

THESIS

AN EXPERIMENTAL INVESTIGATION OF HEATERLESS HOLLOW CATHODE IGNITION

Submitted by

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ABSTRACT

AN EXPERIMENTAL INVESTIGATION OF HEATERLESS HOLLOW CATHODE IGNITION

A hollow cathode is a specially designed plasma source that is capable of driving a large electron emission current throughout the course of a remarkably long lifetime. Given these characteristics, hollow cathodes are commonly used as electron sources in state-of-the-art plasma thrusters. Modern advancements in small-satellite technology have led to an increased demand for low-power electric propulsion systems. Given the high thrust-to-power ratio and flight-proven heritage of Hall-effect thrusters, efforts are currently being made to downsize these thrusters to a considerably small scale. By forgoing the use of a heater, heaterless hollow cathodes provide several advantages that are best realized in miniaturized Hall-effect thrusters. Unfortunately, the lack of a cathode heater gives rise to nontrivial complications in the process of igniting a plasma discharge, along with reason to believe that life-limiting cathode erosion could occur during ignition. These concerns have resulted in a lack of confidence that heaterless hollow cathode technology can endure the rigors of spaceflight qualification. In this research, heaterless hollow cathode ignition behavior was characterized. In doing so, it was found that repeatable and reliable instant start ignition behavior can be achieved when using a high propellant mass flow rate. To provide this flow condition without placing a large burden on a propellant feed system, a novel gas flow mechanism was developed and characterized. To investigate whether instant start ignition causes cathode erosion, a series of tests were performed in which heaterless hollow cathodes were subjected to a large number of ignition cycles. Microscopy revealed no indication of cathodic arc activity, and no other evidence of life-limiting erosion were observed. The instant start ignition process appears to be a viable approach to heaterless hollow cathode ignition, and we believe it provides a means for heaterless hollow cathode technology to be integrated into spaceflight propulsion systems.

ACKNOWLEDGEMENTS

I would like to acknowledge the support and guidance I received from my advisor and colleagues at the Colorado State University CEPPE Lab. I would also like to acknowledge the collaboration of NASA researchers who contributed to, and supported this research along the way. This work was supported by a NASA Space Technology Research Fellowship; grant number 80NSSC18K1156.

DEDICATION

I would like to dedicate this thesis to the fictional character, Dr. Ian Malcolm, from Michael Crichton's novel, Jurassic Park. Without Ian, I believe I would have taken a misguided and undisciplined approach to scientific research.

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Chapter 1

Introduction

Hollow cathodes are a type of plasma generator used in several varieties of state-of-the-art ion engines that provide in-space propulsion for orbital satellites and deep-space probes. For these thrusters to operate, it is necessary to first ignite a plasma discharge in the hollow cathode. After ignition, the hollow cathode discharge is used to ionize propellant gas and/or neutralize the thruster exhaust. The performance of a hollow cathode is primarily judged by its reliability and lifetime in terms of both ignition and operation in various discharge conditions. By forgoing the use of a cathode heater, heaterless hollow cathodes provide an opportunity to improve the state of the art in thruster design; however, the lack of a heater significantly complicates the ignition process. The aim of this research was to investigate the conditions required to achieve reliable ignition behavior in a heaterless hollow cathode, and to assess whether the ignition process could adversely affect cathode lifetime.

1.1 Hollow Cathode Ignition and Operation

A cross-section schematic of a conventional hollow cathode assembly is shown in Figure 1.1 [1]. A hollow cathode is a tubular electrode through which a fraction of the thruster propellant flow is fed (typically 5 to 7% of the total propellant mass flow rate). During hollow cathode operation, the propellant gas is ionized near the downstream end of the cathode tube, where a gaseous electric discharge is maintained. Housed within the downstream end of the cathode tube is a specialized emitter that is made from a material with a low work-function. The low work-function hollow cathode emitter produces a large thermionic electron emission current when held at high temperature (an operating temperature of 1200 °C is nominal for the barium-based porous tungsten emitters used in this research). During normal discharge operation, the emitter is continuously heated by the nearby plasma. A hollow cathode is typically made with a thin tube wall and radiation shielding so that thermal energy is mostly confined to the emitter region. This helps to maintain thermionic

emission in a relatively efficient manner. When a hollow cathode is operating as intended, a high current thermionic arc discharge can be maintained indefinitely.

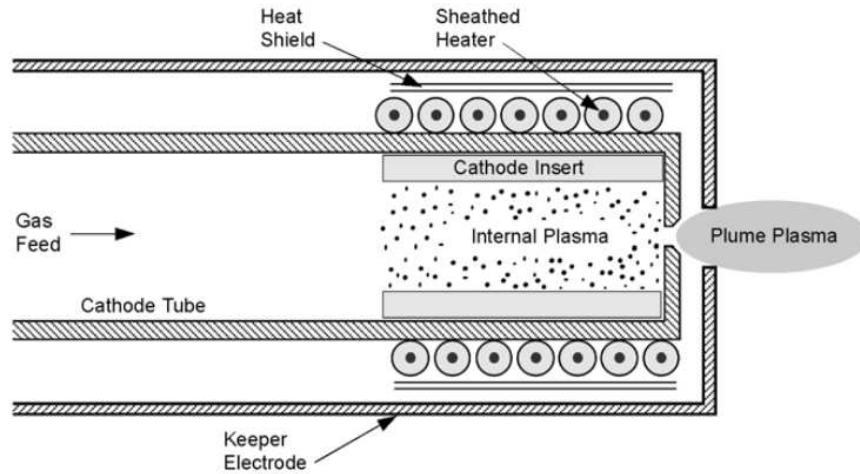


Figure 1.1: Schematic of a conventional hollow cathode assembly [1].

While the primary task of a hollow cathode is to provide plasma electrons during normal thruster operation, a hollow cathode also performs another critical task that is much more sudden and transitory. In a process called ignition, the hollow cathode forms a plasma discharge in a gas that is otherwise comprised of only neutral atoms. Without the ignition of a plasma discharge, a plasma thruster cannot be operated. In a hollow cathode assembly, the cathode tube is enclosed within another electrode called the keeper, which includes an orifice plate that is positioned just downstream of the cathode tube. The keeper electrode is used to ignite and maintain the plasma discharge. The keeper is well-suited for these tasks because it is positioned very close to the cathode, which improves the electric field strength and coupling characteristics. A secondary function of the keeper is to shield the cathode from erosion that can occur from bombardment by high energy ions backflowing from the downstream discharge plasma [2].

A conventional hollow cathode assembly includes a cathode heater; a resistive heating element that is coiled around the cathode tip (Figure 1.2 [3]). The heater is used to thermally prime the cathode emitter, and is used before and during the ignition process. When the cathode emitter is heated to its operating temperature, thermionic emission begins to occur and a cloud of free

electrons is formed near the cathode. When this condition is reached, ignition (i.e. the initiation of a plasma arc discharge) can be achieved by applying a modest bias, often less than 50 V, between the cathode and keeper electrodes while propellant gas is flowing at a nominal flow rate [4]. After ignition, the cathode heater is usually unpowered because the cathode is sufficiently self-heated by the nearby plasma via ion bombardment and ion recombination processes.

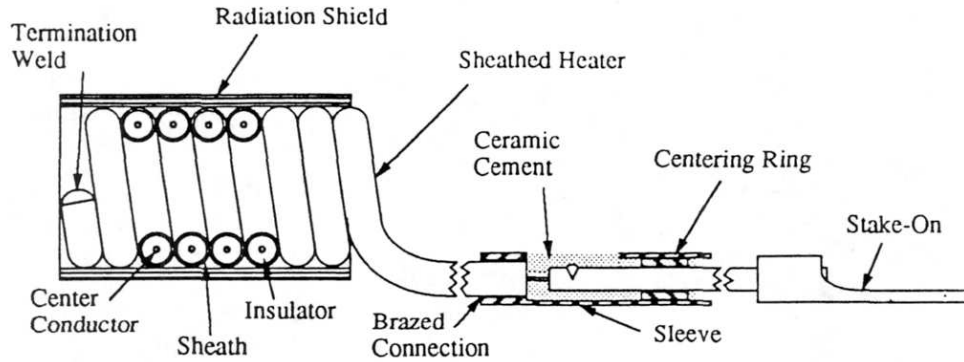


Figure 1.2: Schematic of a hollow cathode heater [3].

1.2 Advantages of Heaterless Hollow Cathodes

While modern heater-utilizing hollow cathodes have shown lifetimes in the tens-of-thousands of hours [5–7], their lifetime can be drastically reduced by premature failure of the cathode heater, which would result in the inability to perform ignition. Cathode heaters are notoriously difficult to engineer, and often include a number of delicate features as shown in Figure 1.2. Even well-crafted heaters will eventually fail when subjected to the thermal fatigue caused by a large number of heating cycles. This poses a higher risk in missions that require many thruster ignition cycles. Because the cathode heater is a single-point failure mechanism of a thruster, heaters must be proven to adhere to strict flight qualification requirements [3,8]. As a result, the development of the heater alone often contributes to a significant portion of the cost of a hollow cathode assembly.

In addition to their cost, cathode heaters can be undesirable because they add to the overall size of a hollow cathode assembly, and an auxiliary power supply circuit is required to power the

heater, which adds to the complexity of the thruster power processing unit. One way to circumvent these issues is to remove the cathode heater entirely. Several studies, dating back to the 1980s, have shown that igniting a plasma discharge in a hollow cathode is possible without the use of a heater, however significantly elevated propellant flow rates and cathode-keeper bias voltages were typically necessary and cathode erosion was documented in some cases [9–14]. If these ignition difficulties were addressed, and it was proven that heaterless hollow cathodes could be ignited reliably, with minimal system-level burden or lifetime issues, then it is likely that many modern plasma thruster concepts would adopt heaterless hollow cathode technology. The reduced size, cost, and complexity of heaterless hollow cathodes make them well suited in efforts to miniaturize Hall-effect thrusters to the sub-kilowatt scale for small satellite propulsion. Given an increasing interest in small-satellite technology, low-power Hall-effect thruster technology has been a popular area of research and development in recent years [14–24], which presently motivates the maturation of heaterless hollow cathode technology.

1.3 Thesis Objectives and Methodology

For heaterless hollow cathodes to become widely accepted as a viable technology for use in spaceflight plasma thrusters, it is necessary to address concerns that the heaterless ignition process may be unreliable, difficult to facilitate, and potentially damaging to the cathode. The goal of this research was to investigate these issues in a procedural manner with aims to improve the state of the art and to advance our understanding of the physical phenomena that occur during the heaterless ignition process. To accomplish this, an experimental approach was used and several unique experiments were performed.

1.3.1 Overview of Experiments

In initial experiments, the goal was to characterize the heaterless ignition requirements in heaterless hollow cathodes of various geometries. In designing a spacecraft system, it is valuable to minimize mass, volume and risk wherever possible. Because heaterless ignition has shown

to require excessive propellant flow and/or voltage [9–14], there are concerns that integration of a heaterless hollow cathode will require that undue complexities be introduced in sub-systems such as the propellant feed system and/or the power processing unit. If efforts are not made to minimize these complexities, heaterless hollow cathodes are likely to remain unfit for spaceflight applications because the advantages they provide could easily be offset by excessive system requirements. The desired outcome of the initial experiments was to find an approach to heaterless ignition that would not place excessive burden on the propulsion system. Through experimentation, it was found that a simple propellant flow mechanism could be used to facilitate an instant start ignition process in heaterless hollow cathodes.

Another common concern with heaterless hollow cathodes is that the ignition process could cause a nontrivial amount of erosion to occur to the cathode. In one of the earliest heaterless hollow cathode investigations, (circa 1985), the cathode surface suffered from a significant amount of damage, and a shiny, pockmarked appearance was reported [13]. This appearance is characteristic of erosion craters left behind by cathodic arcs. A cathodic arc is commonly observed when several amperes of electrical current are driven between cold electrodes. In a cathodic arc, the discharge is fueled by the ionization of cathode material, and as a result, the cathode is eroded by both vaporization and the ejection of macroparticles [25, 26]. Because the heaterless ignition process involves a cold cathode discharge, there is a rational suspicion that cathodic arc activity is involved. If cathodic arc activity showed to be a necessary part of the heaterless ignition process, it would be necessary to characterize and quantify the resulting erosion to determine whether it could impose a significant lifetime limitation. To investigate heaterless ignition erosion, a separate experiment was performed in which newly manufactured cathodes were subject to a large number of heaterless ignition cycles. The cathodes were then examined for evidence of erosion.

Throughout these experiments, two different gas species were used; xenon and krypton. Presently, xenon propellant is strongly preferred in plasma propulsion research and development because its high atomic mass and low ionization energy contribute to optimal thruster performance. Accordingly, hollow cathode testing performed with xenon is the most appropriate; however, it is not

always practical to use xenon due to its high cost. While xenon was used throughout much of this research, lower-cost krypton was used as well, especially in experiments that required a large amount of gas. Krypton is a viable alternative propellant that is especially attractive in space missions that must adhere to budget limitations. Krypton has been investigated as a Hall-effect thruster propellant in both computational modeling and in experimental campaigns [27–30]. In fact, the private aerospace manufacturer, SpaceX, is currently using krypton fueled Hall-effect thrusters onboard a large number of active satellites [31].

1.3.2 Vacuum Test Facility used for Hollow Cathode Experiments

To operate a hollow cathode, it is necessary that the device be situated in a near-vacuum environment. Throughout most of this research, the "Gemini" vacuum chamber at Colorado State University was used. This non-magnetic, cylindrical vacuum chamber is 1.0 m in diameter and 1.9 m in length and is equipped with a turbomolecular pump capable of pumping cold xenon at a speed of approximately 1800 liters per second. A fixture was constructed within the chamber that allowed for a hollow cathode assembly to be mounted along the chamber centerline. The vacuum facility was outfitted with a laboratory gas feed system capable of measuring and/or controlling the flow of expellant gas to the unit under test. A 600 volt, 3.0 ampere DC power supply was used throughout the majority of the research. The leads from the power supply output were routed to high-voltage feedthroughs on the vacuum chamber and then to the electrodes of the hollow cathode assembly within the chamber. To avoid electrical interaction with the facility, electrode electrical potentials were allowed to float with respect to ground. To monitor and record the electrical behavior between electrodes during experiments, an oscilloscope was used to sense both voltage and current flow, and log these data at a high sampling rate. A ballast resistance was placed in series with the electrical load imposed by the keeper-cathode discharge to limit the peak current during ignition testing. Flyback and blocking diodes were also added to protect the power supply from large transient currents that could occur in experiments. A typical ignition test circuit is shown in Figure 1.3.

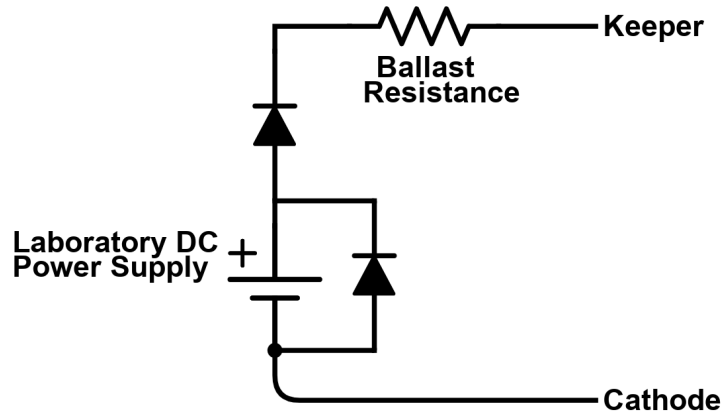


Figure 1.3: Schematic of a typical ignition circuit used in heaterless hollow cathode ignition experiments.

1.3.3 Consideration of Discharge Activity at Triple Junction Locations

During Heaterless Hollow Cathode Ignition Experiments

In preliminary testing, it was not uncommon to observe highly oscillatory electrical behavior for extended periods of time when attempting heaterless ignition. After these tests, visual evidence of electrical arcing were observed near the base of the cathode tube at a location where the cathode was in contact with an electrical insulator as shown in Figure 1.4. It was concluded that this behavior could be attributed to triple junction effects. A triple junction is formed by the interface between a conductor, a dielectric, and vacuum. When the conductor is charged negatively with respect to a nearby electrode, polarization of the dielectric enhances the electric field at the triple junction location. Furthermore, field emitted electrons may bombard the dielectric, causing secondary electron emission, which further enhances the electric field at the triple junction [32, 33]. These effects contribute to an increased likelihood of arc formation at triple junction locations. In a hollow cathode assembly, negatively charged triple junctions are often found near the base of the cathode tube. Discharge activity at these locations is undesirable because it deposits heat far from the cathode emitter, and thus, the emitter is not heated. In all of the research described herein, measures were taken to minimize or eliminate the possibility that discharge activity would occur at triple junction locations or any locations far from the emitter.

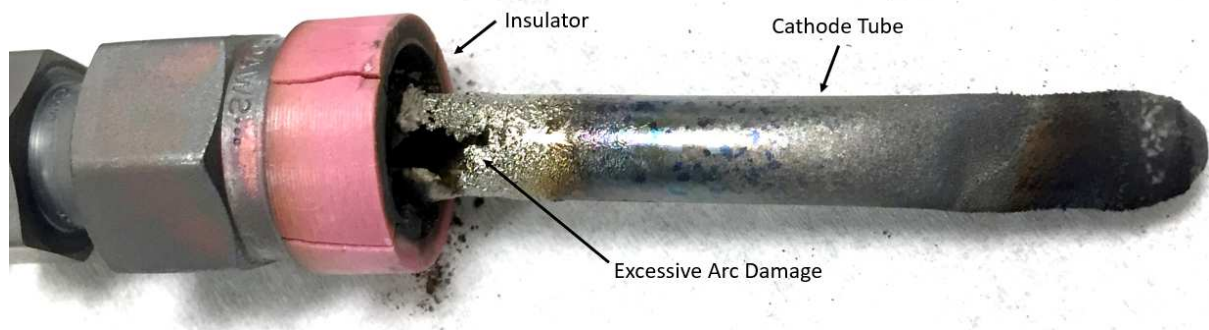


Figure 1.4: Evidence of discharge activity near an electrical isolator (located at the upstream end of the cathode tube). Discharge activity in this area is undesirable because it does not heat the emitter effectively. In this research, care was taken to avoid triple junction discharge activity.

Chapter 2

Conditions Required to Ignite a Heaterless Hollow Cathode

To integrate a heaterless hollow cathode into a modern satellite propulsion system, it is necessary to develop an understanding of the propellant flow and electrical capabilities that are required for ignition. An investigation of these requirements was carried out by performing two separate experiments: (1) discharge initiation in a specially designed apparatus that employed a well-defined electrode separation distance in a parallel plate configuration at uniform and controlled propellant pressures, and (2) discharge initiation in a small, low-power heaterless hollow cathode using an enclosed keeper configuration. The research activities and results described in this chapter were also presented at the 55th Joint Propulsion Conference [34].

2.1 Experimental Investigation of the Conditions Required to Initiate a Plasma Discharge Between Two Electrodes

Because the ignition process in a heaterless hollow cathode begins with the electrical breakdown of propellant gas, (i.e. the formation of a gaseous plasma discharge), a study was performed to determine the conditions that are necessary for this phenomenon to occur. Friedrich Paschen was the first to identify the interdependent factors that contribute to the breakdown of a gas [35]. Electrical breakdown begins when free electrons are accelerated by an electric field that is formed between two electrodes. Electrons that gain sufficient kinetic energy can (upon colliding with a neutral atom) cause an ionization event. For a plasma discharge to form, it is necessary that certain conditions are met such that this ionization process will occur in a runaway fashion. These conditions are dependent upon the strength of the electric field, the secondary electron yield of the cathode material, the electron mean free path, and the ionization cross section and ionization en-

ergy threshold of the gas. Paschen's Law incorporates these conditions into an equation that shows that the voltage required to initiate a plasma discharge in a given gas species is a function of the product of the gas pressure and the distance between electrodes [36,37]. A plot of the breakdown voltage as a function of the pressure-distance product is called a Paschen curve.

The well described Paschen's Law relationship served as a basis for this study. Because the gas pressure between the electrodes in a hollow cathode can be assumed to be related to the propellant mass flow rate, it was hypothesized that a plot of the ignition voltage as a function of propellant mass flow rate would reveal a trend that is similar to a Paschen curve. While a number of studies have generated Paschen curves through either experimentation or theoretical modeling, most of these data are not directly applicable to electric propulsion hollow cathodes due to the materials and/or gasses used. In this study, several Paschen curves were experimentally measured using various electrode materials and electric propulsion propellants. The experimental procedure and results are detailed in the following subsections.

2.1.1 Discharge Characterization Unit

To investigate the conditions required to initiate the formation of a plasma discharge, a discharge characterization unit was developed. A cross-section view of this device is shown in Figure 2.1. The device was situated within a vacuum chamber when performing experiments so that gaseous impurities could be avoided and also so that breakdown events along the exterior of the device were prevented. The discharge characterization unit was connected to a laboratory gas feed system so that high purity gasses could be flowed into the device. By placing electronically controlled solenoid valves at the upstream and downstream ends of the device, an arbitrary pressure of propellant gas could be established and maintained between the electrodes. An additional line, stemming from just upstream of the device was routed to a capacitance manometer so that the static pressure within the cavity could be measured. In this arrangement, the distance and gas pressure between the electrodes was uniform during each discharge initiation test and these parameters were

either known or could be measured. This arrangement also allowed for various propellant gasses and/or electrode materials to be tested with minimal reconfiguration.

