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CONTROL LOGIC FOR A 30 CM DIAMETER ION THRUSTER

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CONTROL LOGIC FOR A 30 CM DIAMETER ION THRUSTER

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Abstract

The 30-cm diameter mercury bombardment thruster[1,2,3,4] is presently being considered for a variety of missions[5,6,7]. These range from near-Earth orbital to deep space rendezvous and flyby missions. The wide variety of possible missions imposes a similar variety of operating constraints and requirements on the thruster. The thermal environment, allowable time to reach steady-state operation, and number of startups required are only three examples. The large variety of requirements in turn requires that the basic control logic be flexible if satisfactory thruster control is to be achieved under all possible conditions. The control logic has been divided into the start-up, run, and shutdown modes of operation. The start-up mode is considered in detail in this paper. The run mode consists of steady-state operation, throttling, and high voltage recycle, the latter two being peturbations of steady-state operation. Steady-state control has been reported in the literature[8]. While high voltage recycle and throttling must both ultimately be defined in detail, only high voltage recycle control is considered in this paper.

Apparatus

Thruster

Two 30-cm diameter mercury bombardment ion thrusters were used for this investigation. A list of components of these thrusters is given in table I, with descriptions detailed in Refs. 1-4, and 9-12. Thruster one was similar to an Engineering Model Thruster (EMT)[1,2] in performance but differed significantly with respect to the thermal characteristics of the cathode feed system (cathode/isolator/vaporizer). Thruster two was similar in all respects to an EMT, and in fact utilized EMT (700 series) hardware for the critical components; specifically the cathode baffle assembly, cathode isolator/vaporizer feed system, and main isolator feed system. The extraction systems used for both thrusters, although not mounted as in the EMT design, provided representative beam extraction capabilities.

Thruster one was used to qualitatively investigate start-up problems and high voltage recycle. Thruster two was used for tests resulting in more quantitative conclusions and thermal information pertaining to the propellant feed system.

Power Processor

The two power processors used for this investigation were those described in Refs. 4 and 8, but with modifications to the control logic. The power supplies were inverter type with flight like output power capabilities and output impedance. The control logic was modified to achieve operating profiles and power supply sequencing as discussed later. Analog signals for beam current, discharge voltage, and neutralizer keeper voltage as well as digital signals defining the status of the main discharge, neutralizer keeper discharge, and high voltage recycle conditions were brought out of the power processor control logic to a separate, auxiliary control system. Timing, sequencing, proportional control, and selection of fixed set-point functions were performed by this auxiliary control system, and analog voltages for programming the power supplies were returned to the power processor control logic. Because the power processor did not include a magnetic baffle supply, digital signals were generated to select one of 16 possible current set points on a separate resistance programmable supply.

In some instances where the power processor heater supply capability was inadequate to achieve the desired thruster thermal conditions, a separate power supply was substituted. Set-point selection was controlled by the auxiliary control system through digital commands.

Instrumentation

Most electrical operating parameters were measured outside the power processor. The d.c. currents and voltages were measured with either shunts or dividers and digital voltmeters. For best accuracy, these measurements were made at the vacuum feed throughs except the discharge chamber potential which was measured with potential leads to eliminate a significant line drop.

The six a-c. (5kHz) heater supplies were connected to their loads through twisted pair conductors. Since the currents were of primary importance, they were measured with current probes and a true r.m.s. voltmeter. The a.c. voltages were measured with the power processor data system at a point inside the power supply.

Propellant flow rates were measured by the standard practice of observing the time variation of the mercury level in a precision bore tube[11].

Several representative temperatures of feed system components were monitored by thermocouple. These locations are shown in Fig. 1. They were (1) the manifold near the main vaporizer, (2) the main and cathode isolator flanges on the discharge side, (3) the three propellant vaporizers, (4) the cathode mounting flange between the isolator and the cathode tip, and (5) the neutralizer tube over the front edge of the insert. All of the thermocouples were spot welded to the surface except for the manifold which was fastened against the back slate under a mounting screw head. All temperatures were measured by chromel-alumel or iron-constantan thermocouples. The thermocouple outputs were measured with high input impedance, direct temperature readout digital meters.

Results and Discussion

Basic Control Philosophy

Phase Description. The three modes of thruster operation; start-up, run, and shutdown, can in turn be subdivided into phases as shown in table II. The phase of operation determines first, which power supplies are on or off, and, if on, what the operating set-point or level is to be. The startup mode consists of the preheat, ignition, and heat phases. The run mode consists of the steady-state, throttling, and high vaotage recycle phases. The latter two phases are short term perturbations of the steady-state phase. Both of these phases result in a return to the steady-state phase within a short period of time after they begin. The term ''run mode'' is used to denote the steady-state phase unless otherwise specified.

The shutdown mode, in its simplest form, consists of one phase where all supplies are simultaneously truned off. This mode may consist, however, of several phases which would generally be dependent on selected criteria for a reliable restart under a variety of thermal conditions.

Start-up Mode

The purpose of the start-up mode and its three phases is to arrive at a set of electrical operating parameters, a thermal profile, and propellant flow rates which will result in stable thruster operation when the high voltages are turned on and an ion beam extracted at the transistion to the run mode. To accomplish this purpose, certain criteria must be satisfied during each of the three phases of the start-up mode. These are discussed separately.

Preheat Phase. The purpose of the preheat phase is to raise the temperatures of those components which govern the speed and reliability of main cathode and nuetralizer ignition and the coupling of the cathode-keeper discharge to the main discharge. These components include (1) main cathode and neutralizer tips and inserts, (2) main cathodes and main propellant feed isolators, (3) cathode vapor feed line, and (4) main propellant feed manifold.

Ignition Phase. During the ignition phase, propellant flow is introduced into the main cathode and neutralizer feed systems and ignition potential is applied to both keepers. In practice there are two ignition phases which begin simultaneously. One pertains to the neutralizer and determines the operating levels of the neutralizer tip heater, keeper, and vaporizes supplies. The second pertains to the discharge and determines the operating levels of the remaining nine power supplies. The neutralizer ignition phase terminates when a neutralizer keeper discharge is established. This condition is defined as neutralizer keeper current being greater than a predetermined level, usually in the range of 0.6 to 1.0 amps. The discharge ignition phase terminates when the main discharge is established. This condition is defined as cathode emission current greater than a predetermined level, approximately 4 amps. The two ignition phases do not necessarily end at the same time.

Heat Phase. The heat phase begins at the completion of the ignition phase. The purpose of the heat phase is to establish the proper propellant flow rates for the transistion to the run mode and, if necessary, to further increase the feed system temperatures by means of the discharge power. As in the case of the ignition phase, there are actually two heat phases, neutralizer and discharge, commencing at the completion of the appropriate ignition phase. Both heat phases are terminated at a fixed time after establishing the main discharge. There is also a requirement that neutralizer be operating in a stable manner before the termination of the heat phase.

At the completion of the heat phase, the high voltages are turned on and an ion beam extracted. Because solar array capabilities may limit power, it is desirable that the initial beam current be relatively low. Therefore the propellant flow rates resulting from heat phase operation must be the proper value which will not result in a beam current overshoot in the initial moments of operation in the run mode.

Test Results

Several tests were conducted to determine the thermal criteria and the power supply operating levels necessary for a successful startup. Tables III and IV show the test conditions for each of 14 tests. Tests T1 through T5 were thermal tests which proceeded only through the preheat phase. No neutralizer or discharge ignition was attempted. Tests 1 through 9 proceeded through the end of the heat phase and in some tests attempted the transistion to the run mode. These tests will be discussed according to the phase under consideration.

Preheat Phase

The power supplies which may be used during the preheat phase are the cathode and neutralizer tip heater supplies, the isolater heater supply, the three propellant vaporizer heater supplies, and the magnetic baffle supply. In the absence of any discharge, the two keeper supplies, the discharge supply, and the two high voltage supplies are open circuited. As a result, these supplies are either turned off or turned on and set to zero voltage or current as appropriate.

The role of each of the power supplies will be considered individually. The preheat levels of the neutralizer and cathode tip heater currents were not varied. (Power levels for the thermal tests were slightly lower than other tests due to a power processor malfunction.) The power levels used are given in table III and were based on successful prelimmiary tests on thruster number one and in those described in Ref. 12. The primary function of these supplies is to heat the tips and inserts to the temperatures necessary for ignition. These temperatures are typically 1000° to 1200° C for the tips and 700° to 900° C on the feed tube above the inserts. A secondary function is to heat the propellant feed lines between the tip and the vaporizer by thermal conduction.

Tests with both thrusters have shown that the time required to achieve ignition of the neutralizer can be shortened somewhat if the neutralizer vaporizer power supply is used during preheat. A vaporizer power level of about 5 watts was used for most of these tests (table III). This raised the vaporizer temperature to 200° - 230° C at the end of the preheat phase. This level is 70° to 100° C less than the normal operating level and corresponds to a negligible flow rate. However, tests described later have indicated that the use of neutralizer vaporizer power during preheat is not necessary.

The cathode and main vaporizer heaters were off during the preheat phase. Both of these vaporizers received enough conducted heat from the isolator heaters to eliminate the need for adding vaporizer heater power.

Because the cathode and main isolator temperatures are important to start-up reliability, the isolator heater is a critical and useful source of power for the preheat phase. Two separate d.c. heater supplies were eventually needed to power the cathode and main isolator heaters. The two power supply approach was used only to expedite testing. A single power supply and parallel heater connection could easily be used by properly selecting the two heater resistances.

The effect of isolator heater power (table III) on isolator and vaporizer temperatures was determined in thermal tests and is shown in Fig. 2. A cathode isolator heater power of 34.9 to 37.2 watts and a main isolator heater power of 27.4 to 29.3 watts were used for most tests with preheat times from 20 to 30 minutes. A set of critical temperatures required to achieve reliable start-up was defined and is discussed later. Figure 2 suggests the power-time tradeoffs which could be made to achieve a specific component temperature. Reduction of the preheat time to less than 20 minutes would require heater powers greater than those shown in Fig. 2.

