High-Current Hollow Cathode Development*†

Christian B. Carpenter
QSS Group, Inc.
MS 16-1
21000 Brookpark Rd.
Cleveland, OH 44135
216-433-3160
Christian.B.Carpenter@grc.nasa.gov

Michael J. Patterson
NASA Glenn Research Center
MS 301-3
21000 Brookpark Rd.
Cleveland, Ohio 44135

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NASA Glenn Research Center is currently developing high power cathodes for a variety of electric propulsion devices and applications. As a part of this endeavor, a high current hollow cathode was designed for testing on high power Hall effect thrusters. A laboratory model high current cathode was fabricated and its performance characteristics were investigated using xenon. The cathode was tested at emission currents up to 100 A. The cathode's characteristic spot and plume modes were also identified.

Introduction

Several recent studies at NASA Glenn Research Center (GRC) have shown that high power ion and Hall effect thrusters (HET) will be well suited for a variety of upcoming missions, including LEO to GEO transfers and non-nuclear transportation for Mars cargo missions.[1-3] As the need for higher thrust, higher power electric thrusters increases, higher current hollow cathodes will be needed for ion generation and beam neutralization.

Two types of high power electric thrusters were analyzed to determine cathode emission current requirements. The results of these analyses are shown in Figure 1. The discharge cathode emission current of a HET operating between 300 V and 1200 V were analyzed. At the 300 V operating point, cathode emission currents of 17 A to 130 A would be required for input powers between 5kW and 40 kW. At the 1200 V case, cathode emission currents of 4 A to 100 A would be needed for input power ranges between 5 kW and 125 kW. The discharge cathode emission currents of a xenon ion thruster operating at a specific impulse of 4000 sec were also analyzed. For input powers between 5 kW and 40 kW, discharge cathode emission currents of 24 A to 144 A would be required. These analyses demonstrate the need for 100 A class hollow cathodes for high power electric thrusters.

At GRC cathodes designed for the International Space Station (ISS) have operated at currents of 12 A for 28,000 hrs. ISS cathode testing indicated that if cathodes are operated below a specified maximum tip temperature, high lifetimes could be achived.[4] In the past, research on high current hollow cathodes has been done at GRC, the Jet Propulsion Laboratory (JPL), Colorado State University (CSU), and at Hughes Research Laboratories. At JPL, two hollow cathodes were operated on xenon for up to 1000 hrs at currents up to 100 A. These tests indicated that high cathode emission currents produced high cathode electron emitter temperatures and increase cathode erosion.[5] Work at Hughes demonstrated that cathodes could be operated at currents up to 30 A with cathode orifice plate temperatures less than about 1220 °C.[6] Early high current cathode experiments at GRC tested various

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cathode orifice diameters to determine their effect on operating conditions. This work achieved cathode operation up to 90 A for up to 110 hrs with little erosion, but with high electron emitter temperatures, for certain orifice geometries.[7] Later, high current cathode tests were conducted at CSU. These cathodes utilized rolled tantalum foil-type electron emitters and were tested at cathode emission currents of up to 60 A. These tests suggested that high energy ions are generated at high current settings and may be responsible for cathode erosion.[8] Later tests at GRC yielded hollow cathodes that could be operated at currents up to 2250 A for very short durations. It was found in these tests that substantial erosion was taking place at high current settings, and that long lifetimes at these currents may be possible if operating temperatures could be reduced.[9] It has been proven that hollow cathodes could operate up to 100 A or for lifetimes up to 28,000 hrs, but no program has produced a cathode that is capable of both high current operation and long life.

To address the need for 100 A class hollow cathodes for the high power ion thruster and HET programs, a high current cathode development program was initiated at GRC. As part of this program, a high current laboratory model hollow cathode was built and tested. The goal of testing was to determine operating and thermal characteristics over a range of emission currents up to 100 A to further develop understanding of high current cathode technology.

