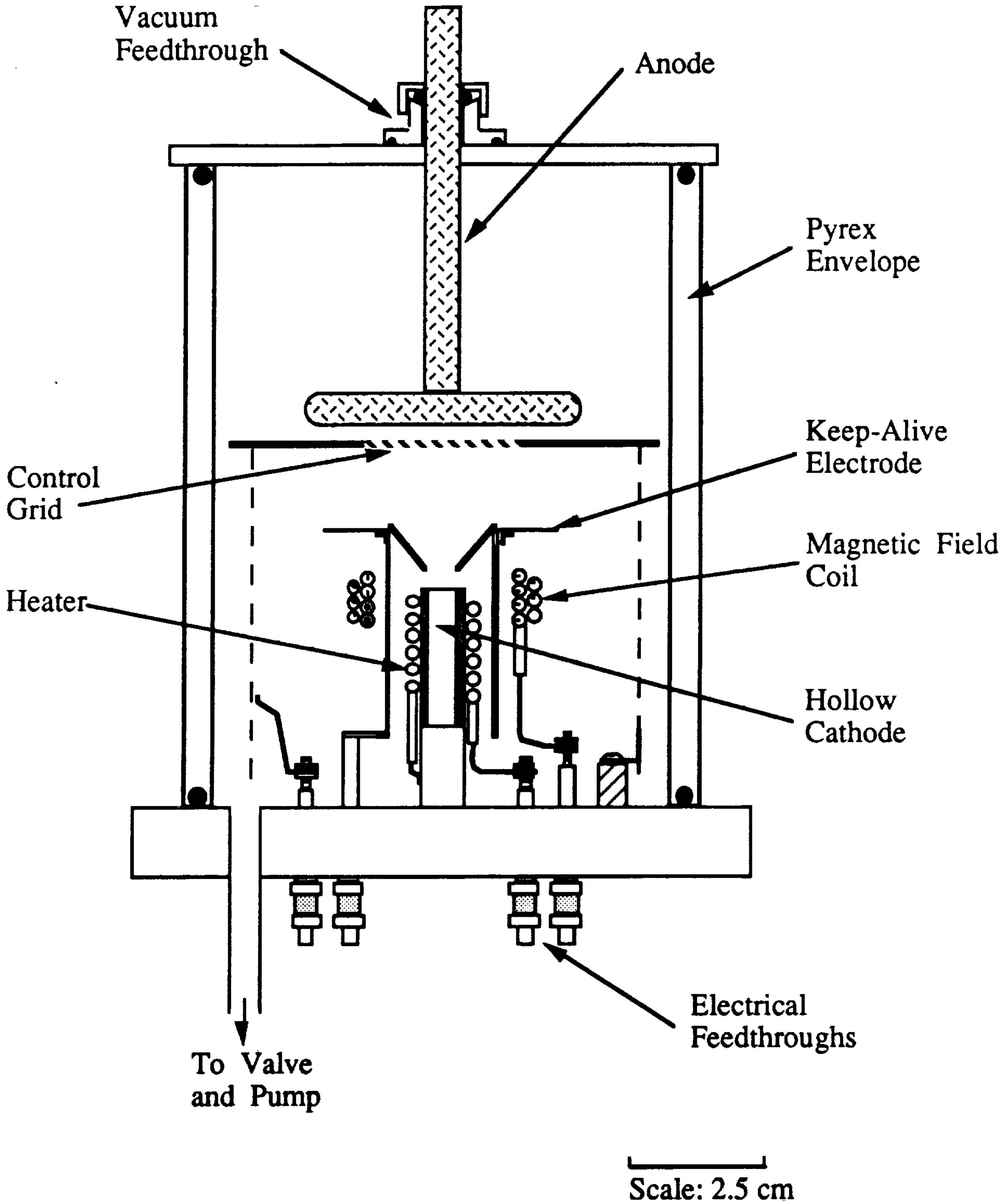

Figure 19. Linear HOLLOTRON switch configuration with diverging magnetic field.

A control grid was positioned 3.5 cm from the hollow cathode. The control-grid consists of a 7.7-cm diameter stainless-steel disk with a 2.8-cm diameter (6 cm^2) aperture. Over the aperture was spot welded a stainless steel mesh with 0.3-mm diameter apertures. The control grid was mounted on a cylinder of the same mesh material, which was supported by ceramic standoffs. A moveable anode was placed 2 mm from the control grid. To visually inspect the shape of the plasma column, the switch was encased in an O-ring sealed, pyrex-glass tube. The base pressure in the switch before operation was typically 4×10^{-7} Torr.

The value of the magnetic field required to constrain the electron motion in the plasma can be calculated from simple diffusion theory. In this theory, the electrons migrate across the applied magnetic field by random-walk collisions with the neutral gas. The perpendicular diffusion coefficient for electron motion across the magnetic field is given by:

$$D_{\perp} = \frac{D}{1 + \omega_c^2 \tau^2} \quad , \tag{1}$$

where D is the normal coefficient for electron ambipolar diffusion in the plasma, ω_c is the electron cyclotron frequency given by eB/m, and τ is the electron-neutral collision period which depends on the neutral gas pressure. When the quantity $\omega_c^2\tau^2$ is much greater than 1, the electrons are magnetized and follow the magnetic field lines. Basically, Eq. (1) states that the magnetic field is effective when the electrons perform many cyclotron orbits before a collision with the neutral gas allows them to move to the next magnetic-field line. A plot of $\omega_c^2\tau^2$ in xenon versus the applied magnetic field is shown in Figure 20.

Experimentally, the HOLLOTRON switch operated in the region shown by the hashed square. At magnetic fields below 150 gauss, the plasma was not well magnetized and the column became visually more constricted. In this case, the maximum current that could be interrupted was about 4 A. Likewise, at pressure above 0.1 Torr, the magnetic field was found to have no effect on the plasma shape due to the high collision rate. The optimum pressure and magnetic field for the Xe HOLLOTRON switch were found to be about 0.06 Torr and 200 gauss.

The linear HOLLOTRON switch has simultaneously produced 5-kV, 12-A square pulses at 2 A/cm^2 peak anode current density, 50% duty, and 20-kHz pulse repetition frequency (PRF). An oscillograph of a single, 25-μsec-wide pulse with these parameters is shown in Figure 21. The upper trace is the anode voltage (2 kV/div), and the lower trace is the anode current (5 A/div). A burst of four pulses at 50% duty is shown in Figure 22(a), where the upper and lower traces area the anode voltage and current, respectively. The pulses are very square and

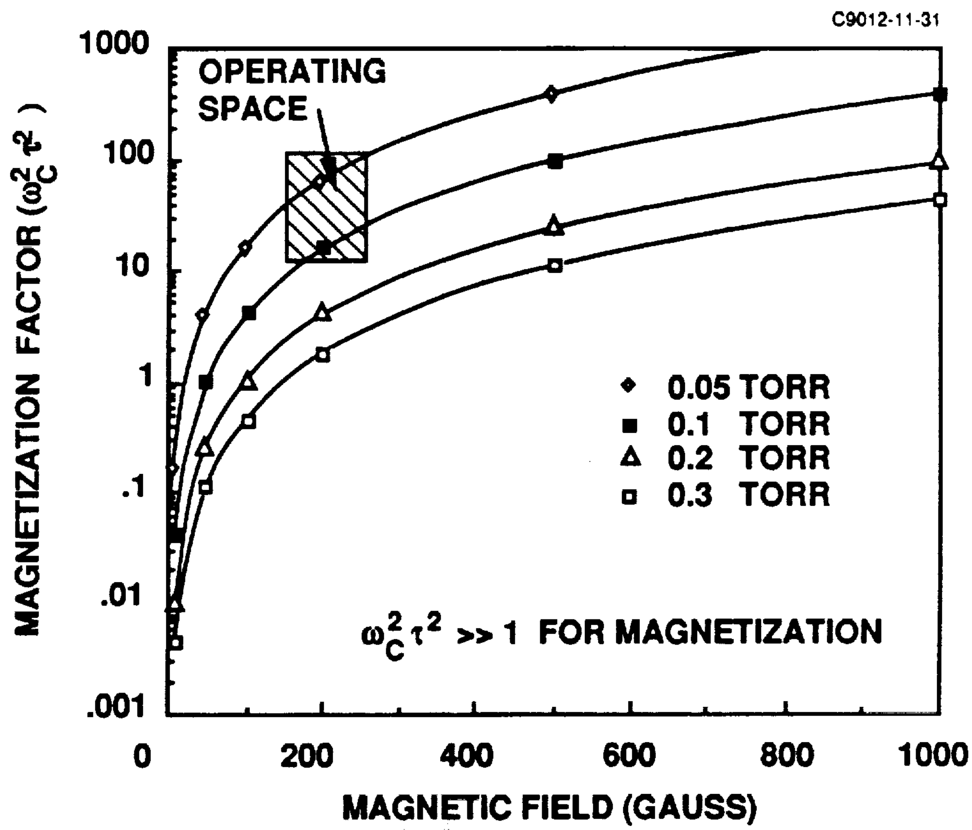

Figure 20. Magnetization plot for the HOLLOTRON plasma.

