7/74

D. 654

UCRL-51482

VOLTAGE HOLDING CONSIDERATIONS FOR DIRECT-COLLECTION UNITS

George H. Miley

December 3, 1973

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

**LAWRENCE
LIVERMORE
LABORATORY**

University of California/Livermore

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ ____*; Microfiche \$0.95

<u>* Pages</u>	<u>NTIS Selling Price</u>
1-50	\$4.00
51-150	\$5.45
151-325	\$7.60
326-500	\$10.60
501-1000	\$13.60

LAWRENCE LIVERMORE LABORATORY
University of California, Livermore, California 94550

UCRL-51482

VOLTAGE HOLDING CONSIDERATIONS FOR DIRECT-COLLECTION UNITS

George H. Miley

MS. date: December 3, 1973

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION STATEMENT IS UNLIMITED

GG

Contents

Abstract	1
Introduction	1
Prior Studies	3
The Experiment	5
Results	9
Emission Currents from Cold Wires	9
Field Enhancement and Whisker Parameters	14
Temperature Effects	16
Polarity Effect	18
Helium-Gas-Pressure Effects	20
Capacitance Effects	21
Breakdown Correlations	21
Cranberg's Clump Hypothesis	24
Slivkov's Model	25
Rabinovitz's Model	25
Limiting Surface - Field Model	26
Kilpatrick's Correlation	26
Summary, Comparison of Breakdown Correlations and Present Data	27
Application to Full-Scale Designs	29
Breakdown Voltages	29
Emission Current Limitation	32
Bombardment Limitation	32
Dynamic Effects	33
Long-Term Damage	34
Recommendation for Future Studies	37
Basic Experiments	37
Bombardment Experiments	38
Mock-up Experiments	39
Acknowledgments	39
References	40

VOLTAGE HOLDING CONSIDERATIONS FOR DIRECT-COLLECTION UNITS

Abstract

Results have been obtained from initial experiments designed to study high-voltage breakdown under conditions of importance to the design of direct-collection units. A coaxial configuration was used to mock-up critical fields near grid wires. With appropriate heat conditioning, fields as high as 9.6×10^5 V/cm were maintained at the surface of a 7-mil-diam tungsten wire. This represents an enhanced field of $\sim 10^8$ V/cm at "whisker" sites. Breakdown criteria

are proposed for three regimes; initial, field-emission, and ultimate, which differ by the amount of prior conditioning applied to the wire. Additional considerations of importance to direct collectors such as the effect of thermionic emission and ion bombardment are discussed.

Further work should be done and specific recommendations are given on basic experiments, bombardment experiments, and mock-up experiments.

Introduction

Direct collection of charged particles from the exhaust plasma of a fusion reactor on high-potential plates is a highly efficient means of energy conversion.¹ Since the voltages required must generally be maintained on relatively high-temperature electrodes which are simultaneously undergoing ion bombardment, problems associated with voltage breakdown could be critical.^{2,3} Thus, the experiments reported here were initiated to study some aspects of such problems.

The overfocused (Post-type) collector,^{1,4} and the venetian blind collector^{5,6} are the two types of direct-collection units of interest at LLL. In

both of these designs the largest electrical fields occur on grid-wire surfaces. In projections for a full-scale over-focused unit, a 815-kV potential difference is maintained on a 0.500-in.-diam grid wire 8.5 in. from the high-voltage collector bucket (Fig. 1). This corresponds to an electric field at the wire surface of 98.4 kV/cm.⁴ In a full-scale venetian blind unit the most critical field occurs at the electron reflector grid (0.025-in.-diam wires), which is held at -13.8 kV while separated from the 90-kV ion collectors by 17 in. (Fig. 2). This corresponds to 66 kV/cm at the wire surface.⁶

The design criterion for the allowable field strength at the wires has been based

Fig. 1. Plot of the potential distribution near the grid wire which operates in the highest-voltage bucket of a full-scale overfocused type unit (taken from Ref. 4).

on an empirical correlation of data from operation of deflector plates in cyclotrons.⁴ However, it is not clear how accurate this criterion is since there are some important differences between the two cases. First, cyclotron deflectors are essentially flat plates (vs the small grid wires). Second, while the inner deflector runs hot due to interception of some of the beam, it serves as the anode so that thermionic emission is suppressed (vs the direct-collector wires which typically run at 1200-1400°C and serve as cathode).

In addition to these differences, it is feared that the grid wires may undergo serious spalling and blistering due to helium bombardment,^{2,3} the helium being

a fusion product (ash) from D-T reactions in the reactor. While this could, indeed, represent a limiting aspect of the design, the present study concentrates on breakdown in cylindrical geometry without

bombardment, but including temperature effects. Once this aspect is fairly well understood, it should be possible to design more meaningful bombardment experiments.

Prior Studies

While the literature on voltage breakdown in vacuum is extensive (e.g. see the general reviews in Ref. 7-10), studies in recent years have largely concentrated on parallel-plate geometry, or in some cases on sphere-plate or needle-point-plate geometries.* Surprisingly little data, and no specific breakdown correlation for cylindrical geometry were found.

The most extensive studies of breakdown by wires were carried out in the 1930s by Ahearn^{11,12} and by Chambers.¹³ Ahearn's results are summarized in Table 1.

These results were too restricted to permit formulation of a breakdown vs wire diameter criterion (Ahearn suggested future experiments to be carried out "with filaments whose diameters were different by a factor of about 10," but there are no indications that he or others did this). Aside from these results, Ahearn reported several important observations, including:

- Breakdown appears to involve a rupture of the cathode structure under the action of local heating and mechanical strain.

*This selection of geometries has been dictated by attempts to study basic breakdown mechanisms. Apparently cylindrical-wire-type geometry is not thought to represent a "clean" situation for such studies.

- The anode had little, if any, effect on breakdown.
- Thermionic emission with the cathode filament below 1400°C had little influence on breakdown.
- Successive breakdowns generally occurred at increasingly higher voltages; however, the field currents also increased following breakdown.
- The increased currents following breakdown could be erased by heating the cathode to 2300°C for several minutes.
- Higher voltages were sustained with the polarity reversed (positive filament).
- The glass envelope containing the filament-collector caused spurious breakdown until it was properly shielded from the filament.
- Breakdown could be suppressed by adding a sufficiently high resistance to the filament circuit ($2.2 \times 10^9 \Omega$ was necessary, vs 10^5 and $10^8 \Omega$ used in most experiments).
- A Fowler-Nordheim β -factor of 120 was obtained for field emission from the 1-mil wire.

Chambers also reported several important observations:

- While field emission normally rose from between 10^5 to 10^{-3} A if the filament was first heated to 2500°C for a

Table 1. Breakdown^a fields for pure and thoriated tungsten filaments reported by Ahearn, Ref. 12.

	Diameter (mil ^b)	Field range (V/cm)	Voltage range (kV)
Thoriated tungsten	1	$1.3 - 2.0 \times 10^6$	11.1 - 17.1
Thoriated tungsten	1	$1.2 - 2.6 \times 10^6$	10.3 - 24.2
Pure tungsten	1	$2.0 - 2.8 \times 10^6$	16.7 - 23.4
Pure tungsten	0.6	$1.5 - 2.67 \times 10^6$	8.4 - 14.9

^aAhearn defines breakdown as the point where the field current suddenly rises by a factor of 10^4 to 10^7 . This differs somewhat from the present experiments which continued until an actual arc was obtained.

^b1 mil = 0.001 in.

Table 2. Breakdown data from tungsten filaments reported by Chambers, Ref. 13.

Wire diameter ^a (mil)	Breakdown voltage (kV)
0.5	11
1.6	23

^aThe diameter of the anode used in these experiments is not listed, but based on sketches of the apparatus, a 2-in. diam will be assumed in order to obtain field values for later comparisons.

brief period, no measurable current (10^{-11} A) was observed prior to breakdown.

- To explain the above point Chambers proposed that breakdown occurred by the emission current (even though $<10^{-11}$ A) freeing positive ions (possibly from absorbed gases) from the anode. The ions then would bombard the cathode, initiating breakdown. As supporting evidence, he found that heating the anode cylinders in an induction furnace allowed the 0.5-mil wire to stand voltages up to 25 kV, although an hour after the heating, breakdown again occurred at 11 kV. Chamber's

breakdown data are summarized in Table 2.

The most recent experiments involving wires are studies by Brodie and Weissman¹⁴ and Maley.¹⁵ However, they were not interested in breakdown, per se; rather, they used the projection screen technique* to study pre-breakdown currents and mechanisms. Brodie and Weissman were mainly interested in the technique itself, but they report that the emission spots from a tungsten wire fluctuate in intensity as various regions activate and deactivate. Further, as the field was increased a given spot typically approached a maximum intensity, then disappeared altogether, indicating whisker "blow-up" or evaporation.

Maley¹⁵ used this technique to compare various methods of conditioning the wire to obtain higher breakdown values. His results are summarized in Table 3. It is seen that heat conditioning leads to

*This technique employs a cylindrical glass anode internally coated with a phosphor, covered on its surface with a thin aluminum film to provide electrical contact. Field emission patterns can be observed from luminescence as electrons strike the anode.

Table 3. Comparison of wire parameters following various conditioning processes (after Maley, Ref. 15). All data are for a 5-mil tungsten filament.

	Conditioning process		
	Electrical ^a	Gas ^b	Heat ^c
β for F-N field emission	110 - 182	53 - 120	198 - 550
Area (cm ²) for field emission	$8 \times 10^{-11} - 4 \times 10^{-8}$	$1 \times 10^{-9} - 7 \times 10^{-6}$	$1 \times 10^{-13} - 9 \times 10^{-11}$
Whisker height (cm)	$2 \times 10^{-4} - 6 \times 10^{-4}$	$5 \times 10^{-6} - 3 \times 10^{-4}$	$6 \times 10^{-4} - 1 \times 10^{-3}$
Critical field (V/cm)	$4.1 \times 10^{-7} - 6.3 \times 10^7$	$3.6 \times 10^7 - 4.1 \times 10^7$	$6.5 \times 10^7 - 7.8 \times 10^7$
Whisker density	25/cm ²	250/cm ²	5/cm ²

^aIncreasing voltage in increments of 12 kV/min.