Experiment Setup

For these tests, a laboratory model 1.27 cm diameter hollow cathode was designed and fabricated at GRC. The cathode's primary components included a cathode tube, electron emitter (or insert), heater, enclosed keeper, and electrical isolators. Figure 2 shows a schematic of some of the major cathode components. The cathode was a refractory alloy tube that was fitted with a refractory alloy orifice plate. The electron emitter was located within the cathode tube and was made of porous tungsten impregnated with a barium compound to provide a low-work function electron source.[10] The heater was a sheathed-type heater that was friction fitted to the downstream end of the cathode tube. The cathode was enclosed with a refractory alloy keeper. The cathode tube was connected to the xenon feed system with a compression fitting. Alumina electrical isolators separated the keeper from the cathode and the cathode mounting assembly. Similar isolators were used for the anode. The anode was a molybdenum plate spaced 10 cm downstream of the keeper.

Figure 3 shows the electrical wiring diagram of the test setup. Three commercially available, current regulated power supplies were used to test the cathode. The heater, keeper, and anode power supplies were current controlled, with a maximum current of 10 A, 25 A, and 125 A respectively. All negative lines were electrically connected to facility ground. The ignitor power supply provided a train of 700 V peak voltage pulses at a frequency of 10 Hz. DC currents were measured at the power supply readouts, while DC voltages were measured with multi-meters. The AC components of the voltages and currents were measured with digital oscilloscopes.

Seven platinum-platinum/rhodium thermocouples were used to take temperature data. Table 1 lists the location of the thermocouples. Figure 2 shows the placement of the thermocouples on the cathode assembly. During testing, thermocouples 2 and 7 had faulty signal wiring, and thus are not shown in the temperature plots. Thermocouple 6 measured the cathode tip temperature.

The cathode was operated with xenon gas. A single propellant line was run from the xenon source to the cathode. A single mass flow controller was used to control the gas flow. This flow controller was calibrated with a multi-meter and a secondary standard by volume displacement technique prior to use.

Test Procedure

Cathode testing was divided into four parts: heater testing, ignition testing, cathode emission testing, and mode testing. Heater testing was conducted to determine cathode tip temperatures as a function of heater input power. Ignition testing was conducted to determine the cathode's requirements for ignition. Cathode emission testing was done to determine the cathode's operating characteristics in all operating configurations. Mode testing was done to identify the cathode's spot mode, plume mode conditions.

Heater testing included setting the heater to various currents, after which the cathode was allowed to come to thermal equilibrium to within ±10 °C. This testing also determined the heater current required for the cathode conditioning process and for cathode ignition.

During heater testing, cathode conditioning was conducted. The conditioning process for this cathode was derived from that of the plasma contactor cathodes on the ISS.[10] The sequence consisted of heating the electron emitter with a series of time-at-temperature steps to remove contaminants and prepare the low-work function insert for electron emission. This process is performed after each cathode exposure to air and prior to ignition. When a required temperature in the conditioning process was achieved during heater testing, the cathode was left at this temperature for the required duration before continuing with the heater test. The heater remained un-powered after the discharge was ignited.

The ignition sequence developed by ISS cathode testing was used as a baseline for cathode ignition.[11] The cathode heater was set to a predetermined current and the keeper power supply was turned on. Next, the high voltage pulser was activated generating a high potential between the cathode and keeper, facilitating ignition.

After the discharge was ignited, it was tested in three configurations: diode, triode, and anode. The diode configuration was defined for this experiment as the cathode emitting to the keeper alone. The triode configuration was defined as the cathode emitting to both the keeper and the anode. Operation in the anode configuration involved a simple cathode to anode discharge. In these configurations, the xenon flow rate, keeper current, and anode current were varied.

Two cathode emission modes were investigated in this test: spot mode and plume mode.[12,13] Spot mode was conservatively defined for this test as the condition where the AC component of the keeper or anode voltage was <300 mV peak-to-peak. At conditions above 300 mV the cathode was considered to be in plume mode. The keeper and anode currents were varied to determine the conditions required to operate in spot mode. The cathode was set to a previously observed operating point and set to emit in spot mode. The keeper and anode currents were then adjusted to until plume mode operation was reached. These tests were conducted for the diode, triode, and anode configurations.