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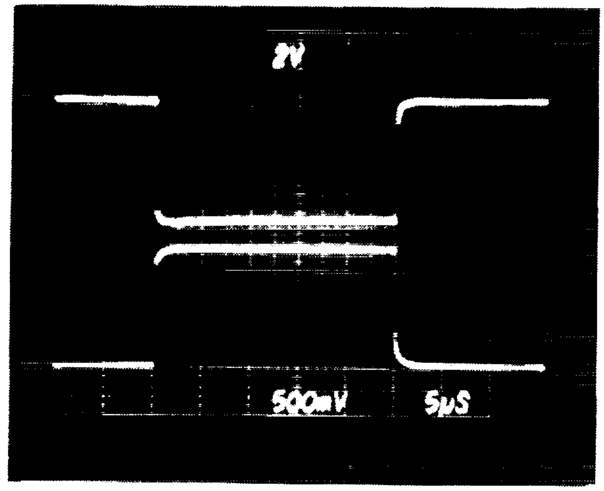
ANODE VOLTAGE
2 kV/DIV

ANODE CURRENT
5 A/DIV



TIME (5 μsec/DIV)

Figure 21. Anode voltage and current for a 5-kV, 12-A square pulse.

reproducible, as demonstrated by the burst of 10 pulses seen in Figure 22(b). The number of pulses that could be achieved was limited by our power supply to about 12, and there was no indication of any limit in the switch modulation capability.

The 12-A, 2-A/cm^2 current-density pulses shown in Figures 21 and 22 were achieved with a measured forward voltage drop from cathode to anode of only 20 V. The forward voltage drop during operation at 0.055 torr and 200 gauss increased with the anode current density as shown by Figure 23. Increasing the gas pressure lowered the forward drop at all currents. The rapid increase in the forward voltage drop at current densities higher than 2.5 A/cm^2 is indicative of space charge limiting of the current flow in the hollow cathode aperture. This effect may be useful in limiting the peak current capability of the inverter switch during faults.

The rise time of the HOLLOTRON current at 2 A/cm^2 was about 200 ns. The control-grid was typically pulsed positive to 150 V for a time of about 1.5 μs. After a delay of several hundred nanoseconds, the control grid voltage decreased rapidly to near the forward drop as the control grid current passed through a 10-Ω current-limiting resistor in the turn-on circuit. The closing performance of the switch is shown in Figure 24(a), where upper trace is the anode voltage (2 kV/div), the lower trace is the anode current (5 A/div), and the time scale is 500 ns/div.

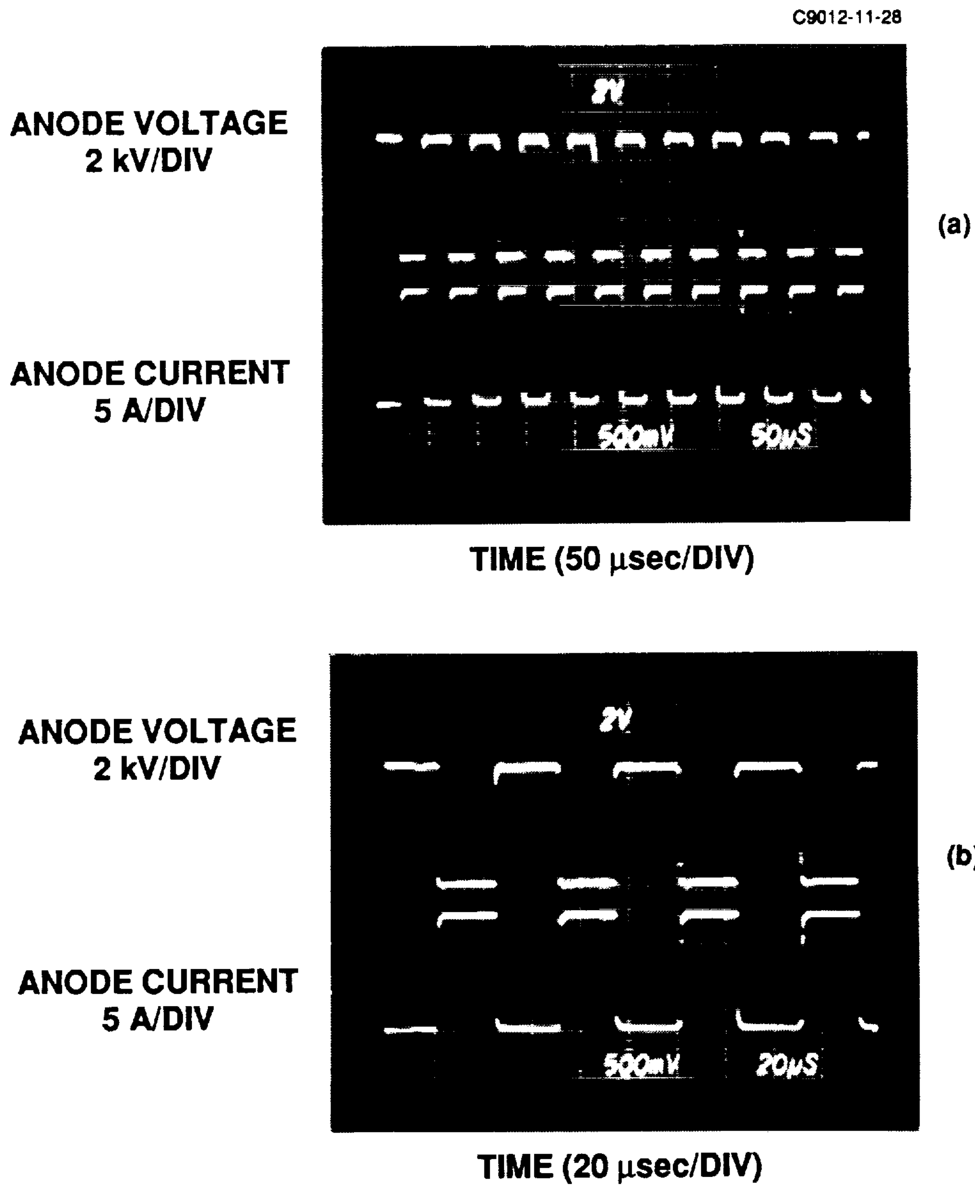


Figure 22. Bursts of 10 (a) and 4 (b) pulses at 50% duty and 20 kHz PRF.