As would be expected from the relative locations of the cathode tip and cathode isolator heaters, the cathode flange temperature is controlled by the tip heater power. Tests T1 and T3 (conducted at different isolator heater powers) showed that the final cathode flange temperature after a 30 minute preheat was 400° C $\pm$ 5° C for the power levels indicated in table III. This temperature is more than adequate to prevent propellant condensation in this area during start-up.

A similar comparison of tests T1 and T3 showed that the manifold temperature did not vary signifi cantly after 30 minutes of preheat for the two power levels. Manifold temperatures were within the range of 50° to 70° C and were increasing at typically the same rate for both tests.

Tests T4 was conducted to determine if there was any significant heating effect due to the magnetic baffle supply. Comparison of tests T1 and T4 showed temperatures for tests T4 to be very nearly the same as those for test T1 after 30 minutes of preheat. The magnetic baffle supply was left off during preheat for all other tests.

Thermal tests T3 and T5 were conducted to determine the effect of the initial temperature on the final temperature for a given power level. As can be seen from Fig. 3, and table V, there is little difference after the first 15 minutes of preheat. Test T5 was performed after an overnight cold soak in vacuo, exposed to the liquid nitrogen cryoliner. Test T3 was initiated after a 1/2 hour cool down from test T5 (no discharge). The minimal effect of initial temperature over this range was also evidenced in a full thruster start-up which is discussed later.

Ignition Phase

The primary factor influencing discharge ignition is the thruster temperature profile at the beginning of the ignition phase. Successful ignition has been accomplished for a variety of conditions. Table VI illustrates the times required to achieve neutralizer, main cathode, and discharge ignition for some of these conditions. The power supply settings used are given in table III for the preheat phase, and table IV for the ignition and heat phases. Tests 1 through 4 utilized a preheat time of 22.5 to 23.5 minutes. Neutralizer ignition was achieved within 16 to 28 seconds and cathode ignition within 8 to 16 seconds after the end of the preheat phase. The cathode keeper discharge coupled to the main anode (discharge ignition) within 10 to 32 seconds of the end of preheat. In tests 1, 2, and 3, the discharge coupled within 10 to 16 seconds of cathode ignition. In test 4 the discharge and cathode ignited simultaneously. This is a result of the significantly higher temperatures at the beginning and end of preheat for the main and cathode feed system components. As will be seen this also resulted in a smoother heat phase and transition from the start-up to the run mode.

Test 5 consisted of an 11 minute preheat resulting in significantly lower temperatures at the beginning of the ignition phase and much longer ignition times. In addition, difficulty was encountered in maintaining a stable discharge during the heat phase for this test. The conclusion was that the cooler feed system temperatures were undesirable and prevented adequate closed loop control of the propellant flow rates.

Tests 1 through 5 suggest a set of temperatures which must be attained at the start of the ignition phase to result in reliable neutralizer and discharge ignition and, as will be seen, to result in a stable heat phase.

The success of test 4 prompted extending the preheat to 30 minutes. Tests 6 and 7 show that the final temperatures were equal or greater than those observed in test 4. Neutralizer ignition times were unchanged. This is expected since neutralizer temperatres approach equilibrium wintin 10 to 15 minutes. Cathode ignition times were similar to test 4 and in both cases, discharge ignition was achieved simultaneously with cathode ignition. The initial thermal condition of the thruster at the beginning of the preheat phase within the limits shown in table VI did not affect the ignition phase as shown by comparing tests 6 and 7.

For test 8, the neutralizer vaporizer was turned off during the preheat phase. The neutralizer vaporizer reached a temperature of 170° C by the end of the 20 minutes preheat due to thermal feedback from the tip. The neutralizer ignited in 52 sec onds, about twice the time required when neutralizer vaporizer preheat power was used. Both the temperature and time required agree with the short preheat conditions of test 5. It appears that the use of a preheat set point for the neutralizer vaporizer results in a savings of only $\sim$1/2 minute, and as mentioned previously, does not contribute to start-up reliability.

In test 8, the isolator heater power was increased and the preheat time shortened to 20 minutes as shown in tables III and VI. This did not result in a smooth start-up. At the end of the preheat phase the cathode isolator reached 273° C as compared to 278° C for successful test 7. The main isolator temperature for test 8 was 25° cooler than for test 7 and the vaporizer temperatures approximately 50° cooler. Since the shortest preheat time to achieve successful start-up with the power settings used for test 7 was 26 minutes, it appears that isolator heater power increases of more than 7 watts would be needed to shorten the preheat time by 25% or more.

Heat Phase

Tests 1, 2, 3, and 8 have been classified as unsuccessful starts, primarily because the heat phase operation was unstable and noisy, and the attemptt to transfer to the run phase was unstable, noisy and, in some instances, resulted in low mode operation. The one major condition these tests have in common is the low temperatures at the end of the preheat phase (table VI and VII) resulting in delayed discharge ignition. A strip chart recording of test 3 is shown in figure 4. At times the excursions of discharges current were as much as ±6 amps about the 10 amp d.c. level during the unsuccessful tests.

The effect of flow rate on heat phase operation can be inferred from the results of test 3. Initially, the main flow rate was extremely low, based on the main vaporizer temperature of 237° C (fig.4) noted two minutes into the heat phase. This was accompanied by cathode vaporizer proportional controller on/off cycling. An oscilloscope trace (fig. 5(a)) taken at the low cathode flow extreme of the cycle showed that the discharge was actually going out for brief periods. Three and a half minustes into the heat phase, the main vaporizer temperature had increased to 252° C which corresponds to approximately 1 equivalent amp of neutral flow. At this point the operation became more stable. The current excursions diminished and figure 5(b) shows that the discharge remained on continuously. As the main vaporizer temperature was raised further and more main propellant flow supplied, the demand for cathode flow was reduced to a point where the cathode discharge began to extinguish. Manual control of the main vaporizer was needed to reestablish low discharge voltage, high discharge current operation. However the high main propellant flow rate during the last few minutes of the heat phase caused large dishcarge voltage and current excursions. This operation was not accompanied by the high speed on/off ecycling shown in figure 5(a). When the sequence was advanced to the run mode, a high voltage recycle occurred which extinguished th the discharge. The discharge was quickly re-established and the high voltages turned on. As in tests 1 and 2, the thruster began operation in low mode.

In each of these four tests the initial moments of the heat phase were characterized by large discharge current and voltage excursions and cathode proportional controller cycling due to insufficient main flow rate. When this condition was accompanied by low cathode flow rate, high frequency on/off operation of the discharge was also noted. In those tests where the main flow rate was permitted to become excessive, large voltage and current excursions were again noted and low mode operation during in the run mode was probable.

These four tests indicate the need for warmer temperatures at the beginning of the heat phase to prevent insufficient flow and the selection of heat phase set points to prevent excessive main flow during the heat phase. Tests 4, 6, 7, and 9 all exhibited higher temperatures at the end of preheat and were generally considered successful, although some minor problems did occur. Figures 6, 7, and 8 show the heat phases of tests 4, 6, and 7 respectively. In test 4 the main vaporizer temperature was warm enough to prevent the problems shown in test 3 (fig. 4). Since the main vaporizer and the isolator heaters were left on during the heat phase (table IV), the main flow rate eventually became excessive and the discharge current excursions began. In test 6 (fig. 7) the temperatures at the end of preheat, especially the main vaporizer were slightly higher than for test 4. In this case the discharge excursions occurred early in the heat phase. However the isolator heaters were turned off during the heat phase and the main vaporizer several minutes later (tabel IV), allowing the main vaporizer to cool down until the excursions diminished. In test 7 (fig. 8), the main vaporizer was off throughout preheat, ignition and heat phases and the isolator heaters turned off at the end of the preheat phase (table IV). This resulted in a smooth heat phase from beginning to end.

Tests 3 and 4 both resulted in a high voltage recycle followed by the discharge extinguishing when the high voltage was first turned on. This is not an uncommon result when high voltage is turned on while the discharge is operating at the 10 amp level [8]. In test 7 (fig. 8) the logic was modified to generate a high voltage recycle command at the completion of the heat phase just prior to turning on the high voltages. With this change incorporated no problems were experienced when turning on the high voltages.

During the heat phase the neutralizer vaporizer was placed in closed loop proportional control. The neutralizer keeper voltage was used to maintain propellant flow rate near the run level desired. When there is no beam current, the neutralizer keeper current must be increased to maintain a minimum required total emission current for stable operation [8]. The value selected for these tests was 2.4 amps. Since the keeper current is higher in the heat phase than during operation in the run mode, the keeper voltage required at a given propellant flow rate is also higher. A separate keeper voltage reference set point was used during the heat phase. Tests with thruster one indicated a tendency to lose proportional control when this was not done. The neutralizer voltage reference was set to provide closed loop control at ~19 volts. This resulted in estimated propellant flow rates of less than 50 equivalent m.a.

Further tests with thruster number one (using the neutralizer described in table I) indicated a tendency for the neutralizer to extinguish if operated for several minutes with no tip heater power. Therefore the neutralizer tip was operated at 6.0 amps and 8.4 volts during the heat phase on tests with thruster number two (table IV). No problems were observed when using this approach. No attempts were made to reduce or eliminate the tip heater power by changing other neutralizer operating parameters such as neutralizer keeper current. It is not evident that tip heater power would be necessary with an EMT neutralizer.

A test to determine the restart capability was conducted. Tables VI and VII show temperatures for test 9. The thruster had been operating for ~5 hours at a 1.0 amp beam current prior to test 9 and had reached the equilibrium temperatures shown in table VI. The thruster was then shutdown by turning off all power. At time = 0, after a cool down of 47.8 minutes, the start-up sequence was begun with the intention of allowing a 30 minute preheat. All power levels and set points for all phases were the same as for tests 6 and 7. In 20 minutes the temperatures had achieved those necessary for the ignition phase to begin (tabel VI and VII). At 21 minutes the main cathode ignited on the low voltage (∿60 V) section of the cathode keeper supply. Rather than let the preheat continue, the sequence was manually advanced to the ignition phase at t = 21.6 minutes. The discharge, which had been set for zero current during preheat, immediately ignited, and the neutralizer ignited in 18 seconds. A power processor logic malfunction permitted the cathode keeper discharge to ignite and reach the 1 amp level since this set point should have been for zero amps.