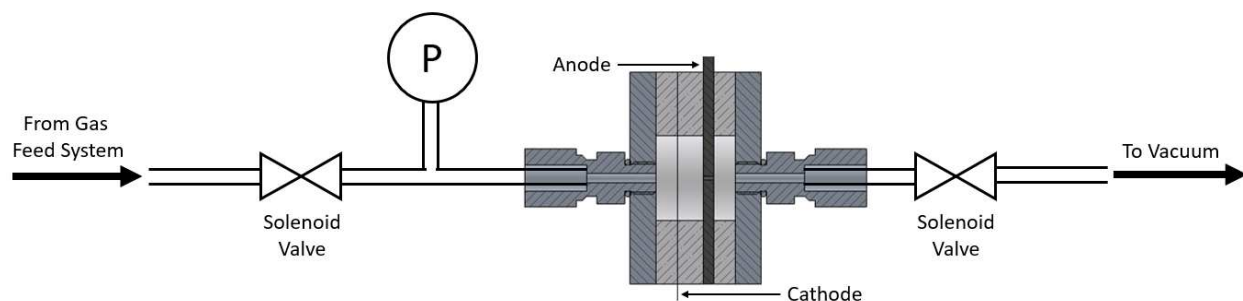


Figure 2.1: Flow schematic and cross-section view of the discharge characterization unit that was used to determine breakdown voltage at a range of internal gas pressures.

2.1.2 Procedure for Determining Breakdown Voltage as a Function of Internal Pressure

To generate Paschen curves for various propellant species and cathode materials, experiments were performed using the discharge characterization unit. During an experiment, a static pressure of high-purity gas would first be established between the two parallel planar electrodes of the discharge characterization unit. Then, the breakdown voltage would be determined for the gas while in this state. This was accomplished with high repeatability and minimal uncertainty using the following steps. First, before acquiring data, a bypass valve was opened to the vacuum chamber, and the feed system (along with the interior of the device) was evacuated for a minimum of 12 hours to remove impurities and residual gasses from the experiment. Afterwards, using a laboratory gas feed system, propellant gas was flowed into the device where it was held at a static pressure by closing the solenoid valves at the upstream and downstream ends of the device. A slowly increasing bias was then applied between the electrodes until an electrical breakdown of the gas was observed. A breakdown event was sensed by an oscilloscope as a flow of current between the electrodes. At the moment that the formation of a plasma discharge was detected, the bias voltage and the gas pressure between the electrodes was recorded, and the power supply was

immediately switched off to avoid excessive heating of the electrode materials. After acquiring breakdown voltage data over a range of internal pressures, a Paschen curve could be formed by plotting the breakdown voltage as a function of the product of the pressure and distance between electrodes. After each test sequence, the propellant gas species could be changed, and/or the device could be reconfigured with different electrode materials.

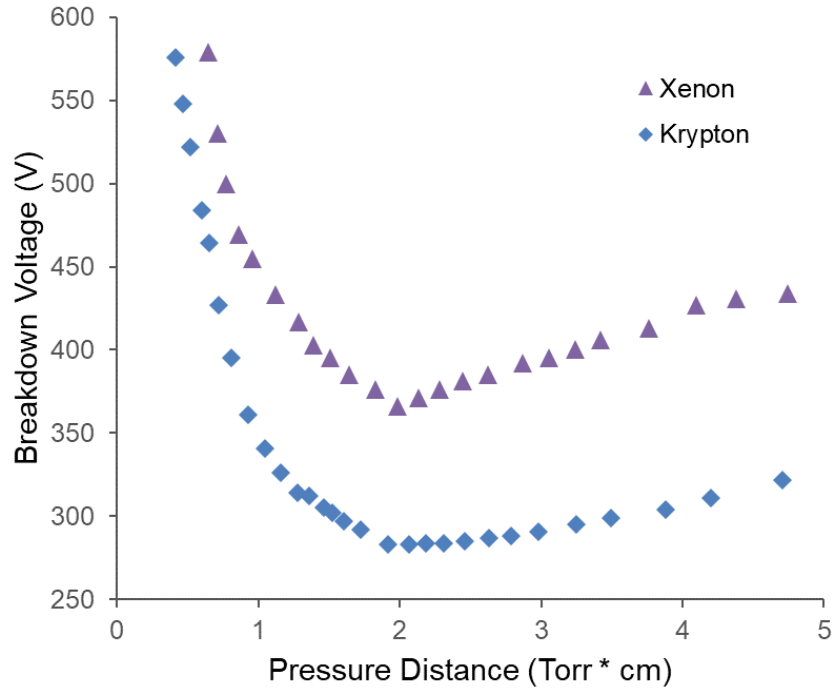
2.1.3 Results of Discharge Initiation Study

For this experiment, a breakdown event was defined as the formation of a glow or an arc discharge. A glow discharge was evidenced by a current flow of several milliamperes, whereas the formation of an arc discharge was evidenced by the power supply switching to current limited operation at 0.5 amperes. Formation of an arc discharge typically occurred at higher inter-electrode pressures, while at lower pressures, glow discharges were more commonly observed. This suggests that an instant start ignition behavior (i.e. an immediate transition to a high-current, low-voltage discharge) may be achieved when a higher neutral density is present between the cathode and keeper electrodes of a heaterless hollow cathode assembly. Because this experiment was performed with the intent to develop Paschen curves, glow discharge and arc discharge events were treated equally and both were considered breakdown events.

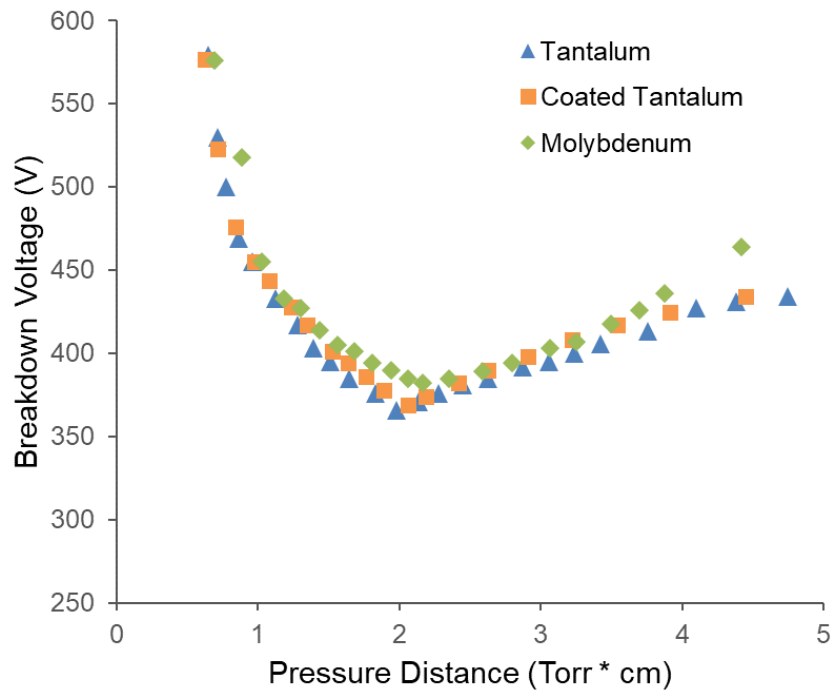
Data were acquired for two common propellant gas species, xenon and krypton, while the device was configured with a tantalum cathode and a graphite anode (materials commonly used in modern hollow cathode assemblies) with a spacing of approximately 6.4 mm. As shown in Figure 2.2a, significant differences in breakdown voltage were observed for the different propellant gas species over a range of internal pressures. Specifically, krypton was found to breakdown at significantly lower voltages than xenon. This result aligns with the theory of Paschen's Law, which asserts that the properties of the gas, specifically the ionization cross section and ionization energy threshold of the gas, play an important role in the breakdown process.

Another factor that affects the shape of a Paschen curve and the location of its minimum, is the secondary electron yield of the cathode due to ion bombardment, which varies depending on the

cathode material and the atomic species and energy of the ion [36,38]. To gauge the significance of this factor, three different cathode materials were tested; tantalum (as-received), molybdenum (as-received), and tantalum that was coated with a thin dielectric film. A coated material was tested because it has been shown that a thin dielectric film upon a metallic material may cause the secondary electron yield of the material to increase by up to three orders of magnitude [39,40]. If the secondary electron yield were affected to this degree, a significant change in the Paschen curve would be observed. To test this theory, an ion sputter deposition system was used to apply a film of titanium dioxide (TiO_2) with a thickness of approximately 10 nanometers. Figure 2.2b shows the Paschen curves for xenon using the three different cathode materials. While each curve is unique, no significant differences are observed. From these data, it can be concluded that the characteristics of the gas species has the most significant effect on the Paschen curve. This suggests that a heaterless hollow cathode would likely demonstrate varied ignition performance between different propellant gas species. In general, these results show that for a given gas species and electrode spacing, there exists an optimal pressure at which a plasma discharge can be formed using a minimal bias voltage.



(a) Comparison of xenon and krypton gasses.



(b) Comparison of various cathode materials using xenon gas.

Figure 2.2: Experimentally measured Paschen curves for different propellant gas species (a) and cathode materials (b).

2.2 Heaterless Hollow Cathode Ignition Experiments

In developing a heaterless hollow cathode for spaceflight applications, one must consider that exceedingly demanding ignition requirements could be problematic in systems that have limited propellant flow and/or electrical power capability. As was shown by the discharge initiation experiment, both the pressure and distance between electrodes have a direct effect on the voltage required to initiate a plasma discharge. Knowledge of this relationship is useful because it suggests that a minimal ignition voltage can be attained by creating an optimal propellant gas pressure between the cathode and keeper electrodes of a heaterless hollow cathode assembly. Despite the well-defined Paschen theory, it remains difficult to predict the ignition voltage in a hollow cathode assembly at a given flow rate because the distance between electrodes is typically non-uniform and the pressure between the electrodes varies with position and is difficult to model. In this study, a qualitative approach was taken in which the effects of two critical dimensions were investigated; the keeper orifice diameter and the distance between the cathode orifice and keeper orifice. The keeper orifice diameter was considered a critical dimension because it was assumed that this feature would have a direct effect on the propellant gas pressure between the cathode and keeper electrodes, with smaller keeper orifice diameters causing higher pressures between the cathode and keeper electrodes. Because electrode spacing is another principal independent variable in Paschen's Law, the distance between the cathode tip and keeper orifice was also considered a critical dimension. In this hollow cathode assembly, the radial distance between the outer wall of the cathode tube and the inner wall of the keeper tube was kept small at approximately 1 millimeter. This dimension was the same for all configurations. To determine whether these geometric parameters affect the ignition process, several hollow cathode configurations were tested and compared.

2.2.1 Heaterless Hollow Cathode Test Article

For this experiment, a 3.2 millimeter (0.125 inch) diameter cathode was selected because it is of a suitable size for low power Hall-effect thrusters; a thruster class that could benefit greatly from heaterless hollow cathode technology. The cathode consisted of a tantalum tube with a formed

hemispherical tip, with a 0.5 millimeter (0.020 inch) diameter orifice drilled into the tip. A porous tungsten barium oxide emitter was housed within the tube near the orifice. To simplify the manufacturing of the small emitter, the emitter does not have the conventional inner bore. In this hollow cathode, propellant gas flows either around the outer surface of the emitter, or through the porous material itself. The hollow cathode assembly utilized an enclosed keeper, which was specially designed to provide experimental flexibility. A threaded cap allowed for the keeper orifice plate to be easily removed and replaced with a keeper orifice plate of a different geometry. The keeper was made from graphite and designed with a slender profile to be representative of an assembly that could be integrated along the centerline of a low power Hall-effect thruster. The baseplate of the assembly was designed so that it was possible to adjust the axial position of the cathode relative to the keeper. This heaterless hollow cathode, shown in Figure 2.3, demonstrated stable operation at discharge currents up to 3 amperes.

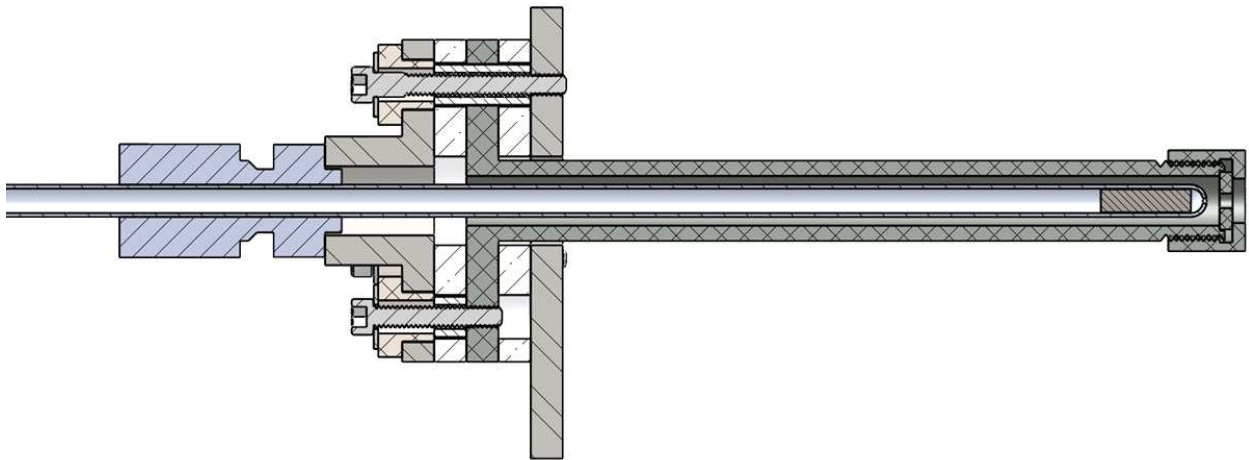


Figure 2.3: Cross-section view of the heaterless hollow cathode that was used in this study. The enclosed graphite keeper includes features at the downstream end that allow for the orifice plate to be removed and replaced.

2.2.2 Procedure for Determining Ignition Voltage as a Function of Propellant Mass Flow Rate

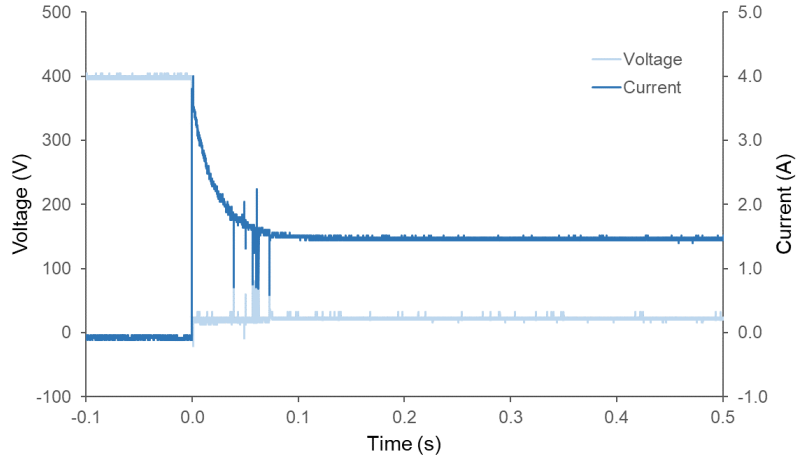
The purpose of this experiment was to determine how the ignition performance would be impacted by varying the keeper orifice diameter or the axial distance between the cathode and keeper. To make qualitative comparisons, each geometric configuration was tested to determine the ignition voltage as a function of propellant mass flow rate. Before each test sequence, the propellant feed system was exposed to vacuum for a minimum of 12 hours to remove gaseous impurities from the experiment. The first step of the test sequence was to establish a propellant mass flow rate through the hollow cathode. The flow rate was held constant by a laboratory mass flow controller. To verify that the flow rate through the cathode was equal to the flow rate through the mass flow controller, the vacuum chamber pressure and the pressure upstream of the hollow cathode were monitored until stable values were reached. Then, a slowly increasing bias voltage was applied between the cathode and keeper electrodes until the ignition of an arc discharge was observed. A successful ignition was most easily confirmed by monitoring the voltage and current with an oscilloscope.

In some flow conditions, a glow discharge of several milliamperes would be formed at a bias approximately 50 volts less than the ignition voltage. Similar to what was observed in the discharge characterization unit, the formation of a glow discharge would occur more often at lower propellant gas flow rates, which in this case, corresponded to lower inter-electrode gas pressures. This further supports the idea that an instant start ignition behavior requires that a large neutral density be present between electrodes. In this experiment, ignition was strictly defined as the transition to a stable 1.5 ampere discharge between the cathode and keeper electrodes. After each ignition, the voltage at which the arc discharge was initiated would be recorded and the discharge would be extinguished within 1 second after arc formation so that the cathode would not be excessively heated. This was done to ensure that subsequent tests were performed with an adequately cold cathode. When switching off the discharge after 1 second of operation, the cathode tip did not appear to be visibly incandescent, indicating a temperature of no more than 700 °C. Alternatively, when extin-

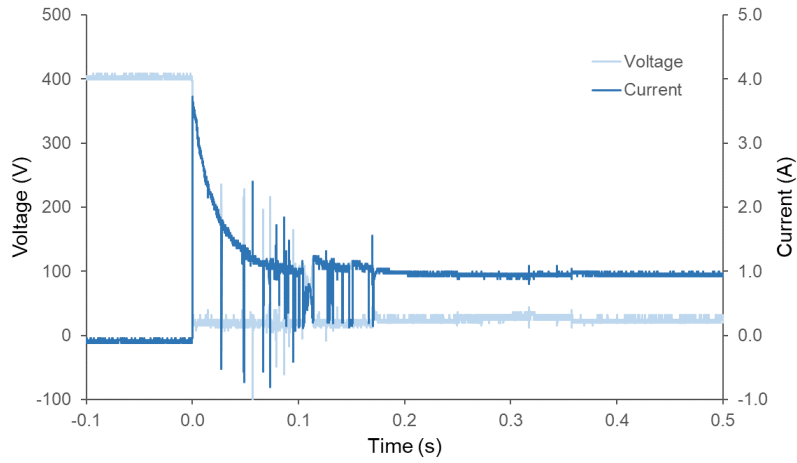
guishing the discharge in the same hollow cathode following steady-state operation, the cathode tip would remain visibly incandescent for approximately 5 seconds after being switched off. To further ensure that all parts of the cathode remained well below thermionic emission temperatures, at least 60 seconds were allowed to pass between each ignition test.

2.2.3 Results of Heaterless Hollow Cathode Ignition Study

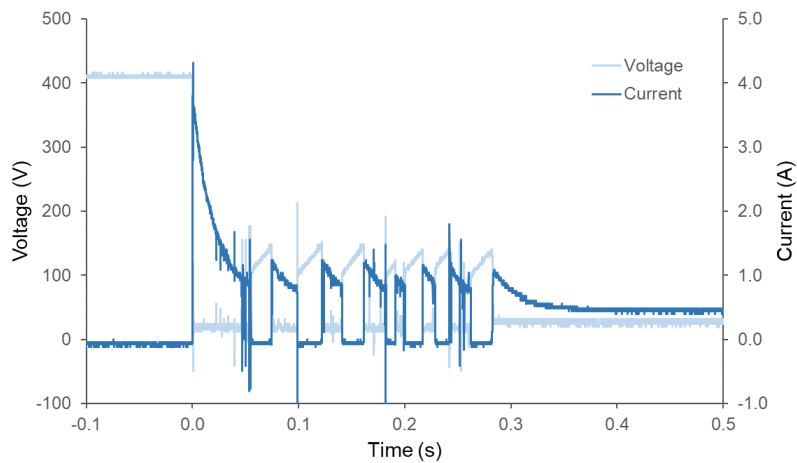
In a preliminary test, the power supply current limit setting was varied to see whether the ignition behavior would be affected. The resulting keeper voltage and current waveforms are shown in Figure 2.4 for ignitions that were performed with 1.5 ampere, 1.0 ampere, and 0.5 ampere settings. The 0.5 ampere setting resulted in highly oscillatory behavior in which the plasma discharge would decouple and reform a number of times before a stable discharge was reached. The 1.0 ampere setting demonstrated similar behavior, although events of decoupling were much less distinct. The 1.5 ampere setting exhibited the most stable behavior and also provided the most consistent and repeatable ignition data across a range of flow rates. For the remainder of the heaterless hollow cathode ignition tests with this cathode, the current limit was set to 1.5 ampere. This behavior was observed with all of the laboratory power supplies that were used in this research, which included power supplies manufactured by Sorensen, TDK-Lambda, and Magna-Power. Although a higher current limit setting resulted in the most reliable and most repeatable instant start ignition behavior, the hollow cathode demonstrated stable operation at a range of current settings after steady state operation was achieved.



(a) Current limit set to 1.5 amperes.



(b) Current limit set to 1.0 amperes.