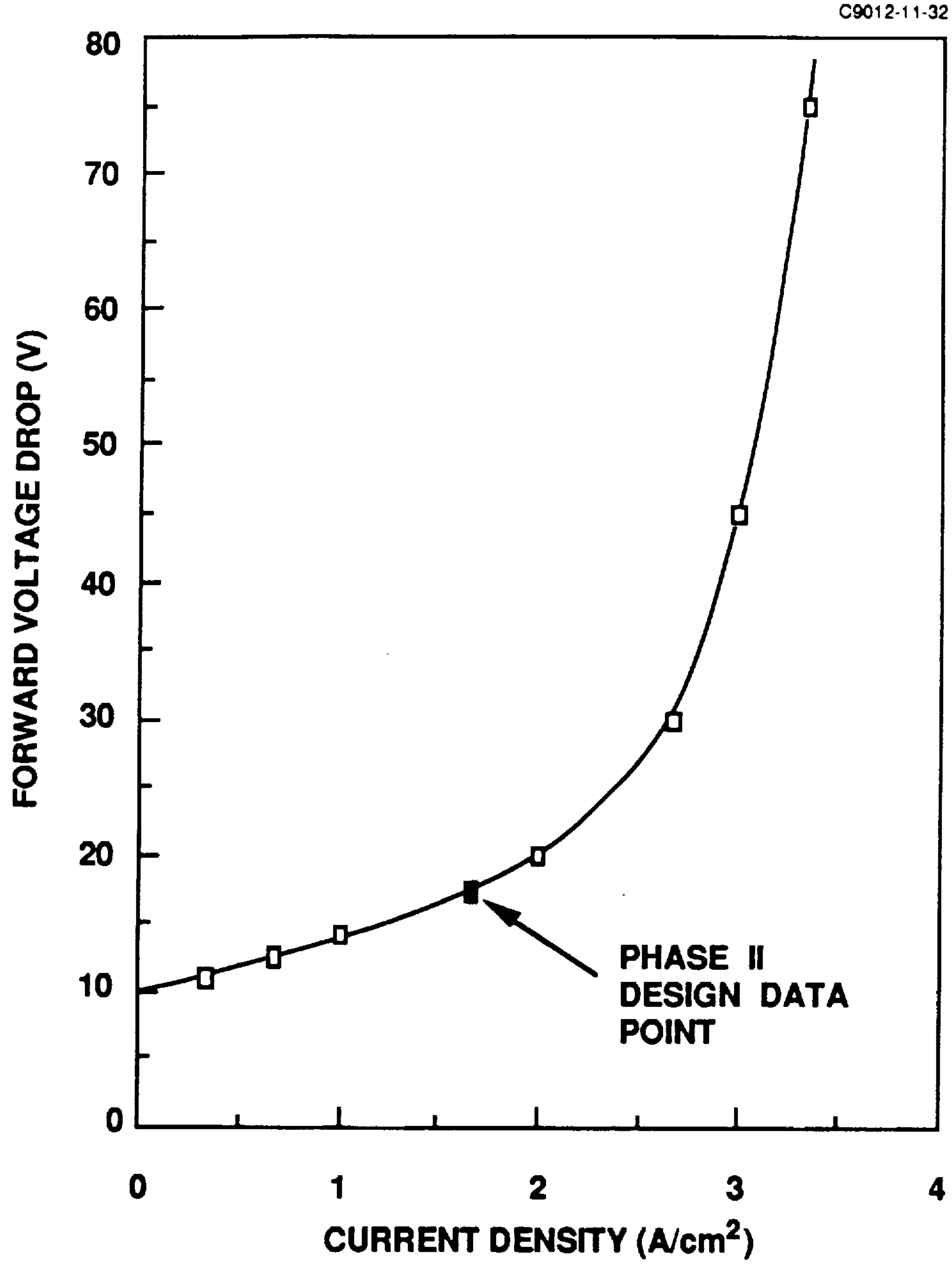


Figure 23. Forward voltage drop versus anode current density.

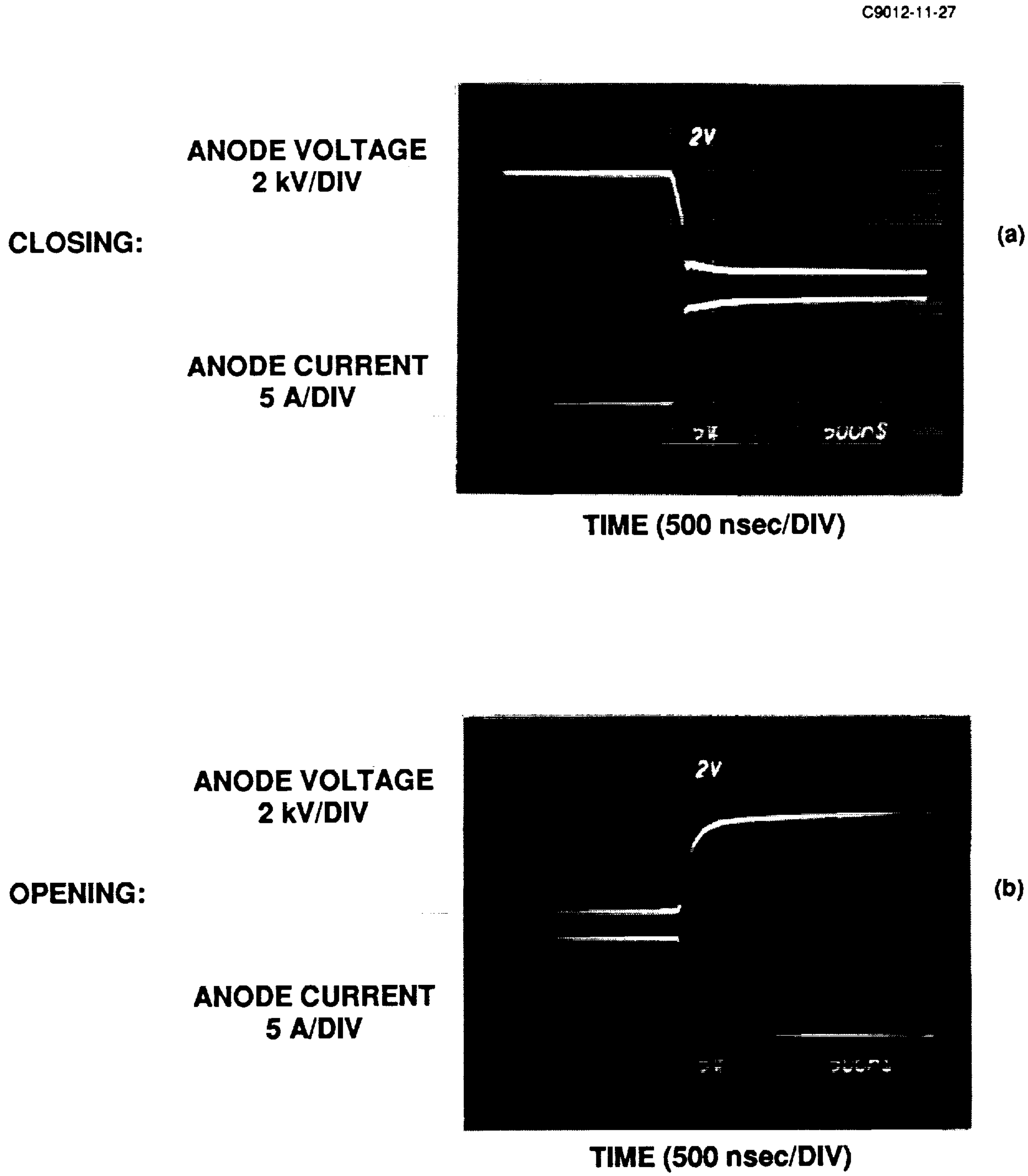


Figure 24. Closing (a) and opening (b) times of the HOLLOTRON switch operating at 2 A/cm^2.

The opening time of the HOLLOTRON current at 2 A/cm^2 was about 300 ns, and varied strongly with the gas pressure and grid negative-bias voltage. The characteristic opening of the switch is shown in Figure 24(b), where the upper trace is the anode voltage (2 kV/div), the lower trace is the anode current (5 A/div), and the time scale is 500 ns/div. The negative bias on the control grid used in Figure 24 was -220 V. Decreasing the negative bias increased the interruption time until the switch simply fails to interrupt. The maximum current density that could be reliably interrupted at a Xe pressure of 0.06 torr versus grid negative bias is plotted in Figure 25. Square pulses at currents of up to 20 A, corresponding to current densities of 3.3 A/cm^2, could be generated reliably by using a negative grid voltage of 270 V. The interruption capability of the switch did not vary significantly when the aperture in the control grid was changed to 3 cm^2, even though this grid was positioned about 0.5 cm closer to the cathode than the larger aperture grid.

The interruption capability of the HOLLOTRON switch is well described by a simple model of the plasma flow through the control grid to the anode. The plasma potential in the anode gap is assumed to be positive relative to the anode, and the electron current to the anode is assumed to be carried primarily by the plasma electrons. The electron current density to the anode, J_A, is

$$J_A = c\,T\,J_R\,, \qquad (2)$$

where c is the fraction of the random electron flux, J_R, that can be collected without significantly disturbing the Maxwellian distribution of the plasma electrons, and T is the transparency of the control grid. A detailed analysis indicates that c is approximately equal to 0.25, above which the distribution is non-Maxwellian and the plasma potential profiles are modified.