This test indicates that the short term restart of the thruster can be readily accomplished, although it is probably necessary to reduce the length of the preheat depending on the thermal history and previous operating conditions.

Control Philosophy Modification

A summary of the set-points used in each of the 3 start-up phases for successful starts is given in table VIII. In addition the table shows the total number of set points required by the start-up mode alone, start-up and run mode, and run mode alone. Only the 6 heater supplies require set points which are not also required for the run mode. These set points total 6.

Table IX shows the same information for a slightly modified approach. First, the function of the isolator heater supply during preheat has been assigned to the discharge supply. This is possible only if the discharge supply and isolator heater supply functions are not required at the same time. Presently it appears that the isolator heater may be needed for supplementary heating when the thruster is operating at beam currents much below 1 amp. If this need could be eliminated by a change in discharge operation at the lower beam currents (i.e. operation at higher discharge losses and power) it might be possible to eliminate the isolator heater power supply. Since both the isolator heaters and the discharge supply (negative output) are referenced to cathode common, the discharge supply (positive output) could be connected to the high side of the isolator heaters through a normally open switch. This switch would be energized only during the preheat phase.

As mentioned previously, the need for the neutralizer tip heater heat phase set-point may be diminished by either a change in operating profile or neutralizer design. However elimination of this set-point would not have any significant advantage unless its need were also eliminated from run mode operation as well. Otherwise the total number of set points remains unchanged.

The elimination of neutralizer vaporizer power during preheat has been discussed. Several tests have been conducted with this set-point off with satisfactory results. The high power set-points used by the cathode and neutralizer vaporizes during the ignition phase could be eliminated if maximum vaporizer heater power required by the proportional controllers were sufficient to reliably accomplish the cathode and neutralizer ignition in an orderly and timely manner.

These changes could result in the replacement of one supply, the isolator heater supply, by one normally deenergized switch having a low duty cycle and the reduction of the number of set-points required for start-up only from 6 to 2 (two tip) heater supply settings).

High Voltage Recycle

The general power supply profile for turning off and reapplying the high voltage after an overcurrent condition (recycle) is detailed in Ref. 8. A strip chart recording of such a recycle is shown in Fig. 9 for the discharge and high voltage supplies. These are the supplies which most directly affect the time required to complete a recycle. The tests described are intended to better define limits on the timing of these functions; specifically the high voltage off time and the discharge current cutback time (fig. 9). It is desirable to reduce these times to minimize off normal or low thrust beam operation and to reduce the possibility of loss of proper control due to the recycle perturbation. The shorter the recycle, the less need there is for any additional thermal input (especially important at low beam current) and the simpler the power profile becomes.

At the start of the recycle sequence, the high voltages are turned off and the discharge emission current reduced to a 0.6 to 0.8 amps level. The high voltages are kept off for 7.6 sec, at which twice the command is generated to turn on high voltage once again. In another 1.8 sec the command is generated to increase the emission current back to its run level of 10 amps. (for a 2.0 amp beam current.) Both beam and emission current go through a period of oscillation and reach a stable mode of operation in another 1.8 sec. Thus the total time required is 11.2 sec. Note that the beam current of this point is only 1.9 amps. The time requiredd to reach an actual 2.0 amp. beam is a function of the vaporizer (cathode and main) control during recycle. This was not investigation here.

The first change was to reduce the high voltage off time from 7.6 to 3.8 seconds. The rest of the recycle remained essentially unchaged, resulting in a shorter successful recycle time of 7.4 seconds. The high voltage off time was then reduced to 1.9 sec. (fig. 10). When the high voltage was reapplied, a second recycle occurred due to a large beam current transient. It also shows that the discharge current had been reduced only to 1.6 amps when the high voltage was reapplied, due to the relative long delay time to reduce the emission current. The emission current was too high at the time the high voltage is turned in resulting in a second recycle.

The control logic circuitry controlling the rate of discharge current decay was modified. It was found that as the rate of decay was increased there was a strong tendency for the discharge to extinguish. This may be due to the negative overshoot of the power supply programming voltage during switching (in which case the problem might be resolved by a change in control circuitry) or simply the typical response of the discharge to a step change. After several interations, it was determined that a decay time of ∿0.1 sec to reach the 1 amp. level gave satisfactory results.

Figure 11 shows this profile. The discharge current decays to 1 amp. in ∿0.1 sec. compared to 3.4 sec. in the previous cases. The high voltage was successfully reapplied in 1.9 sec. The long (3.5 sec.) discharge current cutback time was a result of random control logic timing and was not intentional. The only potentially serious problem appears to be the beam current overshoot associated with the fast increase of the discharge current. Note the discharge and beam current oscillations are not present in this case.

The 1.9 sec. high voltage off time is the minimum attainable with this particular control system. Further tests were designed to minimize the discharge current cutback time. A high voltage off time of 1.9 sec. and a discharge cutback time of 0.32 sec. was attempted but resulted in a second breakdown (fig. 12). Several longer times were also tried, with the shortest successful cutback times falling in the range of 0.55 to 0.80 sec. Figure 13 shows this profile of a successful recycle on an expanded scale. Comparison of Fig. 12 and 13 suggest a reason for the second breakdown occurring in Fig. 12. Note that when the discharge current is increased at 0.32 sec. in Fig. 12 the accelerator current is still decreasing in a transient manner after the reapplication of high voltage. This appeared to be the case in all unsuccessful attempts. However, in Fig. 13 and all other successful attempts, the accelerator current has reached an equilibrium level when the discharge current is increased. It appears that the factor controlling the minimum discharge current cutback time is a grid extraction one. If the screen and accelerator voltages have not reached values to provide sufficient perveance (beam current capability) when the discharge current is increased, overfocusing occurs and causes an accelerator overcurrent condition. It is probable that a reduction in the rise times of the two high voltage supplies would permit a corresponding reduction in the discharge current cutback time.

Figure 13 suggests that a high voltage off time of 0.25 seconds may be realistic. The shortest discharge cutback time demonstrated was 0.55 sec. Figure 13 shows that, based on the discussion of high voltage rise time above, this may be close to the minimum time possible. Thus the minimum combination of times demonstrated has been 2.45 sec. and the minimum anticipated is 0.8 sec.

Technically the recycle is not complete until the beam current has reached its final value, in this case 2.0 amps. Over or under shoot is a function of vaporizer control, but it also depends on the rise time of the discharge current. These tests provide an idea of the effect of rise time on beam current. Table X shows that peak currents of 2.31 amps can result within the first few seconds of discharge current increase for fast rise times. For slow rise times, the peak current is 2.05 amps and the steady beam current is actually less than 2.0 amps. and requires 6.8 sec. to increase.

These results can be affected by variations in proportional controller design, discharge and beam power supply output impedance, constant beam power logic control circuits, fast decay-slow rise time logic for the discharge current, beam current level, etc. However, three general rules do seem to hold for all cases: (1) if the discharge current is reduced too quickly, there is a tendency for the discharge to extinguish, (2) the high voltages cannot be turned on before the discharge current has reached a sufficiently low level otherwise a second breakdown will occur, and (3) the discharge current cannot be increased until the extraction system voltages have reached values to provide sufficient perveance.

Conclusions

Tests with a 30 cm thruster having EMT critical components have defined start-up criteria. Of the three phases which comprise the start-up mode, the preheat phase is intended to heat critical feed system components to desired temperatures. Of the seven supplies available during the preheat phase, only three were found to be useful for purposes of preheating the thruster. These were the cathode and neutralizer tip heater supplies and the isolator heater supply. These supplies were operated between 65 and 85 watts for best start-up results. The two tip heater supplies resulted in equilibrium temperatures within 15 min, but the isolator heaters required times of 25 minutes or greater to attain the desired temperatures. There is a tradeoff between preheat time and isolator heater power, which is in part mission specific, which could possibly reduce the preheat times significantly.

If the needed temperatures are attained during preheat, the ignition phase requires only several seconds. Both neutralizer and cathode keeper discharge ignited within this time. The main discharge ignited simultaniously with the cathode keeper.

The heat phase serves to establish the proper propellant flow rates prior to the transition to the run mode. These times were 8 minutes or less for the most successful start-ups.

Using these techniques, a thruster with initial temperatures in the range of -15 to $+25^{\circ}$ C can be reliably started and provide a 1.0 amp beam, usually within 30 minutes and always within 45 minutes. This time can be shortened when the thruster is warm before start-up.

High voltage recycle time profiles indicate limitations on several time functions. The discharge current cutback must be complete prior to reapplying high voltage. Restaring the discharge current to its run level too soon after the high voltage has been reapplied results in a second high voltage breakdown and recycle apparently shortening the total recycle time to much less than a second may be difficult and impose constraints on the control logic and high voltages supplies which are not warranted by mission considerations. Minimum times demonstrated were 2.45 seconds and minimum anticipated times are $\sim$0.8 seconds.

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11. Bechtel, R. T. "Component Testing of a 30-cm Diameter Electron Bombardment Thruster." AIAA Paper 70-1100, Stanford, Calif. 1970.

12. Mirtich M. J. "Investigation of Hollow Cathode Performance for 30-cm Thrusters." AIAA Paper 73-1138, Lake Tahoe, Nev. 1973.

Table I Thruster Components

	Thruster #1	Thruster #2
Extraction system (dished out)		
% Compensation	0.35	0.40
Screen hole diam.	1.9 mm	1.9 mm
Accel hole diam.	1.52 mm	1.52 mm
Screen % open	67	67
Thruster shell, anode, ground screen, misc. components	400 Series hardware similar to EMT design	Same
Magnets	400 Series hardware, number modified to result in EMT magnetic field	Same
Cathode/baffle assembly, cathode, cathode polepiece, mag baffle coil & mount	300 & 400 Series hardware modified to match EMT deisgn	700 Series (EMT) hardware
Cathode insert	Impregnated porous tungsten	Rolled Ta foil 700 series (EMT) hardware
Cathode keeper	Open loop	700 Series (EMT) hardware
Cathode isolator & vaporizer	Individual components assembled with fittings	700 Series (EMT) hardware - single unit
Main isolator & vaporizer	400 Series hardware similar to EMT design	700 Series (EMT) hardware
Neutralizer cathode, insert, keeper	Swagged Ta heater, open loop keeper rolled Ta foil insert, generally similar to EMT design	Same
Neutralizer vaporizer	Similar to EMT design	400 Series hardware similar to EMT design

EMT Components, Refs. 1 & 2. For other components. Refs. 3, 4, 9, through 12.