Test Results

The heater was tested over a range of 2 A to 9 A. Heater testing showed that a heater input power of 115 W would be needed achieve the temperatures required for ignition. At 115 W the cathode orifice plate was around 1080 °C.

During the first ignition, five minutes of heating and the high voltage ignitor pulses were required for ignition. On all subsequent ignitions the cathode ignited without the aid of the high voltage pulse.

The cathode was operated in diode, triode, and anode configurations for flow rates of 1.2 mg/s to 2.0 mg/s. The cathode's current-voltage characteristics for the 2.0 mg/s case are shown in Figure 4. The cathode was operated in the diode configuration at currents of 8 A to 20 A. The keeper voltage dropped from 16 V at the 8 A setting to 8 V at the 20 A setting as input power increased. In the triode configuration the keeper operated at currents from 9 A to 3 A. Over this range the keeper voltage decreased from 7 V for the 9 A point to 4.5 V at the 3 A point. The anode current in the triode configuration ranged from 12 A to 44 A. The anode voltage increased from 11 V at the 12 A setting to 14 V at the 44 A setting. After reaching 48 A total emission current, the keeper was no longer required to sustain the cathode's discharge and the keeper power was turned off. In the anode configuration the anode was powered from 45 A to 100 A. This voltage increased from 11 V at the 45 A current to 12.5 V at the 100 A current. This rise was essentially linear.

Figure 5 shows the cathode's spot mode-plume mode envelope at the 2.0 mg/s flow setting when specified operating in the triode configuration. At approximately 45 A, the cathode was operating in spot mode in the anode configuration. As the anode current was decreased higher keeper currents were required to sustain spot mode. The maximum keeper current required to maintain spot mode for this cathode was about 10 A. This condition occurred at an anode current of 12.5 A, or a total emission current of 22.5 A. The lowest anode current tested was 2.5 A where the cathode required approximately 6 A of keeper current to maintain in spot mode.

A plot of all temperature data as a function of emission current is shown in Figure 6. These data show a temperature drop at 45 A to 50 A. This was due to the transition from the triode configuration to the anode configuration. After switching the cathode to the anode configuration all temperatures except the tip temperature remained below 840 °C. The cathode tip temperature is especially important, as cathode insert temperature has been directly linked to cathode lifetime. Figure 7 shows a plot of cathode tip temperature as a function of total emission current. The cathode operated with a tip temperature between 1050 °C and 1100 °C at the 16 A emission current. This temperature increased with increasing total emission current. At the 100 A current point the cathode's tip temperature was around 1360 °C to 1400 °C. At 25 A of total emission current, the tip temperature is seen to rise above 1150 °C, which is the generally accepted maximum limit for normal cathode operation.[10] This trend indicates that the cathode would not have significant lifetime at currents above 25 A. Therefore, the cathode will have to be redesigned to yield an adequate lifetime.

Conclusions

To initiate the high current hollow cathode development program at GRC one high current hollow cathode was manufactured, and its performance was characterized. The cathode was tested over a range of 8 A to 100 A of total emission current and flow rates of 1.2 mg/s to 2.0 mg/s. The tests showed that the cathode operated in a stable condition at all emission currents tested, but above an emission current of 25 A the cathode tip temperature was higher than the generally accepted maximum of 1150 °C. The cathode will have to be redesigned to yield long life.

