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HIGH VOLTAGE PULSE IGNITION OF MERCURY DISCHARGE HOLLOW CATHODES

by Edwin G. Wintucky
Lewis Research Center
Cleveland, Ohio

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Edwin G. Wintucky
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

Abstract

A high voltage pulse generated by a capacitor discharge into a step-up transformer has been demonstrated capable of consistently igniting hollow cathode mercury discharges at propellant flows and heater power levels much below those required by conventional cathode starting. Results are presented for 3.2-mm diameter enclosed and open keeper cathodes. Starting characteristics are shown to depend on keeper voltage, mercury flow rate, heater power, keeper orifice size, emissive materials, and electrode to which the pulse is applied. This starting technique has been used to start a cathode over 10,000 times without any degradation of starting capability. The starting reliability, propellant and power savings offered by the high voltage pulse start should favorably impact performance of electron bombardment thrusters in missions requiring many on-off duty cycles.

I. Introduction

An 8-cm electron bombardment mercury ion thruster is currently being developed at the Lewis Research Center to perform satellite attitude control and station-keeping missions.(1) Such missions may require the thruster to undergo as many as 10,000 rapid startup on-off duty cycles with total operating times up to 20,000 hours.(1)

The starting procedure presently used for igniting the hollow cathode discharges is described in References 2, 3, and 4. For a well-designed 3.2-mm diameter enclosed keeper cathode, an optimum starting procedure(2,3) typically consisted of preheating the cathode (14.5 W) and vaporizer (12.5 W) for 3.5 to 10 minutes until the tip temperature was around 1200° K and the flow was nominally 45 mA. The discharge was then ignited by applying 600 V to the keeper cap. The difference between starting and operating propellant flows and heater power levels are most pronounced for the 8-cm neutralizer, which will likely require little or no cathode heater power and roughly 6 mA of propellant flow during thruster operation.(1) With the requirement of thousands of thruster startups, it is clearly desirable to minimize propellant and power losses and high cathode temperature associated with cathode starting. The conventional start has not been entirely reliable, particularly for cathodes which, after many hours of operation, have degraded either because of local depletion of emissive material or because of changes in the tip orifice due to erosion. Higher than normal heater power and propellant flow are usually required to start a cathode in a degraded conditions; often the discharge will not ignite at the prescribed time or may fail to start.

A high voltage pulse technique has been developed which appears to insure reliable cathode starting with minimal heater power and propellant losses. The high voltage pulse start was first used successfully with 30-cm thruster, 6.4-mm diameter open keeper cathodes. The present investigation is intended to demonstrate the feasibility and potential advantages of high voltage pulse starting for 3.2-mm open and enclosed keeper cathodes.

Presented in this paper are test results for pulses applied to both an auxiliary ignitor electrode and to the keeper electrode, showing the dependence of igniting and obtaining a stable keeper discharge on keeper voltage, propellant flow, cathode heater power, emissive materials, and keeper hole size. For comparison the cathodes were also started conventionally when possible.

II. Apparatus and Procedure

Cathode Construction

The basic construction (Fig. 1) of the hollow cathodes used in the high voltage pulse start tests is similar to that of the 5-cm thruster cathodes described in Reference 2. All of the cathodes were constructed from 3.2-mm o.d. Ta tubing with 0.38-mm thick walls and a 1.12- to 1.30-mm thick W - 2 percent ThO tip electron beam welded to the Ta. Table I summarizes the important distinguishing features regarding the insert, keeper configuration, tip orifice, tip heater, and vaporizer. Hours of operation and the corresponding total emission current are also given. Except for the coated foil insert, C-IIA and C-IIB were the same cathode.

C-II and C-III were constructed as alike as possible to allow comparison of the heater power requirements for starting cathodes with rolled foil and impregnated inserts. Both cathodes had flame-sprayed tip heaters and 4.7-mm diameter vaporizers. C-I and C-IV had swaged tip heaters and 3.1-mm vaporizers. Except for C-I, the cathode-vaporizer connections were made with swage-lock fittings. C-I had a Ta over stainless steel 10-32 threaded fitting, which also allowed nondestructive quick disconnections.

All of the cathodes except C-IV had enclosed keepers. The keeper caps, pressed from 0.25-mm thick Ta sheet, were 8.3-mm i.d. and 5-mm long. The three keeper hole diameters of 2.54 mm, 1.15 mm, and 0.83 mm were chosen to correspond to the 8-cm thruster main cathode, the 5-cm thruster neutralizer with a beam current of 25 mA, and a possible 8-cm thruster neutralizer with a beam current of 70 to 75 mA, respectively. The ceramic tubing supporting the keeper caps for C-II and C-III was 7.5-mm i.d., 0.4 mm in wall thickness, and 4.5-cm long. The tubing fit loosely over the flame-sprayed heater and was sealed to the cathode body with a high temperature ceramic cement. The keeper cap-supporting ceramic insulator for C-I was 2-cm long, 7.5-mm i.d., and fit snugly over the swaged heater coil. C-IV had an open ring keeper, made from 1.5-mm diameter Ta wire, with a 4.5-mm diameter hole. The cathode-keeper spacing for both open and enclosed keepers was 1.5 mm.

The rolled tantalum foil inserts used in C-I and C-IV were coated with a commercial alkaline-Earth carbonate mix containing approximately equal parts $BaCO_3$ and $SrCO_3$. The coating on the C-IIB insert contained $CaCO_3$ in addition to $BaCO_3$ and $SrCO_3$. Upon heating, the carbonates convert to the alkaline-Earths and their oxides which subsequently lower the work function of the emitting surfaces.

The porous tungsten impregnated insert used in C-III, similar to the inserts described in Reference 5, was a 1.9-mm diameter solid cylinder, 7.5-mm long with a 90° pointed tip. The impregnant was a mixture of BaO, CaO, and Al_2O_3 in the mole ratio of 4:1:1. The insert was initially activated according to the procedure of Reference 5.