^bDischarge at 10-15 kV, 5×10^{-5} A with 10^{-4} Torr N₂ for 30 min.

^c700°C for 10 min.

a slightly better voltage holding. This is apparently due to a lower number of whiskers per unit area. However, the remaining whiskers are larger and lead to enhanced field emission (larger β -values).^{*} Maley, like Brodie and Weissman, observed spot "blowup" and noted that such discharges, being self-limiting, are "not like breakdown with planar diodes." He suggests that blowup, which Brodie¹⁶ proposes as the mechanism

that initiates breakdown with nickel electrodes, also causes breakdown for tungsten.

In conclusion, while prior studies provide some important facts about breakdown in a cylindrical configuration, the data is insufficient to devise a breakdown correlation for use in direct-collection design studies. Thus, the experiments described below were designed as an initial step in this direction.

The Experiment

A photograph of the filament-collector setup is shown in Fig. 3 and a schematic of the electronic setup is shown in Fig. 4. Commercially available tungsten wire was used for filaments. The surfaces of the stainless steel anode were electropolished after machining, and all edges, including those on the viewing slots, were carefully

rounded. This unit was placed in a glass vacuum tee. Using a combination liquid nitrogen trap and vac-ion pump and very clean surroundings, vacuums to 10^{-7} Torr were obtained. A grounded mesh wire screen was placed inside the glass tee to isolate the test section from the glass enclosure. All vacuum surfaces were carefully cleaned with solvent to remove oils prior to insertion, but as described later the filament was ultimately cleaned and conditioned by in-place heating.

The actual length of the wire contributing to the current collected by the

^{*}As indicated in Table 3, the heat conditioning technique employed by Maley involved lower temperatures and shorter treatment times than we employed. As described later, indirect evidence indicates that the present technique essentially eliminates all whiskers.

Fig. 3. Sketch of the experimental apparatus used for coaxial breakdown measurements.

Fig. 4. Electrical circuits used in the experiment.

3-in.-long anode is somewhat ambiguous in this arrangement. However, since relative values are generally of interest, the addition of top and bottom guard rings was not attempted. The HYPOT* high voltage supply (Model No. 5280 M5) we

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

used was well suited for these studies since protective circuitry automatically crow-bars the output once an arc occurs. Measurements indicated that the effective internal resistance of the HYPOT was about $6 \times 10^6 \Omega$. A 7-ft high-voltage cable was connected from the supply to the test unit. With this setup, most of the energy dumped into the breakdown arc probably originated from capacitive storage in the filament-anode and the

high-voltage cable. This was estimated to be about 0.1 J at 20 kV.

Inclusion of a Keithley $\mu\mu$ ammeter in parallel with the HYPOT ammeter allowed measurements of filament emission currents ranging from 10^{-12} to 10^{-3} A. Voltages were read directly from the HYPOT.

The low-voltage filament supply was used to heat the wire to temperatures as high as 1200°C ; however, above 1200°C thermionic emission exceeded the 2.5-mA limit of the HYPOT.

As summarized in Table 4, several hundred tests were run to breakdown (defined as sufficient arc to trip the protective circuit of the HYPOT^{*}) with 1-, 2-, 4-, and 7-mil wires. Some difficulty was encountered with physical breakage of the smaller diameter wires, but the 4- and 7-mil sizes held up very well.

^{*}On several occasions brief sparks or even microdischarging was encountered which did not draw sufficient current to trip the HYPOT circuit. In such cases the voltage was increased further until complete breakdown occurred.

As will be apparent from the discussion of results, a variety of modes of operation were investigated. In a "typical" run the voltage was increased in increments of 2 kV and the current-voltage readings recorded. Each run required about 0.5 min.

Several observations that pertain to the validity of the experimental design should be noted. First, throughout the study a second worker visually observed the arc-breakdown. A majority of the arcs occurred within the filament-anode region as desired. In a few cases the origin of the flash could not be identified or it appeared to occur on the edge of the anode, higher on the wire or flange, etc. Such runs were discarded. The unit was designed to withstand 45 kV,^{*} and in one test a 7-mil wire was held at 48 kV for 10 min while drawing a current of less than 10^{-9} A.[†] Since most of the

^{*}The high voltage lead-through (Ceramaseal No. 802A0690) was rated at 43.8 kV RMS. Corona began to appear at about 45 kV with the present connections.

[†]In other runs, voltages up to 30 kV have been attained with currents less than 10^{-12} A.

Table 4. Summary of wires studied.

Run No.	Diameter (mils)	Number of breakdowns	Final status
1	7	53	intact
2	1	43	broke
3	1	2	broke
4	2	4	broke
5	2	8	broke
6	2	7	broke
7	4	22	broke
8	4	20	intact
9	4	114	intact

emission currents observed in the present work exceed this, stray leakage was not considered to be a problem in the measurements.

In cases where field emission currents exceeded about 10 μ A, glowing red spots could frequently be observed on the inner surface of the anode (these spots apparently correspond to those observed by Brodie and Weissman and by Maley using the projection screen technique described earlier). The spots varied from circular outlines to long skinny streaks. New spots appeared at higher voltages. Several times the breakdown arc was observed to be associated with a spot.* Occasionally certain spots disappeared after breakdown.

One concern was that the centering of the filament might be critical. This was found not to be so. It was possible to cause the wire holder to vibrate by stomping on the vacuum-pump platform. This was done numerous times and in no instance did the vibration cause either breakdown or disruption of the portion of the anode spot distribution which was observed visually.

Another concern was that the edges of the anode, its view slits, or other geometrical imperfections might disturb the measurement. One indirect indication that this did not occur is that the anode spots were generally randomly located, although in a few instances, spots did occur near electrode edges.

The fear that the small magnetic field associated with the filament heating current might influence breakdown was also unfounded. The filament power supply could be switched on and off at voltages near breakdown without causing breakdown.

Filament temperatures were read with an optical pyrometer. They should only be considered as approximate values since corrections for such things as viewing through the glass tee and for possible reflective films inside the glass were not attempted. The thermionic currents measured for various runs were considered to be the most important data rather than the precise temperature. In fact, temperatures can be calculated quite accurately from the measured thermionic current, and this technique was used in some cases.

Results

EMISSION CURRENTS FROM COLD WIRES

Typical semilog plots of the emission current vs the reciprocal of the applied voltage for the four different wire sizes are shown in Figs. 5-8. The runs shown

were selected and plotted somewhat at random during the progress of the experiments. All of the wires showed the same general behavior, which we will discuss by reference to the 7-mil-wire data (Fig. 5).

First consider operation with the filament cold. The following three distinct regimes of operations can be observed:

- Initial operation prior to extensive conditioning.

* Only a portion of the inner surface of the anode was open to observation. Thus, some arcs may have occurred at hidden spots. In other cases it was simply impossible to identify the exact origin of the arc.

Fig. 5. Current-voltage plots for 7-mil wire. Run numbers and filament temperatures (in parentheses) are indicated. A slash denotes breakdown. Dotted continuation means that the run was repeated immediately following initial breakdown, e.g., 6a followed 6.

Fig. 6. Typical current plots for the 4-mil wire (nomenclature as per Fig. 5). Run 5A, at 1200°C, was the highest temperature run in this series. It achieved 25 kV without breakdown. Runs 6A, 44C, and 3G were all with different wires, and this, plus variation in prior treatment, accounts for the large differences noted.

Fig. 7. Current-voltages plots for 2-mil wire (nomenclature as per Fig. 5).

- Field emission operation after moderate conditioning by heating and successive breakdown (or following a breakdown during operation in the third regime).

- Ultimate operation following lengthy heat conditioning.

Figure 5 illustrates that during initial operation large ($>10^{-5}$ A above 10 kV), somewhat erratic emission currents

Fig. 8. Current-voltage plots for 1-mil tungsten wire (nomenclature as per Fig. 5).

were obtained, and breakdown occurred at relatively low voltages. This is, as might be expected prior to conditioning, due to a combination of absorbed gases and "rough surfaces."^{*}

After heating the wire to about 800°C for 20 min and carrying out some

^{*}In addition to solvent cleaning prior to insertion, the wire had been maintained at 10^{-7} Torr overnight.

additional breakdown operation, run 11 was obtained. It is associated with field-emission operation because of the characteristic exponential increase in current for voltages above ~25 kV. Below 25 kV, currents were generally $<10^{-9}$ A, four orders of magnitude smaller than those obtained in the initial runs.

After further conditioning of the wire by heating it at 800°C overnight, run 12 was obtained. This run is with the filament slightly heated, but this is not thought to be important. In fact a similar result was obtained later with the filament cold and the current 10^{-11} A. In run 12 no field emission was observed prior to breakdown which occurred at 47 kV, one of the highest values obtained with this wire. Note that before conditioning, run 7 which was similar in all other respects, showed field emission above about 25 kV. Likewise, immediately following the breakdown in run 12, run 13 again showed field emission.

Based on these observations, it would appear that the extended heat treatment essentially removed the whiskers that cause field emission from the surface. Hence such a run is termed ultimate operation here. However, once breakdown occurred, new whisker sites were apparently created, causing the field emission to reappear in run 13.

Ultimate operation was obtained with the other wires by similar conditioning; however, conditioning did not always completely succeed. For example, in Runs 1D (Fig. 7; 2-mil wire) and 43A (Fig. 8; 1-mil wire), field emission was delayed, but did begin to appear just prior to breakdown.

The possibility of ultimate operation is consistent with Chambers' observation, noted earlier, that no current flowed until after a breakdown if the wire was conditioned (in his case) at 2500°C for a few minutes. We have simply employed a longer heating period at lower temperatures. This may be advantageous since high temperature operation can weaken the filaments.