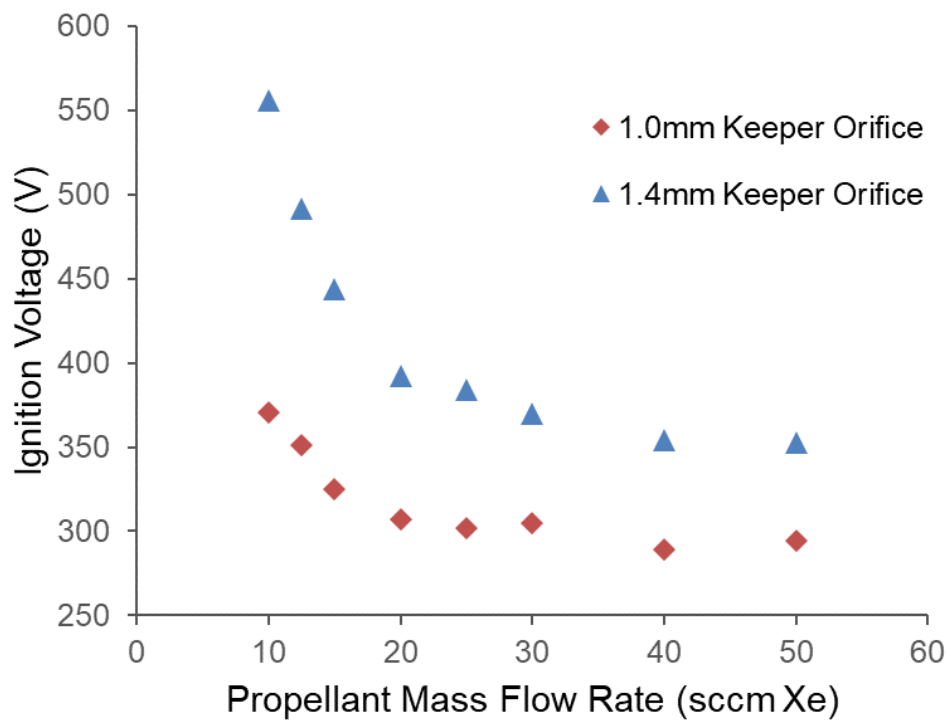


(c) Current limit set to 0.5 amperes.

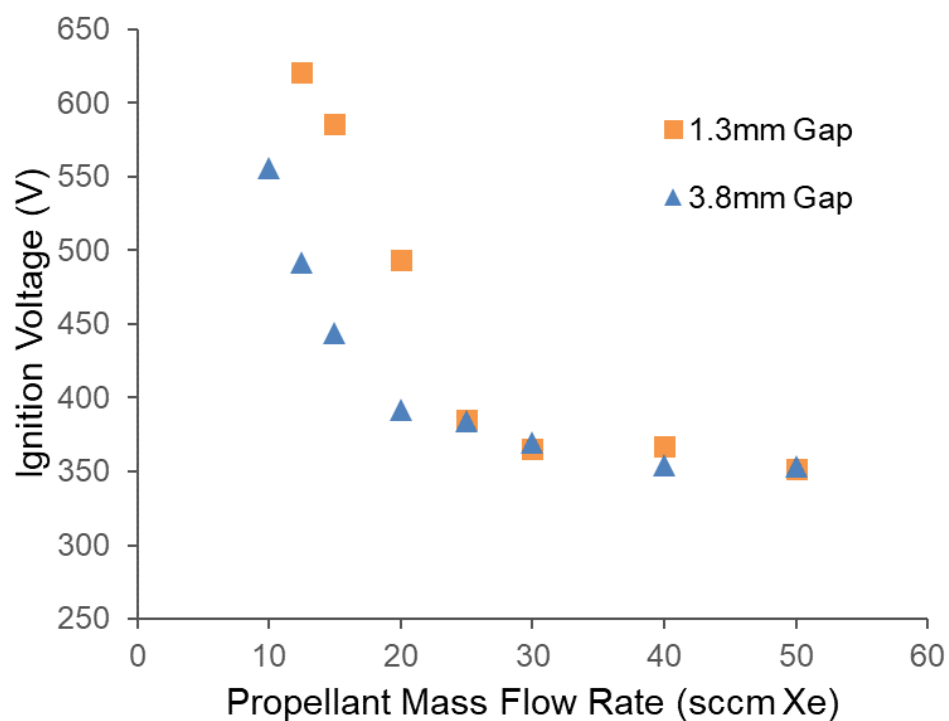
Figure 2.4: Voltage and current flow between the cathode and keeper during ignition with power supply settings of (a) 1.5 amperes, (b) 1.0 amperes, (c) and 0.5 amperes.

The plots in Figure 2.5 show the results of varying the keeper orifice diameter and the axial distance between the cathode and keeper electrodes. In these plots, the average ignition voltage is plotted as a function of xenon mass flow rate for each hollow cathode configuration. In all cases, a downward sloping trend is observed. This indicates that the internal gas pressure and distance between electrodes are such that these data correspond to the region of the Paschen curve that is to the left of the minimum. Figure 2.5a shows there is a distinct difference in ignition voltage at a given propellant mass flow rate depending on the diameter of the keeper orifice. With both of these keeper diameters, the axial distance between the cathode and keeper was approximately 3.8 mm. The lower ignition voltages observed with the smaller keeper orifice can be attributed to the increased flow impedance and thus higher gas pressures between the cathode and keeper electrodes. Figure 2.5b shows ignition voltages for two different axial distances between electrodes. The keeper orifice diameter was 1.4 mm for both of these inter-electrode gaps. As one would predict using Paschen's Law, the smaller distance generally exhibited higher ignition voltages. However, this was only observed at flow rates below 25 sccm. At higher flows, the two hollow cathode assemblies demonstrated similar ignition voltages. Given that these results deviate from the theory of Paschen's Law, it could be the case that electrical breakdown occurred in a non-axial direction at some test conditions. Given inherent non-uniformities in electrode distance and internal pressure, it is possible that the plasma discharge could be initiated at various locations within the assembly depending on the flow condition.

As a general trend, ignition voltages were observed to be more repeatable at higher propellant mass flow rate conditions. Figure 2.6 includes error bars that represent the standard deviations of the data for the hollow cathode assembly that used a 1.4 mm keeper orifice and a 3.8 mm electrode spacing. The smallest standard deviations occurred at the highest flow rate conditions.



(a) Comparison of two keeper orifice diameters.



(b) Comparison of two electrode spacings.

Figure 2.5: Ignition voltage as a function of xenon mass flow rate for varied keeper orifice diameters (a) and axial distances between cathode and keeper electrodes (b).

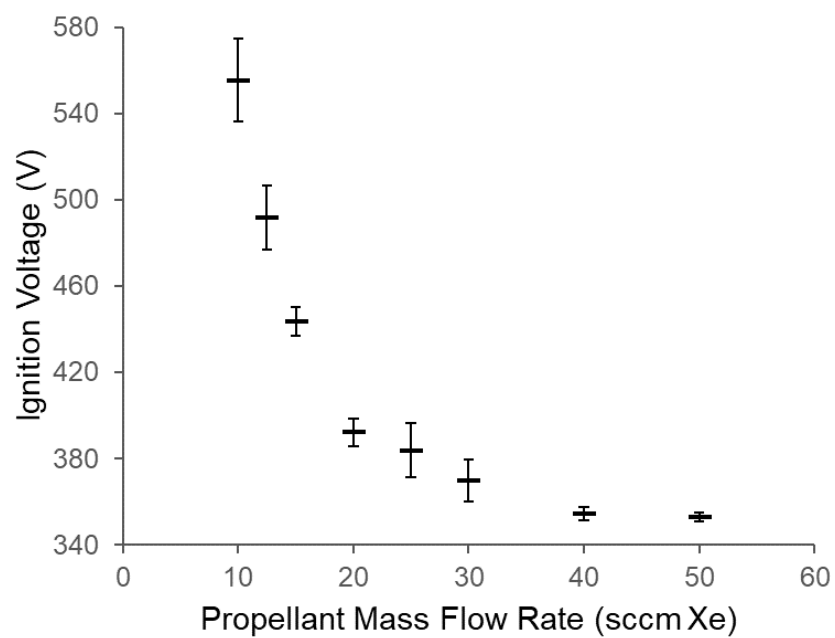


Figure 2.6: Ignition voltage as a function of xenon mass flow rate with error bars that represent the standard deviation of the data sets.

2.3 Discussion

The discharge initiation experiment showed that, in accordance with Paschen's Law, the composition of the propellant gas has a significant effect on the voltage required to initiate a plasma discharge at a given gas pressure and electrode distance. This suggests that a heaterless hollow cathode assembly is likely to exhibit significantly different ignition characteristics between different propellant gasses. In designing and testing a specific heaterless hollow cathode assembly, it may be useful to designate the ignition characteristics of the unit as being unique to a specific propellant gas. If optimal ignition performance is desired, it would be wise to use the appropriate propellant gas during ignition testing and in any cathode development activity.

In the heaterless hollow cathode experiment, it was shown that both the keeper orifice diameter and the axial position of the cathode relative to the keeper have an effect on the voltage required to ignite a plasma arc discharge at a given flow rate. While these results generally align with Paschen's Law, there were some discrepancies that suggest that the inherent nonuniformities in electrode spacing and gas pressure within a hollow cathode assembly must be considered before one can accurately estimate the ignition voltage. A more comprehensive model of the ignition process is judged to be necessary to better predict ignition behavior. Presently, experimentation remains to be the most straightforward means to characterizing the ignition characteristics of a heaterless hollow cathode. To integrate a heaterless hollow cathode in spaceflight electric propulsion system, it is necessary that the propellant feed system and power processing unit are capable of providing the conditions necessary to ignite a plasma discharge in a heaterless hollow cathode.

2.3.1 Involvement of Power Supply Output Capacitance

When ignition is performed in a heaterless hollow cathode, the formation of a plasma arc discharge is accompanied with a dramatic drop in voltage and a simultaneous surge in current between the electrodes as shown in Figure 2.4 above. The spike in current then decays at a finite rate until the current limit setting on the power supply is reached. It was found that the temporal behavior of the excess current closely matches a classical resistor-capacitor discharge model. Figure 2.7 shows

the keeper current as a function of time during the first 7 milliseconds of a heaterless ignition overlaid with a theoretical resistor-capacitor discharge curve.

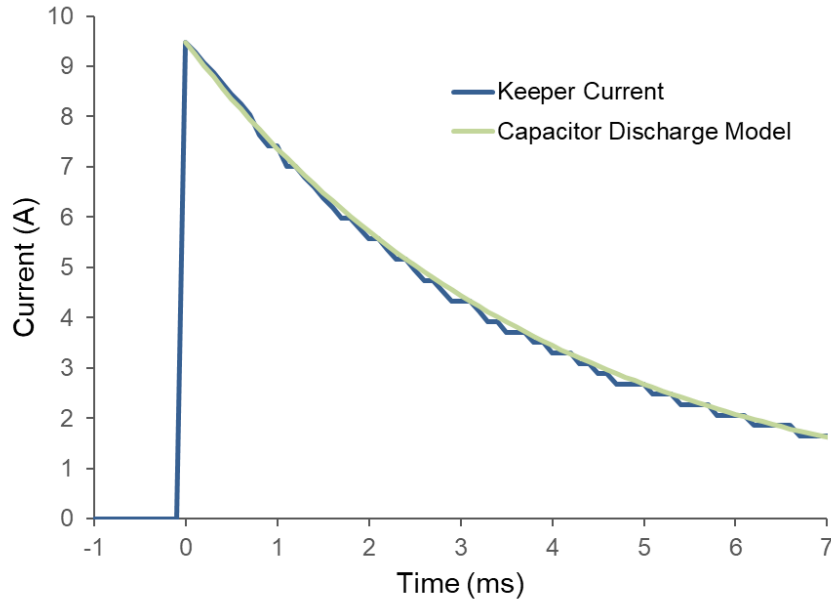


Figure 2.7: Keeper current during the first several milliseconds of a heaterless ignition. The measurement closely matches the exponential decay of current that is characteristic of a resistor-capacitor circuit.

When an open circuit is suddenly closed in a first order resistor-capacitor circuit, the inrush current decays exponentially as a function of time, as is classically described by (2.1); where J is the current, t is the time, and τ is the time constant of exponential decay. The time constant is equal to the product of the resistance and the capacitance as in (2.2). In this case, the total resistance in the circuit is equal to the ballast resistance, $R_{ballast}$, plus the resistance of the plasma load, R_{plasma} . While the plasma resistance is likely not a constant value throughout the ignition process, it was assumed to be so for the sake of simplicity, and was calculated using (2.3). In this test, the ignition voltage, V_0 , was 500 volts, the ballast resistance was 41 ohms, and the peak current, J_0 , was measured to be approximately 9.48 amperes. This yielded an estimated plasma resistance of approximately 11.7 ohms. Finally, the model was curve-fit to the data by varying the value of the capacitance, C , in (2.2). The value of the capacitance was estimated to be 75 microfarads, which was the value used to generate the discharge curve in Figure 2.7.

$$J(t) = J_0 e^{-t/\tau} \quad (2.1)$$

$$\tau = (R_{ballast} + R_{plasma}) * C \quad (2.2)$$

$$R_{plasma} = \frac{V_0}{J_0} - R_{ballast} \quad (2.3)$$

The estimated capacitance value of 75 microfarads is similar to the manufacturer specified 92 microfarad output capacitance of the keeper power supply that was used in this experiment. It is reasonable to conclude that the observed discharge current behavior can be attributed to this output capacitance. In performing this test, the bias voltage was applied before ignition, which would have caused the power supply output capacitance to be charged to the ignition voltage. When the plasma discharge was formed at time $t=0$, the energy stored in the capacitor was released through the ballast resistance and through the plasma. The resulting exponential current decay behavior was seen in all of the heaterless hollow cathode ignition tests that were performed. When no ballast resistance was used, the current reaches considerably higher peak values. In some cases, this resulted in damage to the cathode, other circuit components, or the power supply itself. For apparent reasons, it is prudent to size the ballast resistance appropriately. Furthermore, it is important to consider that the release of electrical energy, which is prolonged by the ballast resistance, may be helpful in the ignition process. While this research did not focus on the design of spaceflight electronics, the use of a well tuned output capacitance and ballast resistance or an inductive circuit element may be a necessary part of a heaterless hollow cathode ignition circuit.

2.3.2 Spaceflight Power Processing Unit Considerations

While specific conditions must be satisfied to trigger the heaterless ignition process, it is also necessary that the plasma discharge be maintained after it is initiated. It is important to acknowledge that a typical spaceflight power processing unit (PPU) may behave quite differently from

a laboratory power supply. For example, the laboratory power supplies used in this study were designed with relatively large output capacitance to minimize ripple current in the output. The energy stored in the output capacitor(s) is released through the circuit at the moment that a plasma discharge is formed. This energy release during ignition may, in fact, be helpful in maintaining the plasma discharge during the moments immediately following the formation of a plasma discharge. A typical spaceflight PPU uses a much smaller output capacitance in the keeper circuit and does not include a large ballast resistance. Additionally, it was shown that the heaterless ignition process is more reliable when a high discharge current is maintained as shown in Figure 2.4. Because the keeper discharge current is typically limited to a low value during thruster operation, most PPUs are not designed to drive 1.5 amperes or more in the keeper circuit. If it is undesirable to modify the keeper module of the PPU to drive a higher discharge current, it may be possible to supplement the discharge using the anode circuit, which is parallel to the keeper circuit, during ignition. In any case, it is recommended that the development of an electric propulsion heaterless hollow cathode involves the parallel development of a PPU so that compatibility between the two can be optimized. Even in the preliminary stages of developing a heaterless hollow cathode for spaceflight, the differences between a laboratory power supply and a spaceflight PPU should be considered because ignition performance could vary considerably.

Chapter 3

Fixed-Volume Release: A Simple Propellant Feed Solution that Enables Instant Start Ignition

By investigating the propellant flow and bias conditions necessary to ignite a plasma discharge in a heaterless hollow cathode, it was found that, to achieve ignition at a minimal voltage, an extremely high propellant mass flow rate is necessary. Furthermore, ignition behavior appeared to be more repeatable and reliable at these high flow conditions. In a laboratory gas feed system, the mass flow rate is usually controlled with a closed-loop, thermal mass flow controller, or similar technology. By configuring such equipment appropriately, one may provide a high propellant mass flow rate (e.g. 100 sccm or more) to a heaterless hollow cathode to enable reliable ignition, after which the flow rate can be set to a nominal value (10 sccm, for instance) for normal cathode operation. While similar hardware could be used for heaterless hollow cathode ignition and operation in a spaceflight system, the use of sophisticated flow-control systems is undesirable given the inherent cost, mass, complexity, and risk of failure. The cost and mass alone may likely be prohibitive in small satellites, which could benefit the most from heaterless hollow cathode technology. This drives a need for a more simplified approach to providing the desired high propellant flow condition. In this study, a propellant flow mechanism was developed and analyzed. The device proved capable of providing a significantly elevated propellant mass flow rate for a period of time using only a few simple components, and showed to successfully facilitate an instant start ignition behavior in a heaterless hollow cathode. Some of the preliminary analyses and results were presented at the 36th International Electric Propulsion Conference [41].

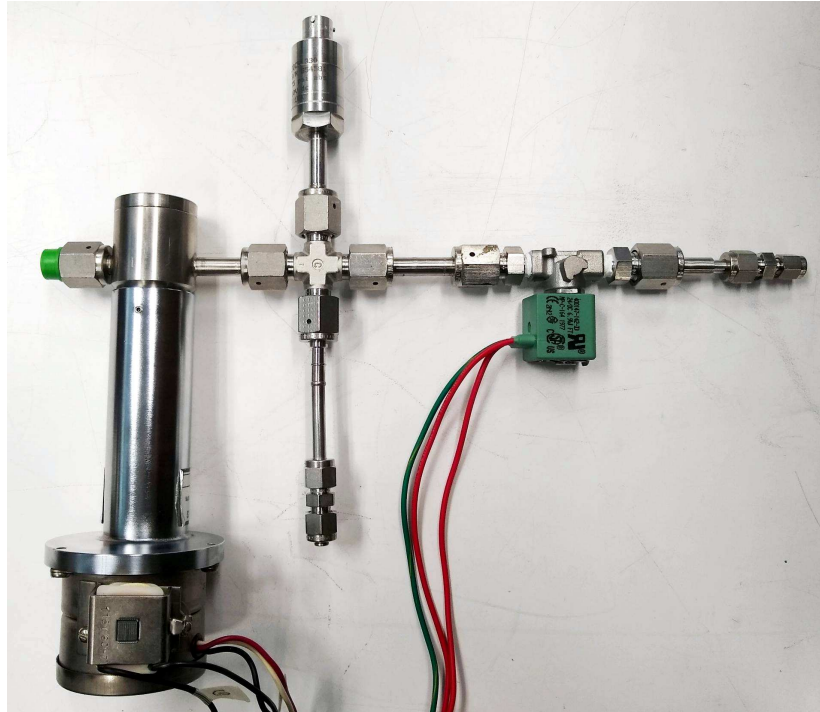
3.1 Experimental Fixed-Volume Release Apparatus

The fixed-volume release concept presented herein was devised to be well suited for integration into a small-satellite propellant feed system. In small-sat systems, a fixed flow control (rather than

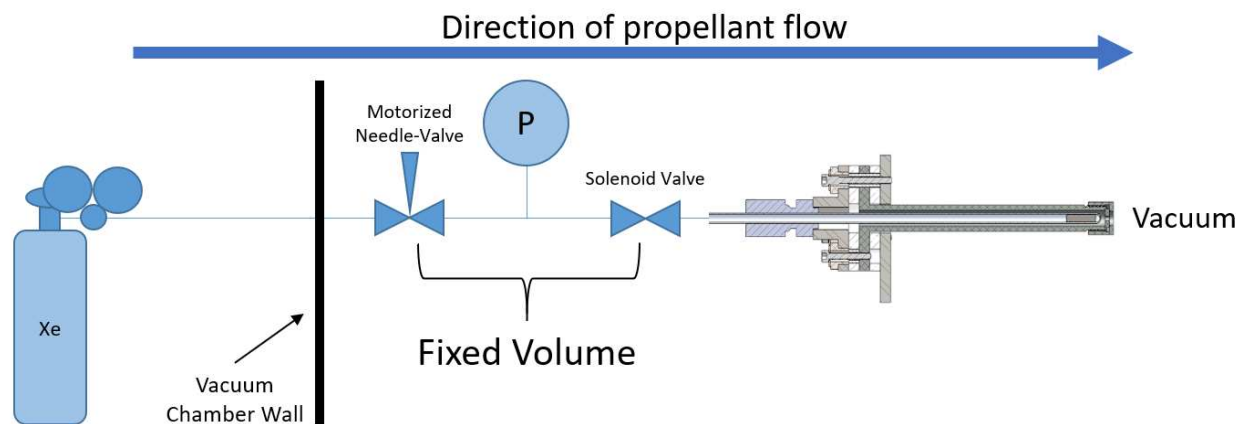
a closed-loop mass flow controller) is the preferred flow control mechanism given its low cost, low mass, and minimal complexity. When propellant supply pressure is well regulated, a fixed flow control, such as a precision micro-orifice or a porous metal flow restriction, is effective for maintaining a steady, predictable propellant flow rate. This can be used to deliver propellant to a hollow cathode during normal operation; however, this type of flow control does not allow for the flow rate to be increased to accommodate the ignition process in a heaterless hollow cathode. With the addition of a single valve, a fixed-volume release can temporarily deliver a significantly elevated propellant mass flow rate to a hollow cathode.

A fixed-volume release system, located upstream of a heaterless hollow cathode assembly, consists of a flow restriction, a valve, and a volume contained between the two (see Figure 3.1b). The flow restriction at the upstream end of the volume is sized such that a nominal propellant mass flow rate is maintained during normal cathode operation. The valve at the downstream end of the volume is used to shut-off propellant flow to the hollow cathode. When the shut-off valve is closed, the gas pressure within the volume rises to, and eventually equalizes with the supply pressure. When this volume is charged to the supply pressure, opening the shut-off valve releases a slug of propellant through the hollow cathode, resulting in a significantly elevated propellant mass flow rate for a limited period of time, after which the flow settles to its steady-state value.