Auxiliary Electrode

The auxiliary electrodes used with the enclosed keeper cathodes were made from 0.75-mm diameter W - 3 percent Rh wire. Figure 1 shows a typical auxiliary electrode arrangement where the wire was positioned parallel to and 0.5 mm from the keeper cap with the electrode tip even with the edge of the keeper orifice. In the case of the open keeper, the auxiliary electrode consisted of 0.5-mm diameter W wire, positioned parallel to and 0.5 mm from the cathode face with the electrode tip even with the edge of the chamfer.

High Voltage Pulse Activity

Figure 2 is a schematic of the high voltage pulse circuit. In operation, the one μf capacitor, charged to 400 volts, was discharged into the primary of a step-up transformer by a manually gated silicon controlled rectifier (SCR). The high voltage transformer used was an automobile ignition coil. The high voltage pulse generated was applied to either an auxiliary electrode or to the keeper. The above circuit produced a single pulse. However, use of linear integrated timer circuits now available would easily allow any number and frequency of pulses.

With 400 volts across the primary and the secondary open circuited, the output pulse amplitude exceeded 20 kV. With a shielded conductor and auxiliary electrode connected to the secondary, capacitive coupling reduced the maximum pulse voltage to around 17 kV. The theoretical upper limit to the pulse energy is the energy stored in the 1-μf capacitor and was 80 millijoules for a charge potential of 400 volts. The pulse rise time was approximately 300 volts per microsecond for a capacitor discharge of 400 volts.

By changing the polarity on the primary, the output pulse could be either initially positive or negative going with respect to cathode ground. For the pulse applied to the keeper, a 10 kV blocking diode was placed in series with the low voltage keeper supply. During cathode operation, the diode constituted a power loss of 3 to 7 watts depending on the magnitude of keeper current. A possible way to avoid this power loss is to bypass the diode with a normally closed high voltage vacuum relay actuated only during cathode starting

Vacuum System and Flow and Temperature Measurements

The high voltage pulse ignition tests were conducted in a vacuum bell jar where the pressure was in the low to middle 10^{-6} torr range depending on the mercury flow. To measure flow rates accurately, starting data were taken with the cathode-vaporizer assemblies in thermal equilibrium. Flow rates were determined by measuring the time rate of change of height of the mercury column in a precision bore capillary tube. Tip temperatures for the enclosed keeper cathodes were estimated with the aid of an optical pyrometer when possible. Cathode IV had a thermocouple attached to the tip.

III. Results and Discussion

General High Voltage Pulse Starting Requirements

The high voltage pulse start can be regarded as a two-part process: (1) a breakdown of the mercury vapor followed by (2) attainment of a stable keeper discharge. The occurrence and voltage required for breakdown depended primarily on mercury flow and cathode temperature. The pulse-to-auxiliary electrode and pulse-to-keeper methods were equally effective in producing breakdowns except at low flows and low cathode temperatures, where breakdowns did not always occur with the latter method. With negative going pulses a cold cathode-auxiliary electrode spacing of 0.5 mm was found adequate to produce breakdowns at mercury flows as low as 4 mA with the smaller keeper orifices and 10 to 15 mA with the 2.54-mm keeper orifices. With the smaller keeper orifices, positive pulses of 15 to 17 kV did not consistently produce a breakdown at flows below about 8 mA, at least for low cathode temperatures.

Once breakdown occurred, a minimum keeper voltage V_k was required to sustain a discharge. The keeper voltages presented in the tables and figures are minimum values required to obtain full keeper current emission for a given flow $\dot{m}$ and tip heater power P_{CH}. For cathodes with emissive material, given adequate $\dot{m}$ and P_{CH}, a starting V_k about 10 V above the operating V_k sufficed to obtain full emission. In the pulse-to-keeper method, the voltage drop across the 10 kV diode prior to igniting the discharge was about 6 V. Consequently the minimum V_k required for starting with a pulse to the keeper was usually around 10 V above that required for the pulse applied to an auxiliary electrode. With the auxiliary electrode, the starting V_k requirement was the same for either a positive or negative going pulse. A low current mode, the glow discharge, resulting from either insufficient thermionic emission $\dot{m}$ or V_k can also occur.[6] The output characteristics of the keeper supply may also affect the minimum voltage required to sustain a discharge but was not investigated in detail. Generally, it was noted that voltage-regulated supplies with a ballast resistance in series required higher voltages than current-regulated supplies with relatively flat volt-ampere characteristics. The results for C-I and some of the results for C-III with a 2.54-mm keeper orifice were obtained with a ballasted supply.

Figures 3 and 4 are a sequence of oscillograph traces of initially positive and negative pulses showing the pulses with (a) no breakdown, (b) with breakdown but no V_k to sustain a discharge, (c) with $V_k = 100$ V producing a discharge, and (d) with a discharge already on. The pulses were applied to an auxiliary electrode on C-I with an 0.83-mm keeper orifice. In figures 3(b) to (d) and 4(b) to (d), the flow was nominally 11 mA. One noteworthy feature is that the breakdown voltage for a negative pulse was typically much less than for a positive pulse. This was generally the case over a wide range of $\dot{m}$. Figure 5 is an oscillograph trace of a pulse with no breakdown applied to the keeper cap of a cathode at 20° C. The diode prevents the pulse from going negative.

Except for a few times when 2 or 3 pulses were needed, a single pulse was sufficient to ignite the discharge in the cathodes with emissive material at minimal levels of V_k and P_{CH}. A high voltage pulse thus allowed the cathode to be started at an exact, prescribed time, which was not always the case with the conventional start.[4]

Enclosed Keeper Cathodes With Emissive Material

Tables II(a) to (c) and III(a) to (c) present thermal equilibrium starting conditions for cathode II-B and cathode III, respectively, and show the dependence of starting on V_k, $\dot{m}$, P_{CH}, breakdown voltage, and keeper hole size. Where a range of flows encompassing more than a few mA is indicated, the data correspond to a number of points within that range. The higher breakdown voltage in the range given usually corresponds to the lower flow. The starting techniques A, B, and C are defined in Table I. The remark "no start" applies only to the conventional starting procedure C. Figure 6 presents thermal equilibrium starting conditions for cathode I. Breakdown voltages were not measured. Although none of the cathodes resemble a flight design from the standpoint of thermal efficiency, meaningful observations and comparisons can be made nonetheless.