FIELD ENHANCEMENT AND WHISKER PARAMETERS

Assuming that the exponential increase in current is due to field emission from whisker sites, it is possible to obtain some information about the whiskers by application of the Fowler-Nordheim (FN) field emission equation.¹⁷ The emission current I_{FN} is given by

$$I_{FN} = \frac{1.54 \times 10^{-6} A K^2 V^2}{\phi t^2(y)} \times \exp \left[- \frac{6.83 \times 10^7 \phi^{3/2}}{KV} v(y) \right] \quad (1)$$

$$K = \beta / \left[r_1 \ln \left(\frac{r_2}{r_1} \right) \right], \quad (2)$$

where A is the emission area in cm^2 , ϕ the work function (4.53 eV for tungsten), V is the applied voltage in volts, r_1 is the filament radius, and r_2 is the inner radius of the can (stainless steel anode). The two functions $v(y)$ and $t(y)$ depend in a complicated fashion on the voltage; however, as shown in Ref. 17, they are essentially unity for the range of parameters considered here. The quantity K defined in Eq. (2) is used to convert the

voltage V to the actual field at the whisker sites. It consists of a product of β , the field-enhancement factor due to the higher fields associated with the whisker tips, and the geometrical factor $[r_1 \ln(r_2/r_1)]^{-1}$ which converts the voltage to the field intensity for a smooth surface wire.

Differentiation of Eq. (1) gives

$$\frac{d(\ln I/V^2)}{d(1/V)} = - \frac{6.83 \times 10^7 \phi^{3/2}}{K} s(y) \quad (3)$$

$$s(y) = v(y) - \frac{y}{2} \frac{dv(y)}{dy} \quad (4)$$

In the present case $s(y)$ can be taken to be unity with good accuracy. Thus K , hence β , can be determined from the slope of a plot of $\ln I/V^2$ vs $1/V$ (the traditional "Fowler-Nordheim" or F-N plot).

Further, the emission area A can be found by using this value of K and solving Eq. (1) with the measured currents.

Typical F-N plots for the various wires are shown in Fig. 9,^{*} and calculated

values of β and A are given in Table 5. Enhancement factors (β) ranging from 85 to several hundred are observed while the fraction of the total surface area associated with emission may only be 10^{-11} to 10^{-12} . These results are generally consistent with values reported earlier by Alpert et al.¹⁸ for flat tungsten electrodes. While there appears to be some tendency for the enhancement factor to decrease with increasing wire diameter, no firm conclusions are possible. The whiskers depend strongly on the conditioning and prior breakdown history of a wire (e.g. note the variation in values for the

^{*}Within the accuracy of the experiment it is not possible to determine whether a plot of I vs $1/V$, as shown earlier, or the F-N plot (I/V^2 vs $1/V$) provides the best fit. Other workers have observed this difficulty, and in fact Chatterton¹⁰ points out that an equally good fit is often obtained with a Schottky-type plot of $\ln I$ vs $V^{1/2}$. Thus, such plots cannot be used to uniquely define the mechanism involved, but F-N emission is generally accepted as the explanation for prebreakdown currents.

Table 5. Whisker and enhancement parameters.

Wire diameter (mils)	Av field enhancement factor, β	A_T , wire surface area (cm ²)	A , whisker area (cm ²)	A/A_T , fractional whisker area
1	240	0.061	2.02×10^{-13}	3.31×10^{-12}
2	125	0.122	2.74×10^{-12}	2.24×10^{-11}
4	150 (340) ^a	0.243	1.70×10^{-11} (7.97×10^{-13})	6.98×10^{-11} (3.22×10^{-12})
7	85	0.426	2.19×10^{-12}	5.15×10^{-12}
b	59-211	9.62	2.8×10^{-11} to 3.0×10^{-10}	2.9×10^{-12} to 3.1×10^{-11}

^aValues for 4-mil wire after extended operation.

^bValues reported by D. Alpert et al.¹⁸ for parallel plate tungsten electrodes with gaps from 5×10^{-3} cm to 0.4 cm.

Fig. 9. Typical Fowler-Nordheim plot of the field-emission regime measurements.

4-mil wire). It was not possible to exactly duplicate conditions from one wire to the next, hence the values shown should only be considered as approximate.

TEMPERATURE EFFECTS

The effect of heating the filament can best be seen by reference to the 7-mil-wire data shown earlier in Fig. 5. Comparison of runs 7, 6, and 8 at 770°C, 1000°, and 1200°C, respectively, shows that the thermionic-emission current dominated at lower voltages (the relatively flat portion of these curves), but for runs 6 and 7, there is a clear transition to field emission at ~30 kV and 25 kV respectively. In the higher temperature run (1200°C) thermionic emission dominated up to the breakdown point;

however, breakdown still occurred at roughly the same value as for cold wires. Similarly, for the other wires studied, temperatures up to 1200°C (the maximum used here) did not affect the breakdown voltage within the accuracy of these measurements.

The explanation for these observations appears to be that thermionic emission originates fairly uniformly from the wire surface (some enhancement occurs at grain boundaries, but this still leads to a

Fig. 10. Current-voltage plots for various temperatures obtained in early experiments by Ahearn.¹²

gross uniformity) as opposed to field emission which originates from whiskers occupying only a small fraction of the total area (see Table 5). Thus, while the total thermionic current may exceed the total field-emission current by several orders of magnitude, the current density of the latter remains much larger. For example, using whisker areas from Table 5 we see that field-emission densities can exceed 10^8 A/cm² at the whisker vs a maximum thermionic current density of 10^{-2} A/cm². Breakdown then appears to be controlled by the highly localized field emission.

The preceding remarks apply to cases where the measurements were made shortly after heating the filament. As stressed earlier, lengthy baking of wires above 800°C can affect breakdown in the sense that whiskers can be annealed from the surface. Even with some thermionic emission no field emission is observed prior to breakdown (Run 12, Fig. 5, the "ultimate" regime of operation).

These observations are entirely consistent with the earlier measurements by Ahearn¹² which are reproduced in Fig. 10.* His data indicates that similar behavior extends to 1700°C.

More recently Slivkov¹⁹ reported the effect of lower temperatures (<800°C) on flat electrodes made of iron, nickel, copper, and aluminum. He found an initial increase in the breakdown voltage which he attributes to desorption of

gases. However, above 500°C for Fe and Ni, 250°C for Cu, and 150°C for Al, the breakdown strength was lowered, possibly due to a corresponding decrease in mechanical strength for these metals. Similar effects were not observed in the present work, probably due to the superior mechanical strength of tungsten during heating and the fact that surface gases had already been removed by conditioning.

It is interesting that Slivkov also observed a slight decrease (~20%) in breakdown strength upon heating the anode. He states that this is not understood but may be associated with increased transfer of material from anode to cathode.

In an indirectly related study, Brodie²⁰ has shown that the presence of a dispenser-type thermionic cathode near two, cold, high-voltage electrodes caused a marked decrease in breakdown strength. This is attributed to the transfer of minute quantities of material from the thermionic cathode to the high voltage surfaces.

Since currents as well as breakdown are important in direct collector design, the voltage at which thermionic and field currents are equal is of interest. The Richardson equation for thermionic emission, including the Schottky effect is²¹

$$I_{TH} = A_{TH} C_1 T^2 \exp\left(-\frac{e\phi - b\sqrt{E}}{kT}\right). \quad (5)$$

where A_{TH} is the emission area, C_1 is a constant (≈ 60 A·cm⁻²·°K⁻² for tungsten), ϕ is the work function in eV, T is the temperature in °K, and E is the electric field at the surface. While the point remains debatable, we will assume here that the field E is the average surface value rather than the enhanced field for

*The cyclotron work noted earlier also involved a heated electrode; but since it was the anode, thermionic emission was retarded by the field. Thus Ahearn's study appears to be the only prior work involving breakdown in the presence of large thermionic currents.

whiskers (the latter undergo true field emission rather than Schottky emission). Then the field dependence of Eq. (5) can be ignored, and equating Eqs. (5) and (1) we obtain

$$-\frac{b_1}{KV} + \frac{b_2}{kT} = \ln \frac{C_2 T^2}{K^2 V^2}, \quad (6)$$

where b_1 , b_2 , and C_2 are appropriate groupings of constants, K is defined by Eq. (2), and k is the Boltzmann constant. Over a limited range of temperatures and voltage, the logarithmic term is roughly constant, hence,

$$\frac{d(1/KV)}{d(1/T)} \approx \frac{b_2}{b_1}. \quad (7)$$

A plot of β/KV vs $1/T$ corresponding to the observed transition from thermionic to field emission is shown in Fig. 11.^{*} The points shown are quite approximate since in addition to normal fluctuations, the precise transition point is difficult to determine.

The preceding analysis is highly simplified, the transition from thermionic and Schottky emission to field emission being the subject of fairly intense theoretical study (see Refs. 17, 22, and 23). For example, Good and Müller¹⁷ have derived an expression for the transition which is similar to Eq. (7), namely:

$$KV > 8.83 \times 10^3 \phi^{1/2} T, \quad (8)$$

^{*} Due to the uncertainties in β , it is treated as a constant in this plot, and this may account for some of the variation with wire size. Note that β/KV is simply $1/E$, where E is the surface field without an enhancement correction.

where ϕ is the filament work function in eV and the other symbols are as before. The theoretical basis for this equation is that for higher temperatures (or lower fields) the current is mainly carried by electrons with energies above the Fermi level so that F-N field emission theory is no longer valid. However, as seen from Fig. 11, the slope predicted by Eq. (8) does not agree very well with the present data.

POLARITY EFFECT

If the polarity of the high voltage was reversed such that the outer can served as the cathode and the filament was the

Fig. 11. Transition voltage where field emission first becomes comparable to thermionic emission as a function of temperature.

Fig. 12. Effect of polarity on the emission current from 4-mil tungsten wire (nomenclature by curves indicates run number, polarity of the outer can relative to filament, and filament temperature; a slash indicates breakdown).

anode, the breakdown strength increased by about 20% (see Fig. 12). In this case prebreakdown currents were quite small, increasing to only 10^{-7} A just prior to

breakdown. This is several orders of magnitude lower than the current observed with the standard polarity. Similar effects were obtained with the filament heated.

Actually, the fact that breakdown occurs as low as 40 kV with reversed polarity is somewhat surprising and must be considered when evaluating breakdown mechanisms. The electric field at the can surface is a factor r_1/r_2 smaller than at the filament. Thus in the present case, at 40 kV, the field at the can is about 2.5×10^3 V/cm compared to about 1.2×10^6 V/cm at the filament (not including whisker enhancement effects). Thus it seems unlikely that the field at the can (the cathode in this case) could be the determining factor in breakdown, implying that the fields at both electrodes are involved. Slivkov²⁴ has proposed a breakdown mechanism involving clumps originating at both electrodes, and as discussed later, the resulting breakdown criteria is reasonably consistent with the present observations.

