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THERMIONIC-FIELD EMISSION GUN

January 1978

W. Hant

Contract N00014-77-C-0469

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Results are presented for a program to validate the technology for thermionic field emission (TF) guns. TF guns are proposed as an attractive alternate to cold cathode guns as high average and high peak current density excitation sources for repetitively pulsed short wavelength lasers.

Among the advantages of TF guns are that they exhibit temporally constant impedance characteristics, are not subject to diode closure restrictions, and

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utilize well understood and controllable electron trajectories. The latter requirement is critical to the achievement of efficient beam transmission through closely spaced cooled ladder and foil support structures.

Major program tasks included: 1) Performance of a theoretical analysis to predict the emission characteristics for a diode experiment and to estimate achieveable beam uniformity; 2) Development and thermal testing of a filament and support structure suitable for large area guns; 3) Design, construction and experimental evaluation of a small area high voltage TF gun.

A small gun, with a 1 cm x 2 cm cathode area, was operated for over 100 shots with beam voltages to 175 kV and anode currents to 20 A. Experimental results indicate that it is possible to achieve high anode current densities for planar TF guns, operated at standard high vacuum conditions and at sufficiently low filament temperatures to avoid appreciable tungsten evaporation.

THERMIONIC-FIELD EMISSION GUN

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TABLE OF CONTENTS

THERMIONIC FIELD EMISSION GUN
FINAL TECHNICAL SUMMARY REPORT

SUMMARY

This report summarizes work performed during six months of a program to validate the technology for thermionic field emission (TF) guns. TF guns are proposed as an attractive alternate to cold cathode guns as high average and high peak current density excitation sources for repetitively pulsed short wavelength lasers.

Included among the advantages of TF guns are that they exhibit temporally constant impedance characteristics, are not subject to diode closure restrictions, and utilize well understood and controllable electron trajectories. The latter requirement is critical to the achievement of efficient beam transmission through closely spaced cooled ladder and foil support structures. The ability of these structures to dissipate heat deposited by the beam, ultimately determines the average current density limits for all laser electron guns.

The long term objective of this program was to extend the existing TF emission technology to the development of full scale, high voltage and high current density electron guns. Major tasks performed during the first six months of a one year incrementally funded program to validate the TF technology included the following: 1) Performance of a theoretical analysis to predict the emission characteristics for a diode experiment and to estimate achieveable beam uniformity; 2) Development and thermal testing of a filament and support structure suitable for large area guns; 3) Design, construction and experimental evaluation of a small area high voltage TF gun.

The required milestone to demonstrate TF emission from a planar gun operating at 160 kV beam voltage, was satisfied during the program. A

small gun, with a 1 cm x 2 cm cathode area, was operated for over 100 shots with beam voltages to 175 kV and anode currents to 20 A. The experimental results indicate that it is possible to achieve high anode current densities for planar TF guns, operated at standard high vacuum conditions and at sufficiently low filament temperatures to avoid appreciable tungsten evaporation.

INTRODUCTION

Electron beam excitation for single-pulsed short wavelength lasers is typically accomplished by means of cold cathode guns with output current densities in the range of 5 A/cm^2 to 20 A/cm^2. These guns are not well suited for efficient repetitively pulsed operation because: 1) the time dependent cathode anode spacing results in a temporal gun impedance variation that cannot easily be matched to a pulse forming network and 2) the indeterminate position of the effective cathode renders accurate electron trajectory control nearly impossible. The latter requirement is critical to the achievement of efficient beam transmission through closely spaced cooled ladder and foil support structures necessary for high average current repetitively pulsed operation. As a consequence of these limitations of the cold cathode gun technology, work was initiated on a new type of large area high peak current density gun that operates in a combined thermionic and field emission (TF) mode. Special features for the (TF) gun include no diode closure restrictions, temporally constant impedance characteristics, and most importantly, promise for the achievement of focusable electron trajectories.

The present work was motivated by the emission experiments of Dyke, et. al.[1] on heated single point emitters. Their results indicate that the

(1) W. P. Dyke, F. M. Charbonnier, R. W. Strayer, R. L. Floyd, J. P. Barbour and J. K. Trolan, "Electrical Stability and Life of the Heated Field Emission Cathode", JAP Vol. 31, pp. 790-805, May 1960.

ultrahigh vacuum requirements ($p < 10^{-11}$ Torr), necessary for stable operation of field emission devices with unheated filaments, may be relaxed to $p \approx 10^{-6}$ Torr. Figure 1 indicates the relationship between emission current density and electric field calculated for tungsten emitters of different temperatures. The gun to be discussed is continuously heated and operates in a hybrid thermionic field emission (TF) mode as shown by the shaded area in Figure 1. An important feature of TF guns for laser applications, is the large available cathode to anode potential difference ($\approx$ 300 kV) which facilitates the achievement of high electric fields and consequently high cathode emission current densities from guns with reasonable cylindrical filament diameters (.5 mils $< d \lesssim$ 2 mils) and easily obtainable interelectrode spacings. The electrode configuration for a large area TF gun is shown schematically in Figure 2. Short filamentary cathodes, at filament potentials V_0 and V_1 are connected in parallel in a 2 dimensional array with one dimension shown perpendicular to the surface of Figure 2. Typically the window foil and ladder support structure operates at ground potential, the filaments are at the high negative anode potential, ($V_{fil} = -V_{anode} + V_0$, $V_{fil} = -V_{anode} + V_1$) and the control electrode operates at or below the filament potential to prevent electron beam interception.

The long term objective of this program was to extend the TF emission technology to the development of full scale, high voltage and high current density electron guns. The program was initiated on the basis of theoretical results obtained during an Electron Gun IR&D program[(2)(3)] and on the experimental demonstration of TF emission from a cylindrical diode.[(4)] As initially conceived,

(2) W. Hant, "Electron Beam Gun Development", Northrop IR&D, Project Description for 1977 Project 77-R-534.

(3) "Development of a New High Current Density Electron Gun", Northrop Technical Proposal NRTC 77-14P PIN 2396, February 77.

(4) W. Hant, "Preliminary Results for the Cylindrical Single Filament TF Gun", Northrop Memo 375-77-15, May 1977.

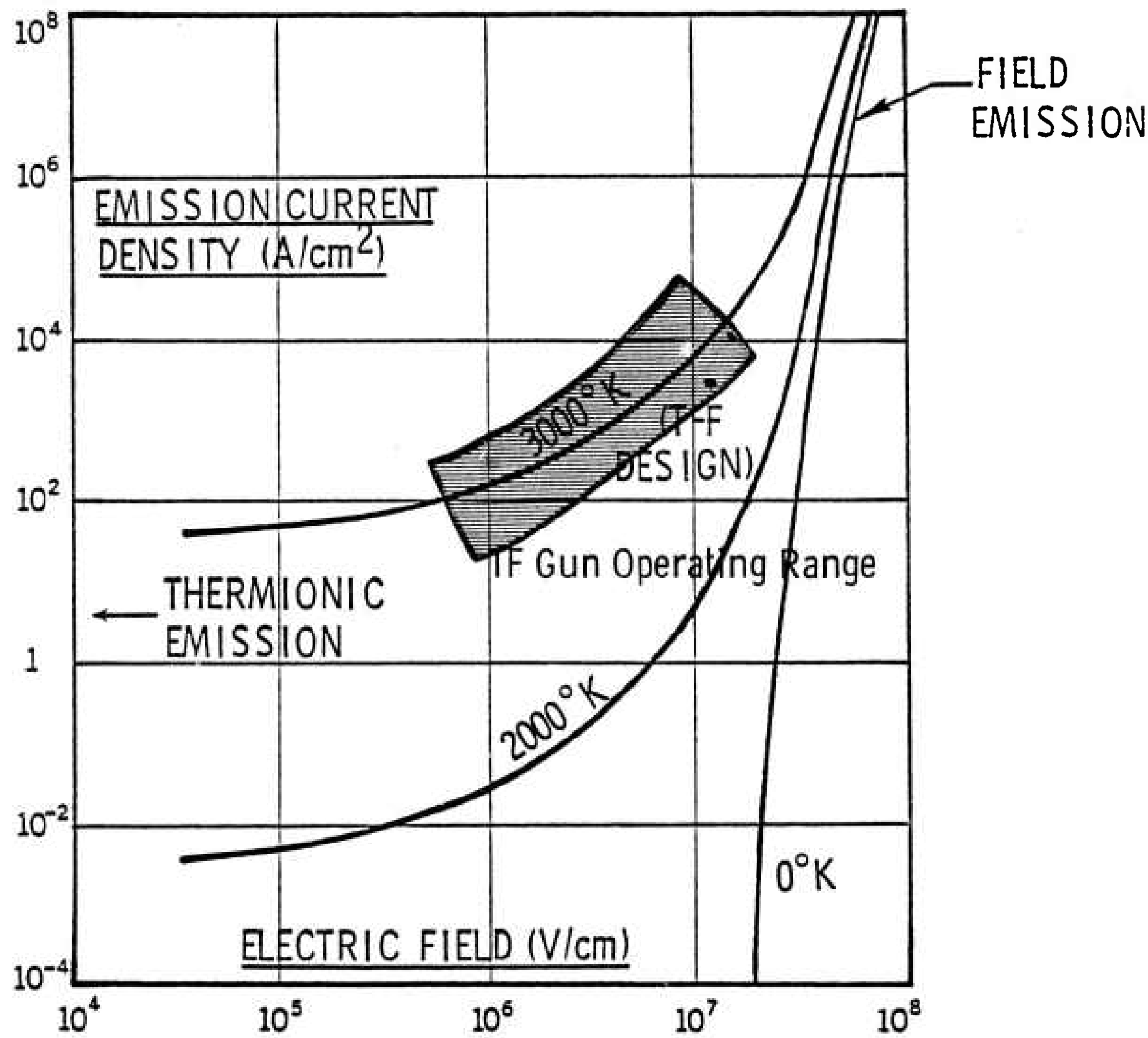

Figure 1. Calculated Emission Current Density vs Applied Electric Field for Tungsten Emitters (W. P. Dyke, Scient. American 210, 108 (1964))