In the initial testing of the fixed volume release concept, the experimental apparatus shown in Figure 3.1a was constructed and integrated into a vacuum facility for testing with a heaterless hollow cathode. The heaterless hollow cathode assembly used in this experiment was the same device that was used in the testing from chapter 2, which is described in detail in section 2.2.1. In this experiment, a 1.4 mm diameter keeper orifice plate was used, and the cathode tip was positioned at an axial distance of 1.3 mm upstream of the keeper orifice plate. In this miniaturized hollow cathode assembly, the emitter housed within the cathode tube did not feature an inner bore. In this design, gas flows either around or through the semi-porous emitter itself. A cross-section view of the hollow cathode assembly is included in Figure 3.1b.



(a) Photo of fixed-volume release system used in this analysis. Components include a motorized needle valve (left of cross), solenoid valve (right of cross), pressure transducer (above cross), and additional volume (below cross).



(b) Schematic view of the experimental fixed-volume release system

Figure 3.1: Photo (a) and schematic (b) of an experimental fixed-volume release system that can be used to provide an elevated propellant mass flow rate to facilitate heaterless hollow cathode ignition.

The experimental fixed-volume release apparatus was designed to be operated in vacuum so that it could be located as close to the hollow cathode as possible, minimizing the volume of propellant feed line downstream of the solenoid valve. For experimental purposes, the upstream flow restriction was provided by a motorized needle valve, which allowed for the inlet flow rate to be adjusted as necessary. A solenoid valve was used at the downstream end of the fixed-volume. To monitor the behavior of the fixed-volume release system, a pressure transducer was attached to the section of propellant feed line located between the needle valve and the solenoid. An arbitrary length of feed line could also be attached to the fixed-volume to allow for its size to be adjusted if necessary. For the research presented in this paper, the volume of the fixed-volume release system was selected to be 13 cm³. The volume was calculated using (3.1) after closing the valve and measuring the rate of pressure rise within the volume. In (3.1), V is the volume, $\dot{m}$ is the mass flow rate into the volume which was measured using a laboratory mass flow meter, R is the gas specific gas constant, T is the temperature, assumed to be 300 K, and $\dot{P}$ is the measured time rate of change of pressure within the volume.

$$V = \frac{\dot{m}RT}{\dot{P}} \quad (3.1)$$

3.2 Fixed-Volume Release Gas Flow Model

To explore the propellant flow conditions that can be produced with a fixed-volume release system, a model was developed to predict the propellant mass flow rate exiting a fixed-volume as a function of time after a propellant release is initiated. The accuracy of the model was evaluated by experimentally measuring the gas pressure in the fixed-volume release system as a function of time, and then using those data to calculate the flow rate exiting the apparatus. After validating the model accuracy, a computer application was developed using MATLAB that allows a user to generate plots of the temporal flow behavior produced by a fixed-volume release system of user-specified parameters.

3.2.1 Testing and Modeling the Initial Prototype

To predict the propellant mass flow rate exiting a fixed-volume release system as a function of time, a control volume was defined, and the flow impedances at the inlet and outlet of the volume were quantified. Using the fixed-volume release configuration described in section 3.1, the inlet to the fixed-volume features a high flow impedance such that a nominal propellant mass flow rate is maintained during normal operation. Downstream of this restriction, flow is relatively unrestricted until the hollow cathode tip is reached. As such, the control volume for this model was defined to be the volume contained between the inlet restriction and the hollow cathode tip as depicted in Figure 3.2. This means that, although the volume between the inlet and the solenoid valve was measured to be 13 cm^3 , the control volume is actually slightly larger as it also includes the volume between the solenoid valve and the cathode tip. The additional volume was determined to be negligible when using a small, 3.2 mm diameter cathode located a short distance downstream of the shut-off valve.

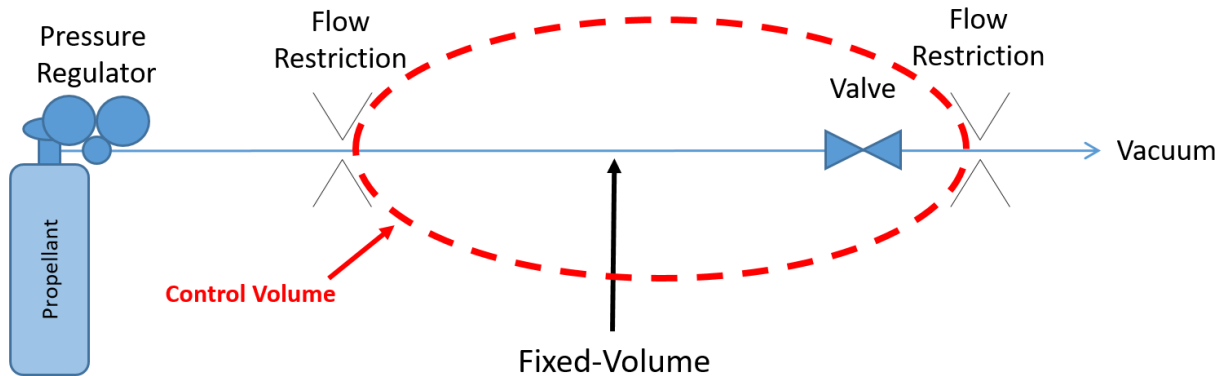


Figure 3.2: The control volume used to develop the propellant release model includes the volume contained between two flow restrictions.

To determine whether the flow is choked at the inlet, equation (3.2) was used. In this equation, p_0 is the upstream (stagnation) pressure, γ is the heat capacity ratio of the gas, and p^* is the critical pressure. When the pressure downstream of the restriction is less than the critical pressure, a choked flow condition exists. When a choked flow condition exists within a circular orifice,

the mass flow rate can be determined by equation (3.3), where $\dot{m}$ is the mass flow rate, C_d is the discharge coefficient, (a dimensionless coefficient with a nominal value of 1), A is the cross-sectional area of the orifice, P is the upstream (stagnation) pressure, T is the temperature of the gas, (generally assumed to be 300 K in this study), and R is the gas specific gas constant. During nominal flow operation, (i.e. valve open indefinitely), the pressure downstream of the inlet was measured to be well below the critical pressure, indicating that a choked flow condition exists when the valve is open indefinitely. Furthermore, initial testing showed that upon initiating a propellant release, (i.e. opening the valve), the pressure in the fixed volume would very quickly drop below the critical pressure. Thus, it was assumed that the flow through the inlet is choked (and the inlet mass flow rate is constant) throughout a propellant release event.

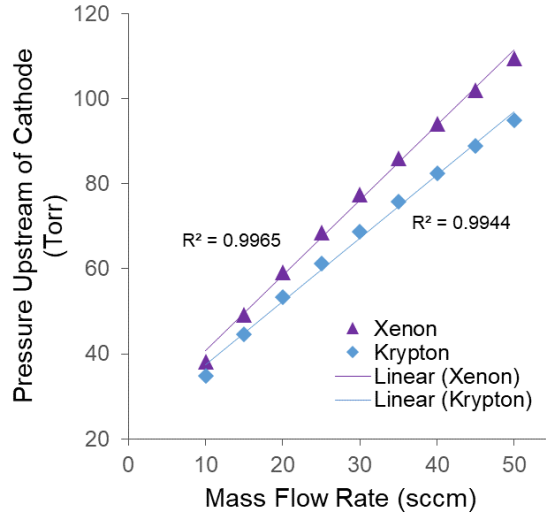
$$\frac{p^*}{p_0} = \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma-1}} \quad (3.2)$$

$$\dot{m} = C_d \frac{A \cdot P}{\sqrt{T}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma + 1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \quad (3.3)$$

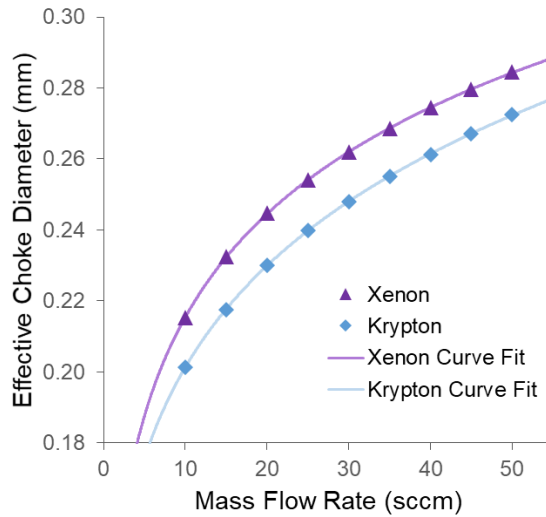
In a hollow cathode assembly, the cathode orifice is typically the smallest and most restrictive feature in the propellant flow path. However, the lack of an inner diameter feature in this particular hollow cathode emitter causes propellant to flow either around or through the emitter. It was suspected that this arduous flow path would cause additional flow impedance. To quantify the flow impedance of this hollow cathode, a capacitance manometer was used to measure the propellant gas pressure just upstream of the device as a function of propellant mass flow rate while the hollow cathode was at room temperature. This relationship, plotted in Figure 3.3a for xenon and krypton gasses, was observed to be nearly linear, suggesting that it may be accurate to assume that the flow is in a choked condition. However, the slight non-linearity in these data indicate that the discharge coefficient is not constant for all flow rates. To account for this, an effective choke diameter was computed for each data point using equation (3.4). This equation is similar to equation (3.3), except that $\pi d^2/4$ (where d is the effective choke diameter) is used in place of $C_d A$ to represent the

effective choke area. The resulting data, shown in Figure 3.3b, were then curve fit so that effective choke diameters could be estimated for a continuous range of values.

$$\dot{m} = \frac{\pi d^2 P}{4\sqrt{T}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma + 1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \quad (3.4)$$



(a) Gas pressure upstream of a room temperature hollow cathode as a function of propellant mass flow rate.



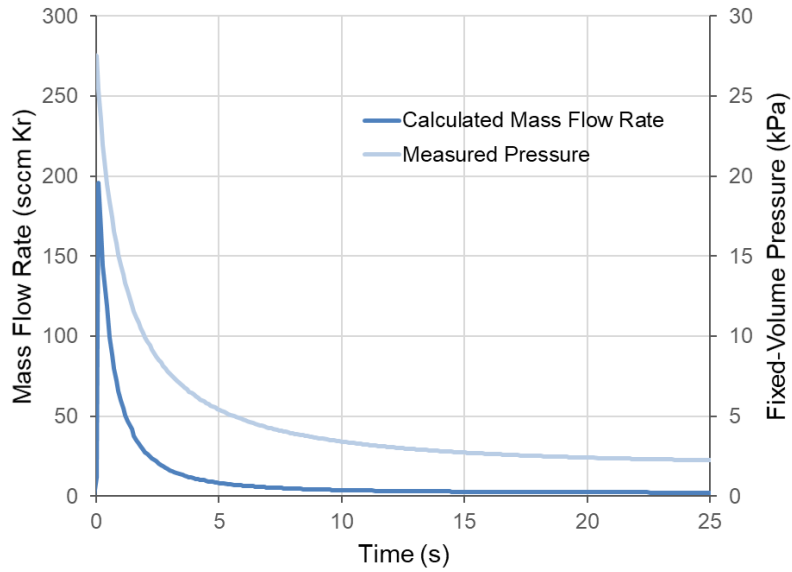
(b) Effective choke diameter as a function of propellant mass flow rate.

Figure 3.3: Upstream pressure data as a function of propellant mass flow rate were used to quantify the flow impedance in a room temperature cathode for both xenon and krypton gasses.

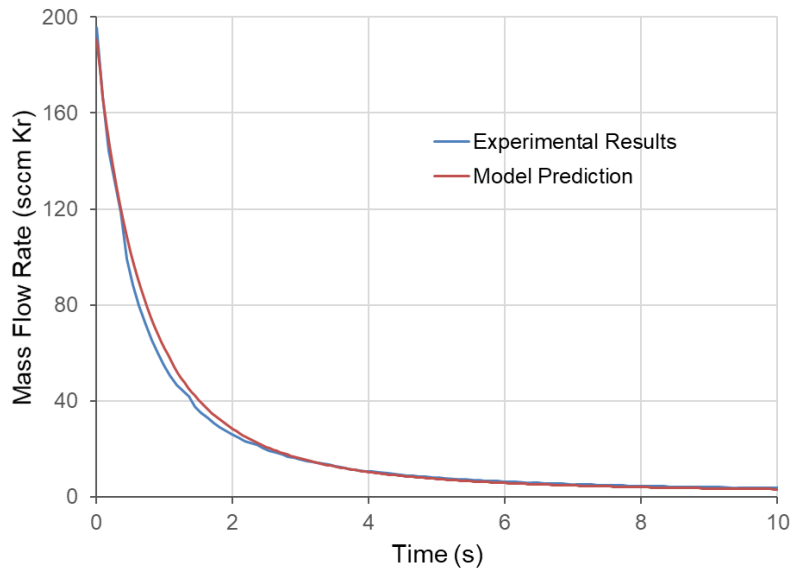
With a control volume defined and inlet and outlet restrictions characterized, the propellant mass flow rate through a hollow cathode could be modeled as a function of time during a propellant release. Starting with a given initial pressure, the mass flow rate exiting the control volume could be found by iteratively solving the choked flow equation (3.4) until the flow rate corresponded with the appropriate effective choke diameter. With both the inlet and outlet mass flow rates known, a straightforward calculation could be performed to find the change in propellant mass within the control volume after a finite-difference in time. The propellant pressure could then be recalculated for the latest time-step using the ideal gas law. This process would be repeated until the propellant mass flow rate exiting the control volume was calculated for each time-step in the desired time domain.

To test the accuracy of this model, experimental testing was performed with a room-temperature cathode (i.e. no ignition operations were performed). The propellant mass flow rate through the hollow cathode during a propellant release was calculated by measuring the gas pressure within the fixed-volume as a function of time and using (3.5); where $\dot{m}_{out}$ is the mass flow rate exiting the fixed-volume, $\dot{P}$ is the time rate of change of pressure within the volume, V is the volume, R is the gas specific gas constant, T is the temperature (assumed to be 300 K), and $\dot{m}_{in}$ is the mass flow rate into the control volume, which is assumed to be a constant value, and was measured before the experiment using a laboratory mass flow meter. The pressure data were curve-fit to eliminate the intensification of noise that would otherwise occur when calculating the derivative of the pressure with respect to time from experimental measurements. Figure 3.4a shows an example of a curve fit of experimentally measured krypton pressure and the calculated flow rate through the hollow cathode as a function of time. Upon opening the valve at time $t = 0$, a significantly elevated propellant flow rate is achieved. The flow rate then decays and eventually approaches a steady value, which is maintained by the inlet flow restriction (1.75 sccm Kr in this case). Figure 3.4b shows these results compared with the behavior predicted by the model. The model predictions were found to agree well with the experimental results.

$$\dot{m}_{out} = \frac{-\dot{P}V}{RT} + \dot{m}_{in} \quad (3.5)$$



(a) Curve-fit of experimentally measured pressure within a fixed-volume release system, and the calculated flow rate exiting the volume as a function of time.



(b) Comparison of the propellant release model and experimental results.

Figure 3.4: These data represent the case in which approximately 13 mg of krypton propellant is released from a 13 cm³ fixed-volume. Time $t=0$ corresponds to the valve opening, which initiates the propellant release.

While experimental data showed strong agreement with the model predictions when a temperature of 300 K was assumed for the gas, it was found that when ignition was performed, the propellant release was significantly prolonged (Figure 3.5). This reveals that the model prediction is largely inaccurate for cases that involve ignition. The altered behavior is likely due to the formation of a plasma and subsequent heating of gas in the cathode tip, which would result in an increased flow impedance. Additionally, plasma production just downstream of the cathode orifice may cause some mass flow to occur in the upstream direction due to ion motion [2]. Because these effects cannot be easily quantified, the model was not modified to account for cases in which ignition was performed. However, detailed in the following subsection is an alternative approach that circumvents this issue.

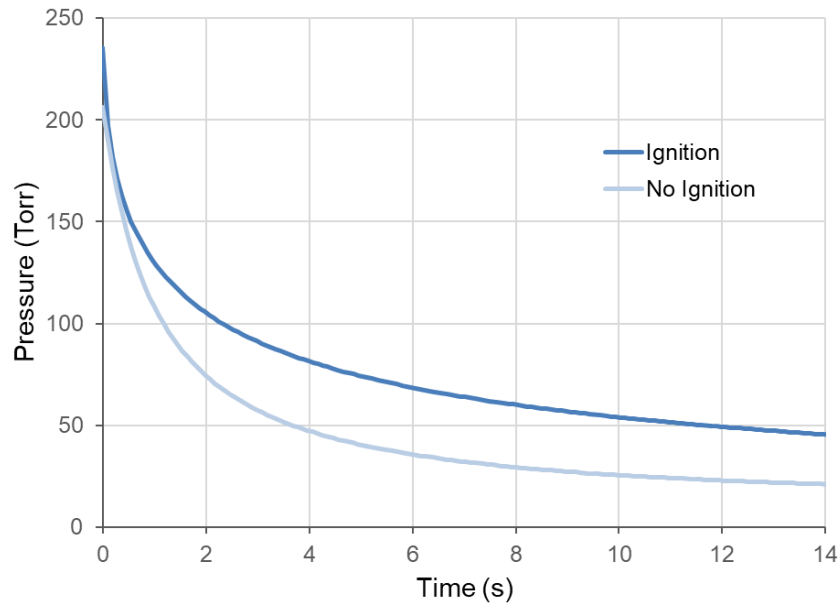


Figure 3.5: Comparison of propellant pressure within the initial fixed-volume release prototype as a function of time with and without an ignition performed. It is suspected that gas heating that occurs in the cathode tip during ignition results in an increased flow impedance.

3.2.2 Improving the Fixed-Volume Release System with an Additional Flow Restriction

Through modeling and experimenting with the fixed-volume release system, it became evident that placing an additional flow restrictor downstream of the shut-off valve and just upstream of the hollow cathode could provide several distinct advantages. One such advantage is that the ignition of a plasma discharge would likely no longer effect on the outlet flow impedance. This would vastly improve the accuracy of the model for cases in which ignition was performed. An additional advantage is that the outlet impedance may be specified, which provides significantly greater design versatility. By fine-tuning the size of the volume, the volume fill pressure, and the size of the outlet restriction, a relatively specific flow behavior could be achieved. Additionally, in conventional cathodes with hollow bore emitters, the flow impedance is presumably much lower than the hollow cathode that was used to test the initial fixed-volume release prototype. When using a hollow cathode with a relatively unrestrictive flow path, the lack of an additional flow restrictor would result in a brief period of excessively high propellant mass flow that would very quickly decay to the nominal flow rate, which could result in a failed ignition. For these hollow cathodes, the additional flow restrictor is likely necessary for the fixed-volume release system to be effective in delivering the propellant flow necessary to achieve reliable instant start ignition.

To test the additional flow restriction concept, a 0.13 mm (0.005 in) diameter flow restriction orifice was added to the downstream end of the fixed-volume release system, and a larger 6.4 mm (0.25 in) diameter hollow cathode was made with a 1.0 mm (0.040 in) orifice and a hollow bore emitter. The relatively unrestrictive flow path in this cathode tube was more representative of a conventional hollow cathode design. A schematic of the updated configuration is shown in Figure 3.6.

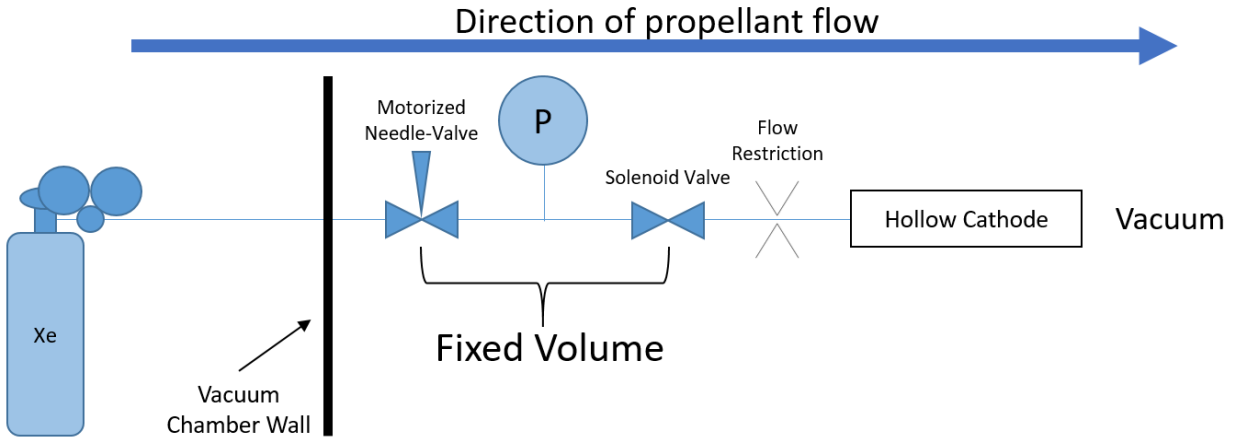


Figure 3.6: Schematic of the updated fixed-volume release configuration, which uses an additional outlet flow restrictor.

In this configuration, the propellant release model was more straightforward to develop because it did not require an in-depth characterization of the flow impedance of the cathode itself. By treating the outlet flow restrictor as a choked orifice of fixed diameter, the model prediction showed excellent agreement with experimental data as shown in Figure 3.7. Additionally, when using the outlet restriction, the propellant flow behavior was nearly identical whether or not ignition was performed as shown in Figure 3.8. This reduces uncertainty in the system performance and improves the applicability of the fixed-volume release model.