Table II Thruster operating modes

Mode	Phase
Startup	Preheat; Ignition; Heat
Run	Steady-State; Throttling; High Voltage Recycle
Shutdown	Single Phase*

*May depend on thermal restart conditions

Table III Summary of preheat set points

Test	Neutralizer Vap. Heater		Cathode Tip Heater		Neutralizer Tip Heater		Main Isolator Heater		Cathode Isolator Heater	
	Amps	Watts	Amps	Watts	Amps	Watts	Amps	Watts	Amps	Watts
T1	1.15	4.2	4.30	64.5	7.8	71.8	1.99*	15.4	1.80*	13.9
T2	1.07	3.6	4.27	64.5	7.48	68.1	2.48*	23.9	2.25*	21.7
T3**	1.11	4.0	4.28	64.2	7.52	69.2	2.98*	34.6	2.70*	31.3
T4	1.07	3.6	4.29	64.4	7.52	68.8	1.99*	15.4	1.80*	13.9
T5	1.11	3.9	4.34	66.8	7.69	70.7	2.98*	34.6	2.70*	31.3
1	1.14	5.0	4.6	76.4	8.45	86.2	2.85	31.7	2.56	28.2
2	1.15	5.1	4.6	76.4	8.40	85.7	2.85	31.7	2.65	30.2
3	1.14	5.1	4.6	76.4	8.30	84.7	2.85	31.7	2.65	30.2
4	1.14	5.1	4.6	76.4	8.26	84.3	2.94	33.7	2.65	30.2
5	1.13	5.1	4.6	76.4	8.40	85.7	2.94	33.7	2.65	30.2
6	1.13	5.1	4.57	75.9	8.22	83.8	2.85	31.7	2.74	32.3
7	1.17	5.2	4.60	76.4	8.26	84.3	2.85	31.7	2.72	31.8
8	0	0	4.61	76.5	8.34	85.1	3.03	35.8	3.00	38.7
9	1.17	5.4	4.62	76.7	8.29	85.4	2.85	31.7	2.72	31.8

*Heaters in parallel - current calculated

**Magnetic baffle on @4.3 amps off for all other tests

Table IV Summary of ignition and heat phase set points

(a) Test points constant for all tests

Supply	Ignition	Heat
Cathode vaporizer	2.05 A at 6.39 V = 13.1 watts max output	Proportional control ΔV_I set point varied (see table IVb)
Neutralizer vaporizer	2.51 A at 8.09 V = 20.3 watts max output	Proportional control VNK set-point 15 to 17 V
Neutralizer tip	Same as preheat level	6.0 A at 8.4 V = 50.4 watts
Cathode tip	Same as preheat level	Off
Discharge	Open circuit	10.0 amps (voltage in closed loop)
Cathode keeper	Open circuit	1.2 to 1.4 amps - voltage unregulated varies from 7.5 to 9.5 V
Neutralizer keeper	Open circuit	1.45 A (voltage in closed loop)

*P.C. ≡ Proportional control

(b) Test points varied from test to test

Test	Phase	Main Vaporizer	Cathode Vaporizer	Magnetic Baffle	Isolator Heaters
1	Ignition	Off	Max	On	On - preheat level
	Heat	Off	P.C. $-\Delta V_I$ set 37 V	On	Off
2	Ignition	Off	I_{Max}	Off	On - preheat level
	Heat	Off	P.C. $-\Delta V_I$ set 32 V	Off	On - switched off during heat
3	Ignition	.8 A, 5.6 W	I_{Max}	Off	On - preheat level
	Heat	.8 A, 5.6 W	P.C. $-\Delta V_I$ set 40 V	Off	On - preheat level
4	Ignition	.8 A, 5.6 W	I_{Max}	Off	On - preheat level
	Heat	.8 A, 5.6 W	P.C. $-\Delta V_I$ set 43 V	Off	On - switched off during heat
5	Ignition	Off	I_{Max}	Off	On - preheat level
	Heat	Off	P.C. $-\Delta V_I$ set 37 V	Off	On - preheat level
6	Ignition	.8 A, 5.6 W	I_{Max}	Off	On - preheat level
	Heat	Switched off during heat	P.C. $-\Delta V_I$ set 43 V	Off	Off
7	Ignition	Off	Max	Off	Off
	Heat	Off	P.C. $-\Delta V_I$ set 43 V	Off	Off
8	Ignition	Off	I_{Max}	Off	Off
	Heat	Off	P.C. $-\Delta V_I$ set 43 V	Off	Off
9	Ignition	Off	I_{Max}	Off	Off
	Heat	Off	P.C. $-\Delta V_I$ set 43 V	Off	Off

Table V Effect of initial temperature on preheat thermal characteristics (temperatures in deg. C)

Temperature location (Fig. 1)	Test	Time		
		0 min	15 min	30 min
Manifold (#1)	T5	-9	21	65
	T3	+4	32	70
Main vaporizer (#2)	T5	-7	141	266
	T3	+27	163	275
Cathode vaporizer (#6)	T5	-6	129	257
	T3	+33	151	270
Cathode flange (#4)	T5	-4	340	411
	T3	+13	334	404
Neutralizer vaporizer (#8)	T5	-2	183	220
	T3	+7	186	221
Neutralizer insert (#7)	T5	-14	748	752
	T3	-10	707	727

Table VI Summary of temperatures at beginning of preheat & ignition phase and time to ignite discharges

Test	Conditions	Temperatures deg. C								Preheat length, min.	Time for neut. to lite, sec.	Time for cath. to lite, sec.	Time for discharge to lite, sec.
		Time, min.	Neut. insert	Neut. vap.	Cath. isolator	Cath. vap.	Manif.	Main isolator	Main vap.				
1	64 Hour storage in vacuo not directly exposed to LN_2 temperatures	0	-8		0	0	-3	0	-1				
		22.1	863	231	248	156	42	258	207	23.5	28	8*	18
2	5 Hour off time since previous run	0	-14	4	17	19	0	21	16				
		22.0	839	224	256	167	45	257	206	22.5	26	16	28
3	14 Hour storage in vacuo not directly exposed to LN_2 temperatures	0	-6	11	5	6	1	5	3				
		22.0	836	226	255	161	46	254	201	22.5	16	16	32
4	1-1/2 Hour off since previous run	0	-1	16	60	75	38	65	66				
		22.0	847	226	278	200	73	275	233	22.7	26	10	10
5	Isolator heat applied prior to start - otherwise same conditions as test 3	0	-8	6	18	22	6	14	16				
		11.0	785	177	203	92	21	183	100	11.5	∿60	250	360
6	Start from ambient - thruster in vacuo ∿1 hour	0											
		0.5	67	44	22	23	19	24	21				
		30.0	846	226	287	220	80	292	263	30.2	22	10	10
7	14 Hour storage in vacuo directly exposed to LN_2 cryoliner[2]	0	-14	-1	-3	-4	-8	-2	-6				
		30.0	747	234	278	203	62	286	254	30.3	26	7	7
8	Same as test 7 used higher isolator heater power	0	-14		-5	-3	-10	-5	-6				
		19.5	793	170	273	158	36	263	197	20.0	52	24	40
9	∿48 min. cool down from end of previous run	End of prior run	535	306	201	233	172	204	256				
		-0.6	27	42	117	131	79	173	123				
		+20.0	734	226	294	226	96	285	250	21.6	+18	-36	0

*1.6 min. delay in turn on of cathode vap. due to logic error

Table VII Summary of successful and unsuccessful start-ups.

	Test	Temperatures °C (at end of preheat)					Cath. iso-lator power, watts	Main iso-lator power, watts	Length of preheat min.	Discharge & cath. lite simultaneously
		Cath. iso-lator	Cath. vap.	Manif.	Main iso-lator	Main vap.				
Successful	4	278	200	73	275	233	37.2	27.4	22.7	Yes
	6*	287	220	80	292	263	34.9	29.3	30.2	Yes
	7	278	203	62	286	254	34.9	28.9	30.3**	Yes
	9	294	226	96	285	250	34.9	28.9	21.6	Yes
Unsuccessful	8	273	158	36	263	197	40.0	35.1	20.0	No
	1	248	156	42	258	207	34.9	25.6	23.5	No
	2	256	167	45	257	206	34.9	27.4	22.5	No
	3	255	161	46	254	201	34.9	27.4	22.7	No

*General test profile repeated 8 times with similar results.

**Cathode lit prematurely

Table VIII Operating levels and number of set points required for each power supply

Supply	Preheat	Ignition	Heat	No. of Set Points			
				Req'd by start-up only	Req'd. by start-up & run	Req'd. by run	Total
Isolator heater-cath. & main	32 W each	(a)	(a)	1	0	1	2
Cathode tip heater	4.6 A 76 W	4.6 A 76 W	(a)	1	0	1	2
Neutralizer tip heater[(b)]	8.3 A 85 W	8.3 A 85 W	6.0 A 50 W	1	1	0	2
Main vap.	(a)	(a)	(a)	0	0	PC[c]	1
Cathode vap.	(a)	2.0 A 13.1 W	PC	1	PC[c]	0	2
Neutralizer vap.	1.1 A 5.1 W	2.5 A 20.3 W	PC	2	PC[c]	0	3
Mag. baffle	(a)	(a)	(a)	0	0	A	A[d]
Neutralizer keeper	(a)	2.4 A	2.4 A	0	1	B-1	B[d]
Cathode keeper	(a)	1.0 A	1.0 A	0	1	C-1	C[d]
Discharge	(a)	10 A	10 A	0	1	D-1	D[d]
Screen	(a)	(a)	(a)	0	0	E	E[d]
Accelerator	(a)	(a)	(a)	0	0	F	F[d]

[a]No power to load - supply either off or turned on with set point for zero current or voltage.

[b]Currents are for swaged heater used. Flame sprayed heater would require different current but typically the same power

[c]PC ≡ Proportional control - vaporizers always in closed loop proportional control during run mode.