The random electron flux in the plasma is related to the ion current density J_i to the sheath edge at the grid by

$$J_R = k\left(\frac{M}{m}\right)^{\frac{1}{2}} J_i\,, \qquad (3)$$

where M is the ion mass, m is the electron mass, and k is a constant of about 0.5. Current interruption occurs when the plasma sheath in the grid aperture expands to the point where the plasma flow is pinched off. This is determined by sheath size and applied voltage, which is described by the Child-Langmuir equation:

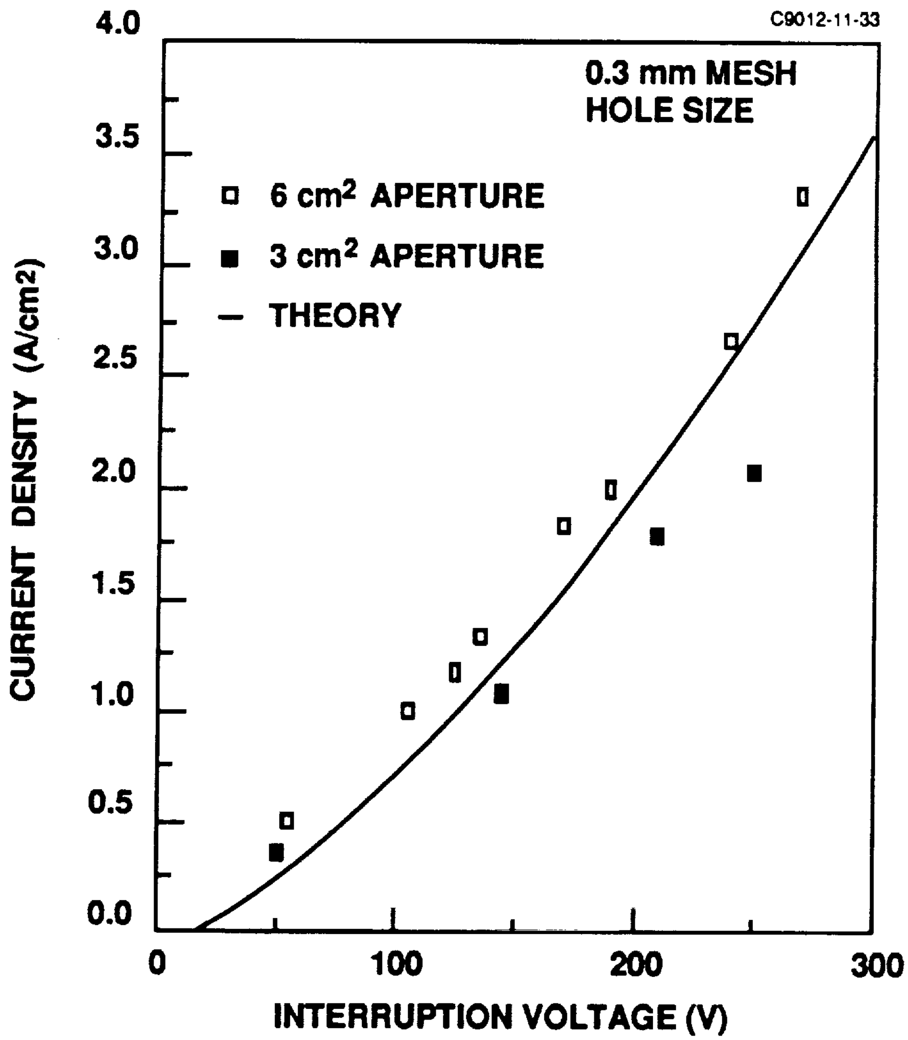


Figure 25. Scaling of the switch interruption current density with grid voltage.

$$J_i = \frac{P\, V^{\frac{3}{2}}}{M^{\frac{1}{2}}\, d^2}\,, \tag{4}$$

where P is a constant (2.33×10^{-6}), V is the applied voltage, and d is the sheath thickness which must be half the aperture diameter. Solving for the interruption voltage results in

$$V = \left(\frac{J_A\, d^{1/2}}{c\, T\, k\, P}\right)^{\frac{2}{3}}. \tag{5}$$

For the experimental HOLLOTRON switch, the grid is 54.6% transparent and the Child-Langmuir sheath thickness "d" that is required to close the grid aperture is equal to 0.15 mm. The results from Eq. (5) are plotted in Figure 25, and agree very well with the experimental data.

This accurate model of the interruption capability of the switch permits us to adjust the mesh aperture size in the Phase II switch design to reduce the required negative bias. As will be shown later, it is desirable to lower the negative grid bias to reduce the sputtering of the grid and increase the life of the switch. This can be achieved by reducing the mesh aperture size in the control grid and the electron current density. Utilizing Eq. (5), the interruption voltage is plotted against the mesh aperture size in Figure 26 for three values of the current density. To reduce the negative bias to less than 100 V, a mesh aperture diameter of 0.2 mm and an electron current density of 1.6 A/cm^2 will be used for the Phase II switch control grid. The smaller mesh hole size is expected to slightly increase the closing time of the switch, but we expect that the Phase II switch will still close in about 300 ns.

The current collected by the control grid during interruption determines the power loading and sputtering of the grid. The peak current collected by the grid is plotted against the total anode current in Figure 27. The grid collects only 20% of the anode current. This is significantly less current than that collected by a CROSSATRON switch control grid during interruption. In the CROSSATRON switch, half the current is carried by the ions, and the control grid must collect a peak current during interruption which is nearly equal to the anode current. The HOLLOTRON control grid collects significantly less current because the current in the switch is carried primarily by the electrons. The plasma density at the control grid is much lower than in CROSSATRON switches, and the available ion current is therefore reduced.

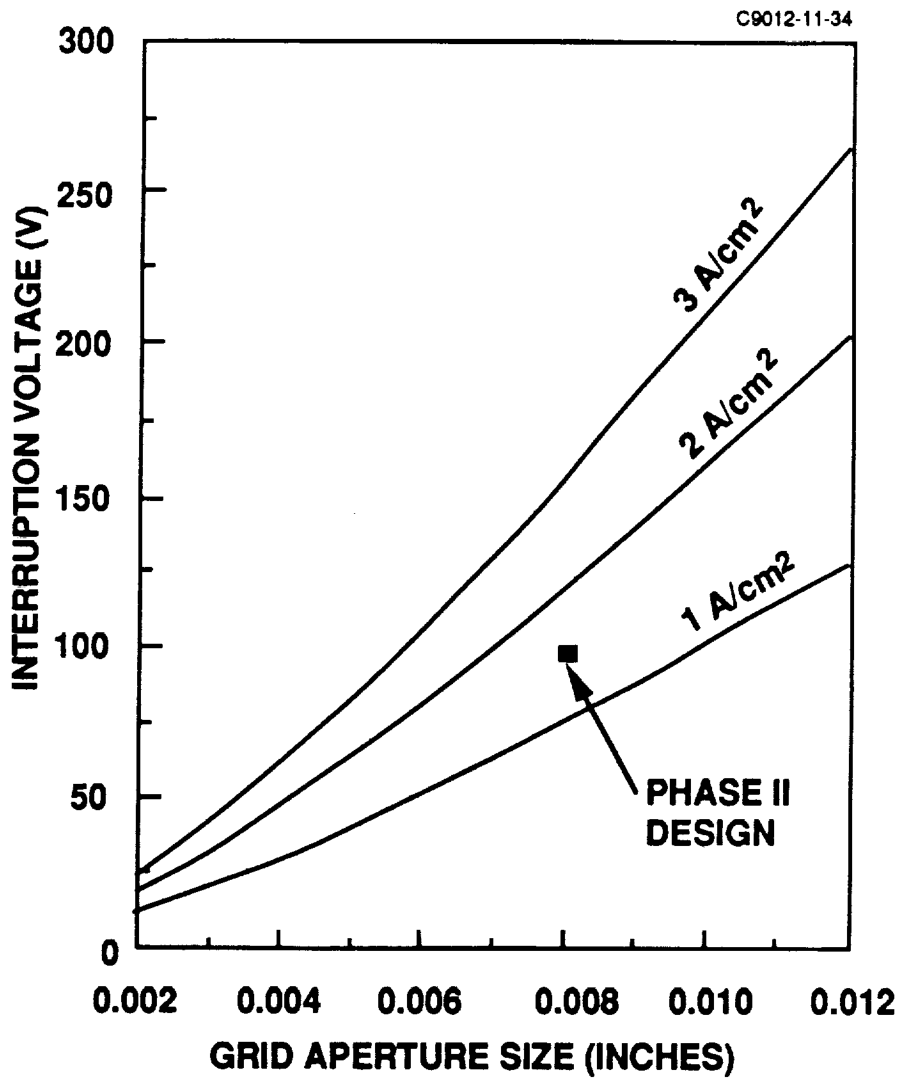


Figure 26. Interruption voltage versus grid-mesh aperture size.