First and foremost, the results for C-I and C-III demonstrate that high voltage pulses applied either to an auxiliary electrode or directly to the keeper are capable of igniting the discharge at P_{CH}, $\dot{m}$, and V_k well below those required by the conventional starting procedure. For example, C-I with an 0.83-mm keeper orifice required P_{CH} = 25 W, m = 40 mA, and V_k = 1000 V with conventional starting. Pulsed starting required only P_{CH} = 5.4 W, $\dot{m}$ < 10 mA, and V_k = 150 V. Other examples can be found in Tables III(a) to (c) and Figure 6.

The differences between the pulse start and conventional start requirements were much less for C-IIB. For example, as shown in Table II(b), after the first 120 hours of operation, C-IIB with a 1.15-mm keeper orifice started conventionally at anomalously low V_k (35 V), $\dot{m}$ (9 to 10 mA), and P_{CH} (10.4 W). There were some indications that this condition was transitory. After 364 hours of operation, a much higher V_k of 400 to 500 V was required for starting at the same $\dot{m}$ and P_{CH}. Furthermore, the minimum P_{CH} required to obtain a full discharge increased from 5.4 W for the first 120 hours of operation to 7.0 W after 364 hours of operation, at approximately equal $\dot{m}$.

Compared with C-I and C-IIB with rolled foil coated inserts, C-III with an impregnated insert required relatively high tip heater power for both the pulse and conventional starts. As shown in Tables III(a) and (b), for the two smaller keeper orifices, tip heater powers of 15 to 17 W sufficed to obtain a full keeper discharge of 300 to 450 mA at low V_k (30 to 50 V) and $\dot{m}$ (10 mA). C-III with a 2.54 mm keeper orifice required a minimum P_{CH} of around 25 W to obtain a full keeper discharge at comparable values of V_k, and $\dot{m}$ at a nominal 15 mA, as indicated in Table III(c). A possible reason for the larger tip heater power requirements of C-III could be a poorly activated insert or poor thermal contact between the insert and cathode body.

As Tables II(a) to (c) and III(a) to (c) indicate, the pulse-to-auxiliary electrode and pulse-to-keeper methods appear equally effective in starting a hollow cathode discharge. The only exception was with C-III at low flows (<10 mA, where breakdowns did not always occur for a pulse applied to the keeper. Tables III(a) to (c) give specific examples. For C-IIB, Tables II(a) to (c) show that the breakdown voltages for the pulse-to-keeper method were substantially lower than for the pulse-to-auxiliary electrode method for all the indicated cathode temperatures, flows, and keeper orifice sizes. For C-III, this was true only for the very high cathode temperatures (>1150° C). Otherwise, as Tables III(a) to (c) indicate, the breakdown voltages for the two methods were comparable. A potential shortcoming of the pulse-to-keeper method, which became very evident with C-III, is electrical leakage across the alumina insulator supporting the keeper cap. The conductivity of the insulator increased at elevated temperatures; the maximum pulse voltage obtainable at 20° C was 12 kV whereas after approximately 950 hours of operation and being heated to above 1150° C a number of times, the maximum amplitude at 1050° C was 6 kV.

In spite of considerable scatter and variation in breakdown voltages, some trends are discernible. Generally, the breakdown voltage increased with decreasing flow and decreased with increasing cathode temperature. The minimum keeper voltage needed to sustain a discharge showed similar trends. The effect of temperature on breakdown voltage and keeper voltage is seen in Table III(c) for C-III at $\dot{m}$ = 15 mA. Figure 5 illustrates V_k decreasing with both increasing flow and increasing cathode temperature for C-I with a 2.54-mm keeper orifice and P_{CH} levels of 9.7 and 13.3 W. For C-IIB and C-III, the changes in V_k were less pronounced than for C-I.

Another factor influencing cathode starting was collector voltage V_c. The principal effect of V_c on starting was that simultaneous application of V_c and V_k reduced the P_{CH} and V_k required to obtain full emission. An example is given in Table II(c) for C-IIB at P_{CH} = 5.4 W. It is also shown there that a sufficiently high $\dot{m}$ (>50 mA) can also produce full emission. The discharge can also be ignited to the collector only. Figure 6 gives an example in which the V_c required to sustain a discharge was less than V_k required for the same conditions. The electrode-collector spacing was approximately 1 cm.

Cathode With Open Keeper

The data in Table V for C-IV show that a high voltage pulse applied to an auxiliary electrode is also capable of igniting the discharge in open keeper cathodes at heater power and mercury flow levels substantially below those required by a conventional starting procedure. C-IV was started 295 consecutive times at a tip temperature of 610° C with a positive pulse at V_k = 70 V and $\dot{m}$ between 28 and 32 mA. For the above values of V_k and $\dot{m}$, a minimum tip temperature of around 600° C was required in order to obtain a full emission current of 0.5 amperes simultaneously with breakdown. The data was taken after 250 hours of cathode operation.

Cathode Without Insert or Emissive Coating

High voltage pulses applied either to an auxiliary electrode or to the keeper were found capable of igniting the discharge in cathodes with no insert or emissive coating at temperatures far below those required for appreciable thermionic emission from the thoriated tungsten tip. One consequence of this was that only a glow discharge was possible; the keeper current was generally less than 15 mA.

Figure 7 shows the dependence of the keeper voltage required to sustain a discharge V_k on $\dot{m}$ for C-IIA with 2.54-mm and 1.15-mm diameter keeper orifices. Tip heater power was 10.4 W and the tip temperature was estimated to be less than 850° C. Changes in the tip heater power over the range tested affected the starting parameters only by means of thermal feedback to the vaporizer. In general, V_k increased with decreasing $\dot{m}$. The larger keeper orifice required higher V_k for the same $\dot{m}$ than the smaller keeper hole; the minimum $\dot{m}$ needed to obtain a discharge was also higher.

One anomaly to be noted in Figure 7 is that for the 2.54-mm keeper hole, the pulse-to-keeper method appears more effective in igniting the discharge, whereas for the 1.15-mm keeper hole it is the pulse-to-auxiliary electrode method. Below about 25 mA flow with the larger keeper orifice, no breakdowns were observed with a 15-kV positive pulse; the corresponding breakdown voltages for a negative pulse and a pulse to the keeper were 12 kV and 6 kV, respectively. At roughly 15 mA flow, only random breakdowns occurred, with the negative pulse amplitude around 15 kV. With the 1.15-mm keeper orifice and the pulse applied to the keeper, the lowest $\dot{m}$ for which the discharge was consistently sustained was nominally 12 mA.