References

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Table 1. Thermocouple Placement

Thermocouple Number	Thermocouple Location
T1	Gas Feed Fitting
T2	Keeper Flange
T3	Keeper Barrel
T4	Keeper Tip
T5	Cathode Tube
T6	Cathode Orifice Plate
T7	Cathode Orifice Plate

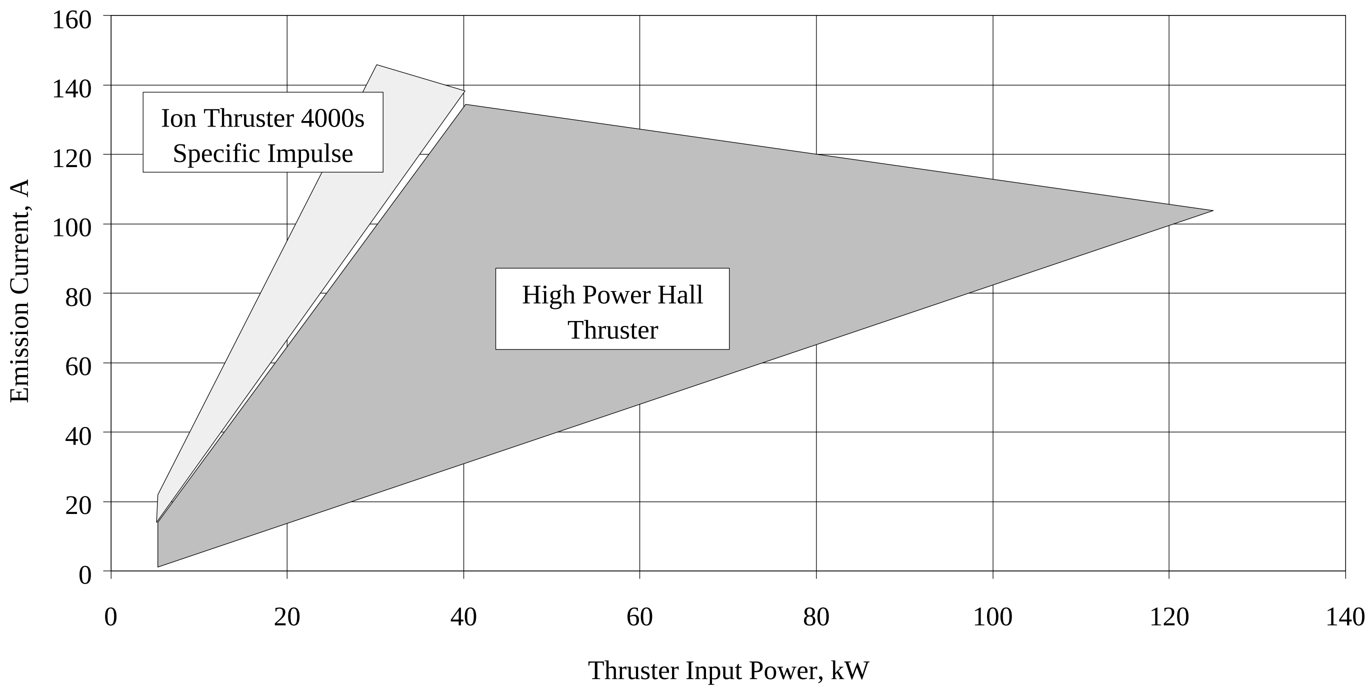

Figure 1 – Cathode emission current requirements as a function of input power for various thrusters using xenon propellant. The line-shaded region corresponds to emission currents required for high power Hall thruster operation. The dot-shaded region corresponds to emission currents required for ion thrusters operating at 4000 seconds specific impulse.