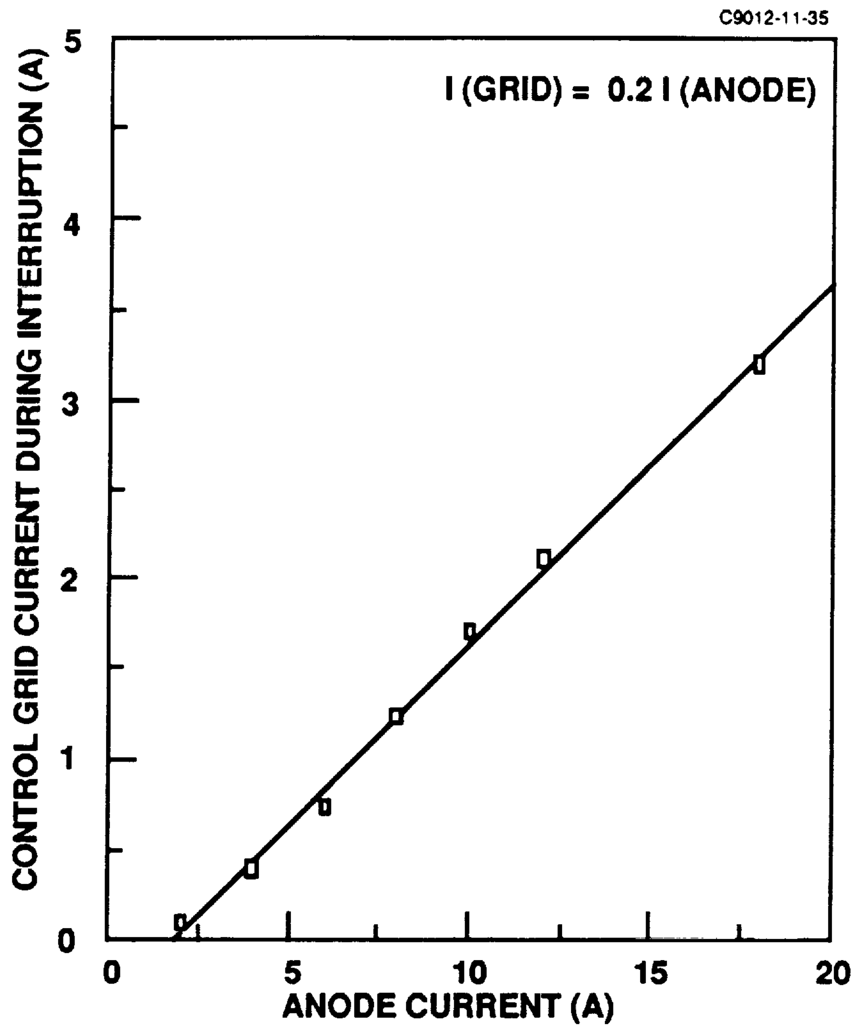


Figure 27. Peak control grid current during interruption versus total anode current.

The lifetime of the switch is primarily determined by sputtering of the control grid. The grid lifetime, τ, is given by

$$\tau = \frac{\rho\, d\, e\, A_v}{W\, J_i\, t\, R\, f} , \qquad (6)$$

where ρ is the density of the material, d is the thickness of the material that is sputtered, e is the electronic charge, A_v is Avogadro's number, W is the atomic weight of the material being sputtered, J_i is the ion current density bombarding the surface, t is the bombardment time, R is the sputtering erosion yield, and f is the pulse repetition frequency (PRF). For a molybdenum control grid, the sputtering yield at 100 V is about 2×10^{-2}. Using Eq. (4), the peak ion current density to the grid is 0.36 A/cm^2. Measurements indicate that the peak current is collected by the control grid for a time of about 0.1 μs. We will also assume that about 35% of the control grid thickness can be eroded before the useful life is ended. Based on these values, the lifetime of the grid is about 1030 hours. This is certainly adequate for the 1-MW power converter.

For longer grid lifetimes, the erosion can be virtually eliminated by reducing the interruption voltage to about 50 V. The threshold for Xe sputtering of molybdenum is 49.3 eV, below which no sputtering occurs and the grid lifetime is virtually infinite. The sputtering yield increases very rapidly as the ion energy increases above this value. Designing the switch with grid-mesh apertures less than 0.15 mm in diameter and operating at current densities between1 and 2 A/cm^2 will increase the erosion-limited switch life to over 10,000 hours. In this case, the switch life would probably be limited by the hollow cathode.

Finally, the HOLLOTRON switch for the 1-MW inverter must be able to supply and interrupt currents in excess of the nominal 200-A value to switch transients during closing and fault conditions. The experimental linear HOLLOTRON switch in Figure 19 achieved a record 100-A closing current at the normal 0.055-Torr Xe pressure and 200-gauss magnetic field. This current was limited only by breakdown on the unshielded electrical feedthroughs on the base of the switch during the high-density plasma generation. During these tests, the switch also interrupted a current of 20 A, corresponding to 3.3 A/cm^2. This outstanding performance is demonstrated in Figure 28, where the anode current waveform is shown for the switch simultaneously closing 100 A and opening 20 A. As will be discussed later, the Phase II switch design takes advantage of the high current density interruption capability to handle high-current (≈400 A) fault conditions. The Phase II HOLLOTRON switch size is minimized by requiring that the switch operate normally at a conservative 1.6 A/cm^2, and interrupt the transient fault conditions at 3 A/cm^2. The experimental HOLLOTRON data indicates that this performance is achievable by a reasonable scaling of the switch size.

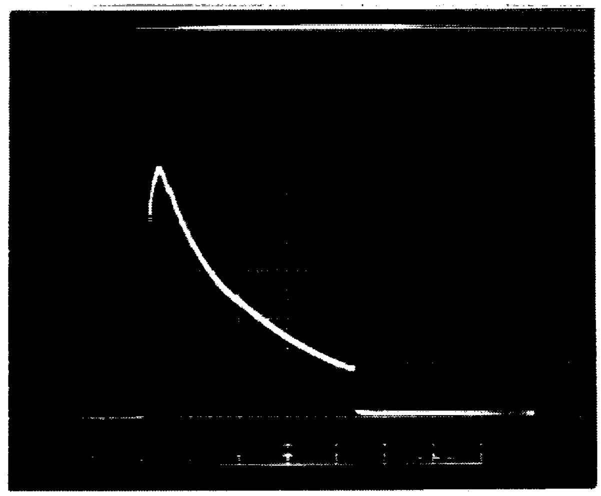


Figure 28. Anode current versus time.

In summary, the experimental, magnetized HOLLOTRON switch simultaneously achieved the full 5-kV, 2-A/cm^2, 12-A peak current, 20-V forward drop, 50% duty, 300-ns switching time, and 20-kHz PRF parameters required for scaling to the full-power inverter switch. The switch demonstrated reduced grid power loading, 100-A closing capability, and interruption at 3.3 A/cm^2 required for transient conditions which occur during closing with the transformer load and during faults. In addition, the performance is well described by theoretical models, which provides confidence that the switch can be scaled with low risk to the full power level.

C. DISCUSSION OF RESULTS

As originally conceived, the HOLLOTRON switch was thought of as a combination of a hollow-cathode plasma source with CROSSATRON current switching technology. As such, the use of a magnetic field was not required for generating the plasma, and we considered this feature an advantage for achieving a lightweight system. When a hollow-cathode is operated at high current, the plasma generated is far too dense for current interruption using the CROSSATRON approach, and Hughes has been evaluating alternatives for expanding the hollow-cathode plasma to meet the requirements of the HOLLOTRON switch concept. On the basis of our 1989 IR&D results, a coaxial switch geometry appeared most promising for controlling the plasma distribution, and we pursued the coaxial configuration under this contract.

We now have collected data for both linear and coaxial switch configurations and we compare the relative merits and deficiencies.