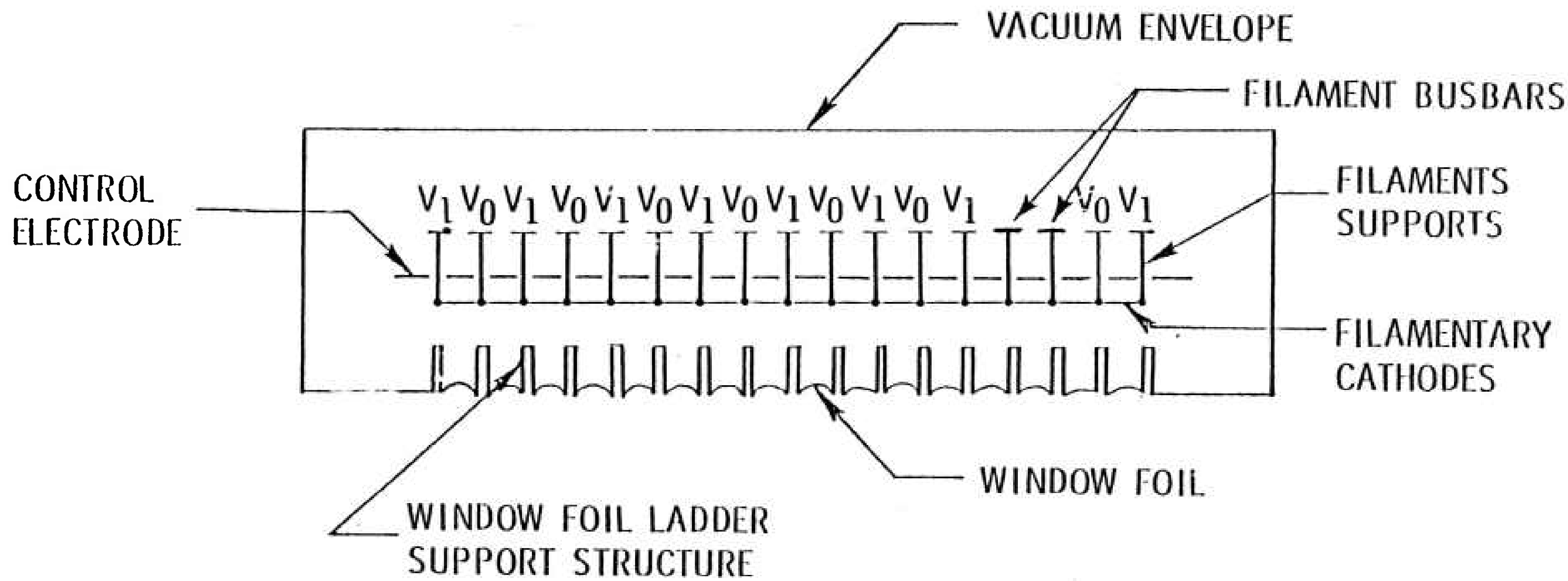

Figure 2. Electrode Configuration for a Large Area TF Gun

the program was intended as a one year, two part incrementally funded effort with major tasks shown in Table I. Major milestones included: 1) demonstration of TF emission from a small area planar gun at V_{anode} = 160 kV for Part A, and 2) experimental evaluation of total current and current density for a larger area (10 cm x 10 cm) gun at full voltage (≈ 300 kV) for Part B. This report highlights the results of the Part A effort.

THEORETICAL ANALYSIS AND PRELIMINARY TESTS

Cathode emission current density for the typical extended Schottky mode of operation of T F guns, is given by[5]

$$J = 70T^2 \exp\left(\frac{-\varphi}{8.6164 \times 10^{-5} T}\right) \exp\left(\frac{.44022\sqrt{E}}{T}\right) \frac{q}{\sin q} \qquad (1)$$

where $q = \dfrac{5.1975 \times 10^{-4} E^{3/4}}{T}$

and J = Emission Current Density (A/cm^2)

φ = Work Function (eV)

T = Temperature ^oK

E = Electric Field (Volts/m)

A computer code was developed that models the cylindrical diode which was previously utilized to demonstrate T F emission.[4] The diode configuration shown in Figure 3, consisted of a heated cylindrical filamentary cathode held at each end by a collet and a concentric cylindrical anode. The analytic expression for electric field between concentric cylinders utilized in the code was modified by results of a numerical analysis to account for edge effects imposed by the collets and by the finite cylinder lengths. The

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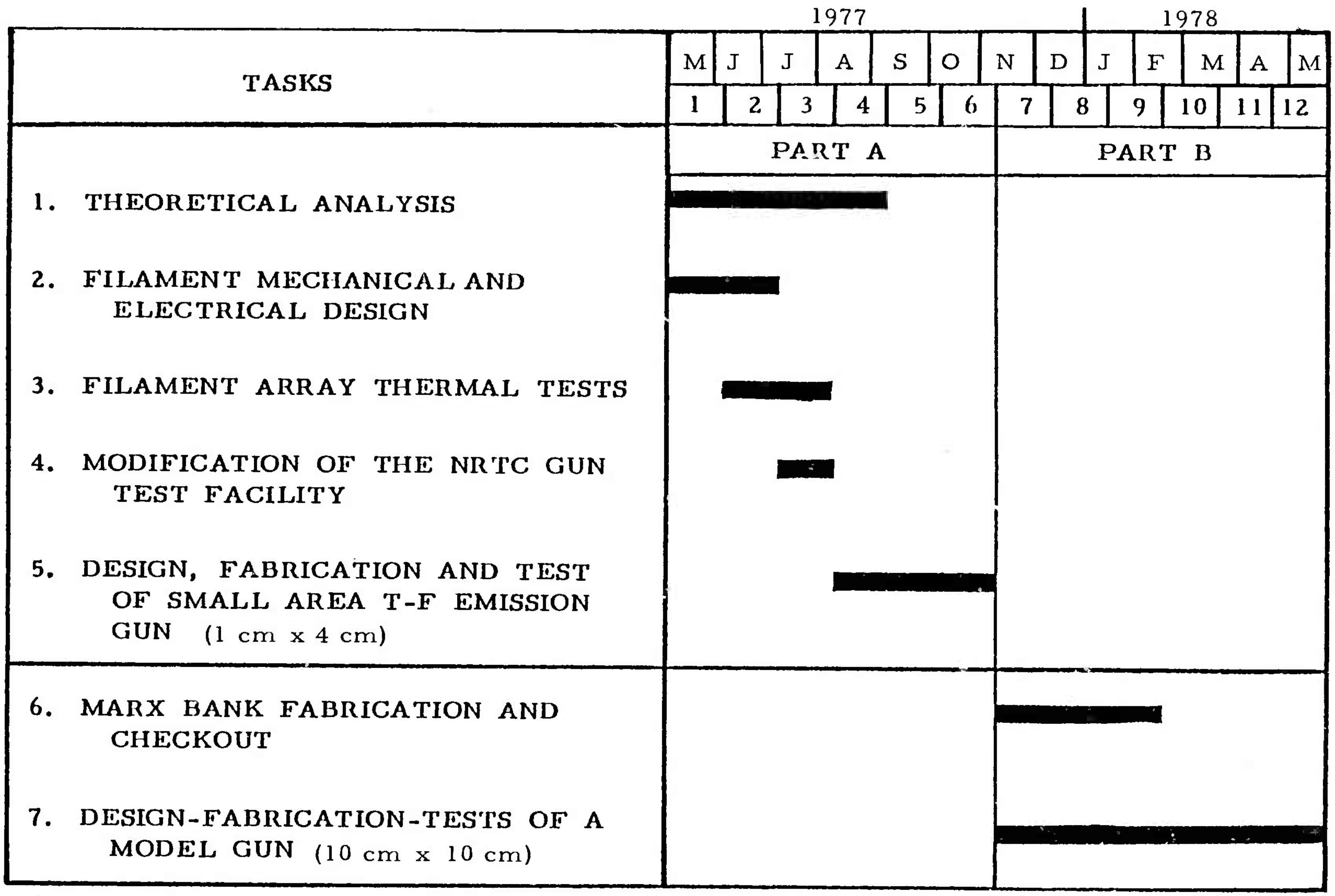
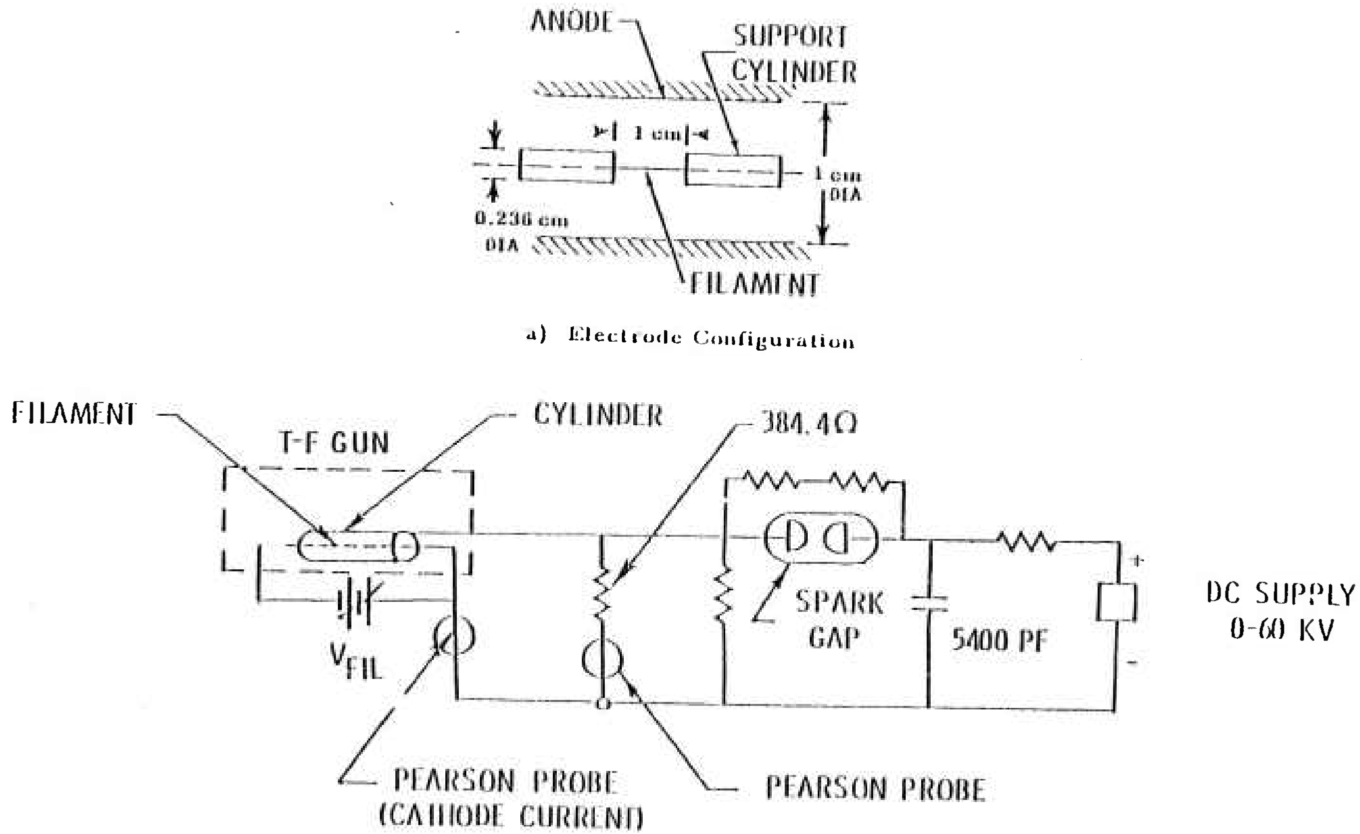
(5) L. W. Swanson and H. E. Bell, "Recent Advances in Field Electron Microscopy of Metals", Advances in Electronics and Electron Physics, Vol. 32, New York, Academic Press, pp. 301-304, 1973.