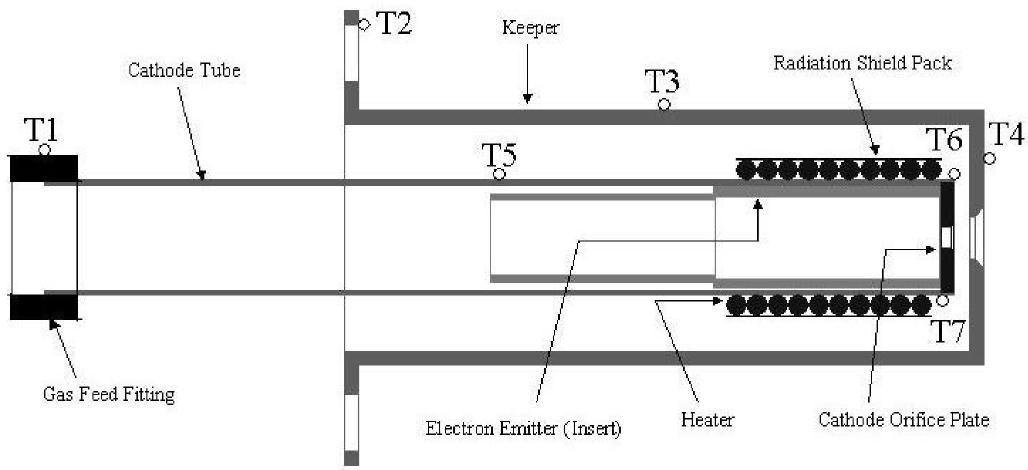

Figure 2 – Thermocouple placement (Drawing not to scale).

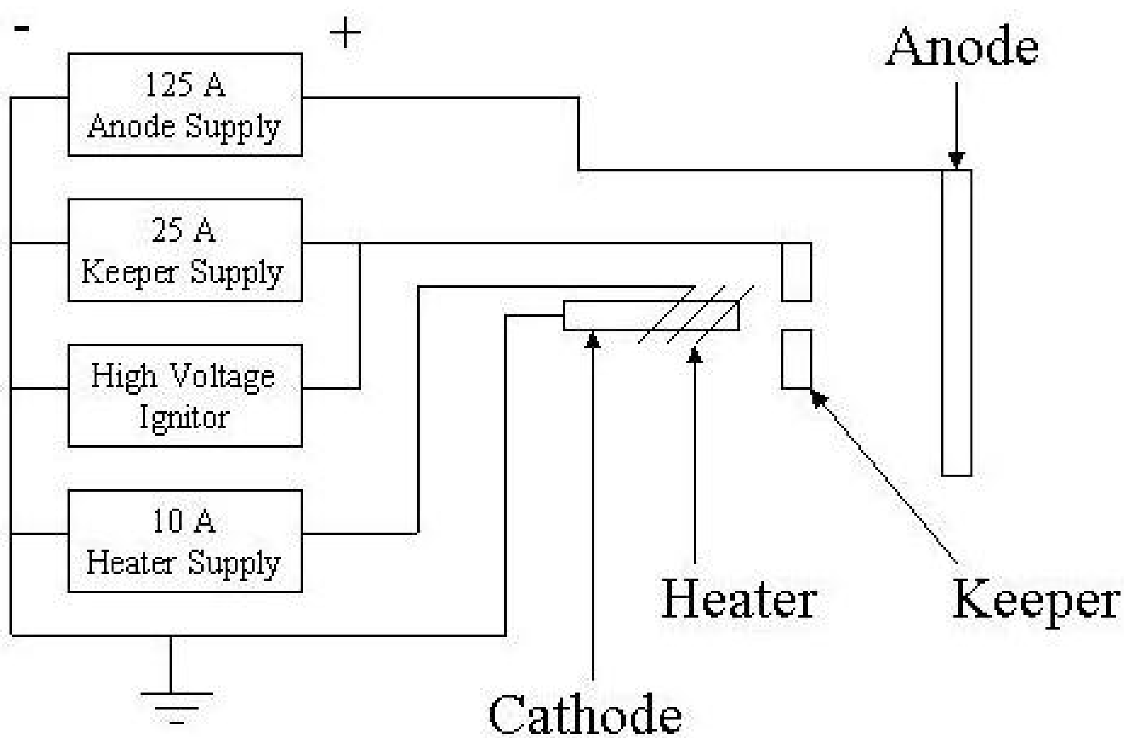

Figure 3 – Electrical wiring diagram of test setup.