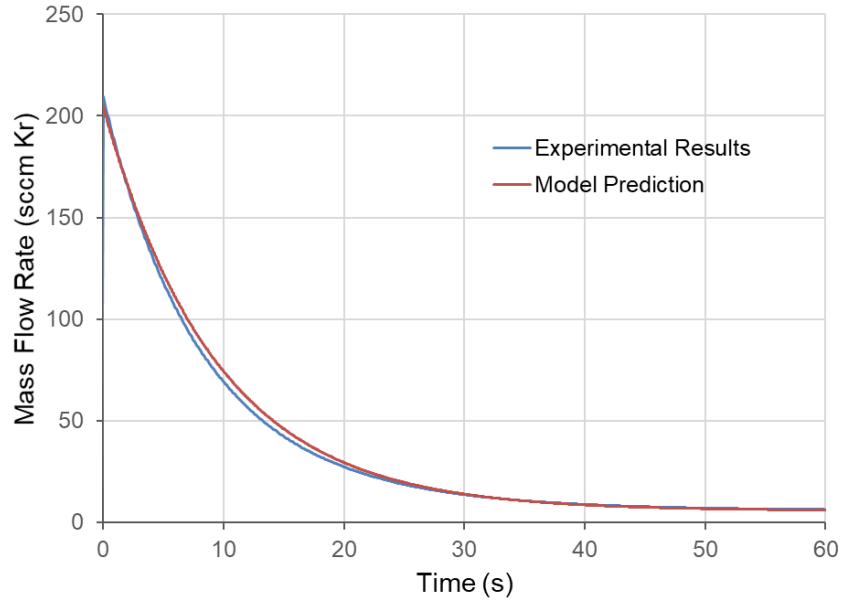


Figure 3.7: Comparison of the propellant release model and experimental results when using an additional outlet flow restrictor.

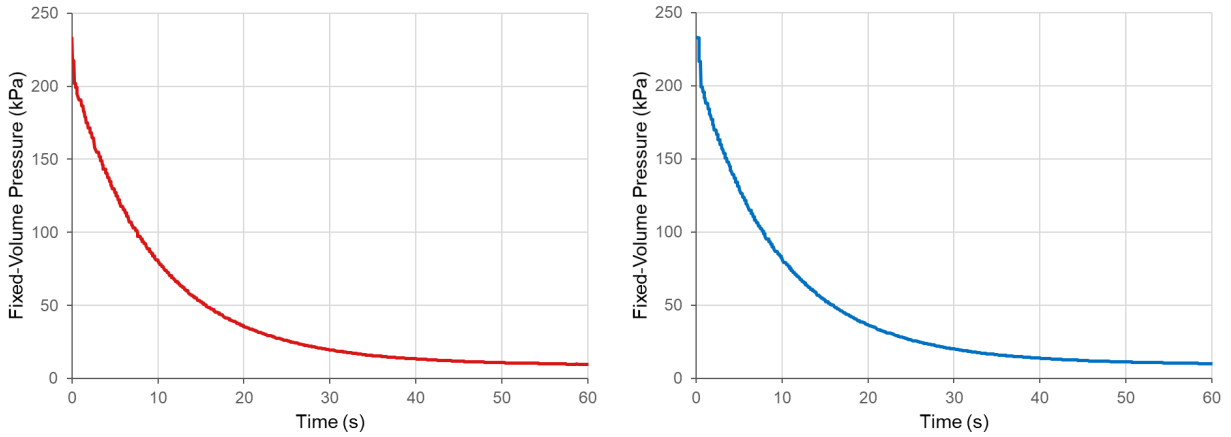


Figure 3.8: Comparison of the temporal pressure within a fixed-volume when ignition was performed (left) and no ignition was performed (right). The two curves are very similar, proving that the use of an additional outlet restriction circumvents the effect of increased flow impedance that is otherwise observed when ignition was performed.

3.2.3 Development of a Computer Application to aid in Configuring a Fixed-Volume Release System

Experimental testing showed that a properly configured fixed-volume release system can provide the propellant flow condition necessary to facilitate instant start ignition in a heaterless hollow cathode. During an instant start, it is necessary that the propellant mass flow rate is sufficiently elevated until thermionic emission is established. To verify whether a proposed fixed-volume release configuration will provide the desired temporal propellant flow behavior, it is useful to model the propellant mass flow rate as a function of time for the propellant release. To streamline the process of evaluating a fixed-volume release configuration, a computer application that uses a graphical user interface (GUI) was developed in MATLAB. A screen-capture of this computer application is shown in Figure 3.9. To use the application, the user must select a propellant gas species or manually enter the heat capacity ratio, molar mass, and temperature of the propellant gas. Then the user must enter the parameters of the fixed-volume release, which include; volume, supply pressure, outlet flow impedance (in terms of choke diameter), and nominal flow rate. By pressing the "Perform Calculations and Generate Plot" button, the user is provided with the effective choke diameter of the inlet, the mass of the propellant charge, and a plot of the propellant mass flow rate as a function of time during a propellant release.

In the example shown in Figure 3.9, a 20 cm³ volume is initially in barometric equilibrium with a 25 psia supply of room temperature xenon. In the bottom-left of the window, the application shows that this propellant charge has a mass of approximately 180 mg. With the nominal cathode flow rate selected to be 2.50 sccm, the effective choke diameter of the inlet was calculated to be approximately 0.0007 inches, which is also displayed in the bottom-left of the window. The plot in the right-hand panel of the application shows the predicted propellant mass flow rate as a function of time during a propellant release through a 0.005 inch diameter outlet. These parameters are representative of a fixed-volume release system that could be used to facilitate instant start ignition in a 6.4 mm (0.25 inch) diameter heaterless hollow cathode.

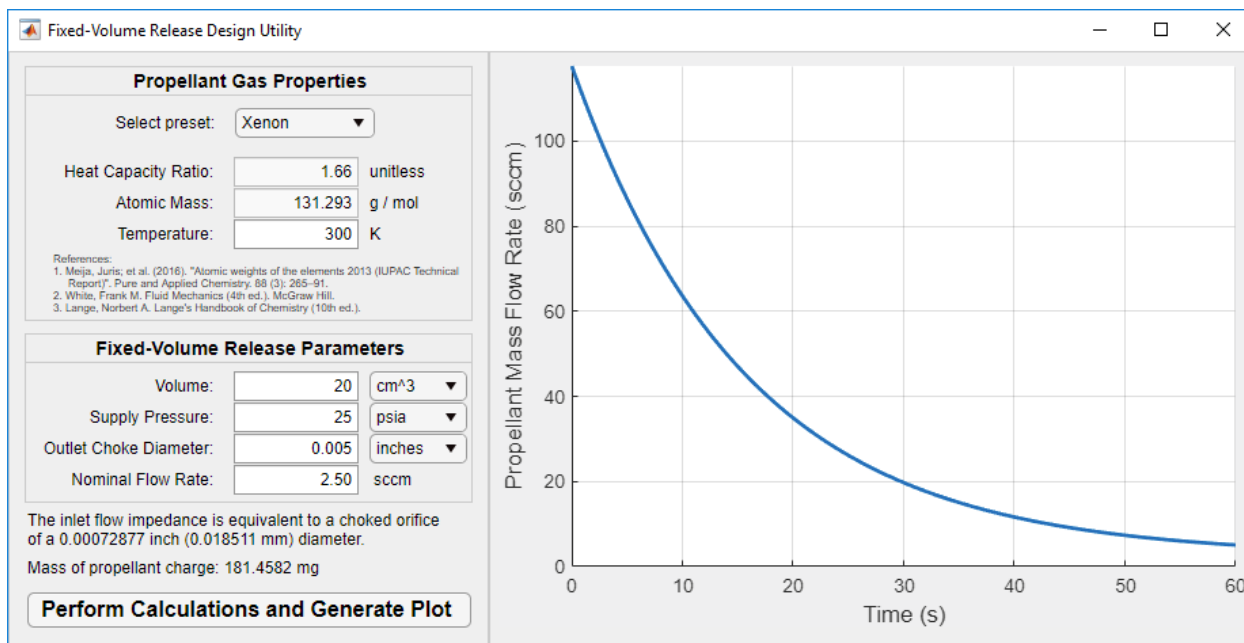


Figure 3.9: The graphical user interface (GUI) of the fixed-volume release design utility.

While the computer application shows the temporal flow behavior of a propellant release, it does not indicate whether the flow condition will be satisfactory for instant start ignition to occur in a particular heaterless hollow cathode assembly. It is presumed that the user of the application has some understanding of the of the propellant flow conditions required to facilitate ignition in the heaterless hollow cathode assembly of interest. When this is the case, the application is a useful tool to quickly determine a fixed-volume release configuration that could be used in a propellant feed system. To use this application, an installation file can be downloaded from the URL: *projects-web.engr.colostate.edu/CEPPELab/FVR_Utility_Installer.exe*. For those with access to MATLAB, an abridged script that provides similar functionality may be found in appendix A. The complete MATLAB code for the GUI application is provided in appendix B.

3.3 Results and Discussion

When using a properly configured fixed-volume release system, an instant start behavior is achieved in which a high-current, low-voltage discharge is established immediately after ignition is initiated. In performing ignition tests with the above described 3.2 mm diameter heaterless hollow

cathode, it was found that the fixed-volume release was capable of providing the flow conditions necessary to facilitate reliable instant start ignitions at a minimal bias for both krypton and xenon propellants. With xenon, approximately 17 mg of propellant was required to facilitate instant start ignition using a 375 V bias. With krypton, instant start ignition could be achieved with a 300 V bias by using approximately 13 mg of propellant. In either case, over 10,000 hollow cathode ignitions could be performed with 200 g or less of propellant.

When performing instant start ignition with a fixed-volume release system, the electrical behavior was highly repeatable and decoupling was not observed. Figure 3.10 shows the voltage and current flow between the cathode and keeper electrodes during an ignition test that was initiated with a room-temperature cathode. In this example, a 375 V bias was applied between the cathode and keeper. At time $t=0$, the valve of the fixed-volume release was opened, and a 17 mg charge of xenon propellant was released through the hollow cathode. At this time, the ignition of a plasma arc discharge is evidenced by the sudden rise in current and simultaneous drop in voltage that occurs. We believe that this instant start ignition behavior is desirable in a spaceflight system because the implementation of more complex electronic schemes are not necessary. Furthermore, the fixed-volume release system facilitates the instant start ignition process in a manner that requires only a small amount of additional propellant.

A fixed-volume release system is highly versatile and can be modified to produce a wide range of temporal propellant flow behaviors. Further versatility is granted by including a flow restrictor between the shut-off valve and the hollow cathode. By adjusting the propellant charge pressure, the size of the fixed-volume, and the flow impedance of the outlet, a fixed-volume release system can be tailored to suit the propellant flow needs of a wide range of heaterless hollow cathode assemblies.

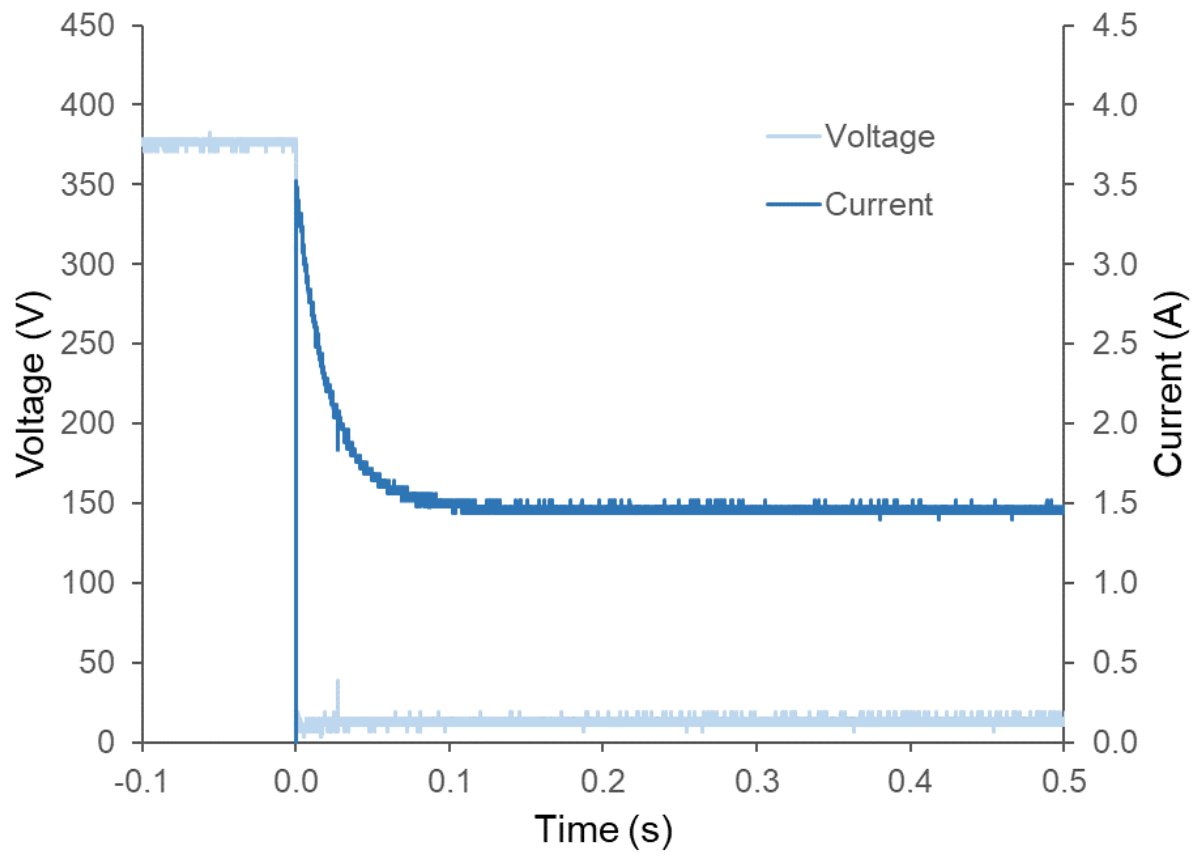


Figure 3.10: Keeper voltage and current waveforms during an instant start ignition that was facilitated by a fixed-volume release system.

Chapter 4

Investigation of Ignition Erosion

In the previously completed experiments, it was found that an instant start ignition behavior could be achieved reliably in a heaterless hollow cathode by providing a high propellant mass flow rate during the ignition process (propellant mass flow on the order of 10x the nominal rate). While the reliability and simplicity of this instant start ignition process are desirable traits for spaceflight applications, there remains to be a concern that the ignition process could cause the cathode to erode, introducing a possible failure mode that would be unique to heaterless hollow cathodes. To better understand and quantify heaterless ignition erosion, an experiment was developed to perform a large number of ignition cycles in an automated fashion. Afterwards, the cathodes were examined to determine the extent by which the instant start ignition process may have damaged or altered the cathode.

It is generally believed that an electrical discharge of several amperes or more, when driven between cold electrodes in either gas or vacuum, is made possible by cathodic arc spots that form on the cathode surface [26]. This supports the hypothesis that an instant start process in a heaterless (i.e. cold) hollow cathode will involve cathodic arc activity. During a cathodic arc, a small area of a cathode surface is vaporized and the cathode material itself is ionized, enabling the electrical discharge. During the time that a cathodic arc is burning, cathode mass is lost through both vaporization and the ejection of macroparticles. A cathodic arc emission site (often referred to as a spot) is known to move along the cathode surface as a function of time. This leaves behind a distinctive chain of craters, each on the order of 1 to 10 micrometers in diameter [25, 26]. Figure 4.1 shows an example of a microscope image of cathodic arc erosion craters [42].

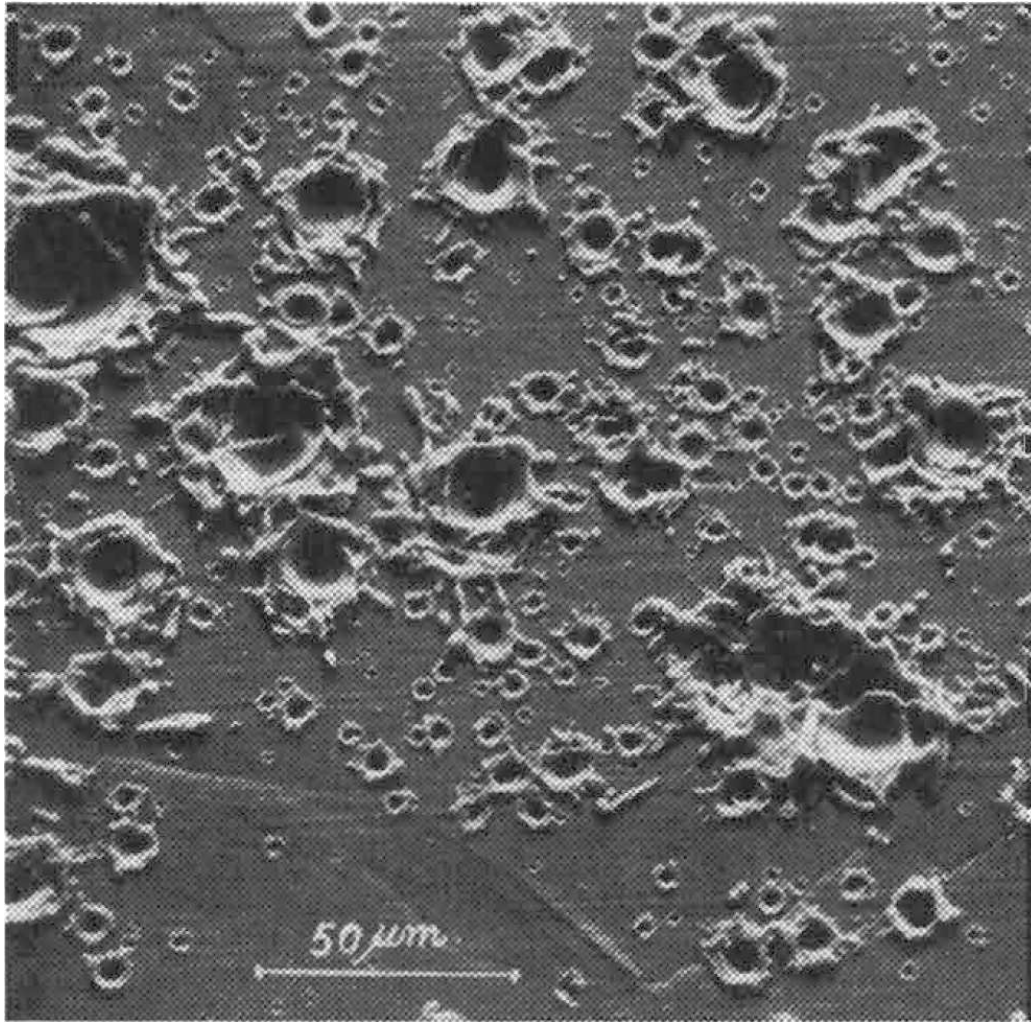


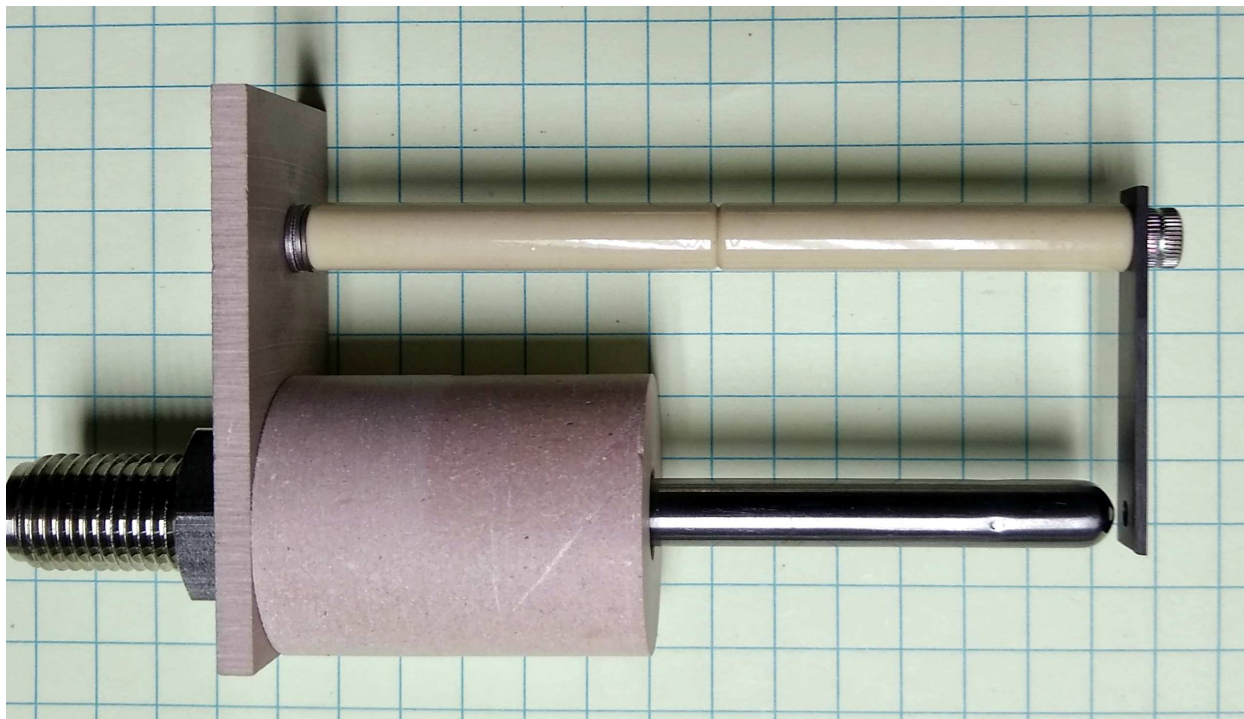
Figure 4.1: An example microscope image of cathodic arc erosion craters caused by a 10 ampere cathodic arc [42].