Finally, it should be noted that the results for reversed polarity were influenced by the relatively dirty surface of the can. There was no way of heating it in place as was done with the filament, so original imperfections, absorbed impurities, as well as debris from prior breakdowns were probably present. If heat conditioning had been possible, high-voltages would no doubt have been achieved.

HELIUM-GAS-PRESSURE EFFECTS

As noted earlier, a concern in direct collectors is that helium bombardment may cause surface damage and result in voltage breakdown. We hope to study this effect in detail in future experiments. However, some very preliminary studies were attempted. The basic concept was

that small amounts of helium gas might be introduced into the vacuum chamber while the filament was hot and at voltage. Electrons from thermionic emission would ionize the helium, and helium ions would then be accelerated by the potential back into the filament. While at low energy (several keV), these ions still could cause damage and perhaps give us a first indication of such effects. We estimate that at an electron current of 10^{-6} A and a helium pressure of 5×10^{-3} Torr, an ion bombardment current of about 10^{-7} A could be obtained; this is a current density of $\sim 8 \times 10^{-7}$ A/cm² for a 2-mil wire. At this rate, roughly 100 h of operation would be required to obtain the fluence of 10^{18} ions/cm² generally regarded as a threshold for blister damage.

To investigate the feasibility of this, a run was initiated with a 2-mil wire. A breakdown measurement after 1.3 h of operation showed that emission currents had decreased somewhat but the breakdown strength was not changed. For unknown reasons the wire broke after 3 h before another test was possible. The vacuum system set-up employed for this work was not well suited for continuous operation with such a high helium pressure, so further runs were not attempted.

An additional effect that is well documented in the literature²⁵ is that the breakdown strength apparently increases with gas pressure in the range of 10^{-4} to 10^{-3} Torr. Below 10^{-5} Torr breakdown is independent of pressure, while above 10^{-3} Torr a glow discharge may be initiated. To confirm this behavior, helium was leaked into the chamber of the apparatus during several

Table 6. Breakdown strength vs pressure for 2-mil wire.

He pressure (Torr)	Breakdown voltage ^a (kV)	
	Polarity of can	
	(+)	(-)
$\sim 10^{-6}$	22	40
$\sim 10^{-4}$	25	44
$\sim 10^{-3}$	24	35
$\sim 8 \times 10^{-3}$	(glow discharge at 1 kV and 8 μ A)	

^aValues shown are averages for several runs.

runs. Results are given in Table 6 below.

The breakdown strength remained essentially constant until a glow discharge developed. The increased strength reported by others has generally been attributed to selective bombardment of whiskers by ions produced by electron bombardment of the background gas.²⁵ In the present runs, voltages were only maintained about 10 min prior to breakdown, and this may not have allowed sufficient time for bombardment. However, this was not pursued further since the main objective was to establish that volt-

age holding did not deteriorate with pressures up to 10^{-3} Torr.

CAPACITANCE EFFECTS

As noted earlier, roughly 0.1 J entered the breakdown arc via capacitive storage in the cable and filament-can arrangement. Some theories suggest that breakdown depends on the capacitance. Further, there appears to be an optimum spark energy generally thought to be in the range 1-10 J, for successive breakdown conditioning. To investigate this, 2400-pf capacitors were added at the high-voltage feedthrough to obtain 0.5- and 1-J arcs. However, no effect was found, either on the breakdown strength or on conditioning. It may be that larger energies are required, or alternatively the time for initiation of the arc may be too short to permit energy flow from the capacitor. Such effects should be investigated more carefully in the future, since actual direct collection devices will involve larger capacitances due to length and arrangement of the grid structure.

Breakdown Correlations

Data showing breakdown voltage vs wire diameter is presented in Fig. 13, along with points from the earlier studies by Chambers and by Ahearn.

Results are presented for each of the three regimes (initial, field emission, and ultimate) corresponding to the characteristic current behavior described earlier. We feel such a presentation is

justified since it is likely that the breakdown mechanisms are different for each regime, e.g. during "initial" operation adsorbed gas and other contamination on the surface may initiate breakdown, in the "field-emission" regime the emission currents from whiskers dominate while in the "ultimate" regime, the absence of

large prebreakdown currents suggests a clump-type initiation.*

Both the "initial" and "ultimate" breakdown data are quite well correlated with an equation of the form

$$V_b = C d^{0.53}, \quad (9)$$

where V_b is the breakdown voltage in kV, d is the wire diameter in mils, and the constant C is 3.6 for the "initial" region or 22.0 for the "ultimate" curve.[†] The data point for breakdown with a 7-mil wire falls below this correlation. Indeed this point exceeds the 45-kV design limit for the experimental unit and extraneous currents could well have caused premature breakdown.

Results for "field emission" runs contain more scatter. This is as expected, however, since such breakdown is associated with whisker effects which depend on the past history of the surface (i.e. the number of previous breakdowns, conditioning by heat, etc). If the 1-mil-wire data were discarded (perhaps

* These and other breakdown theories are discussed in some detail in this section.

† In the next section it is shown that to be consistent with Cranberg's clump model, the constant C should be written as

$$C = C' (\ln r_2/r_1)^\alpha, \quad (9a)$$

where α is 0.5. However to agree with Eq. (9), $\alpha = 0.53$ should be used. The dependence on r_2/r_1 is quite weak, so this does not invalidate Eq. (9). Thus we will use this correlation in future sections and replace d in Eq. (9) by the wire radius r_1 in cm, giving

$$V_b = C' (r_1 \ln r_2/r_1)^{0.53};$$

$$C' = \begin{cases} 48.8 & \text{(initial regime)} \\ 302 & \text{(ultimate)} \end{cases} \quad (9b)$$

Fig. 13. Correlation of breakdown voltage with wire diameter for the three regimes of operation. As indicated, field emission breakdown occurred over a larger range of values than did either initial or ultimate breakdown. Several data points from prior investigations by Chambers and Ahearn are included for comparison.

justifiably since as noted earlier, breakage prevented thorough conditioning of these wires) this data might also be fit with Eq. (9). However, with the scatter involved, alternate correlations cannot be ruled out. As seen from Fig. 13, the linear relation $V_b = 6.8d$ is not entirely unreasonable for this regime.

The electric fields at the wire surface (see Fig. 13) are summarized in Table 7. The column labeled E represents the nominal or macroscopic field whereas the enhanced "whisker-tip" values found using values from Table 5 are in the

Table 7. Breakdown strengths.

Wire diameter (mils)	Initial			Field emission ^{a, b}			Ultimate		
	V (kV)	E (V/cm)	βE (V/cm)	V (kV)	E (V/cm)	βE (V/cm)	V (kV)	E (V/cm)	βE (V/cm)
1	3.6	3.7×10^5	9.0×10^7	7	7.3×10^5	1.7×10^8	22	2.3×10^6	5.5×10^8
2	5.0	2.9×10^5	3.6×10^7	20	1.1×10^6	1.4×10^8	35	2.0×10^6	2.5×10^8
4	7.0	2.2×10^5	3.3×10^7	30	9.5×10^5	1.4×10^8	44	1.4×10^6	2.1×10^8
7	10	2.0×10^5	2.5×10^7	41	8.2×10^5	1.0×10^8	48	9.6×10^5	1.2×10^8

^aAverage values for the series of runs. As seen from Fig. 13, more scatter occurred in these measurements as compared to "initial" or "ultimate" values.

^bAlpert et al.¹⁸ report a βE value of 6×10^7 V/cm for parallel-plate tungsten electrodes in the field emission regime.

column labeled βE . We observed that the enhanced "field-emission"- and "ultimate"-regime fields exceeded 10^8 V/cm. This is somewhat larger than the limiting value of 6×10^7 V/cm reported by Alpert et al.¹⁸ for flat plates.

Alpert et al.¹⁸ argue that breakdown occurs for a constant enhanced field value while the nominal field will vary due to the dependence of β on gap size, etc. The βE values for the "field emission" regime are in fact reasonably constant; however, there are marked variations in the initial and ultimate values with wire diameter (see Table 7). This still may be consistent with Alpert et al.'s observation since they were concerned with small spacings where field emission probably dominates, and it is not clear that their arguments should apply to other regimes of operation. This further emphasizes the importance of separating the results into regimes.

To better understand these results, it is necessary to briefly consider several breakdown criteria derived to explain results from parallel-plate studies. It is generally observed that for a wide range of parameters, most data can be correlated in the form^{*}

$$V_b = C_2 t^\alpha, \quad (10)$$

where C_2 is a constant, t is the gap thickness between electrodes, and the exponent α generally ranges between 0.5 to 0.6. Numerous theories have been proposed to explain this. The most widely accepted view at present¹⁰ is that for small spacings ($t \lesssim 10^{-1}$ cm) field emission initiates breakdown and the dependence on t arises from a variation in the whisker enhancement factor with spacing. At larger spacings, a "clump"-type breakdown such as originally proposed by Cranberg²⁶ is envisioned. Then the dependence on gap spacing is a direct result of the variation in energy imparted to a clump and the requirement of a minimum or threshold energy for breakdown.

For present purposes the most interesting results are the two limiting curves in Fig. 12 which correspond to "initial"

*While this form appears to be similar to Eq. (9), the two should not be confused. Here the spacing t is the key parameter, whereas in cylindrical geometry the grid radius r_1 plays a similar role while the dependence on spacing ($r_2 - r_1$) is weak.

and "ultimate" breakdown. Since, as already argued, neither of these curves seems to be a direct consequence of field emission, we will briefly consider several theories for clump breakdown to explain them. This is particularly interesting since these theories have not previously been applied to data from cylindrical geometry.

CRANBERG'S CLUMP HYPOTHESIS

Cranberg²⁶ assumed a clump of material of area a_1 originates on the cathode surface at voltage V_c . The clump will assume a charge q given by

$$q = a_1 V_c C, \quad (11)$$

where the capacitance C is

$$C = \begin{cases} (\epsilon/r_1) \ln r_2/r_1 & \text{coaxial} \end{cases} \quad (12a)$$

$$C = \begin{cases} \epsilon/t & \text{parallel plates.} \end{cases} \quad (12b)$$

Here ϵ is the gap permittivity. For coaxial geometry, r_1 is the radius of the inner electrode and r_2 is the inner radius of the surrounding electrode while t is the electrode separation for parallel plates.