TECHNOLOGY VALIDATION - PHASE I SCHEDULE





a) Electrode Configuration

b) Schematic

Figure 3. Electrode Configuration and Schematic for the Cylindrical, Single Filament T-F Gun Experiment

computer code also includes effects of space charge[6] and temperature variation[7] along the filaments. Central filament temperatures are obtained indirectly from filament resistance measurements taken at room temperature and at the elevated temperatures. This technique and additional information about the cylindrical diode experiment are discussed in more detail elsewhere.[8] Results of total anode current vs. anode voltage for different calculated and measured central filament temperatures are compared in Figure 4.

Agreement between theory and experiment is good and probably well within the limits of accuracy imposed by the measurements for current and voltage and by the assumption for φ. Maximum emission current density vs. electric field at the center of the filament are depicted in Figure 5 for the range of voltages and temperatures shown in Figure 4. Note that the maximum experimental emission current density of 800 A/cm^2 at $T = 3175^{o}K$ falls within the expected operating range anticipated for large area T F guns.

An error analysis was performed to identify the important parameters and estimate their effect on the emission uniformity to be expected from a large area T F gun. The filament temperature change caused by changes in radius and length for parallel homogenous filaments, excited by a constant voltage source is given by the expression

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(6) J. P. Barbour, W. W. Dolan, J. R. Trolan, E. E. Martin and W. P. Dyke, "Space Charge Effects in Field Emission", Phys. Rev. Vol. 92, No. 1, pp. 45-51, October 1953.

(7) K. R. Chun Private Communication.

(8) W. Hant, "Thermionic Field Emission Diode Experiment", accepted for publication in IEEE Trans. on El. Dev.

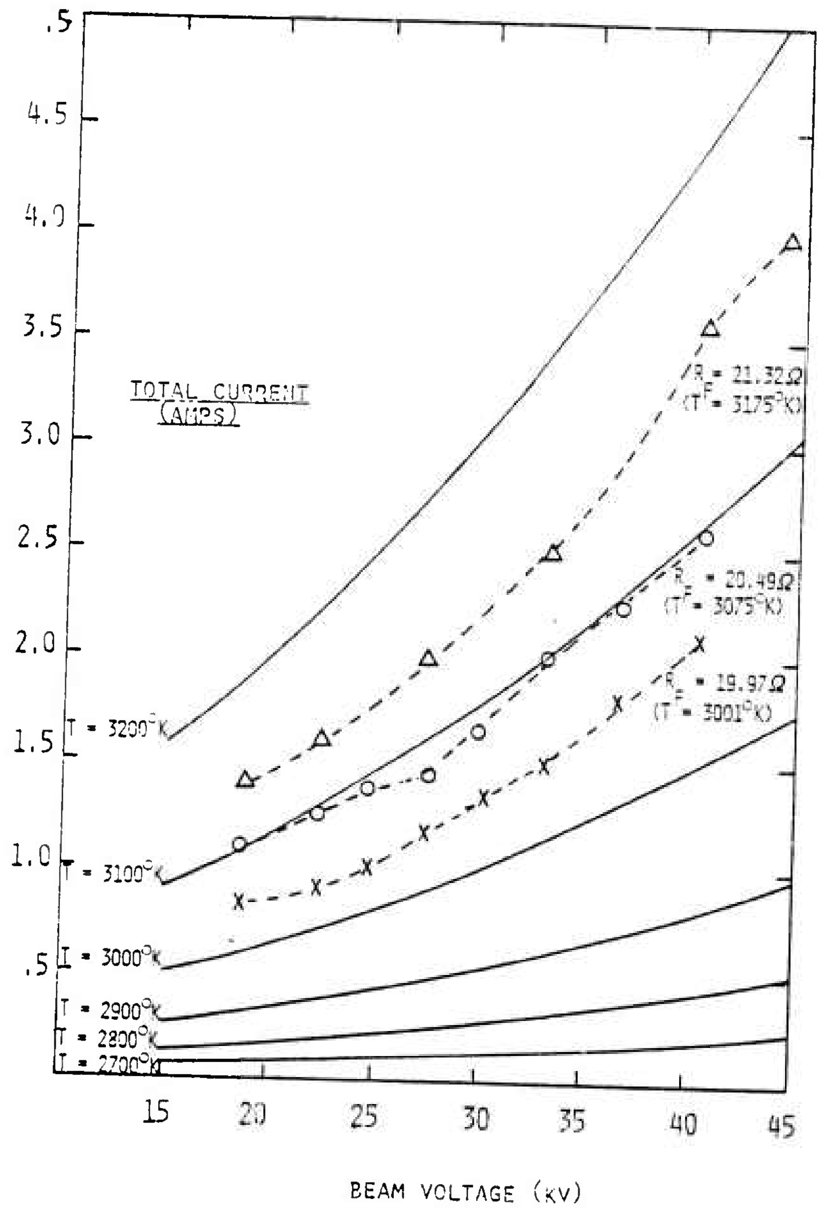

Figure 4. Calculated and Measured Anode Current vs. Anode Voltage for Different Filament Temperatures (Diode Configuration)