10,000 Pulse Start Electrode Durability Test

To demonstrate the durability of the auxiliary electrode and cathode under high voltage breakdown conditions, cathode I, with an 0.83-mm keeper orifice, was started 10,000 consecutive times with a positive pulse. The pulse was observed, at random, a number of times during the test and the initial breakdown voltage ranged from 10 to 13 kV. As seen in Figure 3, breakdowns also occur on the negative portion of the pulse. Therefore in addition to the 10,000 positive high voltage breakdowns, there were possibly up to four times as many negative high voltage breakdowns, ranging from 4 to 7 kV. Other cathode conditions relevant to the test were $\dot{m}$ = 15 to 17 mA, V_k = 100 V, and P_{CH} = 9.5 W, which were not minimum conditions for pulse starting. No temperature measurements were made in this test. A tip heater power of approximately 13.5 W was required to produce a discernible red glow, indicating that at 9.5 W the tip temperature was probably less than 800° C.

No degradation of starting capability occurred. In fact, the same electrode-keeper configuration was subsequently used for at least 500 additional starts and many pulses under varying cathode conditions. Figure 7 shows a photograph of the auxiliary electrode tip enlarged 30 X, after at least 10,500 pulse starts. The point on the originally wedge-shaped electrode tip was eroded to a depth of approximately 0.25 mm. No impairment of starting capability resulted, however.

Other Applications of High Voltage Pulse Start

The high voltage pulse start was demonstrated capable of igniting the discharge in two cathodes which would not restart due to damage from facility failures. The capability of directly extending cathode lifetime was thereby also demonstrated. The pulse was applied to the keeper cap in both cases. One cathode was the neutralizer from a 5-cm thruster[7] after 9500 hours of endurance testing. Tip power was 20 W, V_k was 1000 V, and $\dot{m}$ was estimated at greater than 30 mA. The second cathode was the main cathode from the 9715-hour thruster[7] after 10,500 hours of operation, the last 800 hours taking place in a vacuum bell jar. Here tip power was 18.5 W, V_k was 37 V (reduced from the normal 1000 V), and $\dot{m}$ estimated at more than 50 mA. Breakdown voltages were not measured.

IV. Conclusions

It is concluded that a high voltage pulse applied either to an auxiliary electrode or directly to the keeper is potentially a very desirable way to ignite hollow cathode discharges, particularly for auxiliary propulsion thrusters whose missions will require many thousands of on-off duty cycles. The high voltage pulse starting offers many advantages over the conventional start, namely (1) high reliability and the capability of igniting the discharge at an exact, prescribed time, (2) potential heater power and propellant savings, i.e., the 8-cm thruster neutralizer can be started at cathode temperatures and propellant flows close to or below operating levels, and (3) elimination of the need for a high voltage dc igniter supply. A potential advantage for the 30-cm thruster, particularly for the high emission cathodes, is the capability of igniting the discharge in open keeper cathodes at cathode temperatures well below those required by conventional starting.

The pulse-to-auxiliary electrode and pulse-to-keeper method each have advantages. An advantage to applying the pulse to an auxiliary electrode is that it eliminates the need for a blocking diode in series with the keeper supply. Furthermore, for the enclosed keeper geometry any potential problems associated with the keeper cap-supporting ceramic insulator becoming conductive at elevated temperatures are avoided. Applying the pulse to the keeper may be more desirable from a structural standpoint, especially for the main cathode and also because of the possibility of lower breakdown voltages.

Although the discharge can be ignited consistently at low propellant flows and cathode temperatures, some cathode heating is necessary for a full discharge to occur simultaneously with breakdown. Because of the generally lower breakdown voltages, a negative pulse is preferable to a positive pulse.

V. References

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TABLE I. - SUMMARY OF PULSE START CATHODES

Cathode number	Starting technique[a]	Tip geometry and orifice diameter, mm	Insert geometry and position	Keeper configuration and orifice diameter, mm	Tip heater and vaporizer diameter, mm	Hours of operation	Emission current, A
C-I	A, C	Straight 0.38	0.5 mil Ta foil 1.25 cm long recessed 0.75 mm from tip	Enclosed 0.83, 2.54	Swage 3.1	37 118	0.25 .55
C-IIA	A, B	Chamfered 90° to depth of 0.4 mm 0.25	None	Enclosed 1.15, 2.54	Flame-sprayed 4.7	---	----
C-IIB	A, B, C	Same as C-IIA	0.5 mil Ta foil 1.25 cm long recessed 0.75 mm from tip	Enclosed 0.83, 1.15, 2.54	Flame-sprayed 4.7	118 180 66	0.48 0.65 - 1.05 0.5
C-III	A, B, C	Straight 0.25	Porous tungsten impregnated recessed 0.75 mm from tip	Enclosed 0.83, 1.15, 2.54	Flame sprayed 4.7	677 156 105	0.3 .7 .5
C-IV	A, C	Chamfered 90° to depth of 1 mm 0.23	0.5 mil Ta foil 2.5 cm long recessed 0.5 mm from tip	Open ring 1.5 mm diam Ta wire with 4.5 mm hole	Swage 3.1	250	0.45 - 0.50

[a]A = pulse to auxiliary electrode, B = pulse to keeper, C = conventional.