If this clump tears loose, it acquires an energy qV_c in passing to the anode. Assuming that a minimum energy W_0 is

required for breakdown, we obtain

$$a_1 V_c^2 C = W_0 \quad (13)$$

which gives the following criterion for the breakdown voltage V_b :

$$V_b = V_c |_{W=W_0}$$

$$= k_1 \times \begin{cases} (r_1 \ln r_2/r_1)^{1/2} & \text{cylinders} \\ t^{1/2} & \text{plates,} \end{cases} \quad (14a) \quad (14b)$$

where the constant k_1 is $(W_0/a_1\epsilon)^{1/2}$. This is equivalent to requiring that the voltage-field product at the cathode be constant, i.e. $(VE)_c = \text{constant at breakdown}$.

Since for the present case $\ln r_2/r_1$ does not vary much, this predicts that $V_b \propto r_1^{1/2}$ which is quite close to the results found for the ultimate and initial breakdown regimes [Eq. (9)]. The accuracy of this representation is further illustrated in Table 8 where the measured VE products for these two regimes are seen to be reasonably constant.*

Following the original derivation by Cranberg, various workers have attempted to refine this analysis. One goal has been to justify the experimental observation that the exponent in Eq. (10) is slightly larger than 0.5. An even more important discrepancy relative to the present data, however, is that Cranberg's criterion does not predict the observed polarity

Table 8. Comparison of VE values at breakdown.

Wire diameter (mil)	Voltage-field (VE) product (V^2/cm)		
	Initial	Field emission	Ultimate
1	13.3×10^8	5.08×10^9	5.06×10^{10}
2	14.5×10^8	2.20×10^{10}	7.00×10^{10}
4	15.4×10^8	2.85×10^{10}	6.16×10^{10}
7	20.0×10^8	3.36×10^{10}	4.50×10^{10}

* Results for the field-emission regime are also included although clump theory is not applicable to the regime. Indeed, a slightly larger variation in VE is observed, but admittedly it might be argued that this is due to an error in the 1-mil data.

effect. This observation brings us to a related model proposed by Slivkov.

SLIVKOV'S MODEL

Slivkov²⁴ proposes a more complex clump mechanism wherein clumps become detached from both electrodes, even at low voltages. When the voltage is sufficient, they adhere to the opposite electrode. A higher electric field is then required to free them again, and at sufficiently high kinetic energy they vaporize into a cloud upon striking an electrode. This argument leads him to the expression

$$V_b E_c E_A^{2/3} = \text{constant} \equiv C_2, \quad (15)$$

where E_c and E_A are the macroscopic fields at the cathode and anode, respectively. This leads to a breakdown correlation of the form

$$V_b = \begin{cases} k_2 r_1^{3/8} r_2^{1/4} \left(\ln \frac{r_2}{r_1} \right)^{5/8} & \text{coaxial} \\ k_2' t^{5/8} & \text{plates,} \end{cases} \quad (16a) \quad (16b)$$

for normal polarity where the inner electrode is the cathode in coaxial geometry. Here k_2 and k_2' are constants and the other nomenclature is as defined earlier. If the polarity is reversed [(-)can, in the notation previously used] we obtain

$$V_b = k_2 r_1^{1/4} r_2^{3/8} \left(\ln \frac{r_2}{r_1} \right)^{5/8} \quad \text{coaxial.} \quad (17)$$

In the present work, data was not obtained as a function of radius for re-

verse polarity. However a rough check can be made using breakdown values from Fig. 12. Substitution of values into Eq. (15) for the (-) can gives $C_2 = 1.19 \times 10^4 \text{ kV}^{8/3} \cdot \text{cm}^{-5/3}$, whereas values for the (+) can give $C_2 = 1.92 \times 10^4 \text{ kV}^{8/3} \cdot \text{cm}^{-5/3}$. While there is some discrepancy, this provides a reasonable "first accounting" of the polarity effect. This is perhaps significant, since, to the author's knowledge, no other clump-type model includes this effect. Unfortunately, the exponent on r_1 in Eq. (16a) is somewhat smaller than predicted by the present data. Hence, some modifications are still warranted.

RABINOVITZ'S MODEL

One questionable aspect of the preceding models is that they do not depend on the capacitance of the experimental device. If due to the fast time scale involved, the only energy that can reach the spark is that stored in the electrode structure, a minimum capacitance is required for breakdown. Rabinowitz²⁷ has attempted to incorporate this into a simple model. He set W_o , the minimum energy for breakdown, equal to a fraction f of the stored energy, i.e.

$$W_o = \frac{1}{2} f C V_b^2, \quad (18)$$

which leads to the criterion

$$V_b = \begin{cases} k_3 \left(\frac{\ln r_2/r_1}{l} \right)^{1/2} & \text{coaxial} \\ k_4 \left(\frac{t}{A} \right)^{1/2} & \text{plates,} \end{cases} \quad (19a) \quad (19b)$$

where k_3 and k_4 are constants, ℓ is the length of the coaxial cylinder, A is the plate area, and the other nomenclature is as before.

This result has two failings. It does not at all correlate with the r_1 dependence obtained in the present study and it does not account for the polarity effect. However, this might simply be due to the fact that in the present case much more than the minimum requirement of stored energy was available. This reasoning suggests a combination of Eqs. (14a) and (19a) such that

$$V_b = \begin{cases} k_3 \left(\frac{\ln r_2/r_1}{\ell} \right)^{1/2} & CV_b < W_0 \\ k_1 (r_1 \ln r_2/r_1)^{1/2} & CV_b > W_0 \end{cases} \quad (20a)$$

$$V_b = \begin{cases} k_3 \left(\frac{\ln r_2/r_1}{\ell} \right)^{1/2} & CV_b < W_0 \\ k_1 (r_1 \ln r_2/r_1)^{1/2} & CV_b > W_0 \end{cases} \quad (20b)$$

where W_0 is some critical value of stored energy. The present data does not allow a check of this hypothesis. In actual direct collection units the stored energy will generally be large so that Eq. (20b) remains valid.

LIMITING SURFACE-FIELD MODEL

The conceptual designs for direct collection units have considered breakdown in terms of the electric field at the grid-wire surface.^{4,6} If breakdown occurs once a critical enhanced field E_s^* is reached, the breakdown criterion becomes

$$V_b = \begin{cases} E_s^* (r_1 \ln \frac{r_2}{r_1}) / \beta & \text{coaxial} \\ E_s^* t / \beta & \text{plates} \end{cases} \quad (21a)$$

$$V_b = \begin{cases} E_s^* (r_1 \ln \frac{r_2}{r_1}) / \beta & \text{coaxial} \\ E_s^* t / \beta & \text{plates} \end{cases} \quad (21b)$$

where β is the field enhancement factor.

Such a model is most applicable to the field-emission regime of breakdown. For the flat-plate case, it is generally accepted that β is a function of plate spacing t , and when this is incorporated, one obtains a form similar to the clump model, i.e. a dependence on t^α where α is roughly 0.5. A corresponding dependence of β on r_1 and r_2 for coaxial geometry has not been derived, hence, in its present form, Eq. (21) is not too useful. It might be noted, however, that the use of a constant β predicts roughly a linear dependence on r_1 , which, with the scatter of the field-emission data in Fig. 13, cannot be ruled out for this regime. It would be quite poor for the other regimes, however.

KILPATRICK'S CORRELATION

In the late 1950's W. Kilpatrick²⁸ of the Lawrence Berkeley Laboratory developed an empirical relation to describe a boundary between no-vacuum sparking and possible sparking. This correlation, shown in Fig. 14, is of particular interest here since it covers a wide range of parameters and hence would be especially useful in the extrapolations required for conceptual designs.

For parallel plates, Kilpatrick's correlation can be written in the form

$$\frac{V_b^3}{y^2} \exp\left(-\frac{k_5 y}{V_b}\right) = k_6 \quad (22)$$

where $k_5 = 1.7 \times 10^5$ V/cm, $k_6 = 1.8 \times 10^{14}$ V³/cm², and the quantity y is

$$y = \begin{cases} r_1 \ln \frac{r_2}{r_1} & \text{coaxial} \\ t & \text{flat plates} \end{cases} \quad (23a)$$

$$y = \begin{cases} r_1 \ln \frac{r_2}{r_1} & \text{coaxial} \\ t & \text{flat plates} \end{cases} \quad (23b)$$

To apply this notation to Fig. 14, set W equal to V_b and W/E equal to y .

Predictions using this correlation are compared with present data in Table 9. Quite good agreement with the initial breakdown values is observed, although there is a slight tendency to underpredict the values for smaller diameter wires.*

Kilpatrick's criterion was originally developed to predict the onset of "sparking," so it is not surprising that it correlates with what is termed here the initial regime breakdown, i.e., the onset of breakdown prior to conditioning. However, as seen from earlier sections, the "ultimate" and

"initial" regimes have essentially the same dependency on r_1 . Thus the ultimate regime can also be fit with Eq. (22) by adjusting k_6 (use $k_6 = 1.1 \times 10^{16}$).

SUMMARY, COMPARISON OF BREAKDOWN CORRELATIONS AND PRESENT DATA

For convenience the various breakdown models discussed to this point are summarized in Table 10.

Table 9. Comparison of present data and Kilpatrick's correlation.

Wire diameter (mils)	y (cm)	V_b from Eq. (22) (kV)	Initial breakdown values (Fig. 13) (kV)
1	0.00965	3.07	~ 3.5
2	0.0175	4.64	~ 5.0
4	0.0315	7.03	~ 7.0
7	0.0503	10.3	~10.0

*The point is a little bothersome since it will be noted from Eq. (22) that for small spacings such that $k_6 y/V_2 \ll 1$, we obtain $V_b \sim y^{2/3}$ which suggests that the exponent for y in this limit is too large.

Fig. 14. Sparking correlation devised by Kilpatrick,²⁸ based on a wide variety of experiments. Here W is the maximum ion energy at the cathode in electron volts. W corresponds to the applied voltage and W/E is the spacing for plane parallel fields.