[d]Number of set points required during run mode to determined by mission constraints.

Table IX Modified operating levels and set points required

Supply	Preheat	Ignition	Heat	No. of Set Points: Req'd. by start-up only	Req'd. by start-up only	Req'd. by run only	Total
Isolator heater	(a)	(a)	(a)	0	0	0	0
Cathode tip heater	4.6 A 76 W	4.6 A 76 W	(a)	1	0	1	2
Neutralizer tip heater[b]	8.3 A 85 W	8.3 A 85 W	(a)	1	0	1	2
Main vap.	(a)	(a)	(a)	0	0	PC[c]	1
Cathode vap.	(a)	PC	PC	0	PC[c]	0	1
Neutralizer vap.	(a)	PC	PC	0	PC[c]	0	1
Mag. baffle	(a)	(a)	(a)	0	0	A	A[d]
Neutralizer keeper	(a)	2.4 A	2.4 A	0	1	B-1	B[d]
Cathode keeper	(a)	1.0 A	1.0 A	0	1	C-1	C[d]
Discharge	64 W	10.0 A	10.0 A	0	2	D-2	D[d]
Screen	(a)	(a)	(a)	0	0	E	E[d]
Accelerator	(a)	(a)	(a)	0	0	F	F[d]

[a]No power to load - supply either off or turned on with set point for zero current or voltage.
[b]Currents are for swaged heater used. Flame sprayed heater would require different current but typically the same power.
[c]PC ≡ Proportional control - vaporizers always in closed loop proportional control during run mode.
[d]Number of set points required during run mode to determined by mission constraints.

Table X Effect of discharge current rise time on beam current after cycle

Discharge current rise time (10% → 90%) sec.	Max beam current (transient) amp.	Max beam current (steady) amp.	Time beam current ≠2 amps.
0.05	2.31	2.11	2.28 (>2 A)
..36	2.15	2.04	1.87 (>2 A)
2.0	2.05	1.95	6.80 (<2 A)

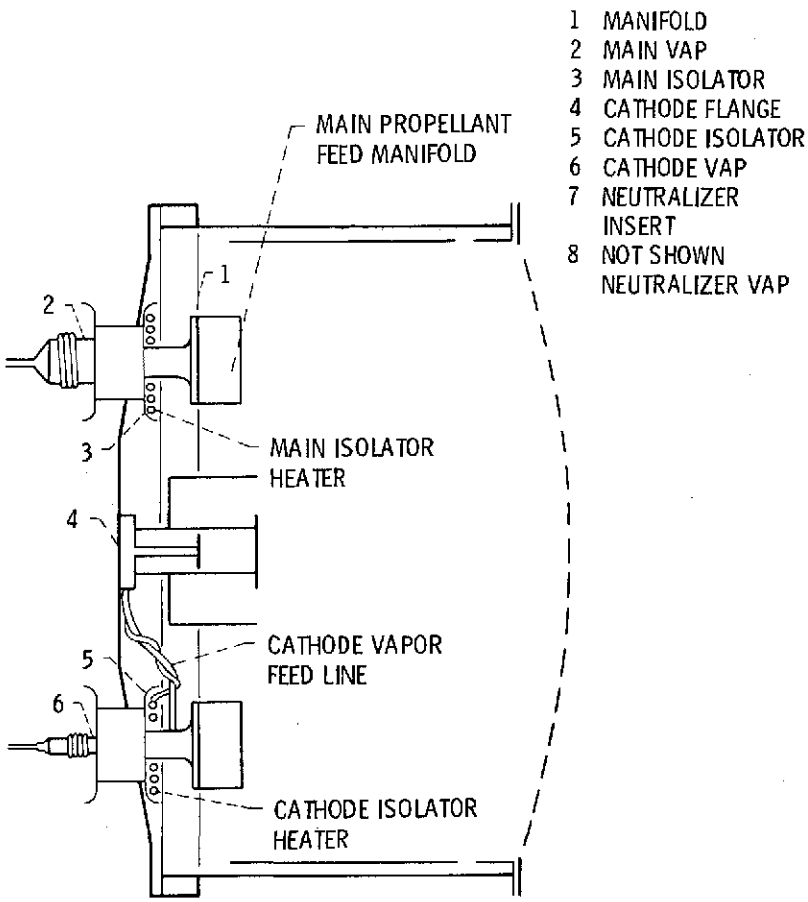


Figure 1. - Location of thermocouples.

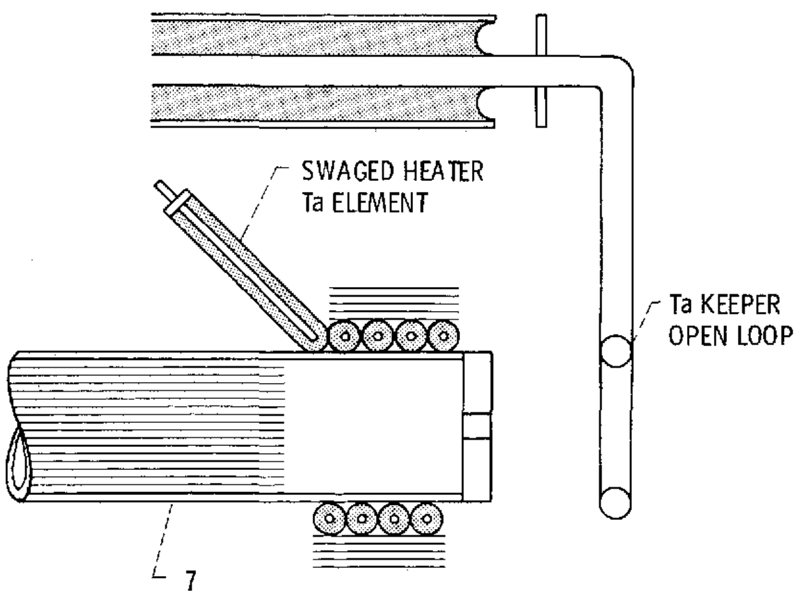


Figure 1. - Concluded.

E-8219

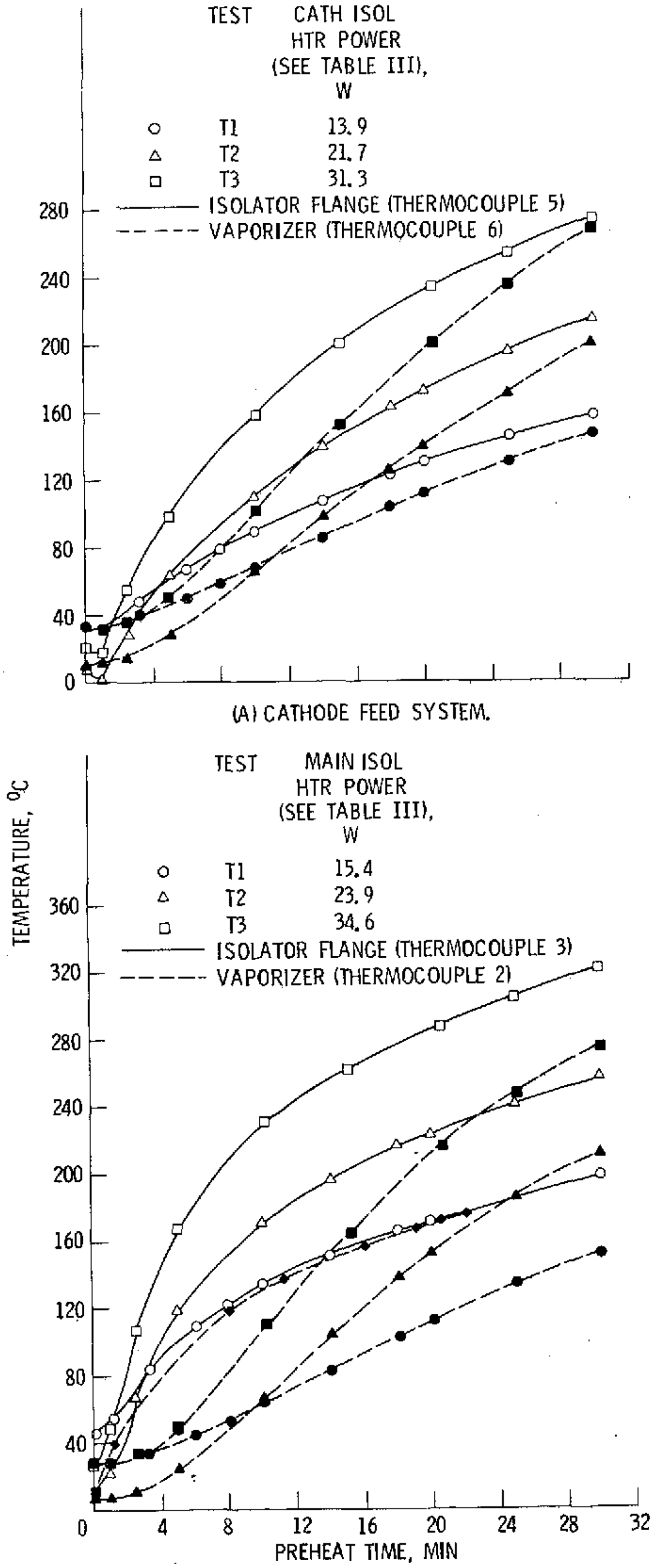


Figure 2. - Effect of isolator heater power on feed system temperature.