TABLE II. - THERMAL EQUILIBRIUM STARTING CONDITIONS FOR C-IIB

(a) Keeper orifice, 0.85 mm

Starting technique	Keeper voltage	Mercury flow rate, mA	Tip power, W	Tip temperature, °C	Breakdown voltage, kV	Remarks
A	25	5-19	7.0	<800	7-9(+), 5-7(-)	
B	35	5-19	7.0	<800	0.5-2.5	
C	600	5-19	7.0	<800	---------------	No start
A	20	10-12	9.1	~825	8(+), 7(-)	
B	30	10-12	9.1	~825	0.5-1	
C	500	10-12	9.1	~825	--------------	After 300 hrs of operation

(b) Keeper orifice, 1.15 mm

A	20-25	5-20	5.4	<700	8-15(+), 4-8(-)	First 120 hrs of operation
B	35-40	5-20	5.4	<700	2.6	First 120 hrs of peration
C	600	5-20	5.4	<700	---------------	No start
A	25-35	9-16	7.0	<800	4-6(+), 4-5(-)	After 364 hrs
B	35-45	9-16	7.0	<800	0.8-1	After 364 hrs
C	600	9-16	7.0	<800	---------------	No start
A	15-20	9-10	10.4	~850	7-8(-)	After 120 hrs
C	35	9-10	10.4	~850	---------------	After 120 hrs
A	20	9-10	10.4	~850	3.4(+), 4(-)	After 364 hrs
B	30	9-10	10.4	~850	0.2	After 364 hrs
C	400-500	9-10	10.4	~850	---------------	After 364 hrs

(c) Keeper orifice, 2.54-mm

Starting technique	Keeper voltage	Collector voltage	Mercury flow rate, mA	Tip power W	Tip temperature, °C	Breakdown voltage, kV	Remarks
A	40	65	10-15	5.4	<700	10-12(-)	16-17 kV(+), no breakdown
B	55	↓	10-15	↓	↓	5-6	
A	35-40	↓	20-40	↓	↓	13-15(+), 8-12(-)	Collector 1.27 cm from keeper
B	40-50	↓	20-40	↓	↓	2-6	
A	35-40	0	50-80	↓	↓	9-15(+), 8-12(-)	
B	45-50	0	50-80	↓	↓	0.3-2	
A	25	--	15-50	7.0	<800	9-13(+), 6-10(-)	
B	35	--	15-50	7.0	<800	0.5-4	
C[a]	600						
C	110-160		45-50	9.5	~825	-----------------	300 hrs of operation

[a]No start for any of above conditions.

TABLE III. - THERMAL EQUILIBRIUM STARTING CONDITIONS FOR C-III

(a) Keeper orifice, 0.85 mm

Starting technique	Keeper voltage	Mercury flow rate, mA	Tip power, W	Tip temperature, °C	Breakdown voltage, kV	Remarks
A	20	4-6	26.3	~1075	6-8(-)	
B	40	4-6	26.3	~1075	None	9-10 kV max
A	20	8-10	26.3	~1075	5-7(-)	
B	40	8-10	26.3	~1075	9	
A	20-30	6-34	20.0	~1000	6-10(-)	
B	35-40	6-34	20.0	~1000	5-9	
A	40	10	16.5-17	~925	6-8(-)	
B	50	10	16.5-17	~925	None	9-10 kV max
A	30-35	12-22	16.5-17	~925	5-8(-)	
B	40-50	12-22	16.5-17	~925	6-7	
A	10	60-65	40.0	>1150	4-5(-)	
B	18	60-65	40.0	>1150	0.5-1	
C	600	60-65	40.0	>1150	-----------------	Start

(b) Keeper orifice, 1.15 mm

Starting technique	Keeper voltage	Mercury flow rate, mA	Tip power, W	Tip temperature, °C	Breakdown voltage, kV	Remarks
A	20	~4	27.5	~1075	7(-)	
B	30	~4	27.5	~1075	None	9 kV max
A	15	5-15	27.5	~1075	5-7(-)	
B	25	5-15	27.5	~1075	5-9	
A	20-30	4-8	21	~1000	12-15(+), 7-10(-)	
B	30-35	4-8	21	~1000	None	9-10 kV max
A	15-20	9-27	21	~1000	7-12(+), 6-8(-)	
B	30-35	9-27	21	~1000	6-9	
A	30	10	15.1	~900	8(+), 5-6(-)	
B	40	10	15.1	~900	9-10	
A	25	15-16	15.1	~900	8(+), 5(-)	
B	35	15-16	15.1	~900	7-8	
A	22	27	15.1	~900	8(+), 5-6(-)	
B	30	27	15.1	~900	5-7	
A	30	6-8	13.5	~850	10(+), 8(-)	Glow discharge only
B	40	6-8	13.5	~850	8-10	Glow discharge only
A	25-30	10-40	13.5	~850	7-10(+), 5-6(-)	Full discharge in 2 min to 1 hr
B	40	10-40	13.5	~850	7-10	(Full discharge in 2 min to 1 hr)
C	600	60-70	40.0	>1150	-----------------	

(c) Keeper orifice, 2.54 mm

Starting technique	Keeper voltage	Mercury flow rate, mA	Tip power, W	Tip temperature, °C	Breakdown voltage, kV	Remarks
A	100-300	12-32	17.5-18.5	~925	(-)	8-10 W P_k[a] for full discharge
B	100-300	12-32	17.5-18.5	~925	None	8-9 kV max
A	30-35	45-63	17.5-18.5	~925	(-)	6-8 W P_k for full discharge
B	40	45-63	17.5-18.5	~925	6-9	6-8 W P_k for full discharge
A	30	43-70	25.3	~1050	4-7(+), 3-4(-)	
B	40	43-70	25.3	~1050	5-7	
A	40	23-33	25.3	~1050	3-5(+), 3-4(-)	
B	45-50	23-33	25.3	~1050	3-6	
A	50	15	25.3	~1050	7(+), 5(-)	Full discharge 10-30 sec
B	55	15	25.3	~1050	6	Full discharge 10-30 sec
A	40	15	30.0	~1100	5-6(+), 3-4(-)	Full discharge 5-15 sec
B	50	15	30.0	~1100	4	Full discharge 5-15 sec
A	40	15	35.0	~1150	5-7(+), 3(-)	Full discharge 3-10 sec
B	50	15	35.0	~1150	3	Full discharge 3-10 sec
A	25	15	40.0	>1150	4(+), 2(-)	Full discharge immediately
B	35	15	40.0	>1150	0.5	Full discharge immediately
C	600	25	40.0	>1150	-----------------	Start
C	600	50	35.0	~1150	-----------------	Start

[a] P_k - additional keeper discharge power.