Without imposition of a magnetic field, the tendency to form high-current-density conduction paths is somewhat less in the coaxial configuration than in the linear configuration, however we found no way to ensure that a high-current path would not form and destroy the control grid when interruption is attempted. Achieving a uniform current distribution in the coaxial configuration is observed sporadically, and probably depends on maintaining dimensions and operating parameters within tolerances that are impractical. Plasma instabilities were evident in the coaxial configuration, and these instabilities may also contribute to formation of filamentary current paths. In either the linear or coaxial switch configuration, imposition of a magnetic field stabilizes the operation.

With the addition of a magnetic field, the linear HOLLOTRON configuration offers an easier geometry for generating the magnetic lines of force so that current conduction is distributed uniformly over the control grid and anode. Based on the experiments performed, we observe that the magnetic field lines must follow the direction in which electron flow is desired. For the coaxial geometry, the lines of force must have a relatively small radius of curvature-a condition that was not effectively achieved in the cathode region of the laboratory model coaxial switch. For the linear switch configuration, placing the cathode in the center of a solenoidal, dipole-like magnetic field generates the diverging field lines necessary to disperse the electron flow and is readily scalable to obtain larger anode area.

From the standpoint of switch construction, the linear configuration has several advantages over the coaxial configuration. Foremost, there is considerably more experience with axial orifice hollow cathodes like the one required for the linear switch, than with an annular aperture cathode that is required for the scaled coaxial switch. Consequently, there is little or no risk in scaling the axial orifice cathode to the 250-A peak current requirement. Also, the mass of cathode and cathode heater is expected to be smaller for the linear switch with its axially located cathode, than for the coaxial switch. Similarly, the mass penalty for addition of a magnetic circuit (coil or permanent magnets) is expected to be smaller for the linear switch configuration.

The dimensional stability under thermal stress is expected to be much better for the spherically domed grid and anode electrodes of the linear configuration than for the thin cylindrical electrodes of the coaxial configuration. This provides an advantage in reliability and range of operation for the linear configuration.

Finally, we have successfully demonstrated all of the required operating characteristics for a scaled HOLLOTRON in the linear configuration, whereas there are still stability and scaling questions to be addressed for the coaxial configuration. The scaled HOLLOTRON switch design resulting from the evaluations performed under this contract is described in Section 3A.

D. CONCLUSIONS

Two configurations of the HOLLOTRON switch concept have been evaluated for use in an ultralightweight megawatt inverter system. The scaled performance characteristics have been demonstrated with a linear HOLLOTRON switch configuration that is considered feasible for scaling to the 0.5 MW power level. A conceptual design of the scaled switch was completed and is expected to meet all the requirements of the megawatt inverter system. We foresee no fundamental obstacles for switch development in proceeding to Phase II of the ultralight megawatt inverter system development as proposed in the next section.

SECTION 3

PROPOSED PHASE II PROGRAM

In this Section we present our proposed Phase II Program to develop 0.5-MW HOLLOTRON switches for the Ultralight Megawatt Inverter. Our approach is based on the linear xenon HOLLOTRON switch and is presented in Section A followed by our Statement of Work in Section B. A detailed program schedule is presented in Section C.

A. APPROACH

Hughes proposes to exploit the linear xenon HOLLOTRON switch configuration to develop the 0.5-MW switch that is required for the NASA Ultralight Megawatt Inverter. The linear design was invented in 1989 and more fully developed in 1990 under Hughes IR&D Project entitled "Pulsed-Power Switches for Military Systems." Two patents on the HOLLOTRON switch are pending.

The HOLLOTRON switch for the 1-MW Inverter must close and open 200 A at 5 kV, with a pulse-repetition-frequency (PRF) of 20 kHz. The switch must also withstand 12-kV transients during normal operation and interrupt 400 A during faults. Scaling of the linear HOLLOTRON switch geometry from the original 2-A peak-current device to the 200-A current level requires that a diverging magnetic field be used in the switch to uniformly expand the plasma over the control grid and anode. Demonstrating that the hollow-cathode plasma could be made uniform over a relatively large area required this modification to the original switch geometry, which was initially pursued under Hughes IR&D in 1989. Our efforts in 1990 developed a magnetized HOLLOTRON switch that produced square pulses at 20-A peak current, at a maximum current density of 3.3 A/cm^2 and a voltage of 5 kV. The rise and fall times at the nominal 2 A/cm^2 were about 300 ns. The interruptible current density as a function of the applied grid voltage is closely predicted by a simple theory developed for this switch geometry, which provides good confidence in scaling the switch to the final size.

For the proposed Phase II, three-year program we will first build a 25-kW scale-up unit for a 50-kW breadboard inverter circuit. This device will use the same switch envelope as the final 0.5-MW tube but the switch will need to interrupt only 10 A. The switch must still close 180 A to charge the same stray capacitance in the transformer, and demonstrate the 300-ns switching times at 20-kHz PRF and 5 kV required for the final converter. Operation of the HOLLOTRON switch in the 50-kW breadboard circuit will scale-up switch performance for the second year effort where we will iterate the internal structure of the switch to achieve full 0.5-MW performance. In the third year we will manufacture and test eight vacuum-sealed switches and assist in integrating and testing them with the two brassboard inverter circuits that Hughes EDSG will deliver to the government.

The proposed design of the Phase II HOLLOTRON switch is shown in Figure 29. The switch envelope is cylindrically symmetric, and has an 18.4-cm outer diameter and 10.1-cm length. The switch features a single hollow cathode located on the axis. The hollow cathode uses a barium-oxide-impregnated tungsten dispenser-cathode as the electron emitter. This cathode is initially heated by a standard sheathed heater, but this is turned off when normal operation of the switch starts because of self-heating of the cathode by ion bombardment. To reduce jitter, a low-density keeper plasma is maintained between pulses by sustaining a low current to the conical keeper electrode located near the hollow cathode exit. The switch is closed by pulsing the control grid positive. The high-density plasma generated by the hollow cathode discharge follows diverging magnetic field lines to uniformly illuminate the control grid and anode. The diverging magnetic field is produced by a $SmCo_5$ permanent magnet placed around the hollow cathode. In the first year effort of the program, an electromagnet will be used to adjust the magnetic field and determine the optimum strength and configuration for switch operation. A suitable permanent magnet will then be designed and installed to eliminate the power required to drive the solenoid.

To maintain a pressure of pure xenon gas in the switch, the reservoir and the getter shown in Figure 29 will be used. The reservoir is a zeolite filled with pure xenon gas, which is heated to an appropriate temperature to provide an equilibrium xenon pressure of about 0.06 Torr. To ensure that the switch maintains ultrahigh vacuum conditions, a ZrAl getter is also installed. This getter is outgassed during processing by heating under vacuum. After the switch is sealed, the getter continuously pumps impurity gases such as hydrogen, water, oxygen, and CO_2.

The molybdenum control grid has a 13-cm-diam (132 cm^2) area of plasma contact. To satisfy the 200-A switching requirement during normal operation, the switch must close and open a current density of about 1.6 A/cm^2. This is less than half the value of the current density already achieved under our IR&D effort where we also demonstrated less than 300-ns switching times at this current density. Based on the scaling from the existing switch, the grid apertures will be about 0.2 mm in diameter, and the voltage applied to the grid to interrupt the current will be less than -100 V. The low interruption-voltage is a very desirable feature; this low voltage insures that ions which strike the control grid will have an energy near the threshold for sputtering. This results in a low sputtering yied and long life of the switch. In the event of a load fault, the switch current can rise at a rate of 200 A/μs. The fault current will be interrupted at a level of about 400 A, which corresponds to a current density of 3 A/cm^2. To ensure that the