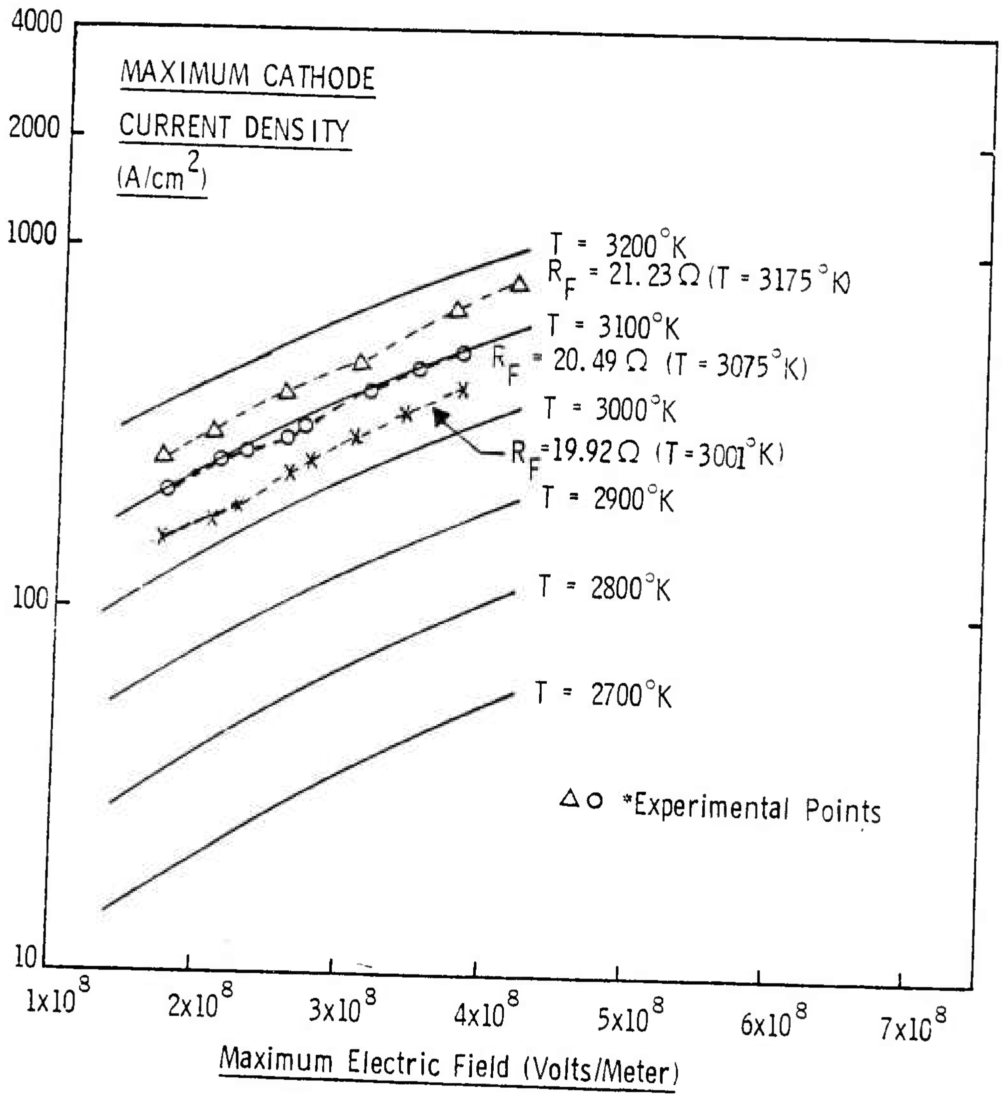

Figure 5. Maximum Cathode Current Density vs Electric Field for Different Filament Temperatures (Diode Configuration)

$$\Delta T/T = \left[(1 + \Delta r/r)(1 + \Delta \ell/\ell)^{-2}\right]^{-(4+\beta)} - 1 \qquad (2)$$

where T = Nominal Filament Temperature

ΔT = Change in Temperature

r = Nominal Filament Radius

ℓ = Nominal Filament Length

β $\approx$ 0.94 for Tungsten-Rhenium

Figure 6 illustrates current density variations, calculated by substituting (2) into (1), for a range of filament electric field, radius and length changes. Since tungsten-rhenium filaments[9] are commercially available with $\pm$0.5% variations in radius, the resultant current density variation is within $\pm$2%. With reasonable care it is possible to maintain $\pm$1% accuracy in filament length and consequently $\pm$ 5% variation in emitted current density from filament to filament in an array. The effect of filament electric field variations, which might be caused by variations in the interelectrode spacings, is the least sensitive of the parameters depicted in Figure 6 and will generally have negligible effect on current density. Variations in current density discussed above are those that can be attributable to the effects of dimensional changes. Potentially the most serious impact on beam uniformity may result from inhomogeneities in the filament material and their effect on work function. The plot of current density variation with work function shown in Figure 7 indicates that 5% decrease in work function accounts for 250% increase in current density. Because of a lack of accurate work function uniformity data for W-Re filaments, it was not possible to theoretically determine the resulting current density variation. An experiment performed to resolve this problem compared the emission currents for separate equal

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(9) GTE Sylvania Metallurgical Products Technical Information Bulletin for W-3% Re Wire 1/71.

Nominal Conditions; T = 3000°K; E = .8 x 10^9 V/m
= 4.5 eV

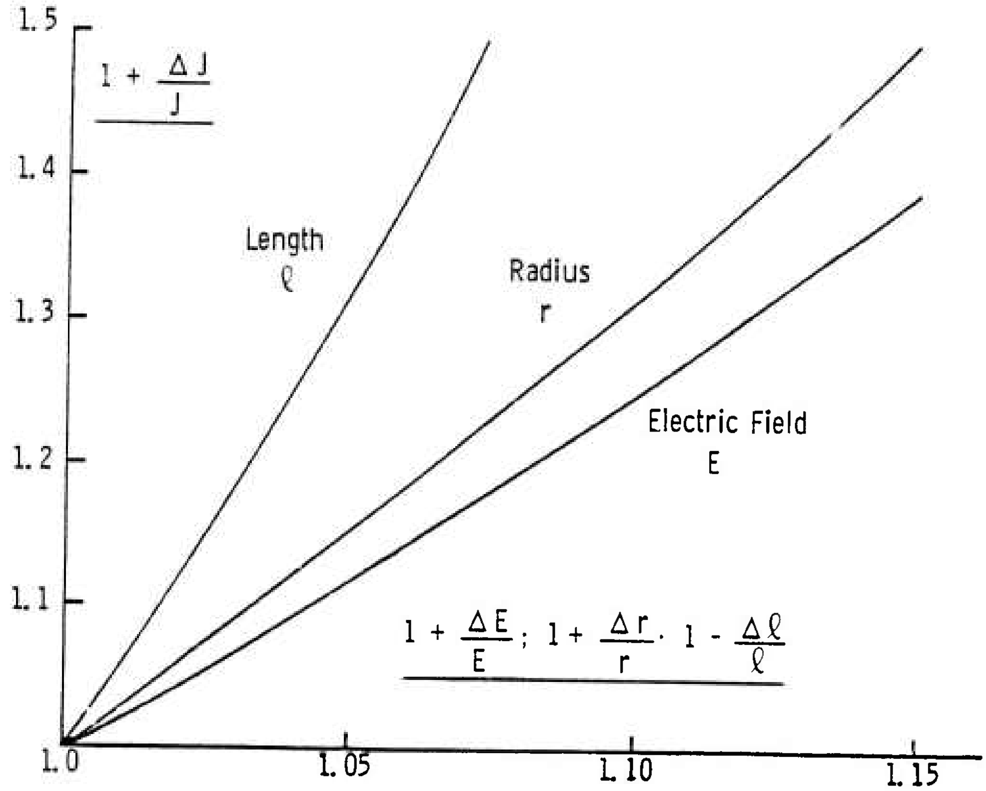


Figure 6. Change of Emission Current Density ΔJ as a Function of Changes in
Electric Field ΔE,
Filament Radius Δr,
Filament Length $\Delta \ell$

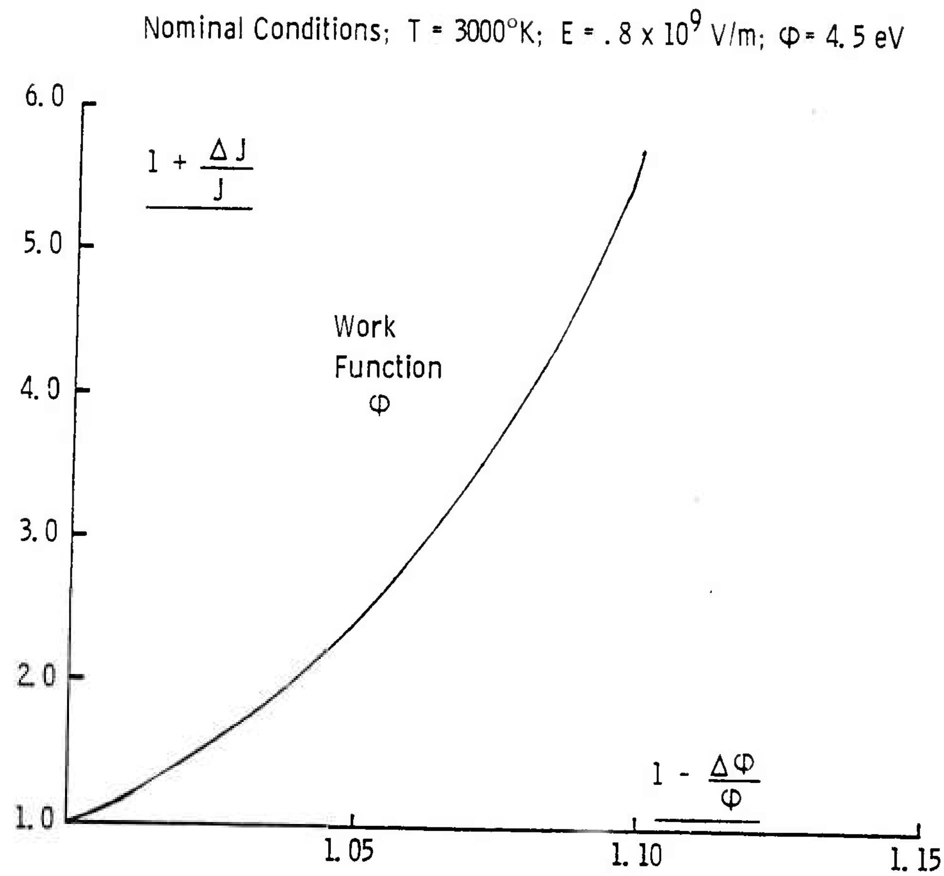


Figure 7. Change of Emission Current Density ΔJ as a Function of Changes in Work Function $\Delta \Phi$

length filaments situated in a common vacuum envelope. Five filaments, excited from a common source, were individually located within concentric anode cylinders and were operated under thermionic emission conditions with negligible space change. This thermionic mode of operation is as sensitive to changes in work function as the TF mode because φ effects only the temperature dependent part of (1). Results obtained from 20 tests indicate that measured emission currents for individual filaments, obtained from random samples supplied by the vendor, were uniform to within $\pm$ 10%. Part of the measured nonuniformity may be attributable to changes in filament lengths resulting from improper clamping. In general, results of the error analysis and emission experiments indicate that with reasonable assembly care, it should be possible to achieve beam uniformities of $\pm$ 10% in a practical array.