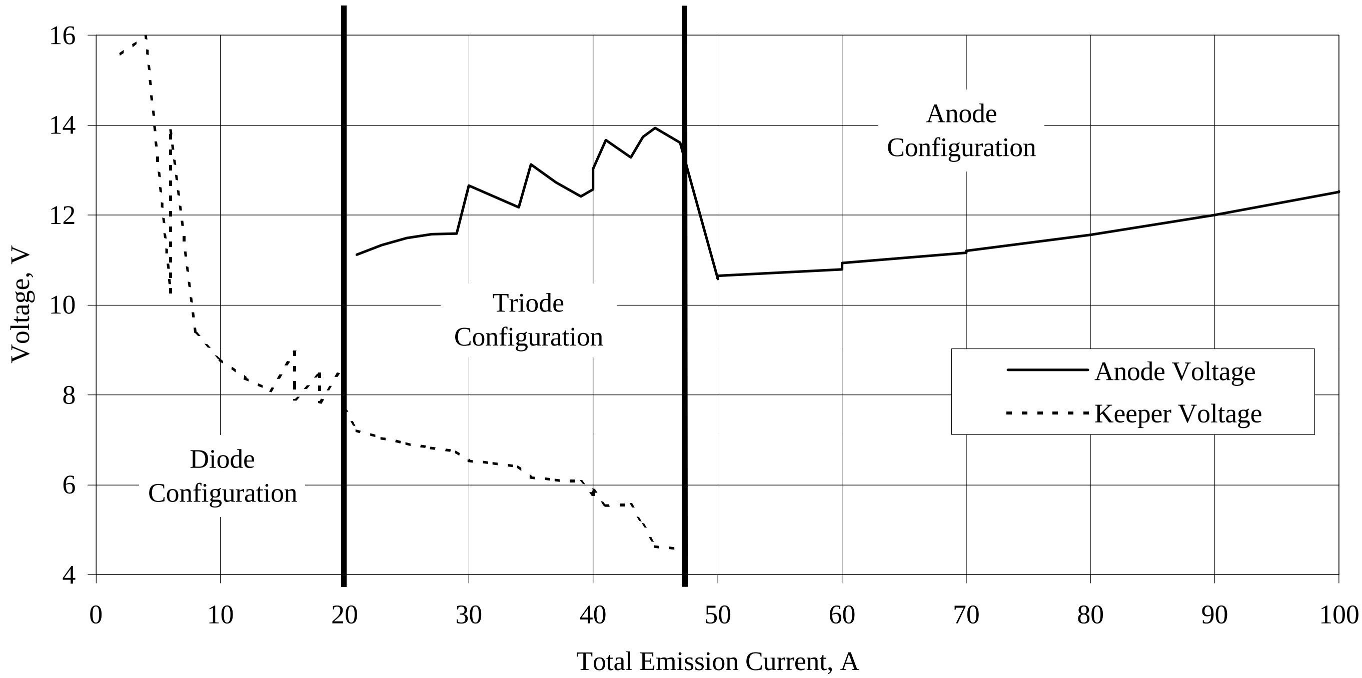

Figure 4 – Voltage as a function of current at 2.0 mg/s xenon flow rate.