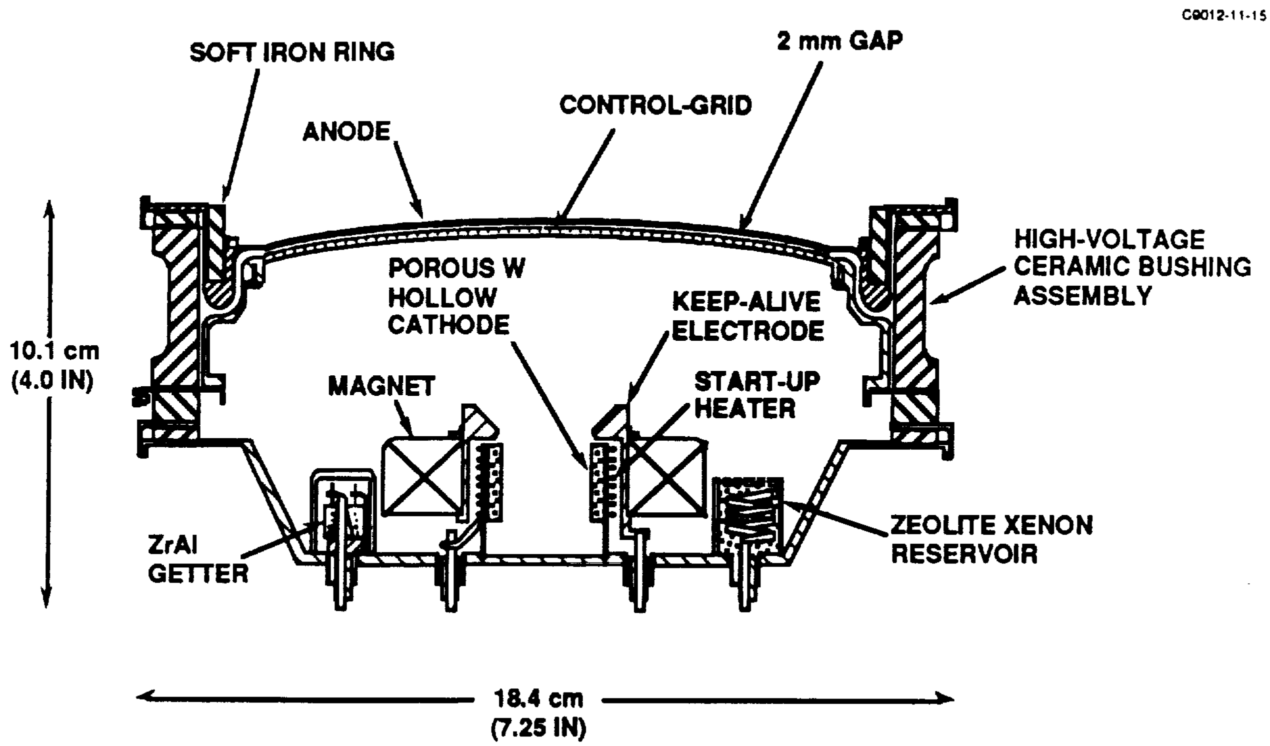


Figure 29. Phase II engineering model of a linear HOLLOTRON switch configuration.

switch interrupts this current density, the control grid negative bias during a fault interruption event will be increased to -200 V. It is also possible to design the switch to limit the total current during faults. In this case, the current in the switch may be engineered to stall at about 300 A due to insufficient plasma density in the gap between the control grid and anode. The voltage drop across the switch increases during the fault condition, and the switch interrupts the current in a time of 1 to 2 μs.

In the first two years of the program, the full-sized switch shown in Figure 29 will be developed using demountable vacuum flanges as shown in Figure 30. The arrangement allows component development to proceed very quickly with minimum cost since multiple cathode/magnet/grid structure configuration can be tested rapidly without having to build a new switch tube at each iteration. Four demountable tubes will be developed in the first year for the Breadboard Inverter, and two full power demountable tubes will be assembled in the second year for full power tests at the Army LABCOM facility. In the third year, eight flangeless tubes (Figure 29) will be manufactured for the two Brassboard Inverter systems that will be tested and delivered to NASA.

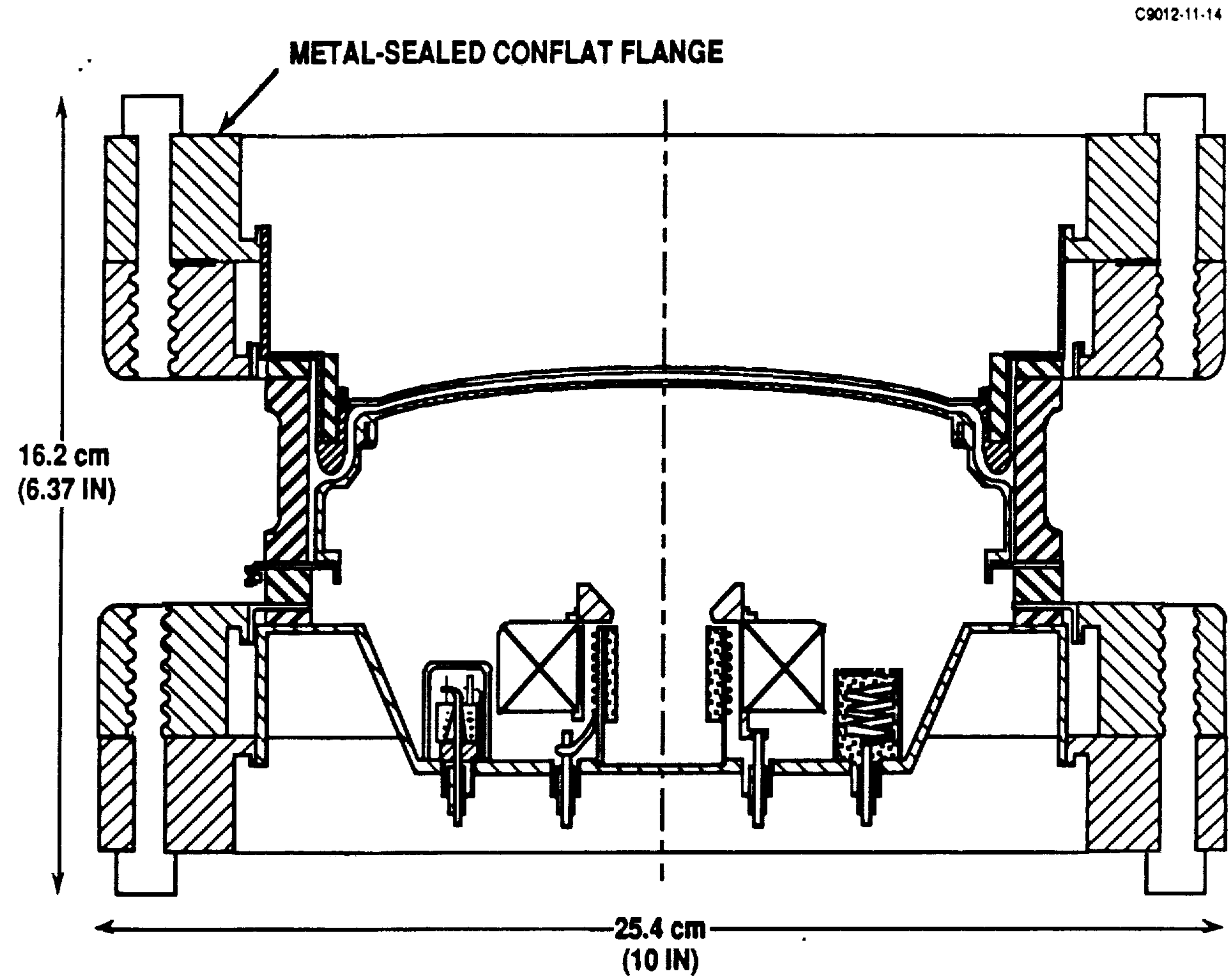


Figure 30. Demountable 0.5-MW linear HOLLOTRON switch.

A detailed program schedule and statement of work for this effort are presented in the following subsections.

B. STATEMENT OF WORK

Hughes Research Laboratories will undertake a three-year Phase II effort to develop a 0.5-MW Xenon HOLLOTRON switch for the Ultralight Megawatt Inverter Program. Specifically, we will scale HOLLOTRON switch performance to high peak (250 A) and average (100 A) currents at open circuit voltage up to 18 kV.

Our approach will be to employ the linear HOLLOTRON configuration with a diverging magnetic field that was developed during 1990 under Hughes IR&D Project entitled "Pulsed-Power Switches for Military Systems." The linear HOLLOTRON switch exploits the xenon ion thruster technique of using a diverging axial magnetic field centered on a single, thermionic hollow cathode to create a uniform, diffuse plasma/current distribution to a large area grid assembly with ultra-low forward voltage drop. As shown earlier in Figure 29, the switch will be constructed inside a high-voltage ceramic bushing assembly with the hollow cathode at the bottom and the anode at the top. The cathode assembly will also consist of a keep-alive electrode ring, a $SmCo_5$ permanent magnet, a zeolite xenon-gas reservoir, and a ZrAl getter. Positioned near the anode, the fine-mesh control grid modulates the conduction of current to the anode. To maintain a 2-mm-gap spacing between the control grid and anode under the thermal stress that will occur during operation, both electodes will be formed in a spherically domed shape and mounted on compliant support structures (similar to the method used for the ion extraction electrodes of ion thrusters). A soft-iron ring positioned outside the anode electrode optimally shapes the outer fringes of the diverging magnetic field lines. These design features will be exploited to achieve the following performance parameters:

TABLE 2. HOLLOTRON Switch Parameters.