Several other studies were initiated during this program. A two dimensional analysis was performed to determine effects of parametric changes in interelectrode dimensions, filament diameters, and filament temperatures on beam current density, and cathode life. Preliminary results indicate that because of trajectory overlap, it may be possible to significantly increase the filament to filament spacings used on the present model gun and thus to simplify future gun assemblies. A three dimensional NASTRAN code analysis was performed to simulate the electrode geometry for the central filament of the present model gun. Calculations of electric field at the filament surface were obtained from a two step procedure which utilizes potentials obtained from the solution of the total problem as boundary points for an expanded region around the filament. Results indicate that the electric field was uniform within $\pm$ 13% over 90% of the 1 cm long filament. Nominally the maximum filament electric field calculated by means of the three dimensional model was 45% of the field calculated for an equivalent two dimensional geometry that neglects edge effects.

Filament Design and Thermal Integrity Tests

A major problem during the preliminary phase of this program was the development of a procedure for bonding thin (.5 mil to 2 mil diameter) filaments to a suitable support structure. Attempts to adapt spot welding techniques, that had been previously implemented successfully for larger diameter filaments, were unsuccessful because of the precise control required for welding thin filaments.

Various other techniques, including laser welding, were also investigated but were discarded because of complexity, expense or unsuitability for large scale implementation. The solution to the filament bonding problem, developed by J. Goldis and adopted for this program, utilizes a mechanical technique of crimping the filaments to concentric collet supports.

Depicted in Figure 8 is a pictorial view of the filament and support assembly of the 1 cm x 4 cm gun which was subsequently used for the high voltage tests. Filaments, initially prebent into a rectangular shape, are inserted into holes in the collets and crimped slightly below the rounded ends. Thus sharp edges caused by the crimps are effectively shielded from initiating arcs to the anode (not shown). The anode is situated above the filaments in a plane parallel to the filaments and the top of the shroud. Thermal integrity tests of the assembly were performed in a bell jar with filaments that were cycled through the entire range between room temperature and $3200^{\circ}K$. These tests yielded satisfactory results and indicated that there was no noticeable distortion of the filaments.

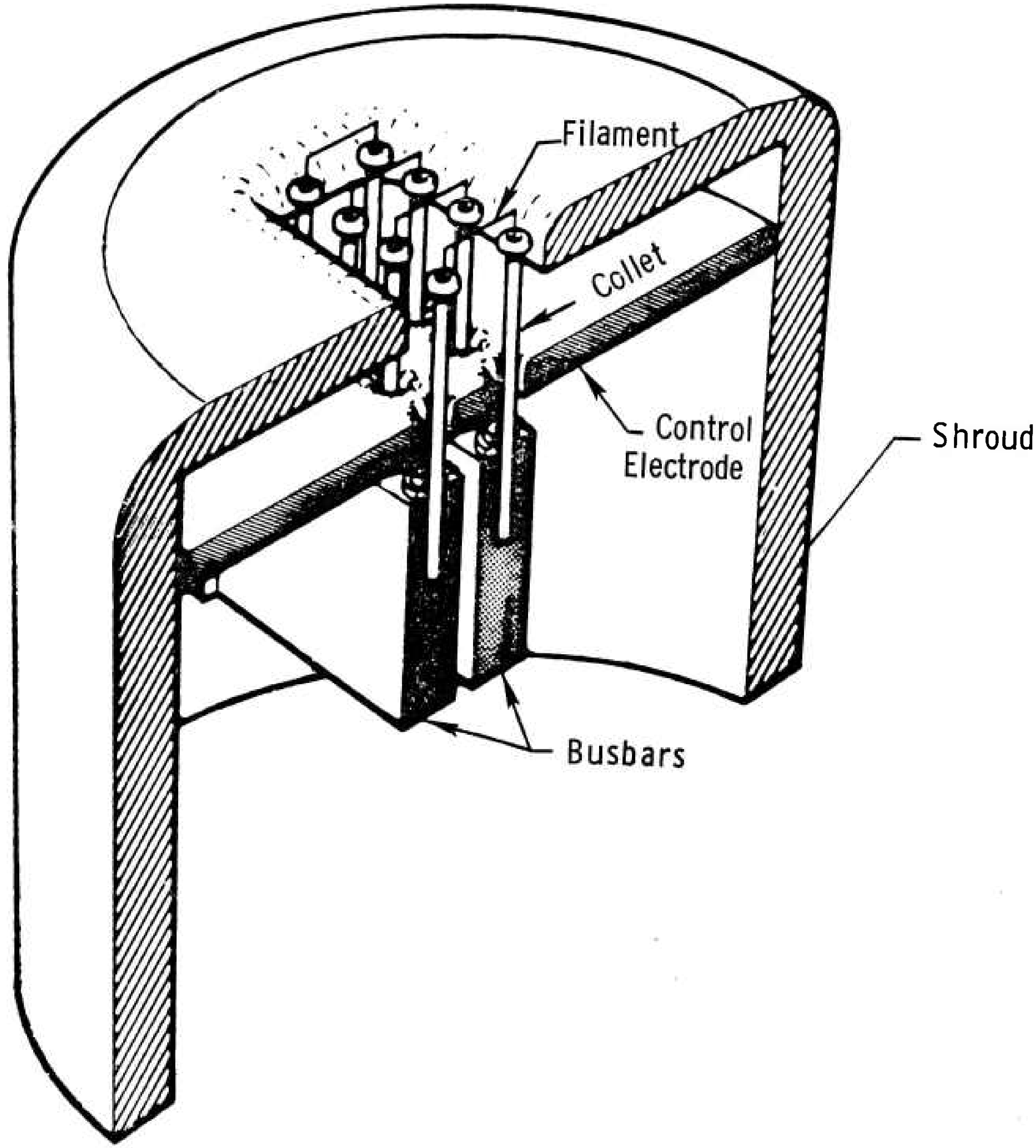


Figure 8. Pictorial View of the (1 cm x 4 cm) Model TF Gun

Test Facility

A photograph of the TF gun test apparatus shown in Figure 9 depicts the stainless steel gun vacuum envelope, aluminum SF_6 gas filled tank that houses the high voltage components, the radiation shield gun test enclosure and the high voltage charging supply. The gun envelope, sorption pumps, 500 liter/sec ion pump, and SF_6 tank were available from previous programs. Modifications to the gun test equipment that were implemented to permit the TF gun tests included; 1) The fabrication of the pumping manifold connecting the vacuum envelope to a high vacuum gate valve and to the sorption and ion pumps, 2) The fabrication of a bottom plate for the gun envelope including an externally adjustable flat disk shape anode, and 3) the assembly of the high voltage capacitive discharge circuit. The capacitive discharge circuit and model gun are shown schematically in Figure 10. Filaments are excited by means of a potentiometer controlled battery supply that may be switched into either a standby or operational mode. The gun is pulsed by means of a capacitive discharge circuit consisting of a .01 μF capacitor connected in parallel to a high voltage 270 ohm resistor. With switches closed, pulsing is initiated when gas breakdown within the series spark gap provides a low resistance path for the stored capacitive energy. With switches open and the spark gap in a non-conducting mode, high voltage is applied directly across the gun in order to condition the electrodes. Total current and anode current are measured by means of Pearson probes located in the ground returns for the capacitor and for the anode circuit respectively. High voltage is determined by the measurement of the ground return current through the 270 ohm resistor.

Test Results

An important consideration in the testing program has been the determination of a processing and high voltage conditioning procedure that is suitable for long life, reliable gun operation.