Table 10. Summary of correlations.

Model	V_b correlation, coaxial cylinders ^a	Comment
Cranberg (simple clump)	$(r_1 \ln r_2/r_1)^{1/2}$	$\left\{ \begin{array}{l} r_1 \text{ dependence close,} \\ \text{initial and ultimate} \\ \text{regimes} \end{array} \right.$
Slivkov (multiple clump)	$\left\{ \begin{array}{l} r_1^{3/8} r_2^{1/4} (\ln r_2/r_1)^{5/8} (+) \text{ can} \\ r_1^{1/4} r_2^{3/8} (\ln r_2/r_1)^{5/8} (-) \text{ can} \end{array} \right.$	$\left\{ \begin{array}{l} r_1 \text{ exponent low} \\ \text{only model with} \\ \text{polarity effect} \end{array} \right.$
Rabinovitz (simple capacitance)	$\left(\frac{\ln r_2/r_1}{\ell} \right)^{1/2}$	$\left\{ \begin{array}{l} \text{not valid for present} \\ \text{case; possibly for} \\ \text{CV}_b < W_0 \text{ as per} \\ \text{Eq. (20)} \end{array} \right.$
Kilpatrick's correlation	$\frac{V_b^3}{y^2} \exp\left(-\frac{1.7 \times 10^5 y}{V_b}\right) = \left\{ \begin{array}{l} \text{(initial)} \\ 1.8 \times 10^{14} \\ 1.1 \times 10^{16} \\ \text{(ultimate)} \end{array} \right.$ $y = r_1 \ln r_1/r_2$	$\left\{ \begin{array}{l} \text{good } r_1 \text{ correlation,} \\ \text{initial and ultimate} \\ \text{regimes.} \end{array} \right.$

^aAs shown in the text, for flat electrodes all of these models effectively lead to a correlation of the form $V_b \propto t^\alpha$ where t is the electrode spacing and α is roughly 1/2. text, for flat electrodes all of these models effectively lead to a

The failure of most models to predict the polarity effect represents a fundamental defect.* However, this is not of direct importance to direct converter

*It must be remembered that previous applications of these models have concentrated on plane geometry as discussed earlier. The use of cylindrical geometry, introduces the polarity effect as a new test of validity, and replaces the dependency on gap spacing with the dual parameters of wire radius and spacing (or r_2/r_1). Thus, cylindrical geometry adds an important additional method of testing models and it seems that in the future more studies should employ this configuration.

designs since the polarity is fixed. Rather, the dependency on filament size is the main variable, and in this respect either the Cranberg model (with the exponent adjusted from 0.5 to 0.53) or Kilpatrick's correlation provide reasonably good fits.

The scatter in the data for the "field-emission" breakdown make it difficult to select a correlation for this regime. However, for present purposes, correlations for the ultimate and initial regimes alone are probably adequate since they set upper and lower limits.

Application to Full-Scale Designs

BREAKDOWN VOLTAGES

To illustrate the implications of our work in typical full-scale units, we will consider the two conceptual designs shown earlier in Figs. 1 and 2. The key parameters are summarized in Table 11.

The irregular geometry involved in these designs presents a basic problem in comparing them with the present correlation. This can be seen from Fig. 15 where the Cranberg- and Kilpatrick-type correlations are presented on a grid voltage (V) vs "equivalent spacing" (either V/E_s or $r_1 \ln r_2/r_1$) plot. For true cylindrical geometry

$$\frac{V}{E_s} = r_1 \ln r_2/r_1,$$

where E_s is the electric field at the grid wire surface; hence, there is no ambiguity. For irregular shapes, however, $r_1 \ln r_2/r_1$ is not strictly defined.

One way to evaluate an equivalent spacing, labeled method A in the figure, is to use the full grid-collector potential difference and simply calculate V/E_s . (The surface field E_s can be found from potential plots as described in Refs. 4 and 6.) This appears plausible, but it would not seem to fully account for geometrical effects. If it is argued that the field and voltage in the vicinity of the grid wire determine breakdown, an equivalent cylinder can be defined as follows. This method, labeled B in Fig. 15, requires a detailed potential diagram such as shown earlier in Figs. 1 and 2. Then the last equipotential line around the grid wire that remains circular and concentric (within a few percent) is viewed as a "virtual" outer electrode. The distance to this line defines r_2 and the equivalent spacing is defined as $r_1 \ln r_2/r_1$. Now the corresponding grid voltage (V) is defined as the grid-wire voltage relative to the potential at r_2 (i.e.,

Table 11. Grid parameters for projected full-scale converters described in Refs. 4 and 6.

	Overfocused (Post) unit	Venetian blind
grid-wire diam (mils)	500 ($r_1 = 0.635$ cm)	25 ($r_1 = 0.0318$ cm)
grid voltage, V (kV) ^a	815	109.8
spacing, l (cm) ^a	21.6	43.2
surface field, E_s (kV/cm)	98.4	66.
"Equivalent" cylinder values		
grid voltage, V (kV) ^b	40.8 (5% line)	4.8 (10 % line)
outer radius, r_2 (cm) ^b	1.22	0.33

^aDistance and voltage relative to closest collector structure.

^bRelative to the "virtual can" defined by the last concentric potential line.

relative to the virtual electrode rather than the actual electrode).

For example, in the overfocused conceptual design, the first circular field line is that 5% line in Fig. 1 which occurs at 1.22 cm from the grid. Using this for r_2 gives an equivalent spacing of 1.2 cm with

a corresponding grid voltage of $V = (0.05) (815 \text{ kV}) = 40.8 \text{ kV}$.

As seen from Fig. 15, these two methods lead to considerably different conclusions. Method B indicates that both designs are quite conservative relative to breakdown, whereas Method A shows both

Fig. 15. Comparison of proposed grid parameters for full-scale converter designs. For points marked A, the overall grid-collector potential is used to evaluate V/E_s ; for B the potential corresponding to an "equivalent" cylinder is used.

falling on or above the "initial" breakdown regime. Further, in the latter case, assuming that extrapolation by Cranberg's correlation is most accurate, the over-focused design approaches the "ultimate" breakdown limit. For equivalent spacings less than ≈ 0.3 cm, the two correlations are in good agreement. Since the present experimental data falls in a range of spacings between 0.01 and 0.1 cm, it cannot be used to resolve the discrepancy between correlations at large spacings. However, despite some scatter, the breakdown data from various operating accelerators shown in Fig. 15 tends to fall below Kilpatrick's correlation at larger spacings. Thus, it would appear to be best to use Cranberg's method until further data becomes available.

Fortunately, most observations suggest that grid conditions dominate in initiating breakdown so Method B would seem to be preferred. However, there are some conflicting points to consider. Slivkov's model, which must be used to explain the polarity effect, involves the electric fields at both electrodes [see Eq. (15)] and this can not be incorporated into a simple equivalent cylinder treatment. Chambers' earlier observation (see Prior Studies) that higher breakdown voltages could be obtained by conditioning the anode in cylindrical-type experiments also tends to support this view. On the other hand, Ahearn's work (also Prior Studies) indicated that anode conditions had little effect in breakdown.*

If the electric field at the anode does indeed play a significant role in breakdown, this effect would appear to be most critical in venetian blind designs, where, as seen in Fig. 2, large fields occur at the edge of the collector surfaces. Since the overfocused design (Fig. 1) involves a flat "bucket" surface, the equivalent cylinder approximation would seem to be more reasonable for it.

Clearly, additional experimental studies are required to determine the most appropriate treatment for irregular geometries. In the meantime, it would seem prudent to employ Method B, but require these points to fall well below the initial breakdown limit such that Method A results fall in the incipient field emission region. The venetian blind design shown in Fig. 15 meets this criterion, but the grid voltages on the overfocused design would have to be reduced somewhat to do so. It would not seem wise to have any design approach the ultimate regime limit until simultaneous bombardment studies have been completed to see whether or not such a regime can be reached during ion bombardment. If bombardment results in surface roughening so that field emission occurs, there is always the risk of spurious breakdown due to the variability and dynamic character of whisker sites. This may force operation near the initial-regime curve. As pointed out earlier, breakdown corresponding to the initial-regime curve probably occurs because of adsorbed gases on the wire surfaces prior to conditioning. Assuming that heat conditioning is feasible in an actual device, such breakdown would easily be avoided. Then while larger voltages could be maintained with conditioned wires, it still

* Ahearn also reported a polarity effect, which, if Slivkov's model is valid, suggests that despite Ahearn's statement, the anode must be involved.

seems wise to stop at the initial-regime curve to insure that field-emission behavior is avoided. This is not only because of the variability of breakdown in that regime, but because, as discussed below, large emission currents might be encountered causing a reduction in efficiency.

EMISSION CURRENT LIMITATION

Electron emission from the grid wires has three principle origins: thermionic emission, field emission, and secondary emission due to ion and electron bombardment. These currents represent a power loss and hence reduce the net conversion efficiency. Estimates for thermionic and secondary emission have been included in the projection for full-scale units^{4,6} where it is attempted to keep these losses below 1%.

For example, in the venetian-blind design, the loss in efficiency due to thermionic emission ($\sim 1 \times 10^{-5}$ A/cm² for grid operation at 1690°K) is estimated to be only $\approx 0.11\%$ and an additional $\approx 0.8\%$ loss occurs due to secondary electron emission (incident ion beam of 25 W/cm² and an emission coefficient of 3.0). As seen from the present experiments (recall Figs. 5-8) field emission currents can be quite large so that this could become another important current. A reasonable design goal would be to keep field emission at a value comparable to or less than thermionic emission, i.e., below $\approx 10^{-5}$ A/cm². As shown earlier in Fig. 11, an approximate relation for equal currents can be obtained on a β/KV (i.e., $1/E_g$) vs $1/T$ plot. The dividing curve is reproduced in Fig. 16 along with projected

Fig. 16. Comparison of present designs and the thermionic - field emission transition curve of Fig. 11. Grid temperatures in the designs are somewhat uncertain, and hence shown as a range. With these designs thermionic emission would dominate even down to quite low temperatures.

ranges for the two conceptual designs of Refs. 4 and 6. In doing this, the tacit assumption made is that the field-enhancement factor β is the same in the full-scale units as in the present experiments. This is reasonable unless surface roughening due to ion bombardment causes an increase in β , a point which must be settled in future experiments. At any rate, as seen from Fig. 16, the present designs fall into the desired thermionic region. Bombardment-induced increases in β would have to be of order ten or more to cause serious trouble.