TABLE IV. - SUMMARY OF STARTING CONDITIONS FOR OPEN KEEPER CATHODE, C-IV

Starting technique	Keeper voltage	Mercury flow rate, mA	Vaporizer power, W	Tip power, W	Tip temperature, °C	Remarks
A	70	28-32	7.0	14.8	610	295 consecutive starts
C	500	70-75	9.0	21.0	950-1000	

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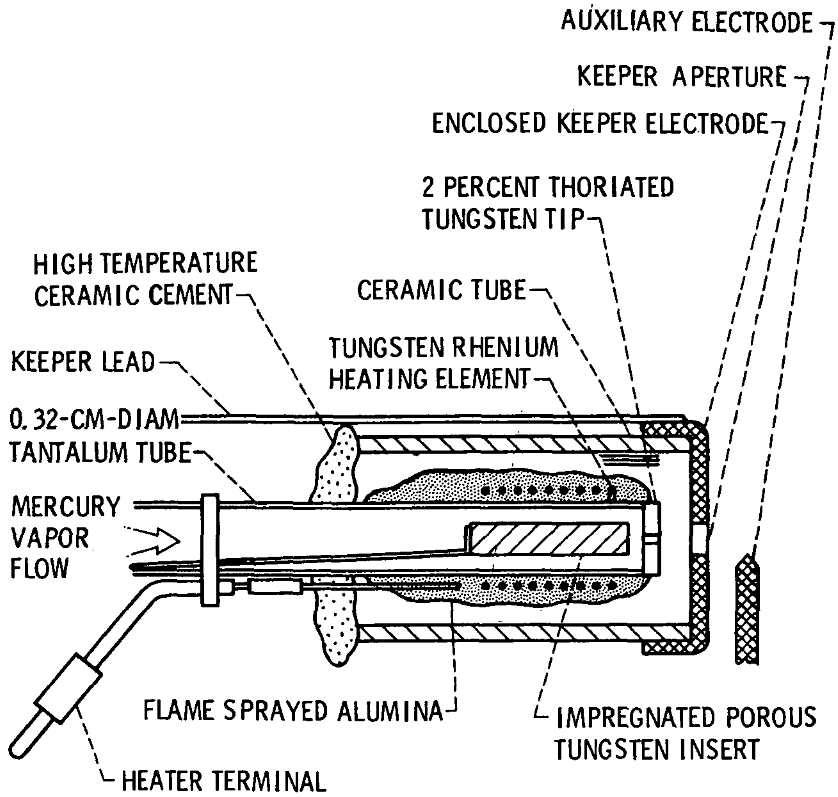


Figure 1. - Cross sectional view of enclosed keeper cathode configuration showing auxiliary electrode.

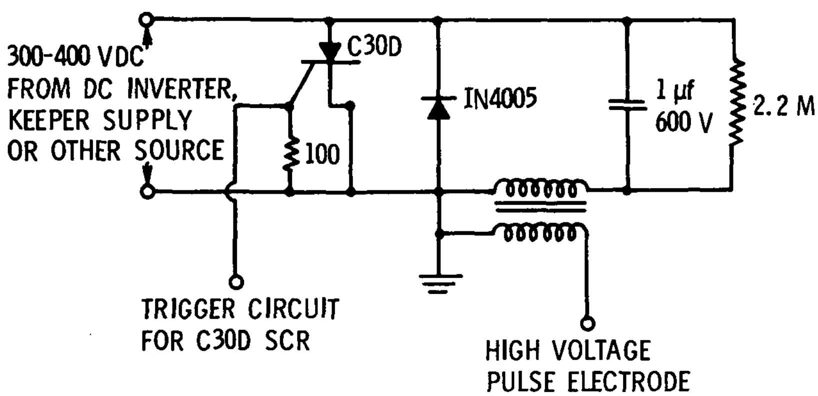
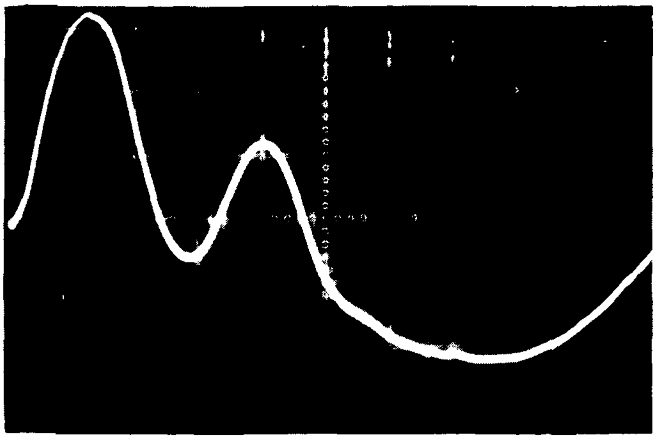
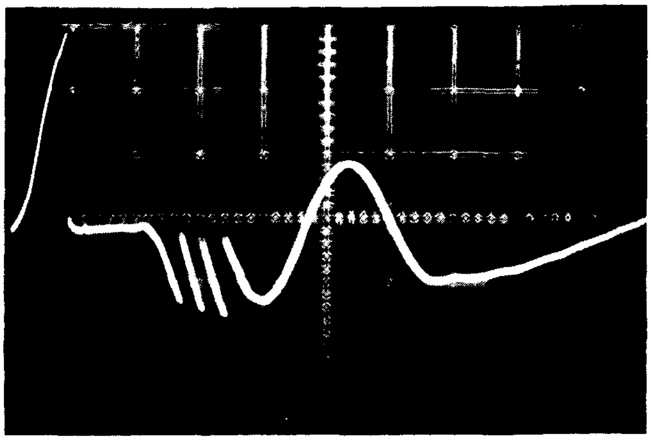


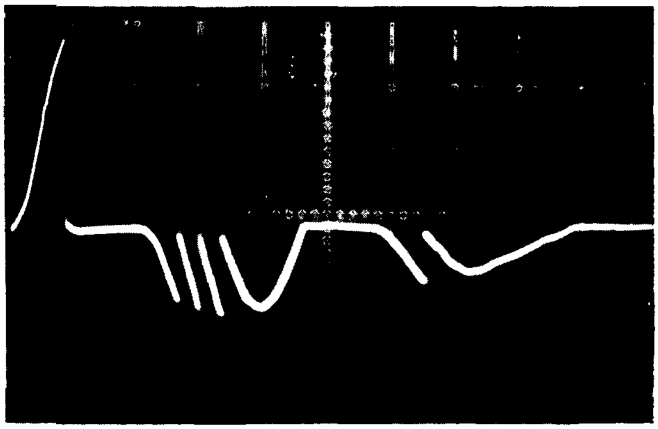
Figure 2. - Capacitor discharge circuit for high voltage pulse.