The erosive nature of a cathodic arc would lead one to believe that; if cathodic arc emission is involved in the heaterless ignition process, then a heaterless hollow cathode could be expected to suffer from altered performance or premature failure after being subject to a large number of ignition cycles. To investigate heaterless hollow cathode ignition erosion phenomena, a straightforward experimental approach was taken in which newly manufactured cathodes were subject to a large number of heaterless ignition cycles before being examined for evidence of erosion. In these tests, a fixed-volume release system was used to facilitate the instant start ignition process.

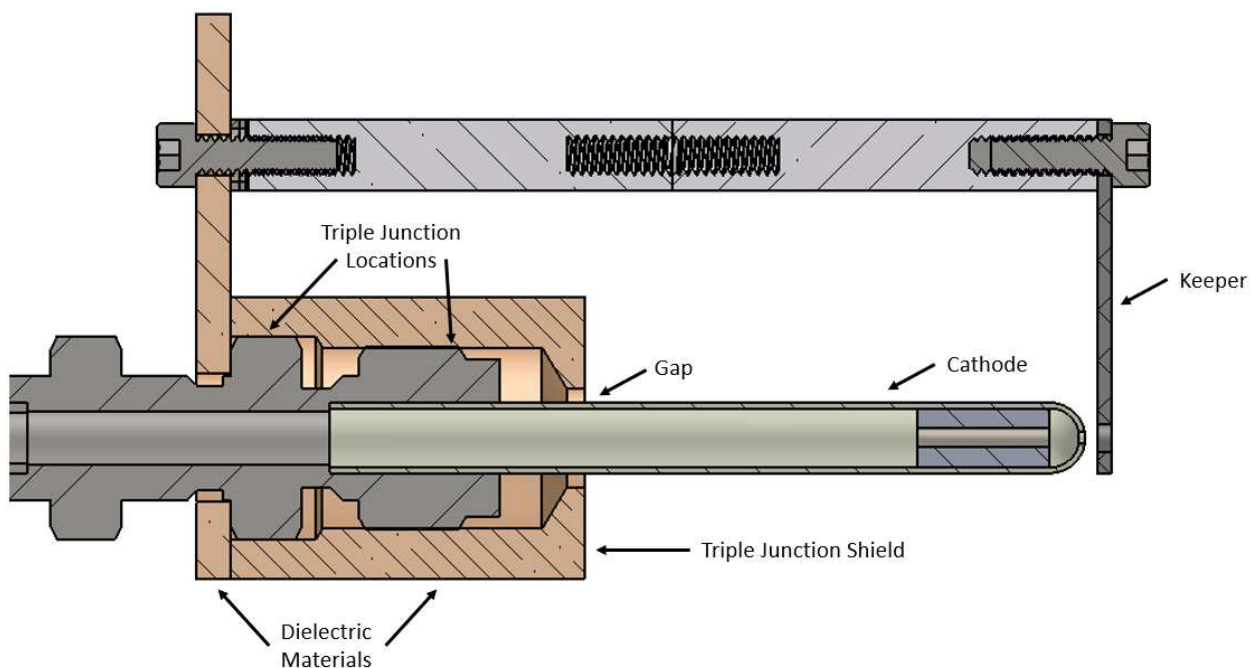
4.1 Hollow Cathode Assembly

A heaterless hollow cathode assembly was designed specifically for this experimental campaign. In this assembly, the cathode tube diameter was selected to be 6.4 mm (0.25 inch) in diameter. The most notable feature of the assembly is its simple, open keeper design. Although an open keeper is not fully representative of a state-of-the-art spaceflight hollow cathode assembly, and a higher flow rate is needed to produce a given gas pressure between the cathode and keeper, this design was chosen for several reasons. First, an open keeper grants much greater accessibility in the attachment of thermocouples. Second, the open keeper allows the cathode to radiate heat to cool surroundings, (facility walls rather than a relatively high temperature enclosure), resulting in a considerably shortened cool down duration. Finally, this design allows for the cathode and keeper electrodes to be easily replaced with new, unused components.

A triple junction shield was included in this hollow cathode assembly to prevent arc activity from occurring near triple junction locations during heaterless ignition. A triple junction is the interface formed at the location that a conductor, a dielectric, and vacuum meet. There are several mechanisms that may lead to electric field enhancement at a triple junction, which could result in the formation of an electric arc near negatively charged triple junctions [32, 33]. The triple junction shield is a dielectric sleeve that blocks line-of-sight between the keeper electrode, and triple junctions formed with the cathode. This prevents the triple junction(s) from being exposed to the electric field formed between the cathode and keeper, thus eliminating the possibility of triple junction field enhancement effects that could cause undesirable discharge activity during heaterless ignition. A photograph of the heaterless hollow cathode assembly is shown in Figure 4.2, along with a schematic that includes labels to describe the functionality of the triple junction shield.



(a) Photo of the heaterless hollow cathode assembly used to evaluate cathode ignition erosion.



(b) Cross-section schematic of the heaterless hollow cathode assembly. Triple junction locations are shielded from the view of the keeper electrode by a triple junction shield.

Figure 4.2: Photo and schematic of the heaterless hollow cathode assembly that was used in the ignition erosion investigation.

4.2 Ignition Cycle Test Protocol

Given the highly repetitive nature of this experiment, a computer program was developed to automate the sequence and perform the operations necessary to ignite a heaterless hollow cathode. In these tests, a fixed-volume release system was used to provide the propellant flow necessary for instant start ignition. Because the fixed-volume release system only requires the actuation of a single shut-off valve, a relatively simple test protocol could be used for each ignition cycle.

To begin an ignition cycle, a bias voltage was applied between the cathode and keeper electrodes of the heaterless hollow cathode assembly. Next, the shut-off valve of the fixed-volume release system would be opened, releasing propellant gas through the hollow cathode and enabling ignition of a plasma discharge. During the first 10 seconds after the opening of the valve, the discharge current and voltage of the power supply would be monitored to verify that ignition had occurred successfully. If a failed ignition was detected, the test sequence would be terminated. After operating the cathode for a pre-determined period of time, the discharge would be switched off and the shut-off valve closed. Before initiating the next ignition cycle, the cathode would be allowed to cool to a low temperature while the fixed-volume release system was re-pressurized.

4.2.1 Selecting Warmup and Cooldown Durations

To acquire pertinent data in this experiment, it was important to ensure that the cathode undergo a complete thermal cycle each time an ignition was performed. To determine the duration of the warmup and cooldown phases, a type-C thermocouple was attached to the outside of the cathode tube near the emitter region. This thermocouple allowed for the cathode temperature to be recorded as a function of time during the warmup phase of ignition, and the cooldown phase that occurred after switching off the discharge. In these tests, the current limit on the power supply was set to 2.5 amperes. At this operating condition, the thermocouple indicated a temperature of approximately 725 °C during steady state operation. At the same operating condition, an optical pyrometer was used and a temperature of approximately 850°C was measured at a location near the thermocouple. The lower temperature indicated by the thermocouple was attributed the lack of radiation shielding

at the thermocouple attachment location. It is believed that radiation cooling of the thermocouple caused lower than expected temperature readings that do not directly represent the temperature of the cathode tube or the emitter. Despite the suspected measurement error, the data collected with the thermocouple remained valuable because they revealed the temporal thermal behavior of the cathode.

Figure 4.3 shows the indicated thermocouple temperature as a function of time for the warmup and cool down phases. The dip in temperature observed at approximately 40 seconds was repeatable in all of the tests performed. The cause of this behavior was not verified, but we suspect that it may correspond with the activation of the emitter and an associated shift to thermionic emission. The results indicate that a relatively steady temperature is reached within 120 seconds after ignition, and that a relatively low temperature of 100 °C is reached 8 to 10 minutes after the discharge is switched off. While the thermocouple is believed to read low when measuring high temperatures, the relatively low rate of radiation heat transfer at lower temperatures is judged to result in a reading that more closely represents the temperature of the cathode tube and emitter.

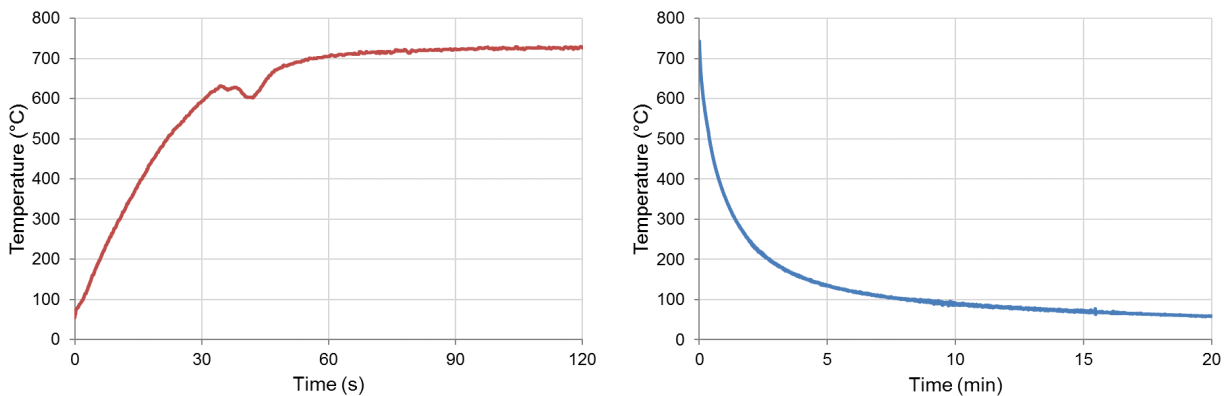


Figure 4.3: Temperature near the cathode tip during warmup and cooldown. During ignition, a relatively steady temperature is reached within 120 seconds. After switching off the discharge, the cathode cools to below 100 °C within 10 minutes.

To verify that a 2-minute warmup and a 10-minute cooldown would be appropriate throughout the course of a long-duration test sequence, temperature data were recorded during a series of automated ignition cycles. These data, shown in Figure 4.4, reveal that the aforementioned warmup

and cooldown durations allow for the temperature of the cathode to consistently drop below 80 °C before each ignition is initiated. This temperature is considered appropriate for heaterless ignition testing because it is well below the thermionic emission temperature of the cathode material(s). The transient behavior of the first several cycles can likely be attributed to heating of the cathode mounting fixture. The data suggest that these components become thermally saturated within the first 10 ignition cycles. After this analysis was completed, thermocouples were not used in subsequent testing due to concerns that they could participate in the ignition process, which could interfere with or alter the results.

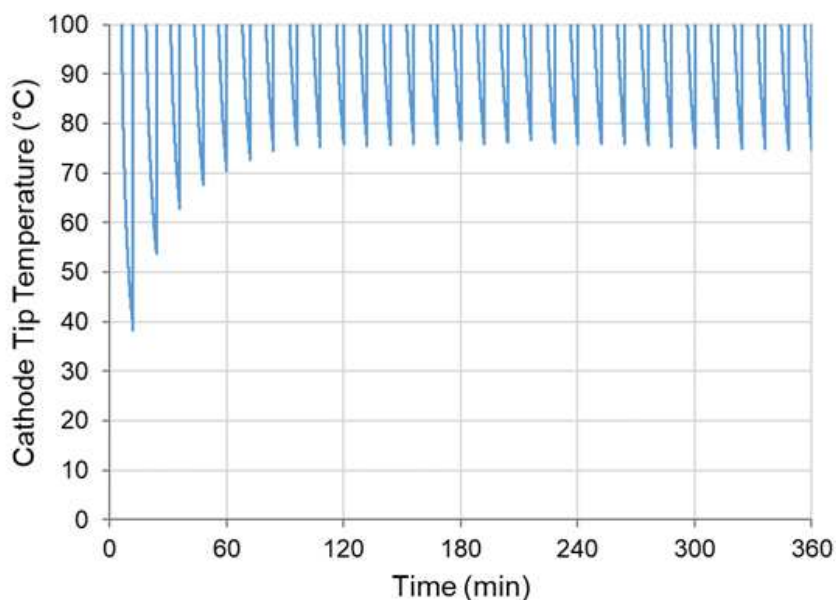


Figure 4.4: Temperature of the cathode tip as a function of time during the first 30 ignition cycles of a test sequence. The y-axis is scaled so that the minimum temperatures are clearly visible. While evidence of gradual warming is seen in the first several cycles, the temperature consistently drops to below 80 °C throughout the test.

While 10 minutes was determined to be an adequate cooldown duration, it was also necessary to verify that the fixed-volume release system would be charged to a sufficient pressure in this time. This was verified by measuring the pressure in the fixed-volume release system as a function of time. Using a supply pressure and inlet flow impedance identical to what was later used in the long-duration testing, it was found that the fixed-volume would charge to approximately

95% of the supply pressure in 10 minutes. At this slightly reduced charge pressure, the propellant flow rate was still sufficient for facilitating instant start ignition. Throughout long-duration test sequences, fixed-volume pressure data showed very consistent, repeatable propellant release behavior. By measuring the rate of change of pressure in the fixed-volume release system, the transitory propellant mass flow rate through the cathode could be calculated. Figure 4.6 shows the typical propellant flow as a function of time during each ignition cycle. Time $t=0$ represents the opening of the shut-off valve, which corresponds to the initiation of the instant start ignition.

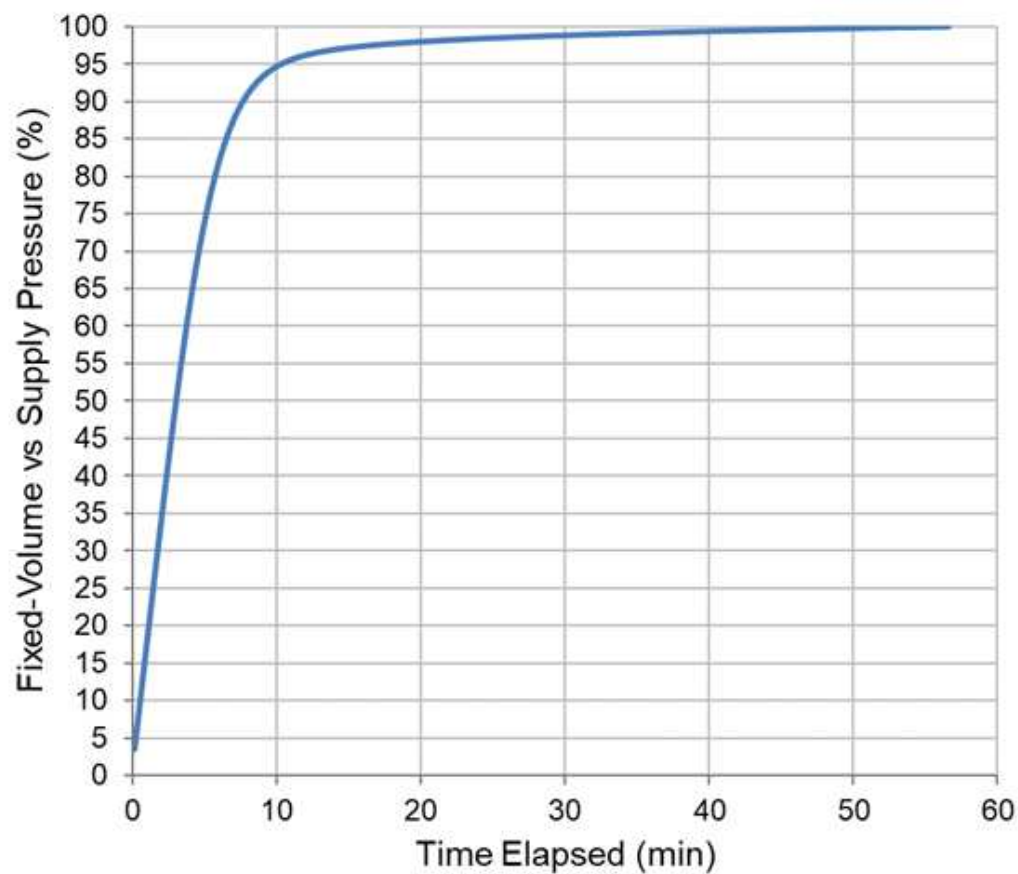


Figure 4.5: Fixed-volume pressure as a function of time after the shut-off valve is closed. These data show that the propellant pressure reaches approximately 95% of the supply pressure in 10 minutes.

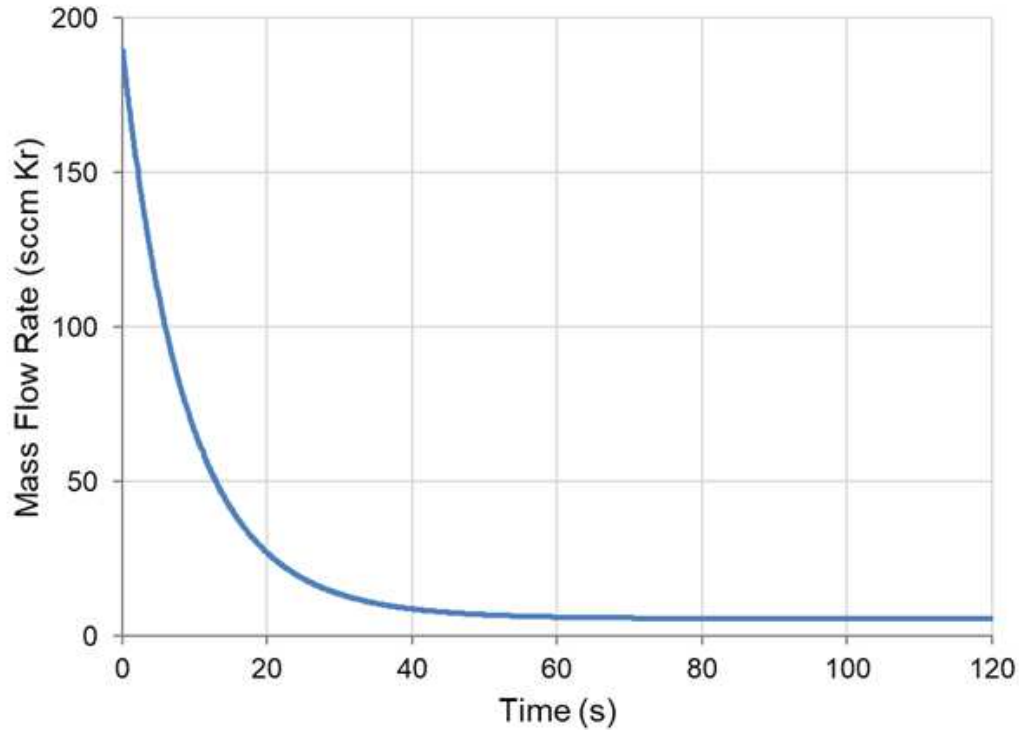


Figure 4.6: Propellant mass flow rate as a function of time during a typical ignition during the ignition erosion test sequences.

Each test sequence was performed with a newly manufactured, previously unoperated, heater-less hollow cathode. When beginning a new test sequence, the first ignition would be followed by operation for an extended period of time. By operating the cathode for 60 minutes, the hollow cathode emitter was given an opportunity to condition. This was done to avoid anomolous behavior that could have ocured as a result of using an unconditioned cathode emitter. It was suspected that operation for 60 minutes would result in the heating of the cathode fixture and surroundings to a temperature greater than what would normally be encountered in the cycle testing. After the 60-minute operation of the hollow cathode was completed, the system was allowed to cool for at least one hour before the remaining ignition cycles were performed using the previously described 12-minute cycle duration.

4.3 Results

Using the protocol described above, a test sequence was performed in which a cathode was subjected to 1000 heaterless ignition cycles using krypton gas. This test sequence was completed without interruption. This cathode was then compared with a newly manufactured, unoperated cathode to compare features and assess cathode erosion. Throughout this investigation, cathodic arc activity was considered to be the erosion mechanism most pertinent to the heaterless ignition process. A relatively straightforward approach to identifying cathodic arc activity is to use a microscope to search for erosion craters that are left behind by a cathodic arc. These craters are formed when a small spot of cathode material is vaporized in the cathodic arc process. An example of such erosion was shown in Figure 4.1.

Just before instant start ignition is initiated, the tip of the cathode tube is exposed to the largest electric field strength. The strong electric field in this location causes the cathode tip to be a likely area for a cathodic arc spot to form. A scanning electron microscope (SEM) was used to closely examine the orifice of an unoperated control sample alongside the orifice of the repeatedly ignited hollow cathode for indications of cathodic arc activity. Figure 4.7 shows images of both the control sample (left), and the sample that had undergone 1000 ignition cycles (right), at three different levels of magnification. The cathode orifice of the test sample appears relatively unchanged from its original dimensions, and no indications of cathodic arc activity are observed.