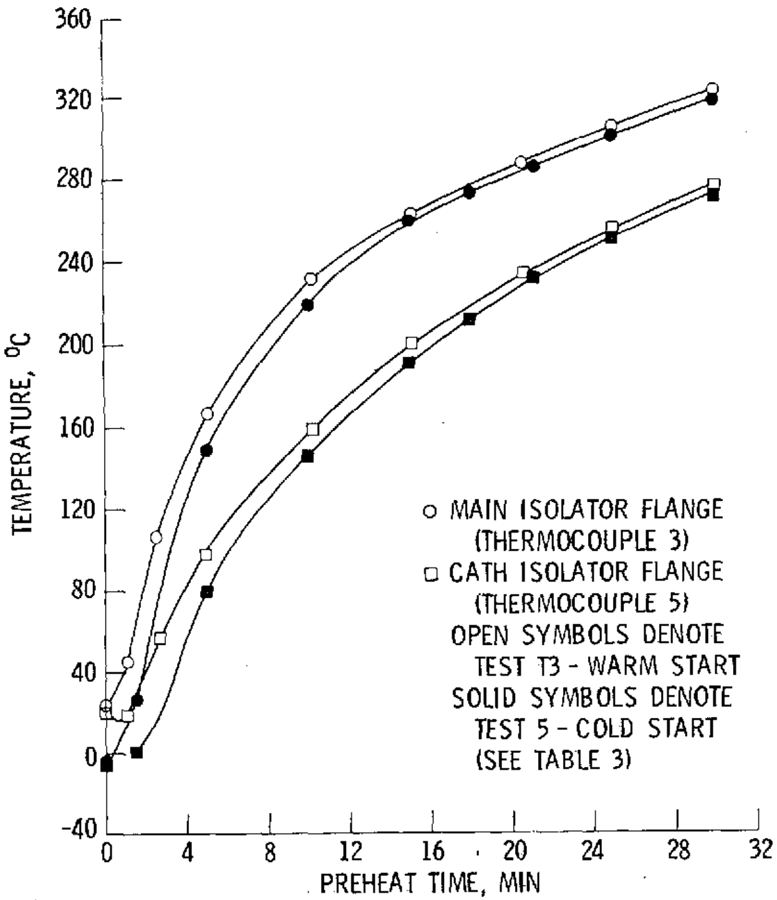


Figure 3. - Effect of initial temperature on preheat characteristics.

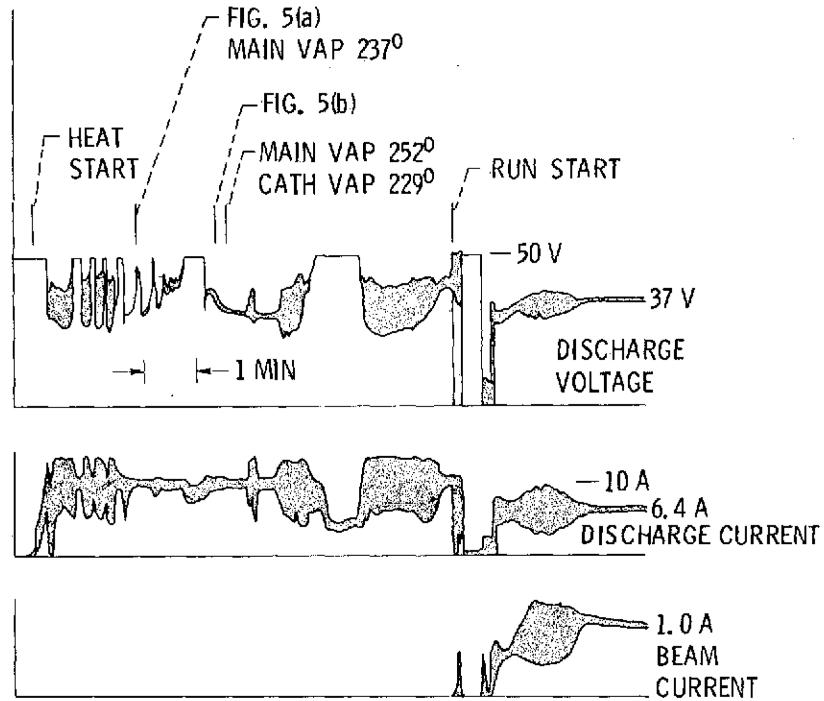
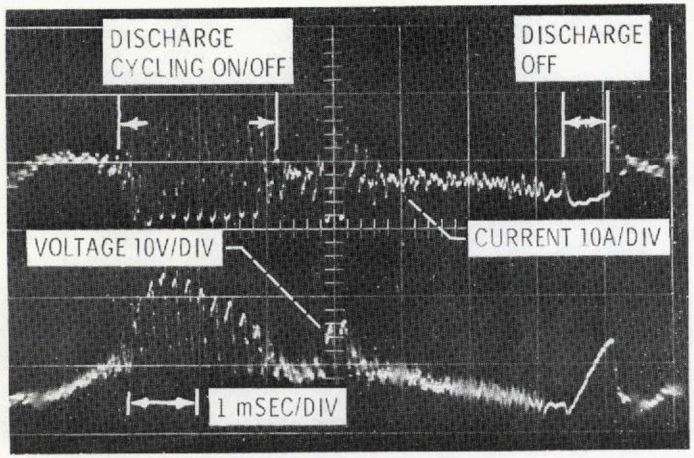
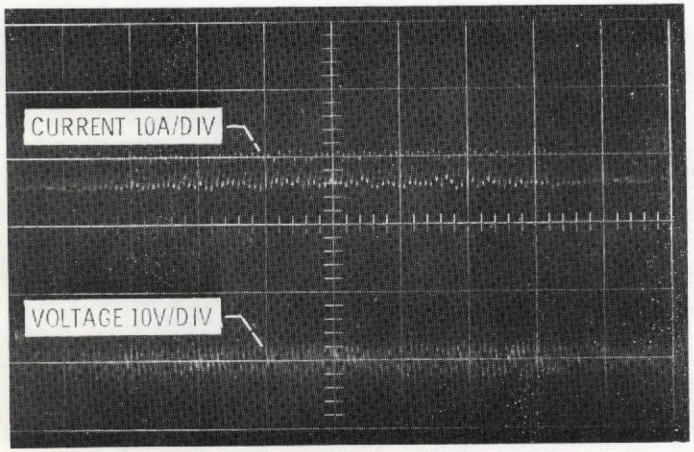


Figure 4. - Heat phase, test 3.



(a) 2.0 MINUTES AFTER START OF HEAT PHASE.



(b) 3.5 MINUTES AFTER START OF HEAT PHASE.

Figure 5. - Discharge current and voltage (ac only) at various times during heat phase of test 3. See also figure 4.

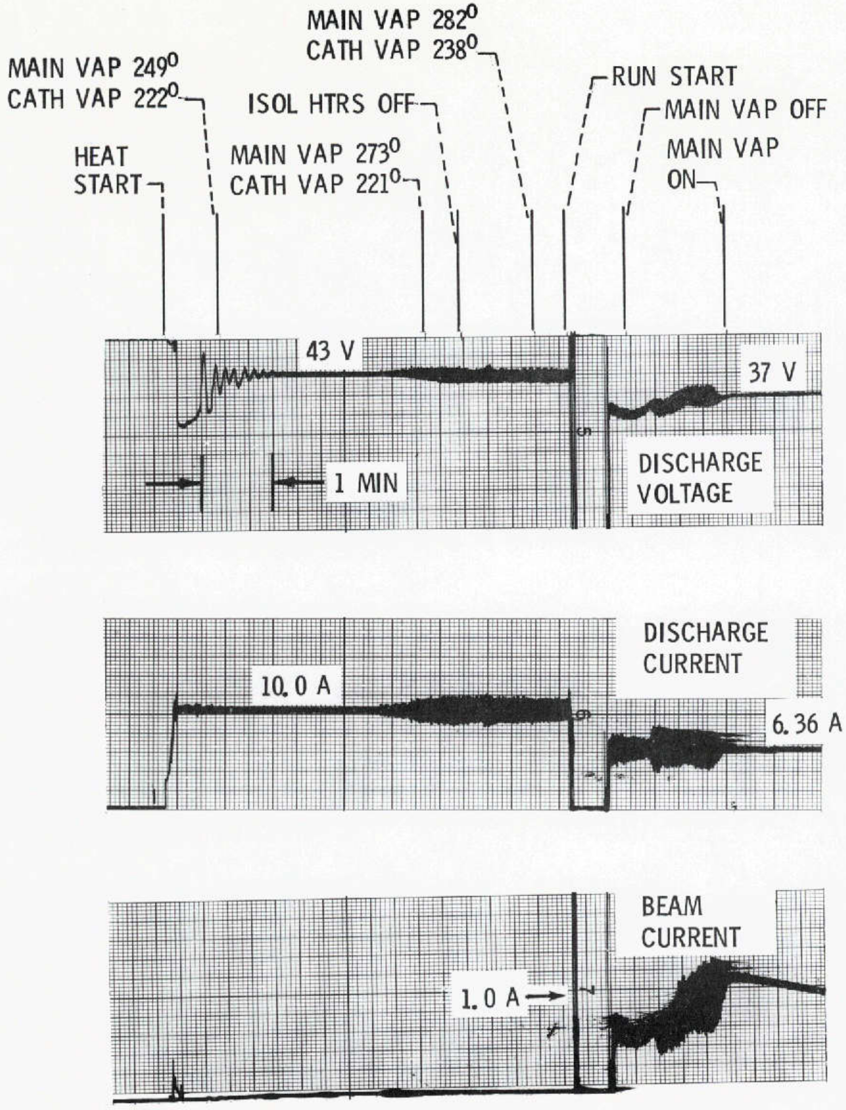


Figure 6. - Heat phase, test 4.