BOMBARDMENT LIMITATION

The effect of ion bombardment on the high-voltage electrodes remains as a

major uncertainty, and experiments to study this effect are discussed under recommendations for future work. The problem can be illustrated through Table 12 which summarizes the anticipated current densities on the reflector grid of the projected 250-MW venetian-blind unit of Ref. 6.

Two aspects must be considered:

- Dynamic effects of bombardment (and resulting sputtering) on wire parameters such as β , the field-enhancement factor and clump formation.
- Long-time damage effects of blistering and spalling. We will briefly consider each.

Dynamic Effects

Both field emission and the breakdown strength of the grid are extremely sensitive to the microscopic condition of the wire surface, i.e., the number, size, and shape of whisker-like projections. As seen from Table 12, the dominate current is due to ion bombardment. The key question is what effect this has on whiskers, e.g., might it result in actual whisker formation, or to the contrary, might bombardment selectively erode existing whiskers away?

As pointed out in the section, Helium-Gas Pressure Effects, it is well established that higher voltages can be maintained with gap pressures approaching 10^{-3} Torr.

Table 12. Anticipated grid currents in the 250-MW venetian-blind unit of Ref. 6.

	Current ($\mu\text{A}/\text{cm}^2$)
<u>Bombarding currents</u>	
Ions (~167-keV mean energy)	
$\text{D}^+ + \text{T}^+$	150
He^{++}	3
Electrons ^a	~0
Sputtered ions from collectors	<1.5 ^b
<u>Emission currents</u>	
Field emission	<10 ^c
Thermonic emission	10
Secondary emission	~225
Sputtered material	~1.5 ^d

^aElectrons are reflected and not involved except at the grounded grid.

^bSputtering yields are highly uncertain. Values of order of 0.1 might be expected prior to the formation of blisters and subsequent flaking.³ The sputtered current would consist of both ions and neutrals, and the ions in particular would be collected on the negative grids.

^cBased on the total surface area. Densities as high as $10^8 \text{ A}/\text{cm}^2$ of whisker area occur.

^dEquivalent neutral beam current. Only sputtered neutrals can escape grid fields.

This is attributed to selective bombardment of whiskers by ions created near the tip of the whisker by the high-emission current densities there (electron current densities near a whisker can exceed 10^8 A/cm²; see the section Field Enhancement and Whisker Parameters). The strong fields at the whisker then focus the ions onto the protruding whisker, causing selective erosion. A similar phenomenon might occur in the direct converter, but this seems unlikely for two reasons. First, rather than being created by electron-neutral collisions,* the ions involved originate from the fusion exhaust and will be fairly uniformly distributed over the area of the grid facing the reactor. Second, with the mean ion energies being high (~167 keV in the design of Table 12), the whisker fields cannot create much focusing. As a result, selective bombardment seems unlikely. In this sense, the ion current is similar to the thermionic current. With it distributed fairly uniformly over the surface, it can be many orders of magnitude larger than the field-emission current without affecting the latter. For example, the ion current density is ~150 μ A/cm² vs 10^8 A/cm² field-emission density at the whisker site.

Thus, the main effect (other than long-term damage) that the ion currents might have would be the creation of new whiskers or clumps on the surface. Ions at this energy are quite disruptive, so this is plausible. The experiment described in Helium-Gas Pressure Effects

*The background gas pressure must be held below $\sim 10^{-5}$ Torr to prevent excessive efficiency losses due to charge-exchange collisions.

was an initial attempt to examine this question. Unfortunately, the ion currents and energies in our experiments were more than an order of magnitude lower than those projected in Table 12. Although the results are inconclusive, no dynamic effects were observed at this level.

Another serious problem associated with bombardment is that the material which is sputtered off of the collector plates and ends up on the grids could form ideal "clumps" which initiate breakdown. A somewhat analogous situation was discussed earlier in connection with Brodie's work²⁰ where he found that minute quantities of material transferred to high-voltage surfaces in the presence of a thermionic cathode seriously reduced the breakdown strength.

These uncertainties are part of the reasoning behind the earlier recommendation that present designs be limited to the initial breakdown regime (rather than field emission or ultimate regimes). Once these problems are better understood it may be possible to confidently design for other regimes.

Long-Term Damage

The main fear here is that surface blistering and the resulting flaking and spalling will initiate breakdown.^{2,3,6} Helium, which is insoluble in most metals can cause blistering, and for temperatures <700°C, stainless steel surface become flaked at a dose of $\sim 10^{18}$ ions cm⁻².^{6,29} Operation at higher temperatures and careful selection of materials might alleviate this problem by increasing the allowable dose. With the 10^{18} ions cm⁻² limit and the He⁺⁺ current of Table 12,

only 40-hr operation is possible before the wires (as well as collectors) must be replaced. If this turns out to be the case, several engineering design solutions have been suggested.²⁻⁶ The grid wire can be on spindles and constantly pulled through the converter unit. Alternatively, it is conceivable that the wire surface could be coated with a material that would sputter away at the same rate that flakes occur.* Another possibility is that the surfaces can be run at sufficient temperature, or they might be periodically heated to high temperature, to anneal out helium bubbles. Clearly, the optimum solution to this problem must await further studies and a better understanding of the blistering phenomena.

It may be instructive relative to voltage breakdown considerations to compare characteristic blister and whisker sizes. A "typical" whisker would be $\approx 10^{-4}$ cm in diameter with a length 2 to 10 times its diameter. Prior to breaking, and depending on the temperature, a typical blister might be hemispherical in shape with a radius of 1 to 5×10^{-3} cm. Upon breaking, the thin skin over the blister is exposed, and its thickness may be of order of 10^{-4} cm. In general, as the temperature is increased, the blister sizes decrease and the edges exposed during rupture are smoother.

This contrast between blisters and whiskers is illustrated conceptually in Fig. 17, which is roughly to scale. Based on this, it is tempting to speculate on the relative field enhancement due to

blisters. Since grid-electrode spacings for typical devices are large (1 in. to 20 in.; see Figs. 1 and 2), the height of either a blister or a whisker is quite small relative to the spacing. Thus, field enhancement is not associated with the height of the projection. Rather it must arise from enhanced fields associated with the thickness (whisker diameter) of the projection. A crude way of looking at this is to envision that the projection is so orientated on the surface that it acts like another anode wire. Then the surface field depends critically on the projection diameter and can be calculated by standard formula [the field-voltage ratio at the surface is simply $(r_1 \ln r_2/r_1)^{-1}$ for coaxial geometry]. Field enhancements estimated in this fashion are given in Table 13.

In this view, field enhancement due to a blister prior to its breaking can be neglected. It is not clear what the broken structure will be like,[†] so in Table 13 an "equivalent" wire with a diameter equal to the projected thickness of the ring-like structure (as viewed from above the surface) left by the broken blister is used. In this admittedly rough model, the thicker blister projections lead to a field-enhancement β -value of about 1/5 of that for whiskers. While the surface density (number/cm²) of burst blisters could exceed the whisker density, since the emission current depends exponentially on β [see Eq. (1)], the current from blister sites can probably be neglected if this model is anywhere near correct. Of

*This solution poses a dilemma. If sputtered material from the grid wires ends up on the collector, or vice versa, it may well initiate clump-type breakdown.

[†]A crater-like structure something like that depicted in Fig. 17 has been observed at lower temperatures with materials crystallographically similar to stainless steel.²⁹

Fig. 17. Schematic comparison of "typical" whisker and blisters. Of course the actual size and shape of both depends strongly on the material, conditions such as temperature and prior surface treatment. This illustration can only be viewed as a rough conceptual comparison.

Table 13. Idealized field enhancement from whisker and broken blister.

Wire radius r_1 (cm)	$(r_1 \ln r_2/r_1)^{-1}$ for $r_2 = 43.2 \text{ cm}^a$	β -value (relative to wire)
0.0318 (grid)	4.4	1
0.001 ("blister")	93.6	21
0.0001 ("whisker")	770.0	177

^aThe reflector grid-collector electrode spacing in the venetian blind design of Fig. 2.

course the bursting of the blister is very disruptive and could well create smaller thickness projections than are envisioned here. From available data, however, it appears that operation above 700°C is likely to leave a fairly smooth, but pock-

marked surface. The main problem then would not appear to be field enhancement but the formation of loose "clumps" of material on the grids (or the collector surfaces) which could initiate a Cranberg, clump-type breakdown.

Recommendation for Future Studies

Planning for future experiments can be divided into three phases: basic measurements; bombardment studies; and mock-up experiments. We will briefly consider each.

BASIC EXPERIMENTS

These studies would extend the range of parameters beyond those in the present experiments. The experimental apparatus would be similar to the present device, the main difference being that the maximum test-voltage capability would be increased to 100 to 150 kV. This would more nearly duplicate the voltages anticipated in actual units. While present results suggest that the voltage-field product is the important scaling parameter (vs voltage alone), higher voltage studies would further verify this and also verify that no new unexpected mechanisms enter at high voltage.

Higher voltages would also allow studies with larger diameter wires (see Fig. 13, ~20-mil wire could be used with a 100-kV test, 40-mil wire with 150 kV), again approaching actual converter conditions.

In addition to varying the wire diameter, the effect of the outer can diameter should be examined. Simultaneously, with larger cans it should be possible to begin studies

of irregular geometries by using non-circular cans, including oblong and square configurations. Ribs could be added to one can to simulate the collector edges in the venetian blind design (see Fig. 2). Additional studies of the effect of capacitance and external impedance could also be carried out.

If, during these measurements, it becomes clear that the can (anode) plays a sensitive role in breakdown, methods to provide in situ heating of it should be considered. Also during these experiments it would be advantageous to build a projection-screen-type can (see the discussion of the work by Brodie and others¹⁴⁻¹⁶ in Prior Studies) for use in standard runs not involving special shapes or heated cans. This would provide valuable experience with emission pattern observations if this technique is employed, as suggested here, in the bombardment studies. Also emission pattern observations would be valuable in further verifying the distinction between mechanisms involved in the various breakdown regimes.