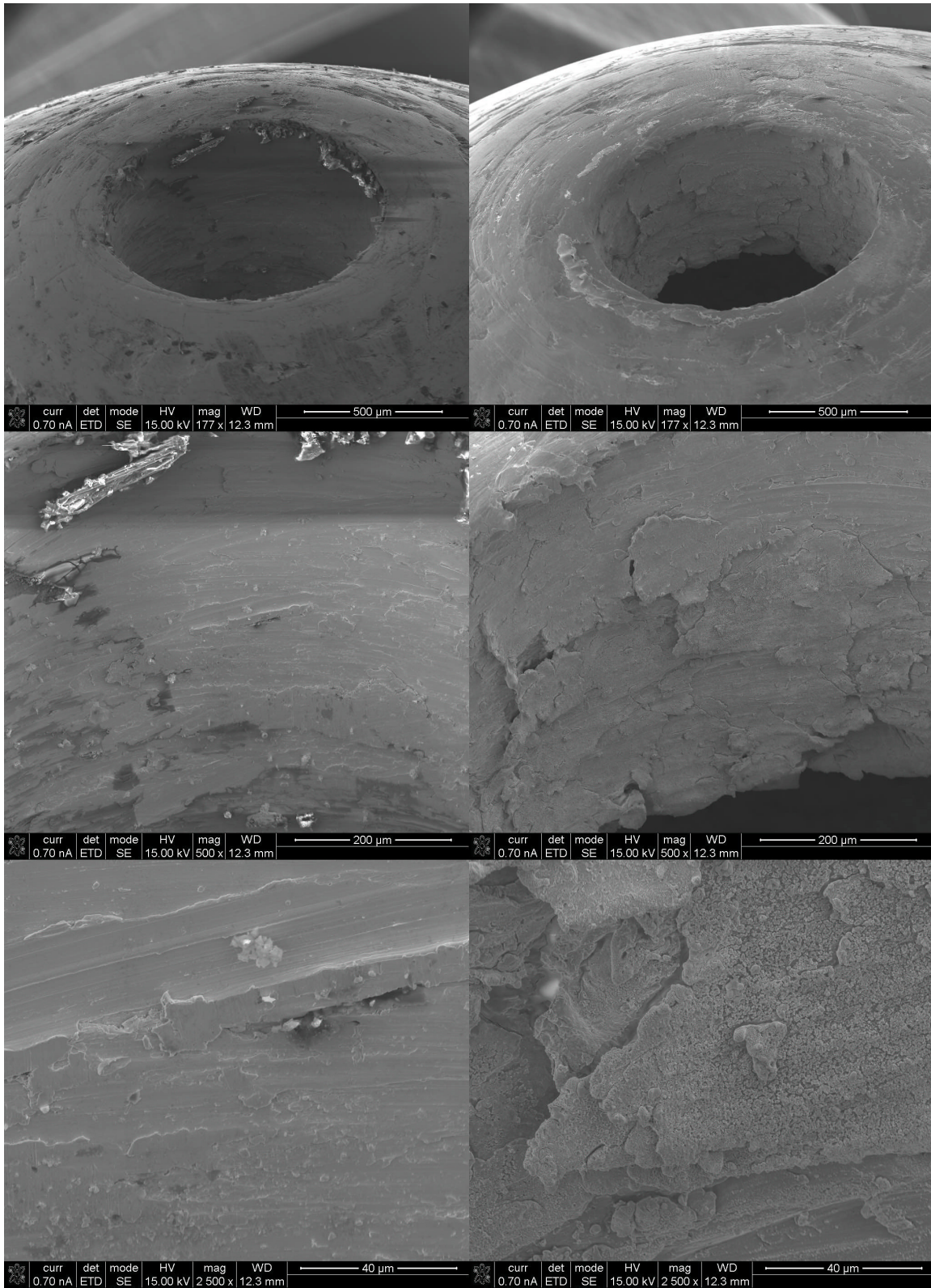


Figure 4.7: Microscope images comparing the orifices of an unoperated hollow cathode (left images), and a hollow cathode which had undergone 1000 heaterless ignition cycles (right images). Cathodic arc erosion craters are not found, and no significant erosion is observed.

Several additional ignition cycle tests were conducted. In the longest duration test, a cathode was ignited 4500 times without interruption, after which the test was voluntarily terminated. In some of these tests, the mass of the cathode tube (including the emitter) was measured before and after the test sequence so that the amount of mass lost during the test could be determined. These data, shown in Table 4.1, show no distinct correlation between the number of ignition cycles and the amount of mass lost. While the small data set does not allow for a strong conclusion to be made, it appears that the first ignition caused a detectable amount of mass loss to occur, while subsequent ignitions did not. In all of the test sequences, ignition cycles showed very little variation in behavior and no significant visual damage or cause for reliability concerns were observed. Keeper voltage and current waveforms for a typical ignition event are shown in Figure 4.8, revealing the desirable instant start ignition behavior.

Table 4.1: Cathode mass loss for several test sequences.

# of Ignitions	Mass Loss (mg)	Gas Species
1	2.2	Xenon
1	2.9	Krypton
200	2.2	Xenon
2000	2.4	Xenon
4500	1.8	Krypton

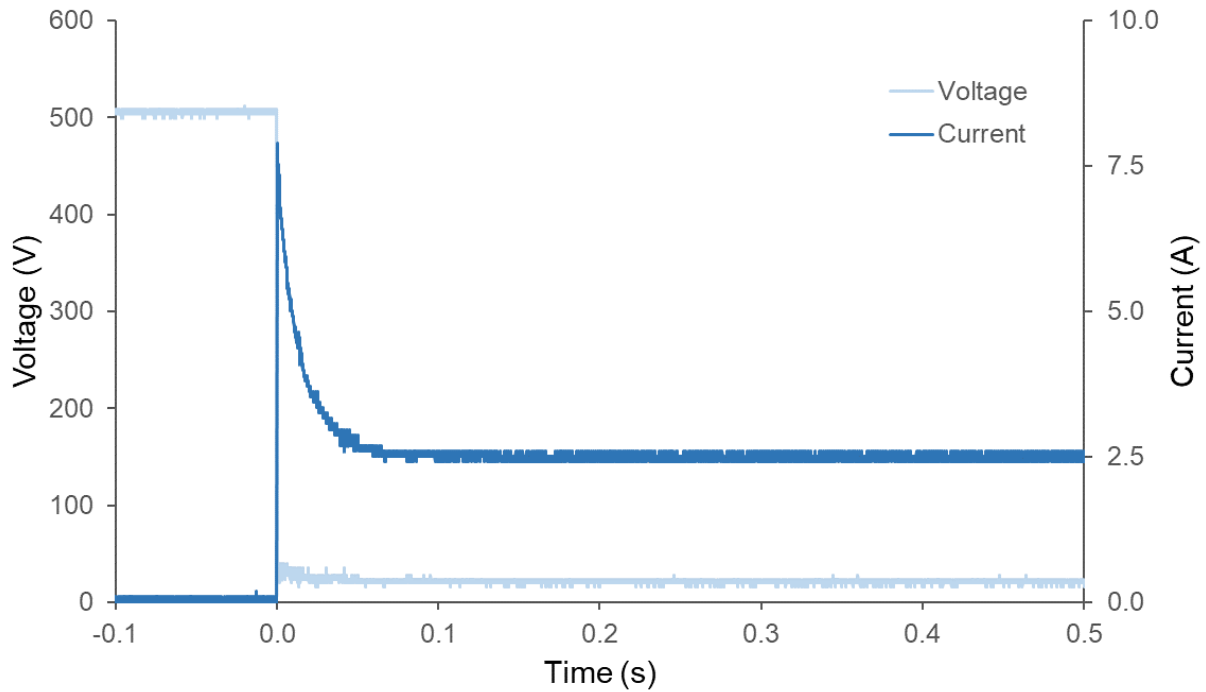


Figure 4.8: Typical keeper voltage and current waveforms measured during an instant start ignition of a long-duration repeated ignition cycle test.

4.4 Discussion - The Instant Start Emission Mechanism

Given the low initial temperature of the cathode and the lack of cathodic arc activity, it can be concluded that thermionic and cathodic arc emission are not participating in the instant start ignition process. This implies that another discharge mechanism must be facilitating the several amperes of electron emission during the warmup phase, which begins with the initiation of the plasma discharge and ends when the discharge transitions to a thermionic arc. No such cold cathode discharge scheme is described in plasma discharge literature.

In this research, it was found that to achieve instant start ignition behavior, it is necessary that the hollow cathode be supplied with a very high propellant mass flow rate for a period of time. It can be assumed that this flow condition would result in an unusually large neutral density inside the cathode and between the cathode and keeper electrodes during the ignition process. Additionally, to prevent decoupling during ignition, it was necessary to drive a relatively large keeper current

(i.e. 2.5 ampere, rather than 1.0 ampere). This leads to a hypothesis that most, if not all, of the discharge current is facilitated by collisional ionization inside the cathode or in the volume between the electrodes. The liberated electrons could then flow from this volume to the keeper, while the ions that are produced could flow to the cathode. Upon impinging the cathode, these ions would be neutralized by electrons from the cathode. Additionally, impinging ions could produce additional free electrons through secondary electron emission. During the ion bombardment and recombination processes, thermal energy is transferred to the cathode surfaces at a high rate. As the cathode is heated and its temperature rises, thermionic emission of electrons begins to contribute to the discharge. When this ignition process is completed, the propellant mass flow rate can be reduced to a normal level for hollow cathode operation.

Chapter 5

Conclusions Drawn From this Work

In contrast with conventional heater-utilizing hollow cathodes, heaterless hollow cathodes exhibit considerably more demanding ignition conditions. In general, heaterless ignition requires that an elevated propellant mass flow rate be used along with a high bias voltage between the cathode and keeper electrodes. To integrate a heaterless hollow cathode in an electric propulsion thruster, it will be necessary that the propellant feed system and power processing unit (PPU) are capable of providing the flow and bias conditions that are necessary to ignite a plasma arc discharge within the hollow cathode assembly. However, in the small-satellite propulsion systems for which heaterless hollow cathodes are being developed, it is undesirable and possibly prohibitive to implement advanced PPU and feed system hardware to accommodate these ignition requirements. To adapt heaterless hollow cathode technology to these systems, there is a need for a solution that enables reliable heaterless ignition behavior with minimal impact to the overall size, mass, and reliability of the propulsion system.

In characterizing the ignition behavior of a heaterless hollow cathode, erratic electrical activity between the cathode and keeper electrodes was often observed and experimental repeatability was very poor in some cases. It was found that the least erratic, most repeatable ignition behavior was achieved when using a very high propellant mass flow rate along with a relatively large keeper current during ignition. To provide this flow condition, a simple propellant flow mechanism was conceived that temporarily produces a significantly elevated propellant mass flow rate using only a small mass of additional propellant. This mechanism, called a fixed-volume release system, consists of very simple, low-risk components that would introduce minimal additional complexity to an electric propulsion propellant feed system. Testing showed that properly configured fixed-volume release systems could provide temporal flow conditions that enabled reliable instant start ignitions in 3.2 mm and 6.4 mm diameter heaterless hollow cathodes. A fixed-volume release system could be configured to suit a wide range of heaterless hollow cathode assemblies.

It was additionally shown that the instant start ignition behavior facilitated by a fixed-volume release does not cause considerable erosion, damage, or mass reduction of the cathode. This finding is significant because it shows that this approach to heaterless ignition does not limit the lifetime of the hollow cathode. No evidence of cathodic arc activity was detected after 1000 and 4500 ignition cycles were performed. It is possible that a volumetric ionization process provides up to 100% of the discharge current during the early stages of an instant start ignition. As the plasma quickly heats the cathode, thermionic emission of electrons begins to occur. This process is relatively simple to facilitate, and it overcomes the ignition difficulties that are faced when a cathode heater is not used. The high reliability, repeatability and the absence of erosion observed when using this ignition scheme suggests that heaterless hollow cathodes may be suitable for spaceflight applications.

5.1 Future Work

It is my hope that this thesis will serve as a starting point for future efforts to further study and characterize the ignition process in heaterless hollow cathodes. One such follow-on study could involve the ignition testing of heaterless hollow cathodes using a variety of cathode materials. While instant start ignition behavior has shown to be promising in regard to low propellant mass requirements, relatively low initial voltage, and minimal to no erosion; it should be noted that the hollow cathodes used in this research were all similarly manufactured with a tantalum cathode tube and a barium-based emitter. For the findings presented in this thesis to be applied to a wider range of hollow cathode designs, it will be necessary to assess alternative cathode tube and emitter materials to determine whether similar results are observed. It may also be valuable to further investigate the ignition process through the use of various plasma diagnostics or high speed camera imaging. Regarding electrical hardware, it is likely that a spaceflight keeper power supply will behave differently than the laboratory power supplies that were used throughout this research. To integrate heaterless hollow cathodes into spaceflight systems, it may be necessary to develop and test a flight-like keeper power supply that exhibits desirable electrical behavior during the heaterless ignition process. Additionally, by studying the necessary propellant mass flow rate as

a function of time in greater detail, it may be possible to reduce the amount of propellant mass required to facilitate the instant start ignition process. For example, a fast acting piezo-electric gas valve could be used to quickly vary the propellant mass flow rate as a function of time, producing an optimal temporal flow behavior. In this research, it was shown that instant start ignition behavior is more commonly observed when a large propellant mass flow rate is provided and a relatively high keeper current is maintained. As stated previously, the initial moments of the instant start ignition process are thought to rely heavily upon ion production and consequent ion current. To test this hypothesis, a model could be developed to theoretically show whether this process could, in fact, facilitate the discharge while the cathode is being heated. Additionally, this model would likely reveal the reasons why a large neutral gas density and large discharge current are necessary during the instant start ignition process. The model could be based upon energy-balance concepts that are used in zero-dimensional hollow cathode models [1, 43–45]. By comparing the model predictions with experimental data, the physics involved in heaterless ignition may be better understood, which could guide future optimization of the ignition process.

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Appendix A

MATLAB Script for Modeling the Propellant Flow Behavior Produced by a Fixed-Volume Release System

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Ryan Ham
%Fixed-Volume Release Application (No user interface)
%For more information, see: Ham, RK 2020, 'An Experimental Investigation of
%Heaterless Hollow Cathode Ignition', MS Thesis, Colorado State University,
%Fort Collins.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clearvars;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% USER INPUT VARIABLES %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Volume = 20; %cubic centimeters
SupplyPressure = 25; %psia
InletFlow = 2.5; %sccm
OutletDiameter = .005; %inches
HeatCapacityRatio = 1.66; %xe = 1.66; kr = 1.68
atomic_mass = 131.293; %xe = 131.293 g/mol; kr = 83.798 g/mol
Temperature = 300; %Kelvin

duration = 240; %length of model (s)
timeStep = .001; %duration of each step (s)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

V = Volume * 1e-6; %convert from cm^3 to m^3
pressure(1) = (SupplyPressure / 14.6959) * 101325; %convert from psia to Pa
gamma = HeatCapacityRatio; %xe = 1.66; kr = 1.68
T = Temperature;
time=linspace(0,duration,duration/timeStep);

%calculate sccm to kg/s conversion factor; 1.02e7 for xe and 1.61e7 for kr
sccm_per_kgs = 60/(26867805000000000000*atomic_mass*1.66053906660e-27);

%calculate gas specific gas constant; 63.33 for Xe and 99.22 for kr
R = 8.31446261815324 / (atomic_mass/1000);

A_inlet = 1/((pressure(1)/(sqrt(T)*(InletFlow/sccm_per_kgs)))*...
    sqrt(gamma/R)*((gamma+1)/2)^(-1*((gamma+1)/(2*(gamma-1)))));
InletDiameter = sqrt(A_inlet/pi())*2*1000/25.4;
disp(strcat('Inlet diameter (inch):',{ ' ' }, num2str(InletDiameter)));
A_outlet = pi()*((OutletDiameter * 25.4 / 1000)/2)^2;
```

```

%inlet flow is calculated in kg/s(assuming choked flow)
inflow = (A_inlet*pressure(1)/sqrt(T))*sqrt(gamma/R)*...
    ((gamma+1)/2)^(-1*((gamma+1)/(2*(gamma-1))));

%initial propellant mass and pressure
pressure(1) = pressure(1);
mass(1) = (pressure(1)*V)/(R*T);
disp(strcat('Propellant Charge Mass (mg):',{ ' ' },...
    num2str(mass(1)*1000000)));

%initial outlet flow is calculated
flowrate_kgs(1) = (A_outlet*pressure(1)/sqrt(T))*sqrt(gamma/R)*...
    ((gamma+1)/2)^(-1*((gamma+1)/(2*(gamma-1))));

%iteratively solve for mass flow for each time step in time domain
for (i=2:(duration/timeStep))
    mass(i) = mass(i-1) - flowrate_kgs(i-1) * timeStep + inflow * timeStep;
    pressure(i) = mass(i)*R*T / V;
    flowrate_kgs(i) = (A_outlet*pressure(i)/sqrt(T))*sqrt(gamma/R)*...
        ((gamma+1)/2)^(-1*((gamma+1)/(2*(gamma-1))));
end

flowrate_sccm = flowrate_kgs * sccm_per_kgs;

% Plot the modeled flow as a function of time
plot(time, flowrate_sccm,'LineWidth',2);
xlabel('time (s)');
ylabel('Propellant Mass Flow Rate (sccm)');
xlim([0 60]);
ylim([0 inf]);
grid on;

```

Appendix B

MATLAB Code for the Fixed-Volume Release GUI

Application

```
classdef FVR_Designer_Utility < matlab.apps.AppBase

    % Properties that correspond to app components
    properties (Access = public)
        FVR_UtilityUIFigure          matlab.ui.Figure
        GridLayout                    matlab.ui.container.GridLayout
        LeftPanel                     matlab.ui.container.Panel
        FixedVolumeReleaseParametersPanel  matlab.ui.container.Panel
        VolumeLabel                   matlab.ui.control.Label
        VolumeEditField               matlab.ui.control.NumericEditField
        DropDown_Pressure             matlab.ui.control.DropDown
        SupplyPressureEditFieldLabel  matlab.ui.control.Label
        SupplyPressureEditField       matlab.ui.control.NumericEditField
        DropDown_Outlet              matlab.ui.control.DropDown
        OutletChokeDiameterEditFieldLabel  matlab.ui.control.Label
        OutletChokeDiameterEditField  matlab.ui.control.NumericEditField
        NominalFlowRateEditFieldLabel matlab.ui.control.Label
        NominalFlowRateEditField     matlab.ui.control.NumericEditField
        DropDown_Volume              matlab.ui.control.DropDown
        sccmLabel                     matlab.ui.control.Label
        PropellantGasPropertiesPanel  matlab.ui.container.Panel
        HeatCapacityRatioLabel        matlab.ui.control.Label
        HeatCapacityRatioEditField    matlab.ui.control.NumericEditField
        AtomicMassEditFieldLabel      matlab.ui.control.Label
        AtomicMassEditField           matlab.ui.control.NumericEditField
        TemperatureEditFieldLabel     matlab.ui.control.Label
        TemperatureEditField          matlab.ui.control.NumericEditField
        unitlessLabel                 matlab.ui.control.Label
        gmolLabel                     matlab.ui.control.Label
        KLabel                         matlab.ui.control.Label
        SelectpresetDropDownLabel     matlab.ui.control.Label
        GasPresetDropDown             matlab.ui.control.DropDown
        Label                         matlab.ui.control.Label
        GeneratePlotButton            matlab.ui.control.Button
        Label1                        matlab.ui.control.Label
        Label2                        matlab.ui.control.Label
        Label3                        matlab.ui.control.Label
        RightPanel                    matlab.ui.container.Panel
        ModelPredictionUIAxes         matlab.ui.control.UIAxes
    end

    % Properties that correspond to apps with auto-reflow
    properties (Access = private)
```

```

onePanelWidth = 576;
end

% Callbacks that handle component events
methods (Access = private)

% Button pushed function:
% GeneratePlotButton
function GeneratePlotButtonPushed(app, event)
    %%%%%%%%%%%%%%%%% MODEL PARAMETERS %%%%%%%%%%%%%%%
    duration = 240; %length of model (s)
    timeStep = .001; %duration of each step (s)
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    %When the "Generate Plot" button is pressed, first all input
    %values are stored.
    if strcmp(app.DropDown_Volume.Value, 'cm^3') %cm^3 is selected
        %convert input from cm^3 to m^3
        V = app.VolumeEditField.Value * 1e-6;
    elseif strcmp(app.DropDown_Volume.Value, 'in^3') %in^3 is selected
        %convert input from in^3 to m^3
        V = app.VolumeEditField.Value * 61023.7;
    end
    if strcmp(app.DropDown_Pressure.Value, 'psia') %psia is selected
        %convert input from psia to Pa
        pressure(1) = (app.SupplyPressureEditField.Value / ...
            14.6959) * 101325;
    elseif strcmp(app.DropDown_Pressure.Value, 'kPa') %kPa is selected
        %convert input from kPa to Pa
        pressure(1) = app.SupplyPressureEditField.Value * 1000;
    end
    if strcmp(app.DropDown_Outlet.Value, 'inches') %inches is selected
        %convert input from inches to meters
        OutletDiameter = app.OutletChokeDiameterEditField.Value * ...
            25.4 / 1000;
    elseif strcmp(app.DropDown_Outlet.Value, 'mm') %millimeters is ...
        selected
        %convert input from millimeters to meters
        OutletDiameter = app.OutletChokeDiameterEditField.Value / ...
            1000;
    end
    InletFlow = app.NominalFlowRateEditField.Value; %sccm
    gamma = app.HeatCapacityRatioEditField.Value; %unitless
    atomic_mass = app.AtomicMassEditField.Value; %g/mol
    T = app.TemperatureEditField.Value; %Kelvin

    %generate x-axis (time) values
    time=linspace(0,duration,duration/timeStep);