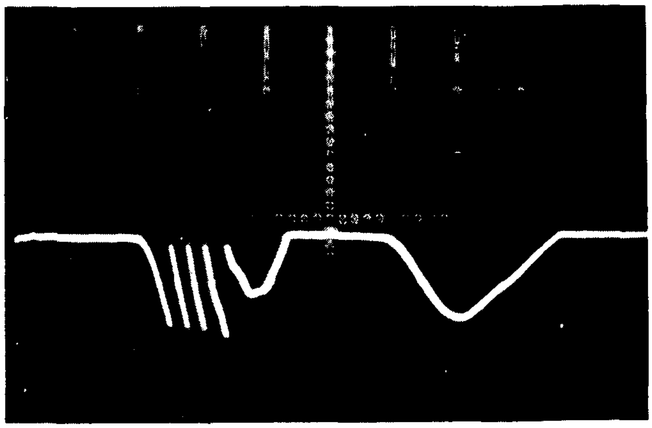
(A) NO BREAKDOWN.



(B) Vk = 0, BREAKDOWN BUT NO IGNITION.



(C) Vk = 100 v, DISCHARGE IGNITED.



(D) DISCHARGE ON, Vk ~ 13 v.

Figure 3. - Positive pulse applied to auxiliary electrode. Vertical scale: 5 Kv/div, horizontal scale: 50 μsec/div. Mercury flow approximately 11 ma.

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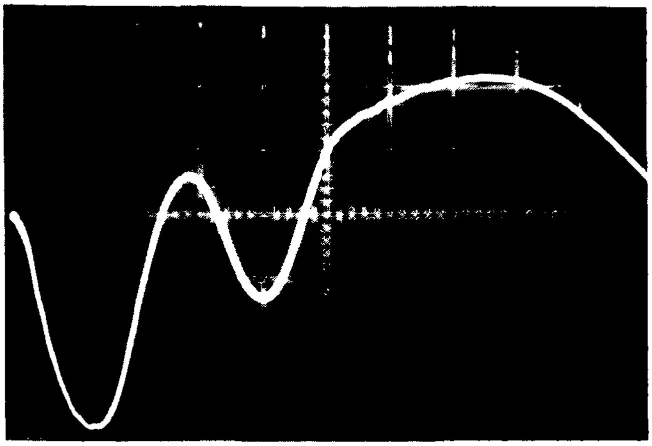
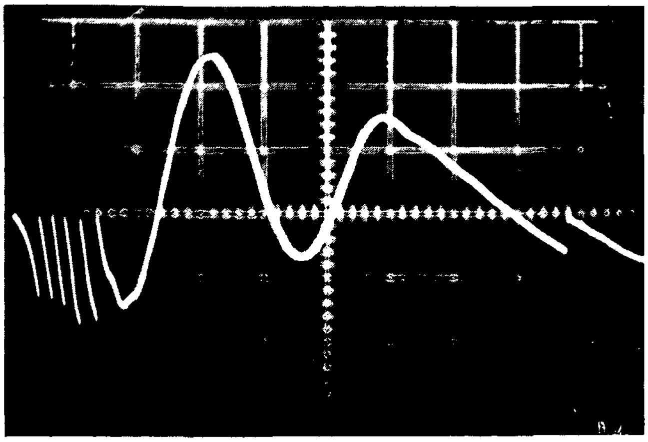
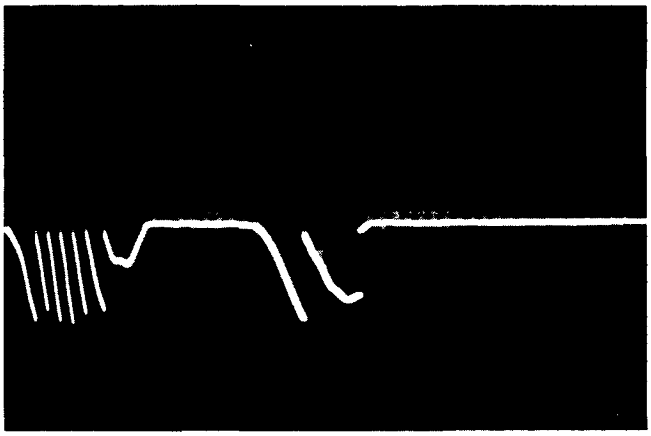


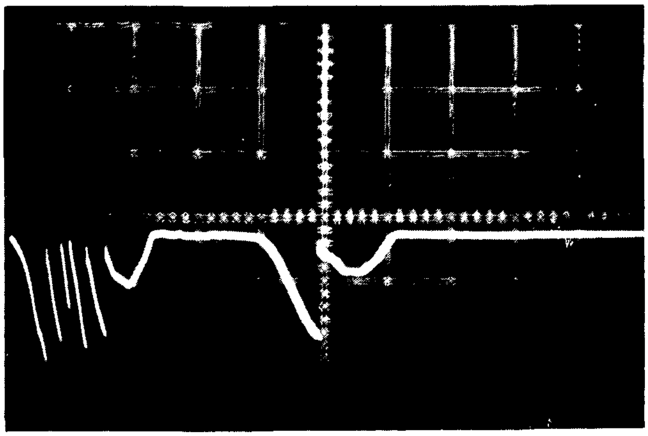
(A) NO BREAKDOWN.



(B) Vk = 0, BREAKDOWN BUT NO IGNITION.



(C) Vk = 100 v, DISCHARGE IGNITED.



(D) DISCHARGE ON, Vk ~ 13 v.

Figure 4. - Negative pulse applied to auxiliary electrode. Vertical scale: 5 Kv/div, horizontal scale: 50 μsec/div. Mercury flow approximately 11 ma.