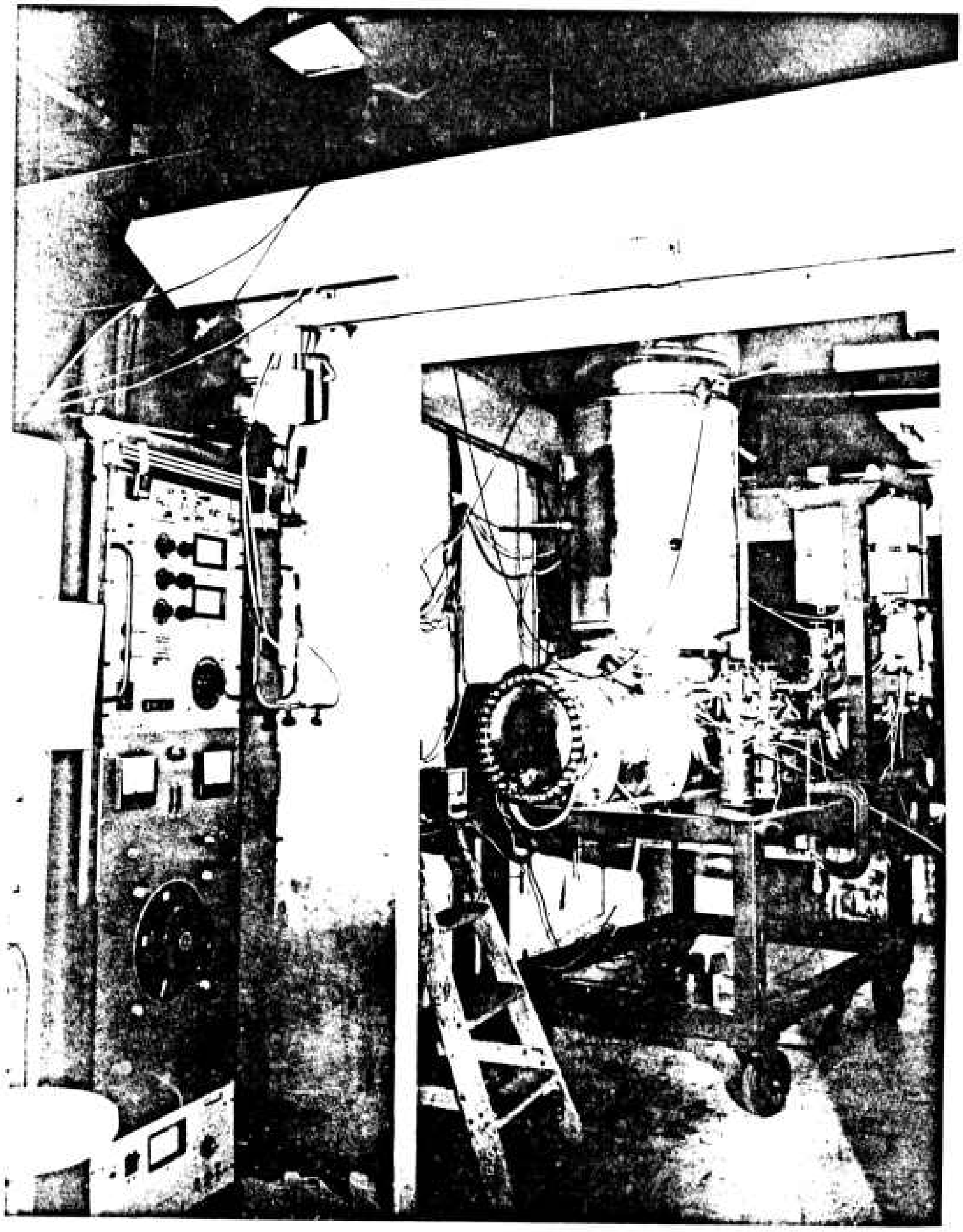


Figure 9 View of the TF Gun Test Apparatus

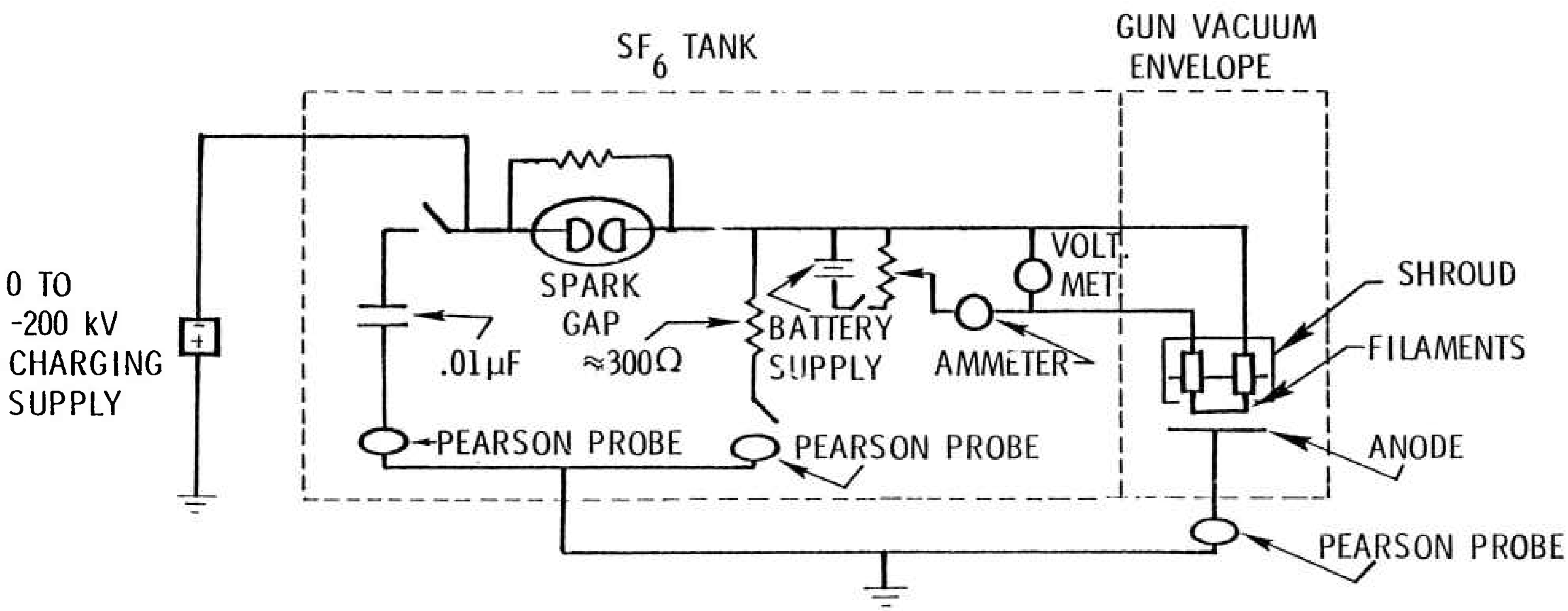


Figure 10. Schematic for the 1 cm x 4 cm Model Gun Experiment

During the initial series of experiments, the gun was high voltage conditioned for several hours at D.C. voltages between 50 kV and 90 kV and at sufficiently low filament temperatures to prevent measurable emission. This conditioning procedure which preceded the high voltage pulse tests resulted in two separate effects. First, the strong D.C. electric field permanently distorted the filaments from the rectangular shape shown in Figure 8 to a shape where the center of the straight emitting filament section is pulled toward the anode. Second, high voltage arcs between the filaments and anode that occurred during the conditioning procedure permanently damaged the filaments. These two effects are shown in the photographs of Figure 11 and 12b respectively. Figure 11 depicts a bell jar view of the filament assembly showing the bent filaments. Figure 12 compares electronmicrographs of three separate filaments that were subjected to various procedures. As initially supplied by the vendor, the filament shown in Figure 12a indicates long horizontal marks caused by a wire drawing die. These marks disappear after filaments are subjected to emission temperatures near 3000°K. Damage shown in Figure 12b is typical of all filaments that were subjected to the D.C. voltage conditioning procedure. Elimination of D.c. high voltage conditioning of the filaments prior to pulse operation was shown to prevent this damage. The ultra smooth section of filament shown in Figure 12c is typical of four filaments that were removed from an 8 filament gun after the gun had been pulse operated for over 40 shots at high beam voltage and full emission current density. Pulsed gun operation also eliminated the filament distortion depicted in Figure 11. Based on these test results, a gun conditioning procedure was adopted that eliminates high voltage D.C. conditioning after the filaments are installed.

The new procedure includes first D.C. high voltage conditioning and high vacuum bakeout of the shroud and anode electrodes prior to filament installation, followed by pulsed conditioning at successively higher beam voltages after the filaments are installed. A preliminary evaluation of this