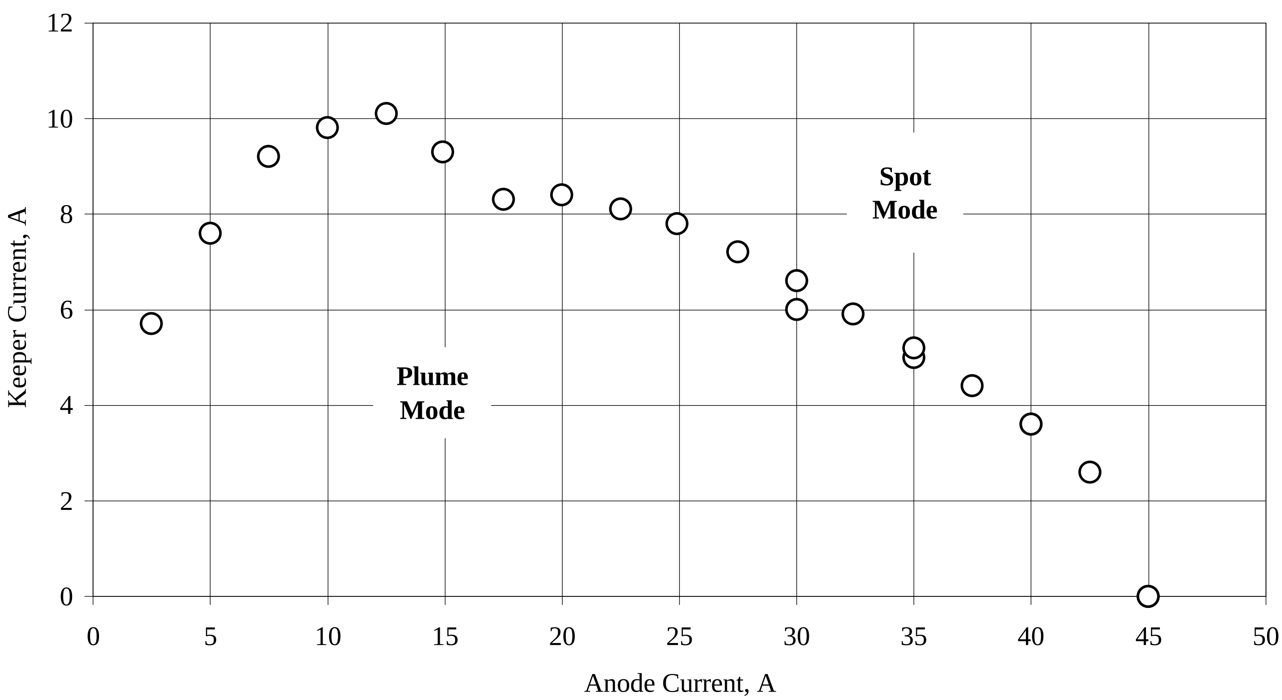

Figure 5 – Keeper current as a function of anode current showing conditions required to maintain spot mode at 2.0 mg/s.