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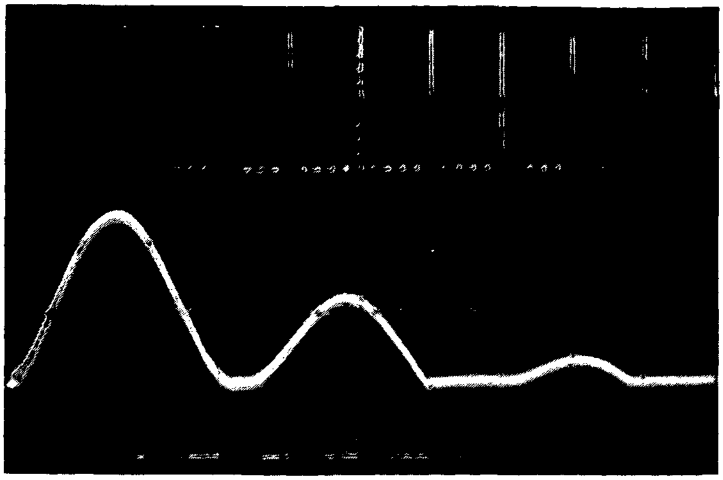

Figure 5. - Oscilloscope trace of pulse applied to keeper, no breakdown. Vertical scale: 5 Kv/div, horizontal scale: 50 μsec/div.

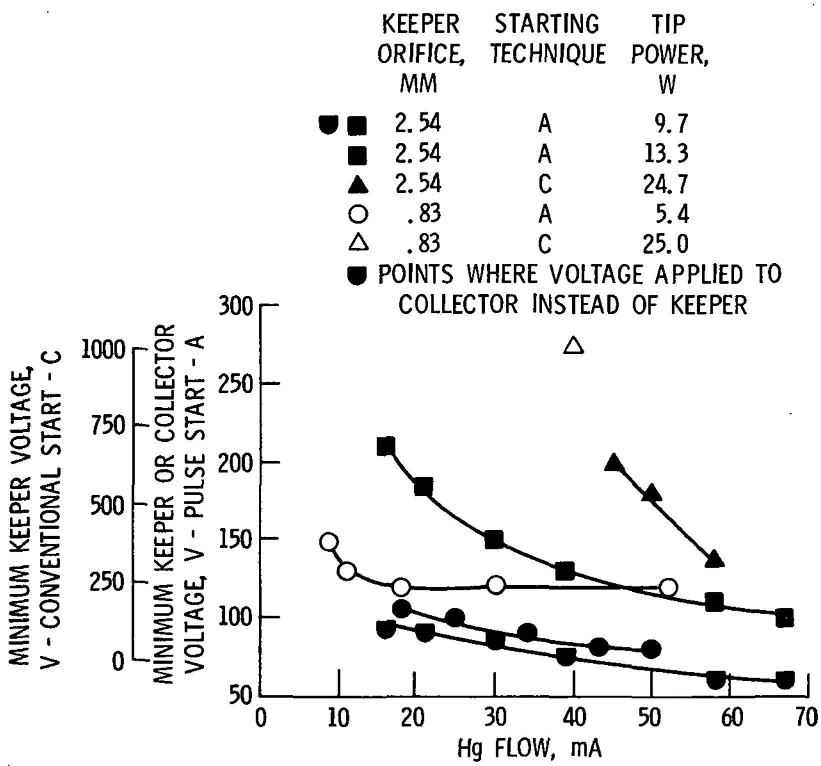

Figure 6. - Minimum keeper and collector voltage vs Hg flow for C-I.

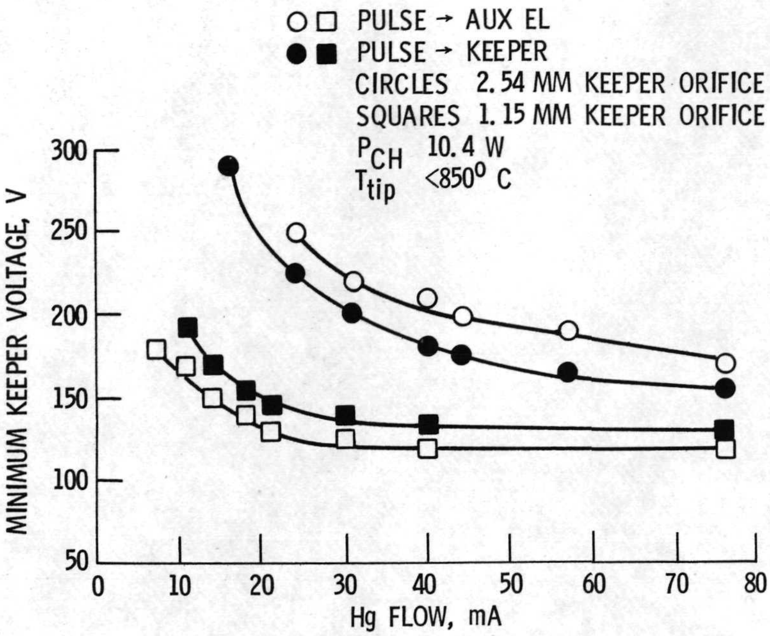

Figure 7. - Minimum keeper voltage vs Hg flow for C-IIA with no emissive material.

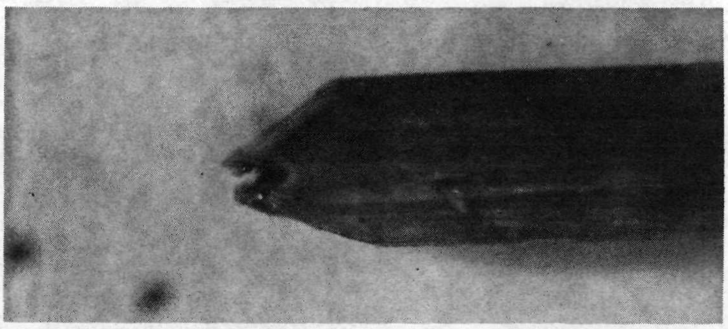

Figure 8. - Auxiliary electrode tip after more than 10 000 pulse starts. X30.

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