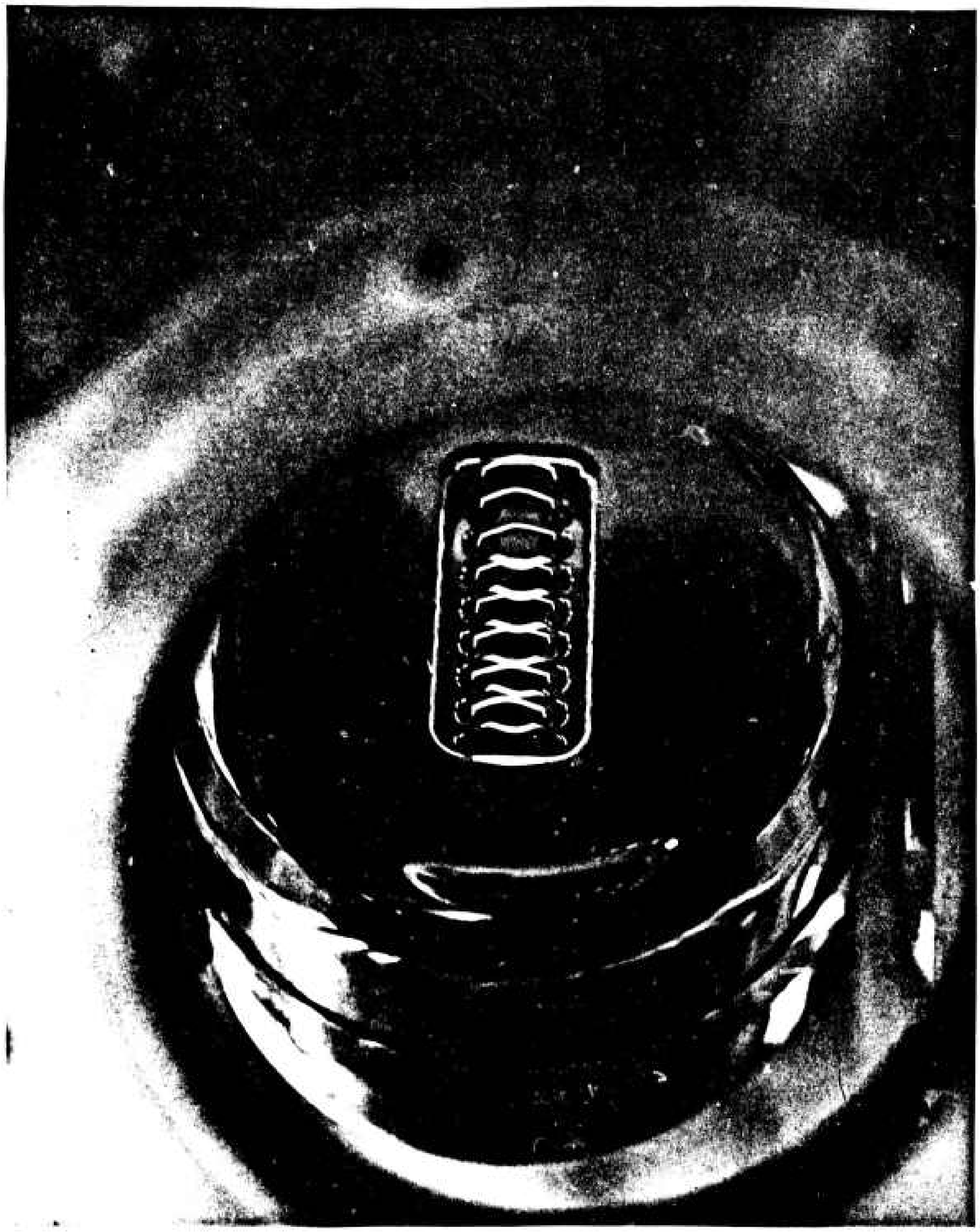
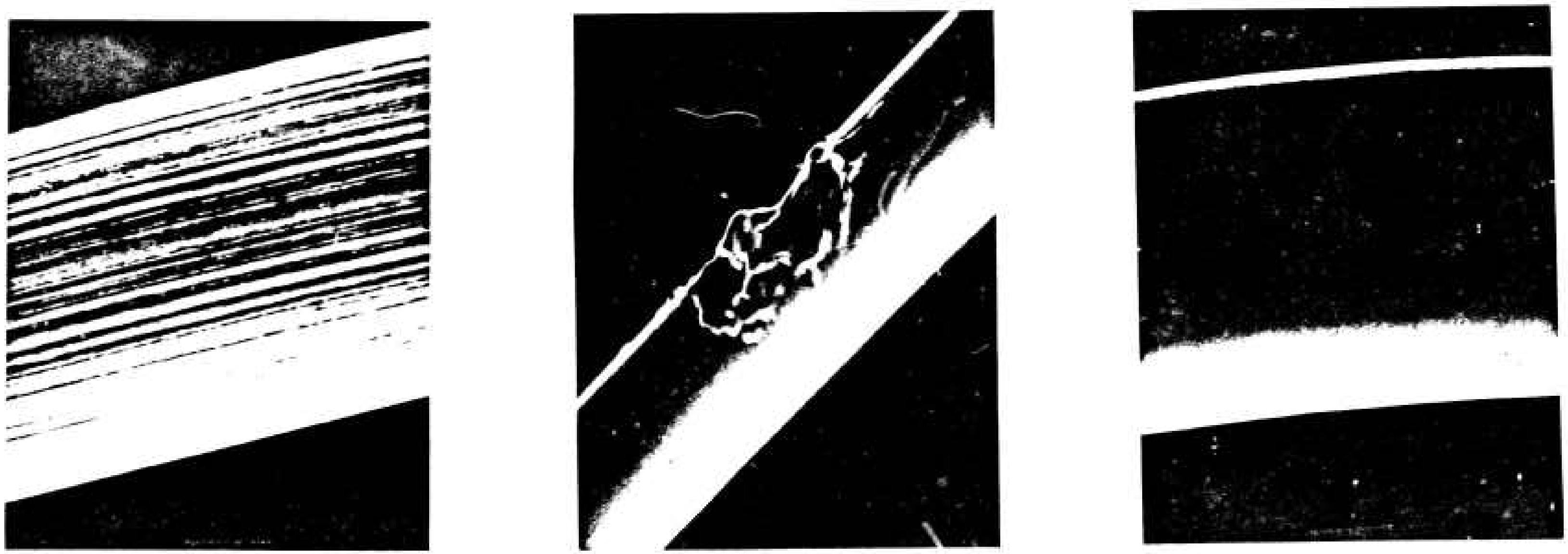


Figure 11 View of the Filament Assembly after Exposure to a D. C. Electric Field



Vendor Supplied Filament (2500X)

(a)

Filament heated to 1500^{0}K and exposed to high voltage DC conditioning (1300X)

(b)

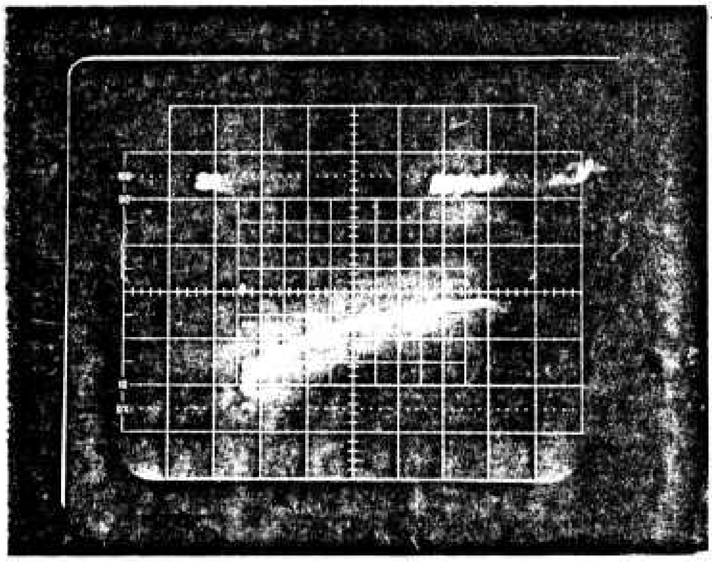
Filament heated to 3000^{0}K and operated at high pulsed voltage (2500X)

(c)

Figure 12 Photographs of different 1 MIL Diameter Filaments procedure performed on a 4 filament gun indicates that no damage was sustained by the filaments during 100 pulses of a high voltage test. Additional, more extensive high voltage life testing is required to fully evaluate and possibly improve the conditioning procedure. A problem still to be solved is the control or elimination of arcs between the anode and cathode structures. Typically these arcs occurred from 600 to 1000 nanoseconds after initiation of the pulse as the gun was operated at successively higher voltages. Direct arcing to the filament near the collet support destroyed the filaments and terminated the tests. If instead, the arc was drawn toward the shroud without damaging the filaments, it was possible to subsequently operate the gun at successively higher voltages and currents without additional arcing. The exact failure mechanism requires further investigation. Future experiments should include the investigation of redesigned filaments for which the cooler sections are situated within a deeper potential well, and the implementation of higher bakeout temperatures for the anode.

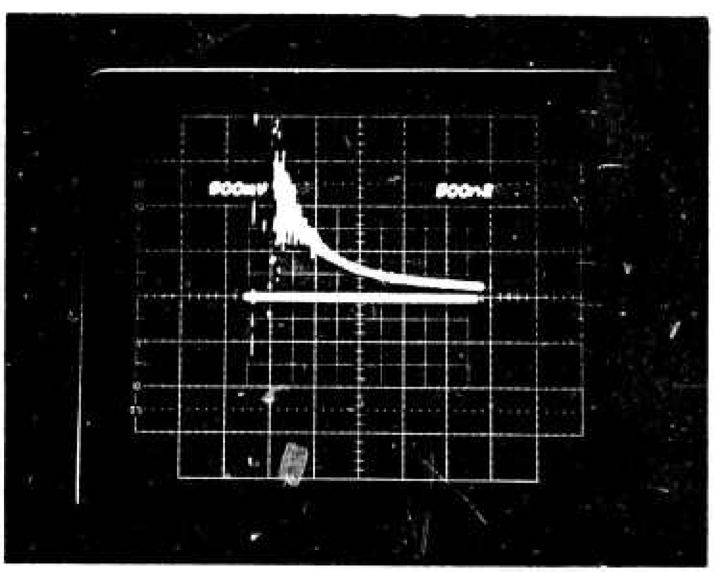
Typical anode voltage and current waveforms obtained for the experiments are shown in Figure 13. Ringing observed during the beginning of the current pulse is attributable to the mismatch between the high diode impedance of the 1 cm x 4 cm gun and the impedance of the connecting transmission line. This mismatch will become less significant for larger area guns with lower impedances.