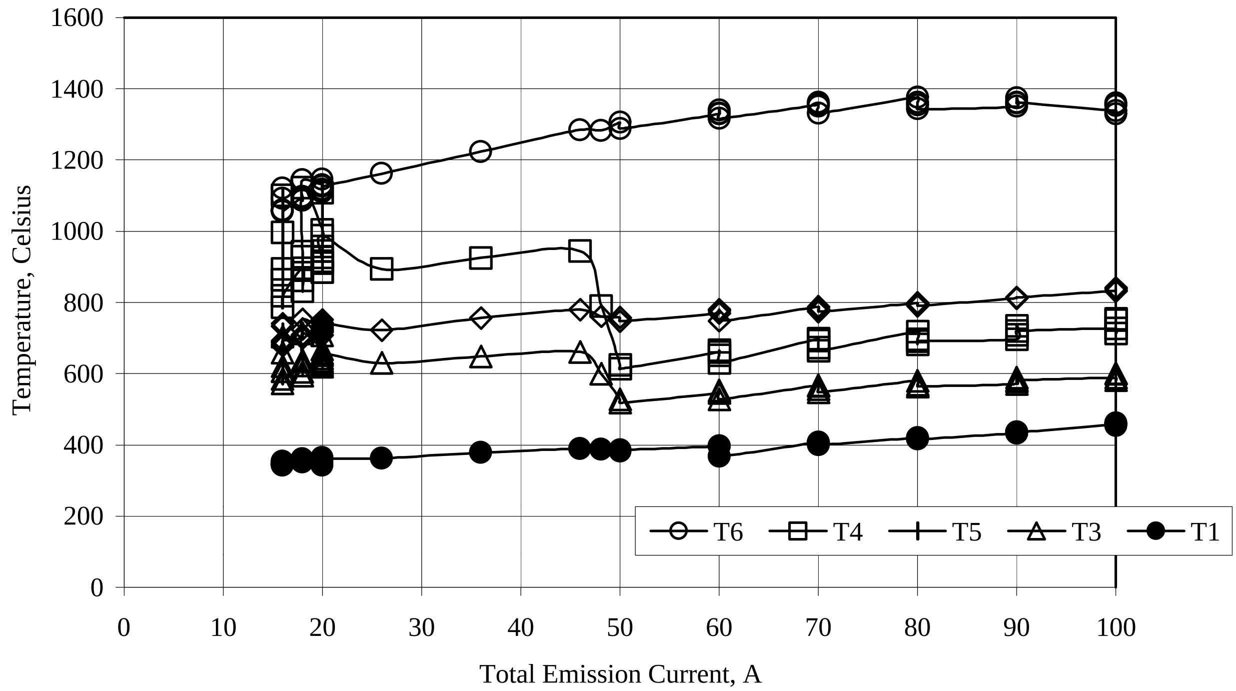

Figure 6 – Temperature as a function of total emission current in triode and anode configurations at 2.0 mg/s.

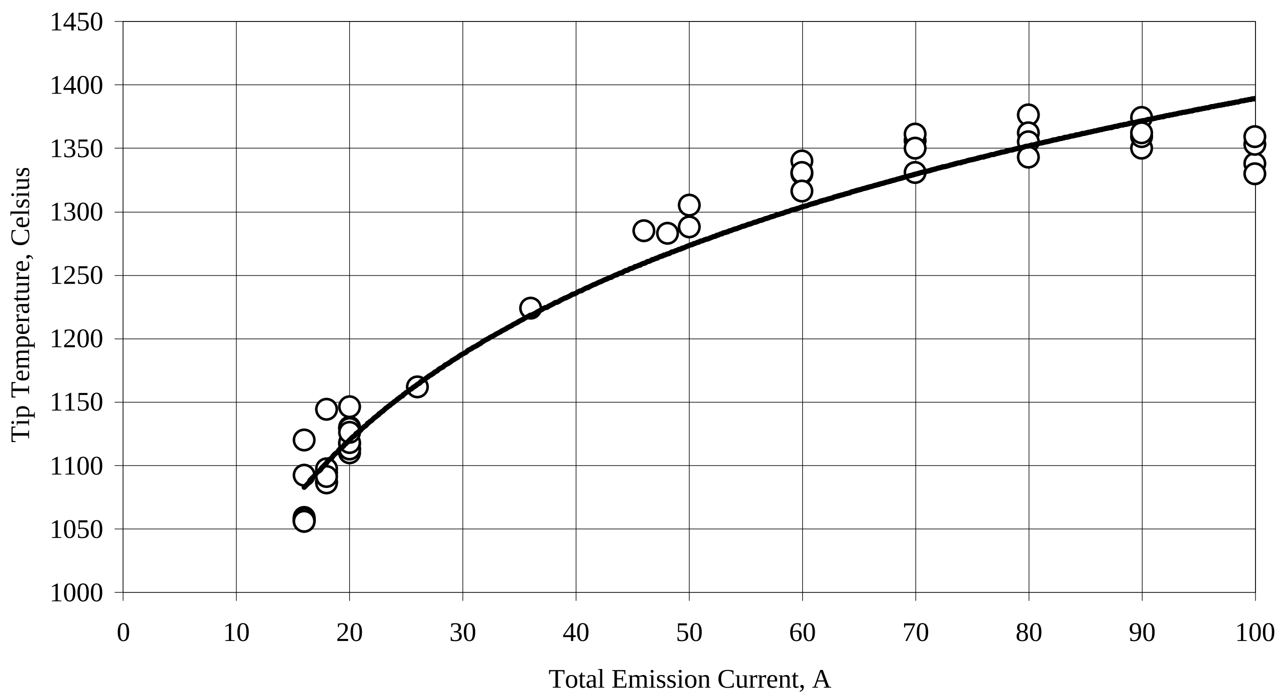

Figure 7 – Cathode tip temperature (Thermocouple 6) as a function of total emission current at 2.0 mg/s.