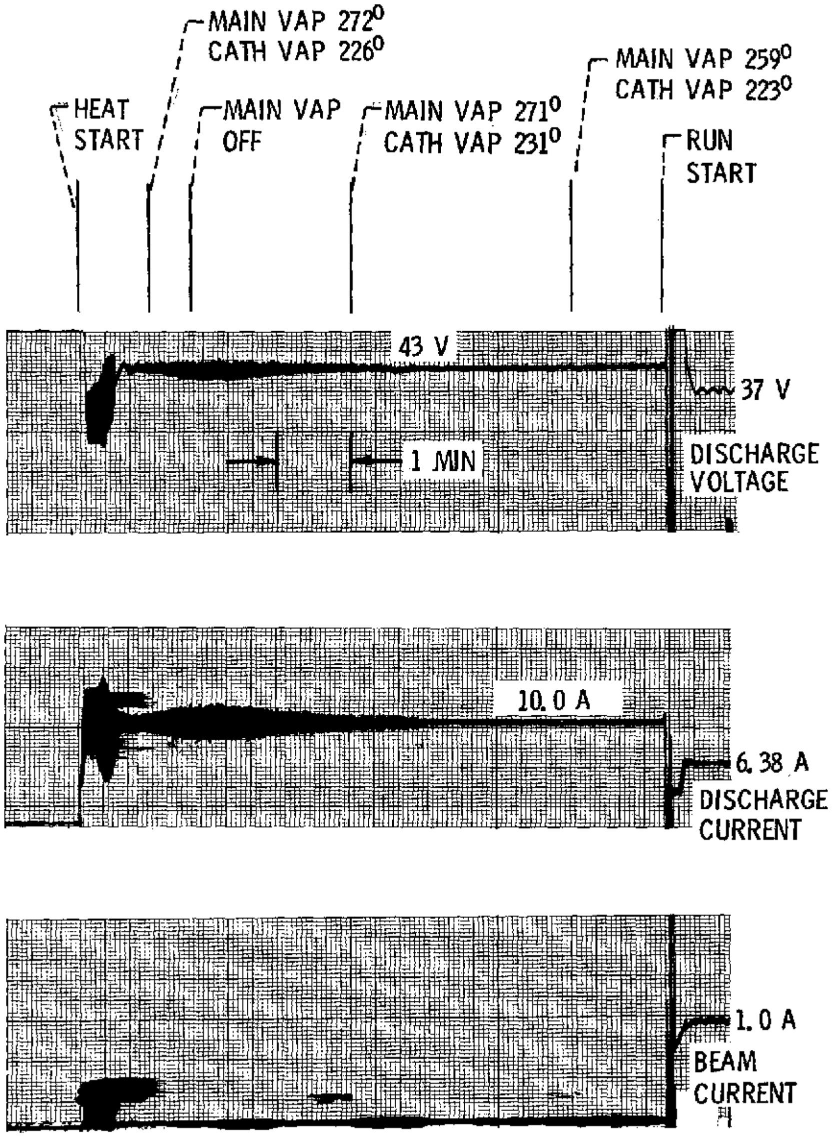


Figure 7. - Heat phase, test 6.

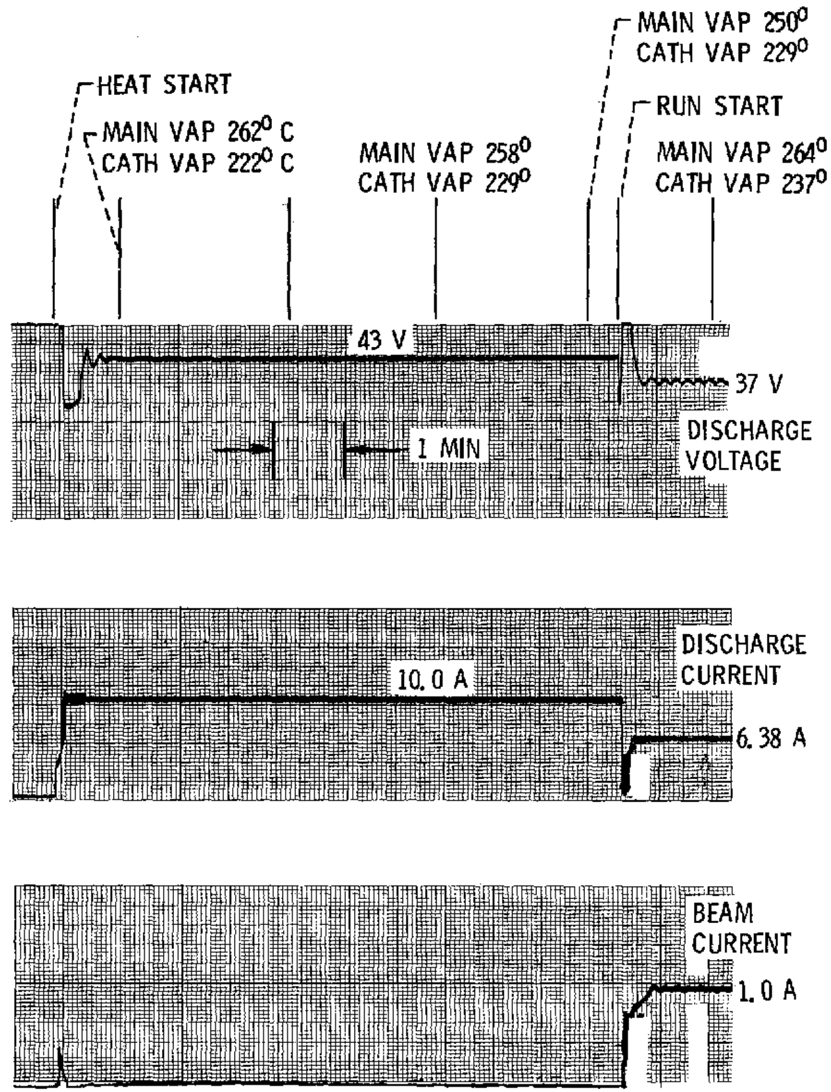


Figure 8. - Heat phase, test 7.

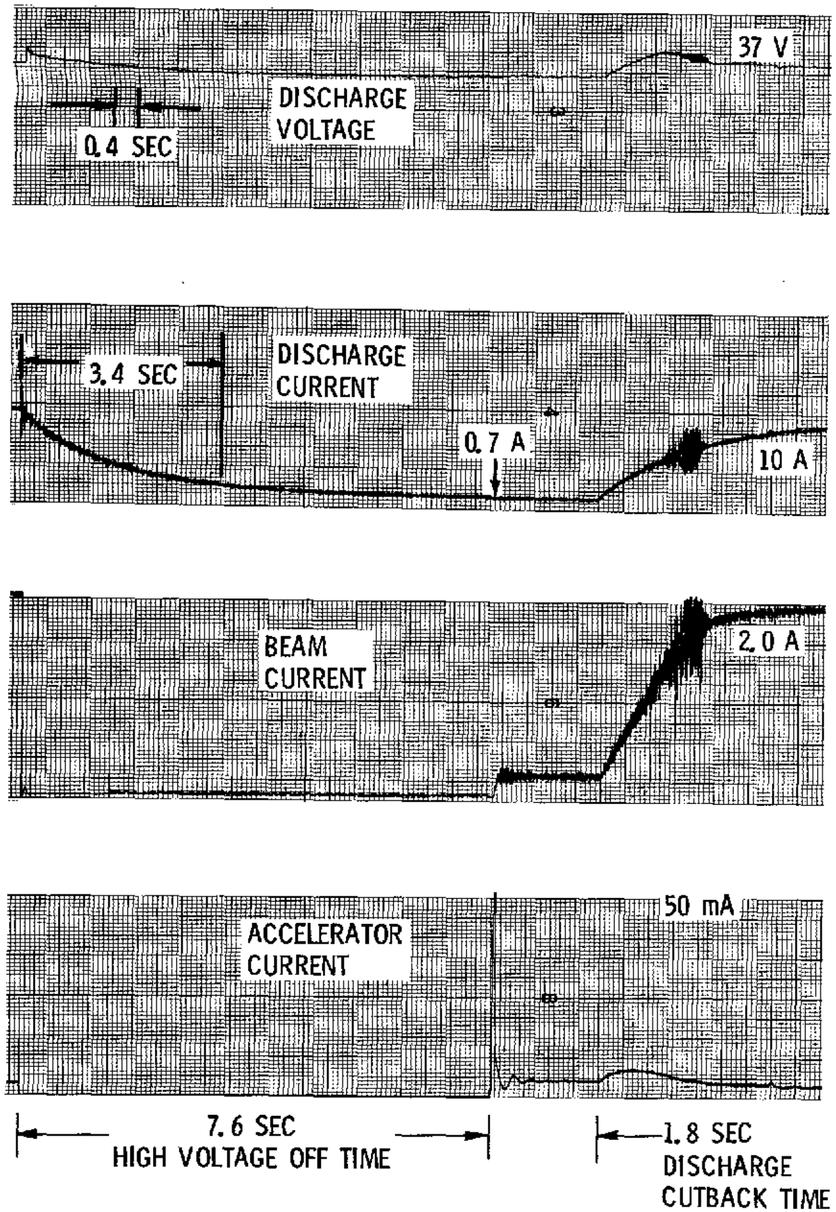


Figure 9. - High voltage recycle profile of reference 8.

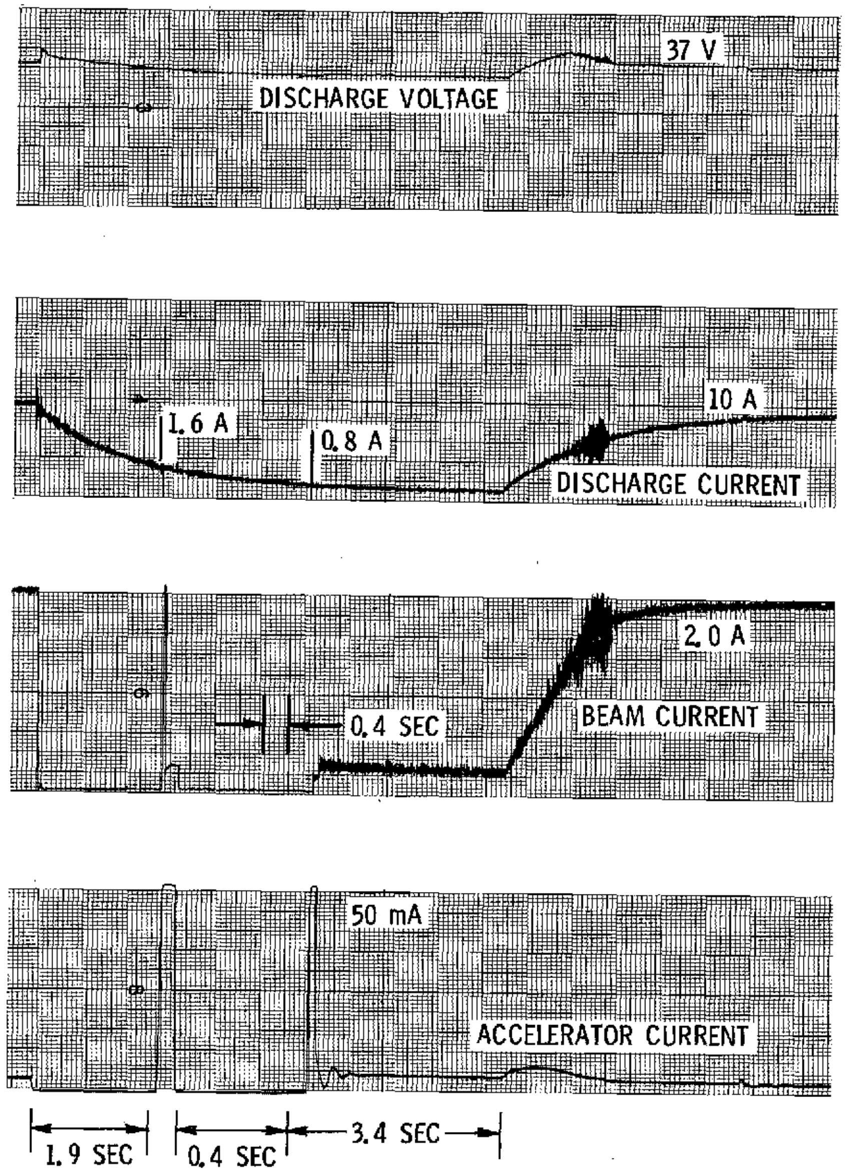


Figure 10. - High voltage recycle.