Measured results of anode current vs. anode voltage for different filament temperatures are summarized in Figure 14 for four separate tests. The first two tests were performed with long term (> 2 hours) D.C. high voltage conditioning of the filaments; the last two tests with pulse conditioned filaments. Filaments for the latter tests were subjected to a short term (≈ 2 sec) D.C. field in order to acquire the bent shape and thus simulate the electrode configuration that resulted for the initial tests. Filament damage



VOLTAGE

CURRENT THROUGH 270 ohm RESISTANCE; .5 μsec/cm



CURRENT

INTERCEPTED BY ANODE; .5 μsec/cm

Figure 13. Typical Anode Voltage and Current Waveforms

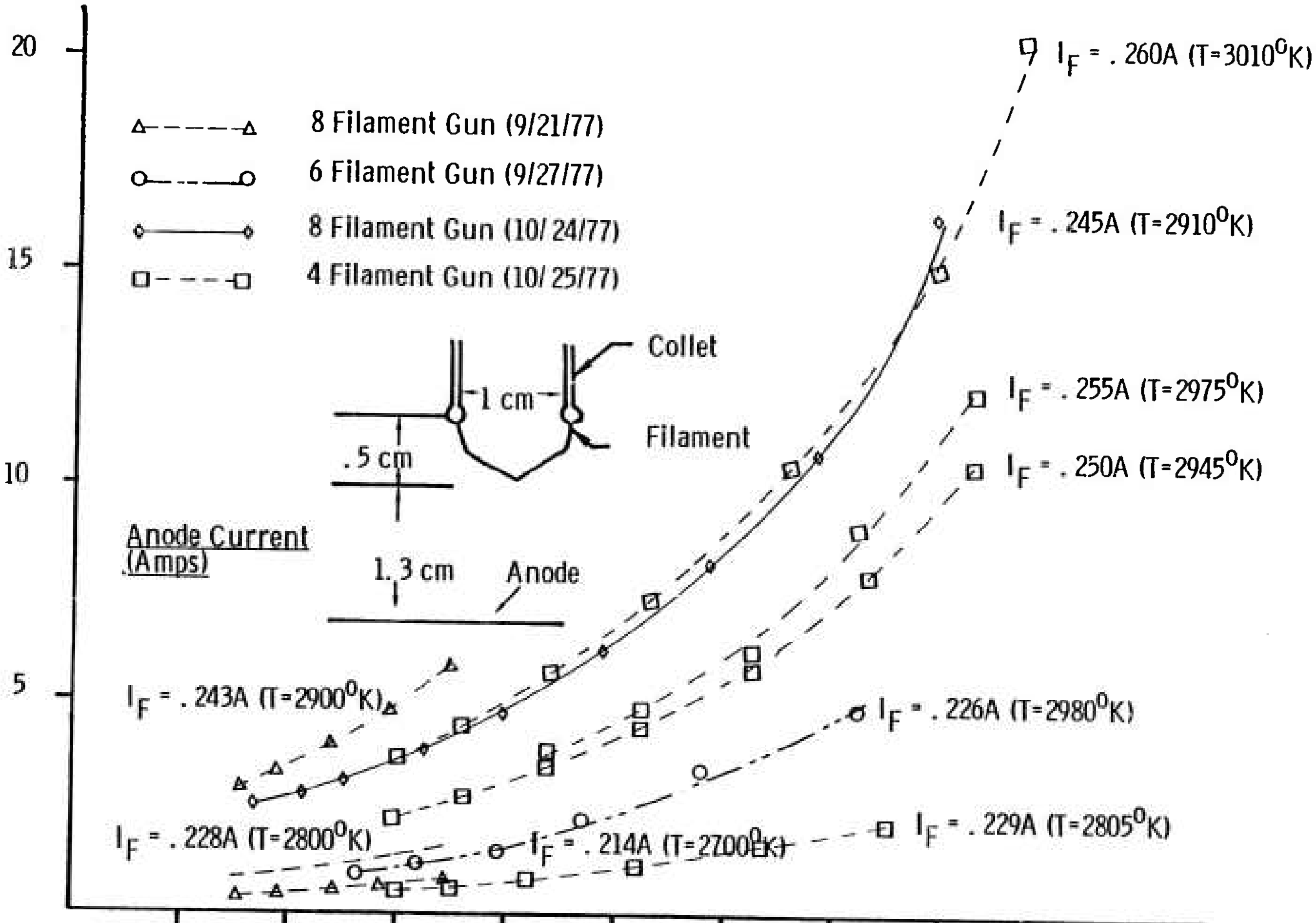


Figure 14. Measured Anode Current vs Anode Voltage for Different Tests of the Planar TF Gun

during this short term exposure was negligible. The highest measured anode current of 20 A was achieved at voltage of 175 kV for a 4 filament gun with 1 cm long filaments spaced .5 cm apart. For the assumption of uniformly distributed anode current over the 1 cm x 2 cm area subtended by the filaments, the average current density is 10 Amps/cm^2. The same experimental results shown in Figure 14 are presented in Figure 15 with anode current averaged over the number of filaments. These results illustrate the expected trend that anode current increases with anode voltage and filament temperature. Both the 8 filament and 4 filament guns were tested with no missing filaments between the first and last filament. The 6 filament gun consisted of 4 filaments, two blank spaces followed by two additional filaments. Because of less electric field shielding for filaments near the blanks, electric field and consequently emission current per filament are higher than for a gun with uniformly spaced filaments. This effect probably explains why the current per filament for the 6 filament gun at 2780^{o}K is higher than for the 4 filament gun at 2805^{o}K.

Conclusions and Suggestions for Further Work

Progress during the initial phase of this program to validate the technology for TF guns was very encouraging. Simple and reliable techniques were developed for shaping of the thin filaments and for their attachment to the collet supports. These techniques are readily adaptable to modularization and automatic assembly procedures that would be required for large area guns. The principle program milestone, to demonstrate TF emission from a planar gun operating at 160 kV beam voltage, was achieved. Experimental results indicate that it is possible to achieve high anode current densities for planar TF guns operated at standard high vacuum conditions and at sufficiently low filament temperatures to avoid appreciable tungsten evaporation. One gun with 1 cm x 2 cm cathode area was operated for over 100 shots with beam voltages to 175 kV and anode currents to 20 A.

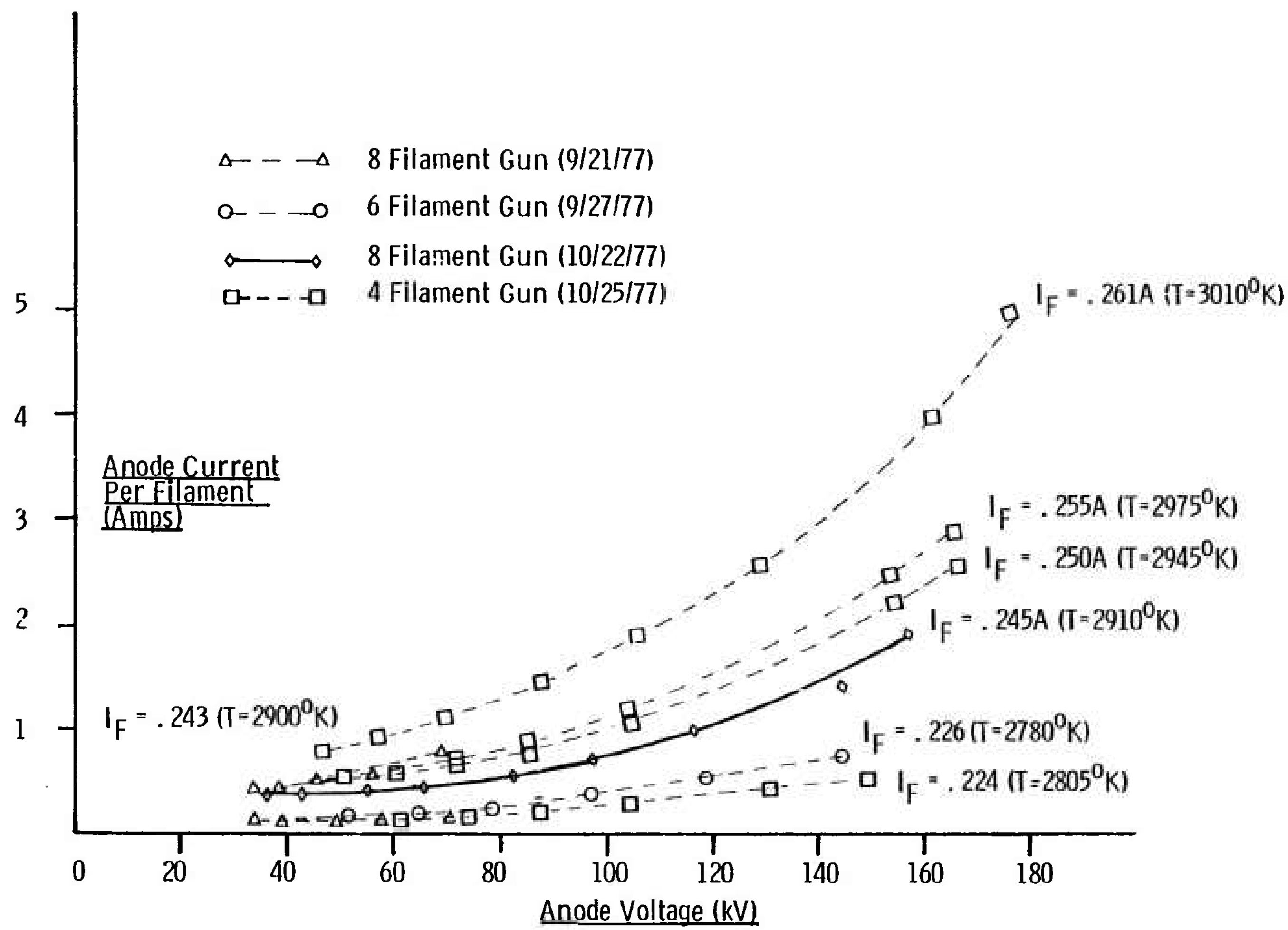


Figure 15. Anode Current per Filament vs Anode Voltage for Different Tests of the Planar TF Gun

Additional work should be performed to either eliminate or control the occasional arcing that was observed during the pulsed high voltage conditioning procedure. Future theoretical emphasis should be directed toward the determination of electron trajectories as calculated from both two and three dimensional models. The objective of this analysis would be to compare the electron optical properties of different beam shaping techniques and to theoretically optimize beam transmission through closely spaced foil and ladder support structures. Finally, effectiveness of the fabrication, arc suppression and beam shaping techniques should be determined experimentally by full voltage, high current density tests of a medium size (10 cm x 10 cm) gun.