Average Power	0.5 MW
Maximum Anode Voltage	18 kV
Average Current	100 A
Peak Current	250 A
Fault Current	400 A
Anode/Control-grid Gap Spacing	2 mm
Switching Time (10 to 90% on Rise/Fall)	300 ns
Forward Voltage Drop at 200 A	20 V
Mass	4.1 kg
Diameter	18.4 cm
Length	10.1 cm
Power Dissipation	4 kW

The full-power switch will be developed and integrated into a pair of Brassboard Inverter Circuits in three steps:

(1) 50 kW Breadboard Switch Development:
In this task we will develop four full-size, but reduced performance (18 kV, 10 A), switches using demountable flanges. We will test the switches individually, and assist their integration and test in a 50-kW Breadboard Circuit at Hughes EDSG.

(2) 1 MW Brassboard Switch Development:
In this task we will re-design the cathode magnet, and grid structures for the full 200-A peak current using the same demountable envelope. We will build and test two switches at the full 0.5 MW power level at the Army LABCOM facility.

(3) Brassboard Switch Fabrication and Test Support:
In this final task we will fabricate eight flangeless, vacuum-sealed switches and assist their integration and test in the two Brassboard Inverter Circuits.

C. PROGRAM SCHEDULE

The 0.5-MW average-power switch will be developed, integrated, and tested with the Ultralight Megawatt Inverter in a three-step, three-year program. A detailed schedule outlining this program is presented in Figure 31.

In the first year we will develop a 50-kW Breadboard Inverter using full-size, but not necessarily full performance, components. The switch will be constructed with demountable vacuum flanges to facilitate performance optimization by easily iterating the configuration of internal components such as the cathode magnet, and control grid. We will fabricate four switches in this first step, two for the breadboard circuit, and two as spares. Prior to delivery to Hughes EDSG, we will test the switches at 5 kV, 10 A peak current, 20 kHz, and 50% duty (5 A average current). At the ninth month of the first year we will deliver the breadboard switches to EDSG and assist with their integration into the Breadboard Circuit. Finally, we will support the 50-kW tests of the complete system at EDSG.

The second year of the program is aimed at the development of full-power components. At HRL, we will extend the peak current capability of the HOLLOTRON switch to 250 A by redesigning the hollow cathode magnet, and grid assembly to handle the higher current. Specifically, we will increase the size of the cathode and the open area of the grid, and reduce the grid-aperture diameter. We will build two new demountable switches using these new components and we will test these switches at full voltage, but reduced current; full current but reduced voltage; and at full current and full voltage but in a short burst of 20-kHz, 1-MW pulses. We will iterate the cathode/grid design based on these tests, and then test the switches at full simultaneous parameters using the "CHIPS" 6.4 kV, 320-A test stand at the Army LABCOM pulsed-power facility at Fort Monmouth, New Jersey. By the end of the second year, we will

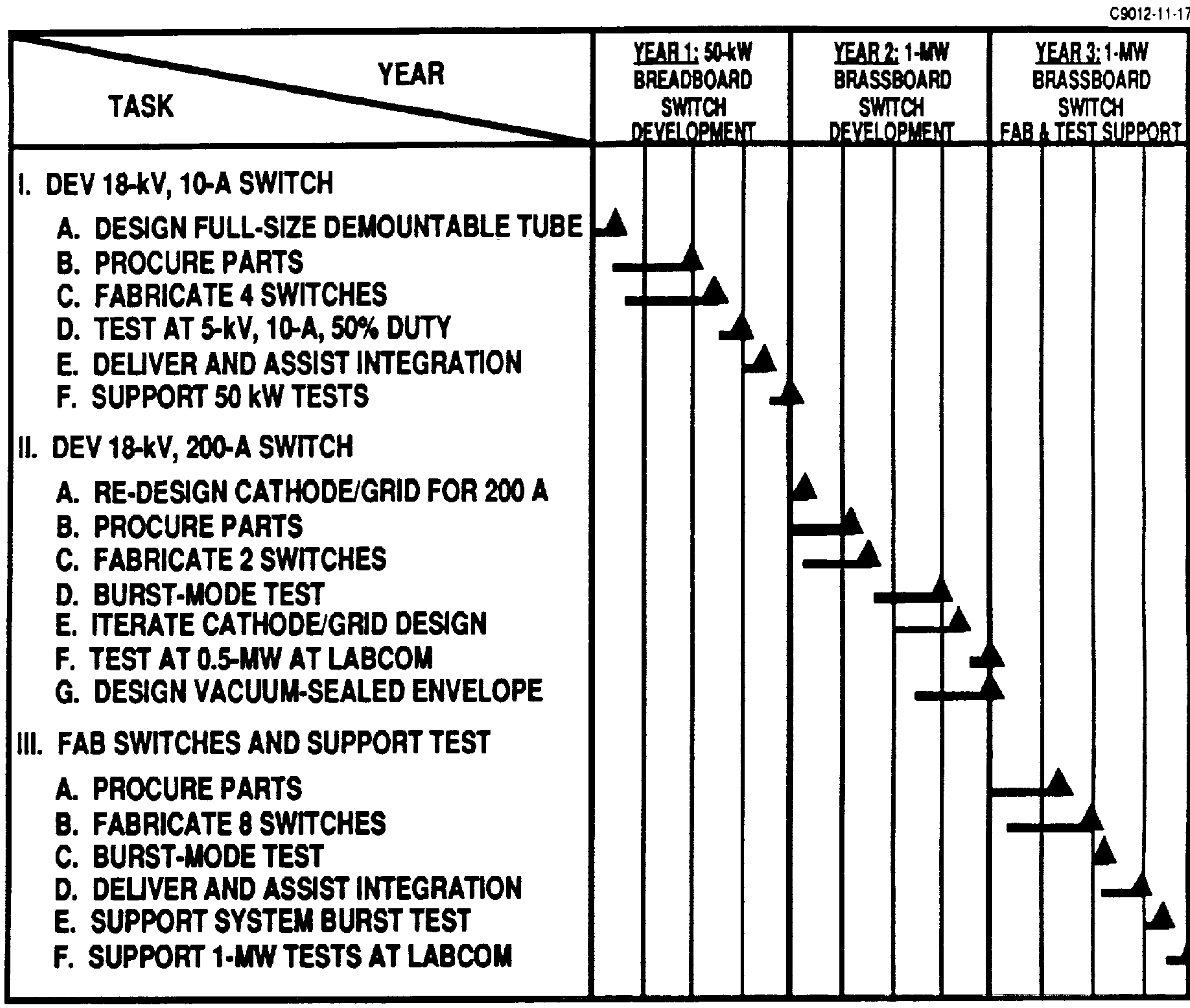


Figure 31. HOLLOTRON inverter switch Phase II development schedule.

have demonstrated the full 0.5-MW power-modulating capability of the xenon HOLLOTRON switch in a simple square-wave, resistive-load circuit. As shown in the Schedule in Figure 31 we will complete the design of a flangeless, vacuum-sealed envelope in parallel with the switch tests such that the engineering model switch will take on the outer dimensions shown earlier in Figure 29.

In the third year of the program we will exploit the full-performance design to manufacture eight prototype 0.5 MW HOLLOTRON switches for the two Brassboard Circuits. Four tubes will be available as spares. At six months into the third year, the first brassboard switches will be completed and they will be tested in the same manner as described above for testing switches during the second year (i.e., reduced power and short-burst evaluations). These switches will be integrated into the brassboard circuits and we will then assist in short-burst, full-power tests of both circuits at EDSG. Finally, both brassboard circuits will be shipped for full-power, full 16-minute-burst tests at the Army LABCOM facility. HRL will support these tests with engineering personnel to assure full switch performance. Following the completion of full-power brassboard inverter tests, HRL will assist EDSG in the preparation of a final report.

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