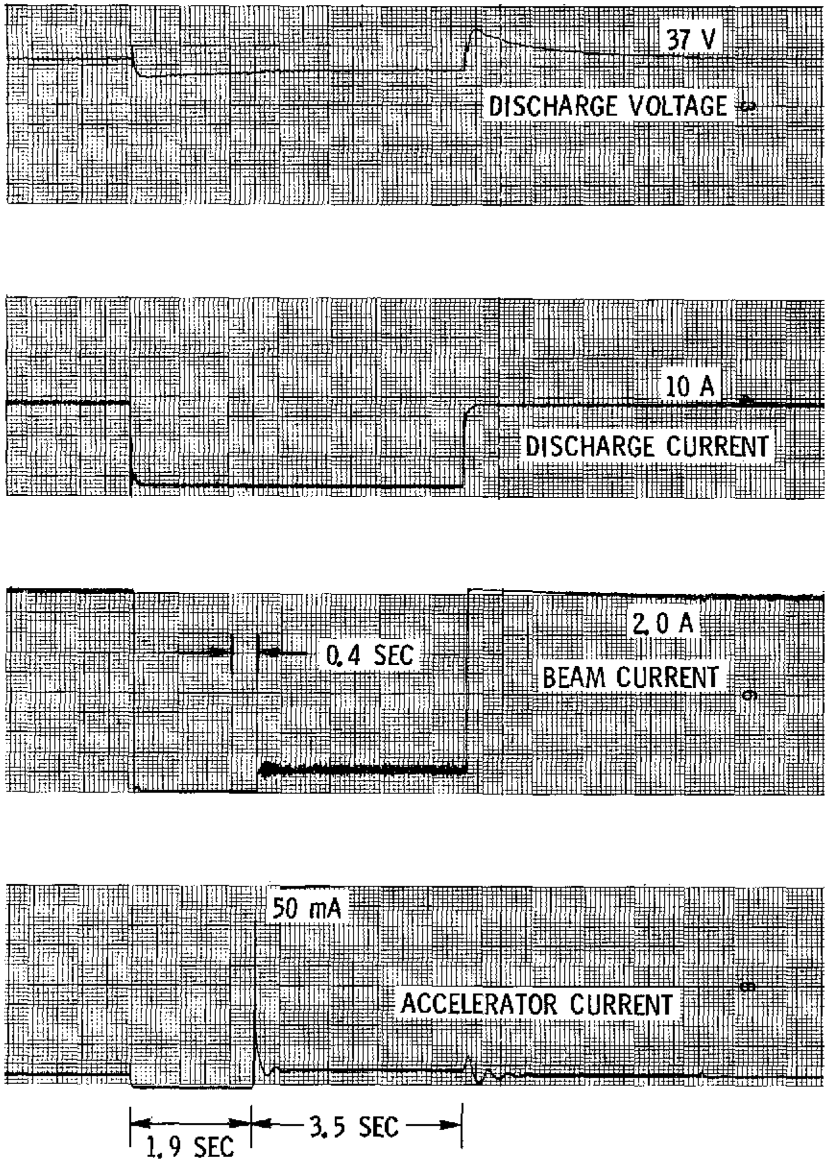


Figure 11. - High voltage recycle.

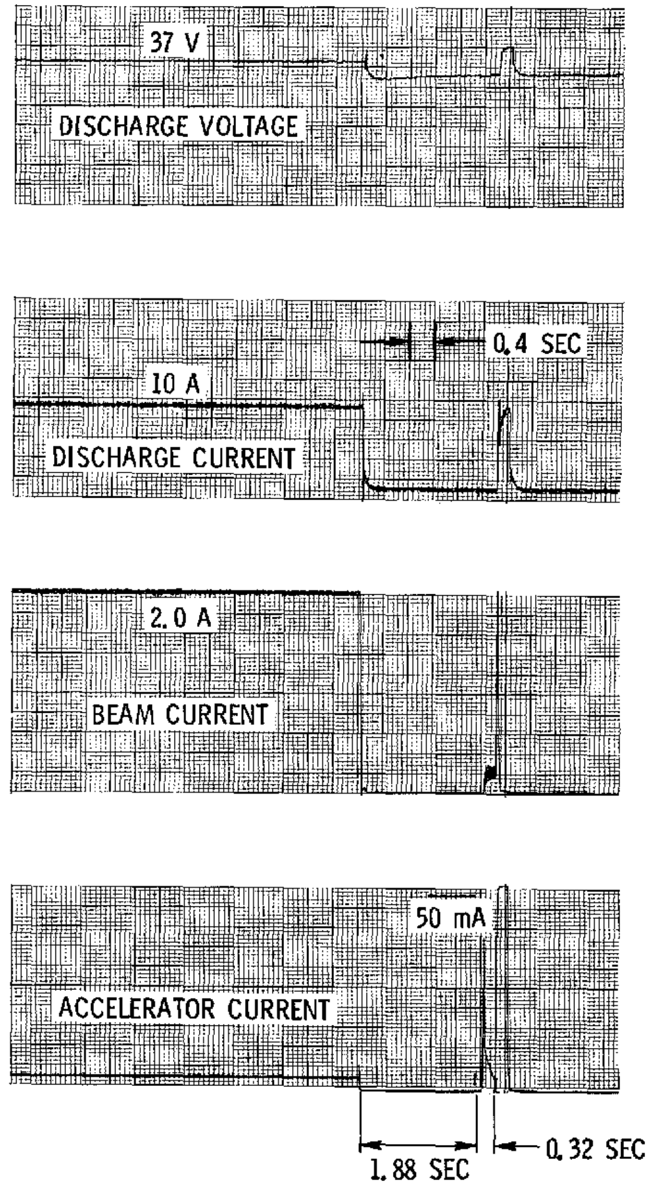


Figure 12. - High voltage recycle with succeeding recycle.

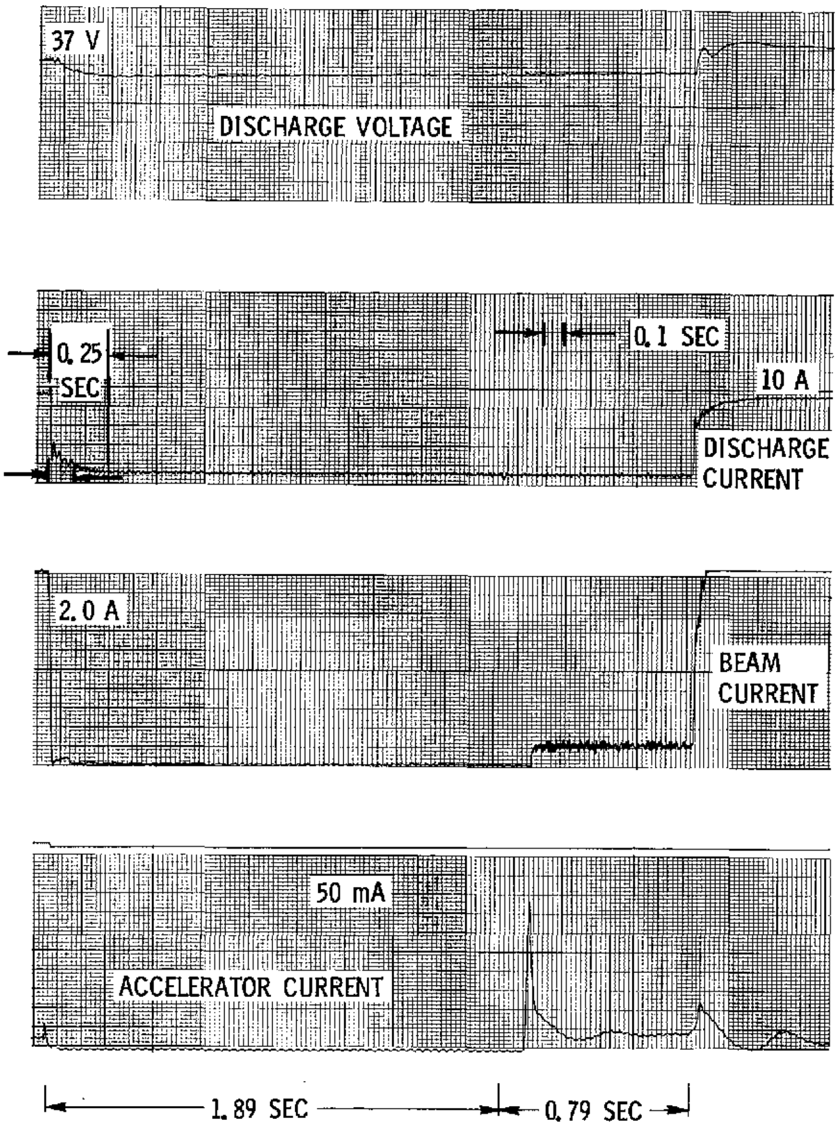


Figure 13. - High voltage recycle.