Microscopic photographs of wire surfaces in several select runs prior to use, after conditioning, and after breakdown would provide specific data about protrusions which would be useful

for comparison with photographs taken during later bombardment studies. These observations might also be correlated with and supplement the projection screen studies.

BOMBARDMENT EXPERIMENTS

Bombardment studies to examine both dynamic and long-term damage effects would be carried out in three phases.

Phase 1

Using the apparatus described above for basic studies, helium would be leaked into the chamber and the grid wire heated to provide large thermionic currents while at voltage.* Such an experiment was described in the section, Helium-Gas Pressure Effects, and a preliminary attempt described there indicates the approach should be feasible if a larger size wire (4 mil or larger) is employed to prevent possible wire breakage. The ion energies and currents obtained in this fashion are lower than desired, but this provides a fast cheap way to obtain a "first look" at the problem.

If possible, a projection-screen should be employed in these experiments. The thermionic current might mask field emission patterns during the bombardment period, but when periodic breakdown tests are run, any changes in prebreakdown emission would become evident.

Phase 2

Tungsten wires could be bombarded in a helium-ion accelerator to obtain

*The possibility of adding a weak magnetic field to obtain some P. I. G. action and hence increase the ionization rate might also be explored.

various degrees of damage. The surfaces would be carefully photographed in order to classify the type of damage, and then the wires would be inserted in the voltage test unit used in the basic studies above. In addition to gross voltage-current measurements, use of a projection screen would allow correlation of emission patterns with the type of damage.

Phase 3

In this phase, we would attempt to duplicate the projected helium bombardment conditions as closely as possible during actual voltage tests. There appear to be two possible ways to do this: a) a voltage-test unit such as used in present studies could be placed in the beam line of a helium-ion accelerator, or b) an ion source such as that being used in present LLL converter studies could be located in the vacuum chamber used in the present studies. Before a decision is made as to the best approach, both should be considered in more detail. However, it appears that the accelerator approach has some distinct advantages. For example, the accelerator used by W. Bauer of Sandia Livermore Lab²⁹ could deliver $\sim 200 \mu\text{A}$ (He^+)/ cm^2 at 300 keV under well-controlled conditions. The beam could be focused through a slit in the can (similar to the viewing slit in the present can). Any beam missing the grid wire would pass through an exit slit in the can and enter a beam dump. The existing Sandia beam-line and vacuum chamber appear to be large enough to accommodate a test unit of the size used in the present work (i.e., $\sim 50\text{-kV}$ max). A key consideration would be instrumentation. Again, a projection screen would be

invaluable in this work. The Sandia vacuum chamber is all metal, but several side ports might be fitted with glass covers to provide a view of the screen.

In contrast, it would appear that more extensive development work is required to obtain comparable beams with a small ion source in the vacuum tee used in present studies.

In designing these experiments, care should be taken to insure that both dynamic and long-term damage effects are investigated. In this respect, the bombarding currents used in dynamic experiments should duplicate the total $D^+ + T^+$ current as well as He^{++} (see Table 12).

An auxiliary experiment in this phase might be to direct the ion beam so that it bombards the inner can wall, but not the grid wire. The effect of sputtered material that might then collect on the grid would be examined. This would simulate sputtering from the collector plates in an actual device (Table 12).

Acknowledgments

This work was carried out when the author was at LLL on a 2-month summer appointment. The problem was originally suggested by R. W. Moir, and many discussions with and help by him and W. L. Barr are gratefully acknowledged. Discussion with R. R. Smith, R. W. Werner, G. A. Carlson, E. J. Lauer, and W. Bauer (Sandia Livermore) were

Mock-up Experiments

Those experienced with high-voltage handling generally recommend mock-up type experiments because of the complicated nature of breakdown. In principle the basic experiments described here should provide sufficiently accurate correlations to enable the design of full-scale units. However, with the complicated geometries and conditions involved, intermediate mock-up experiments would still seem to be appropriate to insure that no new, unforeseen problems enter. This would be particularly critical if it becomes desirable to operate near the upper limits of breakdown strength.

These experiments require a larger vacuum vessel which could incorporate full-scale subsections of converter units similar to those of Figs. 1 and 2. It could be that normal breakdown experiments alone would be sufficient. However, depending on the results of the basic bombardment studies, it might be necessary to include an ion source.

also most valuable. The experiments would not have been possible without the continued help from W. J. Gould and J. D. Kinney, both in setting up the equipment and taking data. L. L. Reginato and P. S. Maslin also contributed to circuit designs and equipment procurement, and the expert machining job by C. L. Hansen is appreciated.

References

1. R. F. Post, "Mirror Systems: Fuel Cycles, Loss Reduction and Energy Recovery," in Proceedings of the British Nuclear Energy Society Conference on Nuclear Fusion Reactors, (Culham Laboratory, Culham, England, 1969) UKAEA (1970) 88-111.
2. R. W. Werner, Materials Problems in Direct Conversion Systems, Lawrence Livermore Laboratory, Rept. UCRL-73560 (1972).
3. R. W. Werner, The Sputtering/Spalling/Arcing Interactions in Collector Structure, Lawrence Livermore Laboratory, Memo TRM-40 (February 15, 1973).
4. B. H. Smith, R. J. Burleigh, W. L. Dexter, and L. L. Reginato, An Engineering Study of the Electrical Design of a 1000 Megawatt Direct Converter for Mirror Reactors, Lawrence Livermore Laboratory, Rept. UCRL-74047 (1972) and Proceedings of Texas Symposium on Fusion, (Austin, Texas, Nov. 1972) (in press).
5. R. W. Moir, and W. L. Barr, "Venetian Blind Direct Converter for Fusion Reactors," Nuclear Fusion **13**, 35 (1973).
6. W. L. Barr, R. J. Burleigh, W. L. Dexter, R. W. Moir, and R. R. Smith, A Preliminary Engineering Design of a Venetian Blind Direct Energy Converter for Mirror Fusion Reactors, Lawrence Livermore Laboratory, Rept. UCRL-74636 (1973).
7. R. Hawley, "Vacuum as an Insulator," Vacuum **10**, 310 (1960).
8. P. R. Little, "Electrical Breakdown in Vacuum," IEEE Transaction on Electron Devices, **77** (Feb. 1965).
9. W. H. Kohl, Handbook of Materials and Techniques for Vacuum Devices (Illus), (Van Nos, Reinhold, 1967).
10. P. A. Chatterton, "The Present Status of Vacuum Breakdown Research," in Proceedings, Discharges, and Electrical Insulation (Univ. of Waterloo, Sept. 1970.) (Addenda.)
11. A. J. Ahearn, "The Effect of Temperature, on the Emission of Electron Field Currents from Tungsten and Molybdenum," Phys. Rev. **44**, 277 (1933).
12. A. J. Ahearn, "The Effect of Temperature, Degree of Thoriation and Breakdown on Field Currents from Tungsten and Thoriated Tungsten," Phys. Rev. **50**, 238 (1936).
13. Carl C. Chambers, "Emission of Electrons from Cold Metal Surfaces," J. of the Franklin Institute **218**, 463 (1934).
14. I. Brodie and I. Weissman, "The Use of a Cylindrical Projection Tube for the Study of Pre-Breakdown Emission from Protrusions on Extended Surfaces," Vacuum **14**, 299 (1964).
15. J. J. Maley, "Effects of Some High-Voltage Conditioning Processes on Tungsten Electrodes," J. of Vacuum Sci and Tech. **8**, 697 (1971).

16. I. Brodie, "Studies of Field Emission and Electrical Breakdown Between Extended Nickel Surfaces in Vacuum," J. Appl. Phys. **35**, 2324 (1964).
17. R. H. Good, Jr. and E. W. Müller, "Field Emission," in Encyclopedia of Physics, Vol. XX, S. Flügge, Ed. (Springer-Verlag, Berlin, Germany, 1956) p. 176-231.
18. D. Alpert, D. A. Lee, E. M. Lyman, and H. E. Tomashke, "Vacuum Breakdown for Broad Area Tungsten Electrodes," in Proceedings, Insulation of High Voltage in Vacuum (MIT, 1964).
19. I. N. Slivkov, "The Influence of the Electrode Temperature on the Electrical Breakdown Strength of a Vacuum Gap," Soviet Phys. Tech. Phys. **3**, 708 (1957).
20. I. Brodie, "Vacuum Breakdown in the Presence of Thermionic Cathodes," J. of Vac. Sci and Tech. **2**, 249 (1965).
21. W. B. Nottingham, "Thermionic Emission," Encyclopedia of Physics Vol. XX, S. Flügge, Ed. (Springer-Verlag, Berlin, Germany, 1956) pp. 1-102.
22. E. L. Murphy and R. H. Good, Jr., "Thermionic Emission, Field Emission, and the Transition Region," Phys. Rev. **102**, 1464 (1956).
23. W. W. Dolan and W. P. Dyke, "Temperature-and-Field Emission of Electrons from Metals," Phys. Rev. **95**, 327 (1954).
24. I. N. Slivkov, "Mechanism for Electrical Discharge in Vacuum," Soc. Phys. Tech. Phys. **2**, 1928 (1957).
25. H. E. Tomashke, D. Alpert, D. A. Lee, and E. M. Lyman, "The Role of Electrode Projections in Electrical Breakdown," Proc. Insulation of High Voltages in Vacuum, (MIT, 1964) pp. 13-31.
26. L. Cranberg, "The Initiation of Electrical Breakdown in Vacuum," J. Appl. Phys. **23**, 518 (1952).
27. M. Rabinowitz, "Electrical Breakdown in Vacuum: New Experimental and Theoretical Observations," Vacuum **14**, 59 (1965).
28. W. D. Kilpatrick, "Criterion for Vacuum Sparking Designed to Include Both rf and dc," Rev. Sci. Inst. **28**, 824 (1957). Also see UCRL-2321.
29. W. Bauer and G. J. Thomas, "Helium Re-Emission and Surface Deformation in 316 Stainless Steel During -170°C to 700°C Implantations," J. Nucl. Materials **47**, 241 (1973).