    %calculate sccm to kg/s conversion factor
    sccm_per_kgs = ...
        60/(26867805000000000000*atomic_mass*1.66053906660e-27);

    %calculate gas specific gas constant

```

```

R = 8.31446261815324 / (atomic_mass/1000);

%calculate area of inlet orifice as function of supply ...
    pressure and
%nominal mass flow rate
A_inlet = 1/((pressure(1)/(sqrt(T)*(InletFlow/sccm_per_kgs)))*...
    sqrt(gamma/R)*((gamma+1)/2)^(-1*((gamma+1)/(2*(gamma-1)))));
%calculate the diameter of the inlet in millimeters and inches
InletDiameter_mm = sqrt(A_inlet/pi())*2*1000;
InletDiameter_in = InletDiameter_mm/25.4;
%calculate area of the outlet orifice
A_outlet = pi()*(OutletDiameter/2)^2;

%Update GUI to show inlet choke diameter
app.Label1.Text = 'The inlet flow impedance is equivalent to a ...
    choked orifice';
app.Label2.Text = strcat('of a',{' ' ...
    '},num2str(InletDiameter_in), ' inch ...
    (' ,num2str(InletDiameter_mm), ' mm) diameter.');
```

```

%inlet flow is calculated in kg/s(assuming choked flow)
inflow = (A_inlet*pressure(1)/sqrt(T))*sqrt(gamma/R)*...
    ((gamma+1)/2)^(-1*((gamma+1)/(2*(gamma-1)))));

%initial propellant mass is calculated using ideal gas law
mass(1) = (pressure(1)*V)/(R*T);
%update GUI to show mass of propellant release
app.Label3.Text = strcat('Mass of propellant charge:',{' '}, ...
    num2str(mass(1)*1000000), ' mg');
```

```

%initial outlet flow is calculated
flowrate_kgs(1) = (A_outlet*pressure(1)/sqrt(T))*sqrt(gamma/R)*...
    ((gamma+1)/2)^(-1*((gamma+1)/(2*(gamma-1)))));

%iteratively solve for mass flow for each time step
for (i=2:(duration/timeStep))
    mass(i) = mass(i-1) - flowrate_kgs(i-1) * timeStep + ...
        inflow * timeStep;
    pressure(i) = mass(i)*R*T / V;
    flowrate_kgs(i) = ...
        (A_outlet*pressure(i)/sqrt(T))*sqrt(gamma/R)*...
        ((gamma+1)/2)^(-1*((gamma+1)/(2*(gamma-1)))));
end

%convert mass flow rate from kg/s to sccm for plot
flowrate_sccm = flowrate_kgs * sccm_per_kgs;

% Plot the modeled flow as a function of time
plot(app.ModelPredictionUIAxes, time, ...
    flowrate_sccm,'LineWidth',2);
xlim(app.ModelPredictionUIAxes,[0 60]);
ylim(app.ModelPredictionUIAxes,[0 inf]);
end
```

```

% Callback function
function DebugButtonPushed(app, event)
    app.Labell1.Text = app.DropDown_Volume.Value;
end

% Value changed function: GasPresetDropDown
function GasPresetDropDownValueChanged(app, event)
    %%%%%%%%%%%%%%%%%%%%%%%%%% REFERENCES %%%%%%%%%%%%%%%%%%%%%%%%%%
    % Meija, Juris; et al. (2016). "Atomic weights of the elements ...
    % 2013 (IUPAC Technical Report)".
    % Pure and Applied Chemistry. 88 (3): 265 91. ...
    % doi:10.1515/pac-2015-0305.
    %
    % White, Frank M. Fluid Mechanics (4th ed.). McGraw Hill.
    % Lange, Norbert A. Lange's Handbook of Chemistry (10th ed.). ...
    % p. 1524.
    %%%%%%%%%%%%%%%%%%%%%%%%%%

    value = app.GasPresetDropDown.Value;
    if strcmp(value, 'User Defined') %User Defined is selected
        app.HeatCapacityRatioEditField.Editable = true;
        app.AtomicMassEditField.Editable = true;
    elseif strcmp(value, 'Argon') %argon is selected
        app.HeatCapacityRatioEditField.Value = 1.67;
        app.AtomicMassEditField.Value = 39.948;
        app.HeatCapacityRatioEditField.Editable = false;
        app.AtomicMassEditField.Editable = false;
    elseif strcmp(value, 'Krypton') %krypton is selected
        app.HeatCapacityRatioEditField.Value = 1.68;
        app.AtomicMassEditField.Value = 83.798;
        app.HeatCapacityRatioEditField.Editable = false;
        app.AtomicMassEditField.Editable = false;
    elseif strcmp(value, 'Xenon') %xenon is selected
        app.HeatCapacityRatioEditField.Value = 1.66;
        app.AtomicMassEditField.Value = 131.293;
        app.HeatCapacityRatioEditField.Editable = false;
        app.AtomicMassEditField.Editable = false;
    end
end

% Changes arrangement of the app based on UIFigure width
function updateAppLayout(app, event)
    currentFigureWidth = app.FVR_UtilityUIFigure.Position(3);
    if(currentFigureWidth ≤ app.onePanelWidth)
        % Change to a 2x1 grid
        app.GridLayout.RowHeight = {439, 439};
        app.GridLayout.ColumnWidth = {'1x'};
        app.RightPanel.Layout.Row = 2;
        app.RightPanel.Layout.Column = 1;
    else
        % Change to a 1x2 grid
        app.GridLayout.RowHeight = {'1x'};
        app.GridLayout.ColumnWidth = {354, '1x'};
        app.RightPanel.Layout.Row = 1;
    end
end

```

```

        app.RightPanel.Layout.Column = 2;
    end
end
end

% Component initialization
methods (Access = private)

    % Create UIFigure and components
    function createComponents(app)

        % Create FVR_UTILITYUIFigure and hide until all components are ...
        % created
        app.FVR_UTILITYUIFigure = uifigure('Visible', 'off');
        app.FVR_UTILITYUIFigure.AutoResizeChildren = 'off';
        app.FVR_UTILITYUIFigure.Position = [100 100 918 439];
        app.FVR_UTILITYUIFigure.Name = 'Fixed-Volume Release Design ...
        UTILITY';
        app.FVR_UTILITYUIFigure.SizeChangedFcn = ...
            createCallbackFcn(app, @updateAppLayout, true);

        % Create GridLayout
        app.GridLayout = uigridlayout(app.FVR_UTILITYUIFigure);
        app.GridLayout.ColumnWidth = {354, '1x'};
        app.GridLayout.RowHeight = {'1x'};
        app.GridLayout.ColumnSpacing = 0;
        app.GridLayout.RowSpacing = 0;
        app.GridLayout.Padding = [0 0 0 0];
        app.GridLayout.Scrollable = 'on';

        % Create LeftPanel
        app.LeftPanel = uipanel(app.GridLayout);
        app.LeftPanel.Layout.Row = 1;
        app.LeftPanel.Layout.Column = 1;
        app.LeftPanel.Scrollable = 'on';

        % Create FixedVolumeReleaseParametersPanel
        app.FixedVolumeReleaseParametersPanel = uipanel(app.LeftPanel);
        app.FixedVolumeReleaseParametersPanel.TitlePosition = 'centertop';
        app.FixedVolumeReleaseParametersPanel.Title = 'Fixed-Volume ...
        Release Parameters';
        app.FixedVolumeReleaseParametersPanel.FontWeight = 'bold';
        app.FixedVolumeReleaseParametersPanel.FontSize = 14;
        app.FixedVolumeReleaseParametersPanel.Position = [12 106 330 125];

        % Create VolumeLabel
        app.VolumeLabel = uilabel(app.FixedVolumeReleaseParametersPanel);
        app.VolumeLabel.HorizontalAlignment = 'right';
        app.VolumeLabel.Position = [90 75 49 22];
        app.VolumeLabel.Text = 'Volume: ';

        % Create VolumeEditField
        app.VolumeEditField = ...
            uieditfield(app.FixedVolumeReleaseParametersPanel, 'numeric');
    end
end

```



```

app.VolumeEditField.Limits = [0 100000000];
app.VolumeEditField.Position = [154 75 92 22];
app.VolumeEditField.Value = 15;

% Create DropDown_Pressure
app.DropDown_Pressure = ...
    uidropdown(app.FixedVolumeReleaseParametersPanel);
app.DropDown_Pressure.Items = {'psia', 'kPa'};
app.DropDown_Pressure.Position = [254 52 72 22];
app.DropDown_Pressure.Value = 'psia';

% Create SupplyPressureEditFieldLabel
app.SupplyPressureEditFieldLabel = ...
    uilabel(app.FixedVolumeReleaseParametersPanel);
app.SupplyPressureEditFieldLabel.HorizontalAlignment = 'right';
app.SupplyPressureEditFieldLabel.Position = [42 52 97 22];
app.SupplyPressureEditFieldLabel.Text = 'Supply Pressure: ';

% Create SupplyPressureEditField
app.SupplyPressureEditField = ...
    uieditfield(app.FixedVolumeReleaseParametersPanel, 'numeric');
app.SupplyPressureEditField.Limits = [0 100000000];
app.SupplyPressureEditField.Position = [154 52 92 22];
app.SupplyPressureEditField.Value = 40;

% Create DropDown_Outlet
app.DropDown_Outlet = ...
    uidropdown(app.FixedVolumeReleaseParametersPanel);
app.DropDown_Outlet.Items = {'inches', 'mm'};
app.DropDown_Outlet.Position = [254 29 72 22];
app.DropDown_Outlet.Value = 'inches';

% Create OutletChokeDiameterEditFieldLabel
app.OutletChokeDiameterEditFieldLabel = ...
    uilabel(app.FixedVolumeReleaseParametersPanel);
app.OutletChokeDiameterEditFieldLabel.HorizontalAlignment = ...
    'right';
app.OutletChokeDiameterEditFieldLabel.Position = [8 29 131 22];
app.OutletChokeDiameterEditFieldLabel.Text = 'Outlet Choke ...
    Diameter: ';

% Create OutletChokeDiameterEditField
app.OutletChokeDiameterEditField = ...
    uieditfield(app.FixedVolumeReleaseParametersPanel, 'numeric');
app.OutletChokeDiameterEditField.Limits = [0 100000000];
app.OutletChokeDiameterEditField.Position = [154 29 92 22];
app.OutletChokeDiameterEditField.Value = 0.005;

% Create NominalFlowRateEditFieldLabel
app.NominalFlowRateEditFieldLabel = ...
    uilabel(app.FixedVolumeReleaseParametersPanel);
app.NominalFlowRateEditFieldLabel.HorizontalAlignment = 'right';
app.NominalFlowRateEditFieldLabel.Position = [29 6 110 22];
app.NominalFlowRateEditFieldLabel.Text = 'Nominal Flow Rate: ';

```

```

% Create NominalFlowRateEditField
app.NominalFlowRateEditField = ...
    uieditfield(app.FixedVolumeReleaseParametersPanel, 'numeric');
app.NominalFlowRateEditField.Limits = [0 10000000];
app.NominalFlowRateEditField.ValueDisplayFormat = '%.2f';
app.NominalFlowRateEditField.Position = [154 6 92 22];
app.NominalFlowRateEditField.Value = 2.5;

% Create DropDown_Volume
app.DropDown_Volume = ...
    uidropdown(app.FixedVolumeReleaseParametersPanel);
app.DropDown_Volume.Items = {'cm^3', 'in^3'};
app.DropDown_Volume.Position = [254 75 72 22];
app.DropDown_Volume.Value = 'cm^3';

% Create sccmLabel
app.sccmLabel = uilabel(app.FixedVolumeReleaseParametersPanel);
app.sccmLabel.Position = [257 6 33 22];
app.sccmLabel.Text = 'sccm';

% Create PropellantGasPropertiesPanel
app.PropellantGasPropertiesPanel = uipanel(app.LeftPanel);
app.PropellantGasPropertiesPanel.TitlePosition = 'centertop';
app.PropellantGasPropertiesPanel.Title = 'Propellant Gas ...
    Properties';
app.PropellantGasPropertiesPanel.FontWeight = 'bold';
app.PropellantGasPropertiesPanel.FontSize = 14;
app.PropellantGasPropertiesPanel.Position = [12 240 330 188];

% Create HeatCapacityRatioLabel
app.HeatCapacityRatioLabel = ...
    uilabel(app.PropellantGasPropertiesPanel);
app.HeatCapacityRatioLabel.HorizontalAlignment = 'right';
app.HeatCapacityRatioLabel.Position = [23 99 116 22];
app.HeatCapacityRatioLabel.Text = 'Heat Capacity Ratio: ';

% Create HeatCapacityRatioEditField
app.HeatCapacityRatioEditField = ...
    uieditfield(app.PropellantGasPropertiesPanel, 'numeric');
app.HeatCapacityRatioEditField.Limits = [0 10000000];
app.HeatCapacityRatioEditField.Editable = 'off';
app.HeatCapacityRatioEditField.Position = [154 99 92 22];
app.HeatCapacityRatioEditField.Value = 1.66;

% Create AtomicMassEditFieldLabel
app.AtomicMassEditFieldLabel = ...
    uilabel(app.PropellantGasPropertiesPanel);
app.AtomicMassEditFieldLabel.HorizontalAlignment = 'right';
app.AtomicMassEditFieldLabel.Position = [61 76 78 22];
app.AtomicMassEditFieldLabel.Text = 'Atomic Mass: ';

% Create AtomicMassEditField

```

```

app.AtomicMassEditField = ...
    uicontrol(app.PropellantGasPropertiesPanel, 'numeric');
app.AtomicMassEditField.Limits = [0 10000000];
app.AtomicMassEditField.ValueDisplayFormat = '%11.6g';
app.AtomicMassEditField.Editable = 'off';
app.AtomicMassEditField.Position = [154 76 92 22];
app.AtomicMassEditField.Value = 131.293;

% Create TemperatureEditFieldLabel
app.TemperatureEditFieldLabel = ...
    uicontrol(app.PropellantGasPropertiesPanel);
app.TemperatureEditFieldLabel.HorizontalAlignment = 'right';
app.TemperatureEditFieldLabel.Position = [63 53 76 22];
app.TemperatureEditFieldLabel.Text = 'Temperature: ';

% Create TemperatureEditField
app.TemperatureEditField = ...
    uicontrol(app.PropellantGasPropertiesPanel, 'numeric');
app.TemperatureEditField.Limits = [0 10000000];
app.TemperatureEditField.Position = [154 53 92 22];
app.TemperatureEditField.Value = 300;

% Create unitlessLabel
app.unitlessLabel = uicontrol(app.PropellantGasPropertiesPanel);
app.unitlessLabel.Position = [254 99 46 22];
app.unitlessLabel.Text = 'unitless';

% Create gmolLabel
app.gmolLabel = uicontrol(app.PropellantGasPropertiesPanel);
app.gmolLabel.Position = [254 76 42 22];
app.gmolLabel.Text = 'g / mol';

% Create KLabel
app.KLabel = uicontrol(app.PropellantGasPropertiesPanel);
app.KLabel.Position = [254 53 25 22];
app.KLabel.Text = 'K';

% Create SelectpresetDropDownLabel
app.SelectpresetDropDownLabel = ...
    uicontrol(app.PropellantGasPropertiesPanel);
app.SelectpresetDropDownLabel.HorizontalAlignment = 'right';
app.SelectpresetDropDownLabel.Position = [61 135 79 22];
app.SelectpresetDropDownLabel.Text = 'Select preset: ';

% Create GasPresetDropDown
app.GasPresetDropDown = ...
    uicontrol(app.PropellantGasPropertiesPanel);
app.GasPresetDropDown.Items = {'User Defined', 'Argon', ...
    'Krypton', 'Xenon'};
app.GasPresetDropDown.ValueChangedFcn = createCallbackFcn(app, ...
    @GasPresetDropDownValueChanged, true);
app.GasPresetDropDown.Position = [155 135 103 22];
app.GasPresetDropDown.Value = 'Xenon';

```

```

% Create Label
app.Label = uilabel(app.PropellantGasPropertiesPanel);
app.Label.FontSize = 8;
app.Label.Position = [21 5 301 45];
app.Label.Text = {'References: '; '1. Meija, Juris; et al. ...
    (2016). "Atomic weights of the elements 2013 (IUPAC ...
    Technical'; '    Report)". Pure and Applied Chemistry. 88 ...
    (3): 265 91.          '; '2. White, Frank M. Fluid ...
    Mechanics (4th ed.). McGraw Hill.'; '3. Lange, Norbert A. ...
    Lange''s Handbook of Chemistry (10th ed.).'};

% Create GeneratePlotButton
app.GeneratePlotButton = uibutton(app.LeftPanel, 'push');
app.GeneratePlotButton.ButtonPushedFcn = ...
    createCallbackFcn(app, @GeneratePlotButtonPushed, true);
app.GeneratePlotButton.FontSize = 16;
app.GeneratePlotButton.FontWeight = 'bold';
app.GeneratePlotButton.Position = [14 14 327 26];
app.GeneratePlotButton.Text = 'Perform Calculations and ...
    Generate Plot ';

% Create Label1
app.Label1 = uilabel(app.LeftPanel);
app.Label1.VerticalAlignment = 'top';
app.Label1.Position = [14 79 326 22];
app.Label1.Text = '';

% Create Label2
app.Label2 = uilabel(app.LeftPanel);
app.Label2.VerticalAlignment = 'top';
app.Label2.Position = [14 65 326 22];
app.Label2.Text = '';

% Create Label3
app.Label3 = uilabel(app.LeftPanel);
app.Label3.VerticalAlignment = 'top';
app.Label3.Position = [14 44 326 22];
app.Label3.Text = '';

% Create RightPanel
app.RightPanel = uipanel(app.GridLayout);
app.RightPanel.Layout.Row = 1;
app.RightPanel.Layout.Column = 2;
app.RightPanel.Scrollable = 'on';

% Create ModelPredictionUIAxes
app.ModelPredictionUIAxes = uiaxes(app.RightPanel);
title(app.ModelPredictionUIAxes, '')
xlabel(app.ModelPredictionUIAxes, 'Time (s)')
ylabel(app.ModelPredictionUIAxes, 'Propellant Mass Flow Rate ...
    (sccm)')
app.ModelPredictionUIAxes.FontName = 'Arial';
app.ModelPredictionUIAxes.FontSize = 14;
app.ModelPredictionUIAxes.XGrid = 'on';

```

```

        app.ModelPredictionUIAxes.YGrid = 'on';
        app.ModelPredictionUIAxes.LabelFontSizeMultiplier = 1.2;
        app.ModelPredictionUIAxes.TitleFontSizeMultiplier = 0.1;
        app.ModelPredictionUIAxes.Position = [7 14 551 419];

        % Show the figure after all components are created
        app.FVR_UtilityUIFigure.Visible = 'on';
    end
end

% App creation and deletion
methods (Access = public)

    % Construct app
    function app = FVR_Designer_Utility

        % Create UIFigure and components
        createComponents(app)

        % Register the app with App Designer
        registerApp(app, app.FVR_UtilityUIFigure)

        if nargin == 0
            clear app
        end
    end

    % Code that executes before app deletion
    function delete(app)

        % Delete UIFigure when app is deleted
        delete(app.FVR_UtilityUIFigure)
    end
end
end
end

```

Appendix C

How to Build a Heaterless Cathode Assembly Using an Automotive Oil Drain Plug

Heaterless cathodes provide a vast amount of design flexibility when compared with heater-utilizing cathodes. When a cathode heater is used, the geometry of the assembly must accommodate the heater along with an additional electrical lead. By circumventing these design requirements, a wide variety of creative designs become possible. For example, a highly unique cathode assembly was made using scrap materials, including an oil drain plug purchased from an auto parts store. In this design, a planar barium-based cathode emitter was enclosed in several layers of radiation shielding and attached to a sheet of tantalum foil. The cathode and its tantalum foil base were then spot-welded to a stainless steel socket head bolt as shown in Figure C.1. The socket head bolt was modified to accommodate the planar cathode by drilling a hole through the centerline of the screw. Additional holes were added to the tantalum foil to allow for gas to flow through the screw and to the region where the planar cathode was housed.

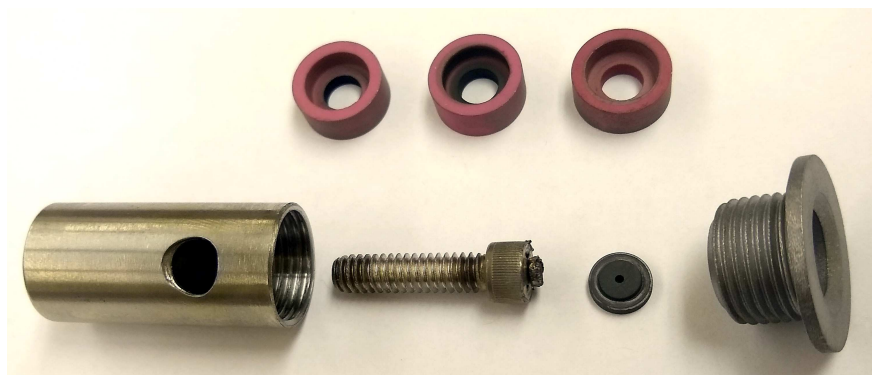


Figure C.1: A barium-based cathode emitter mounted upon a modified socket head screw.

The cathode was housed within a stainless steel tube that was designed to contain three ceramic isolators. The isolators allowed for an electrically isolated keeper electrode to be included in the assembly. The assembly, shown in Figure C.2, was held together in compression with a modified oil drain plug.



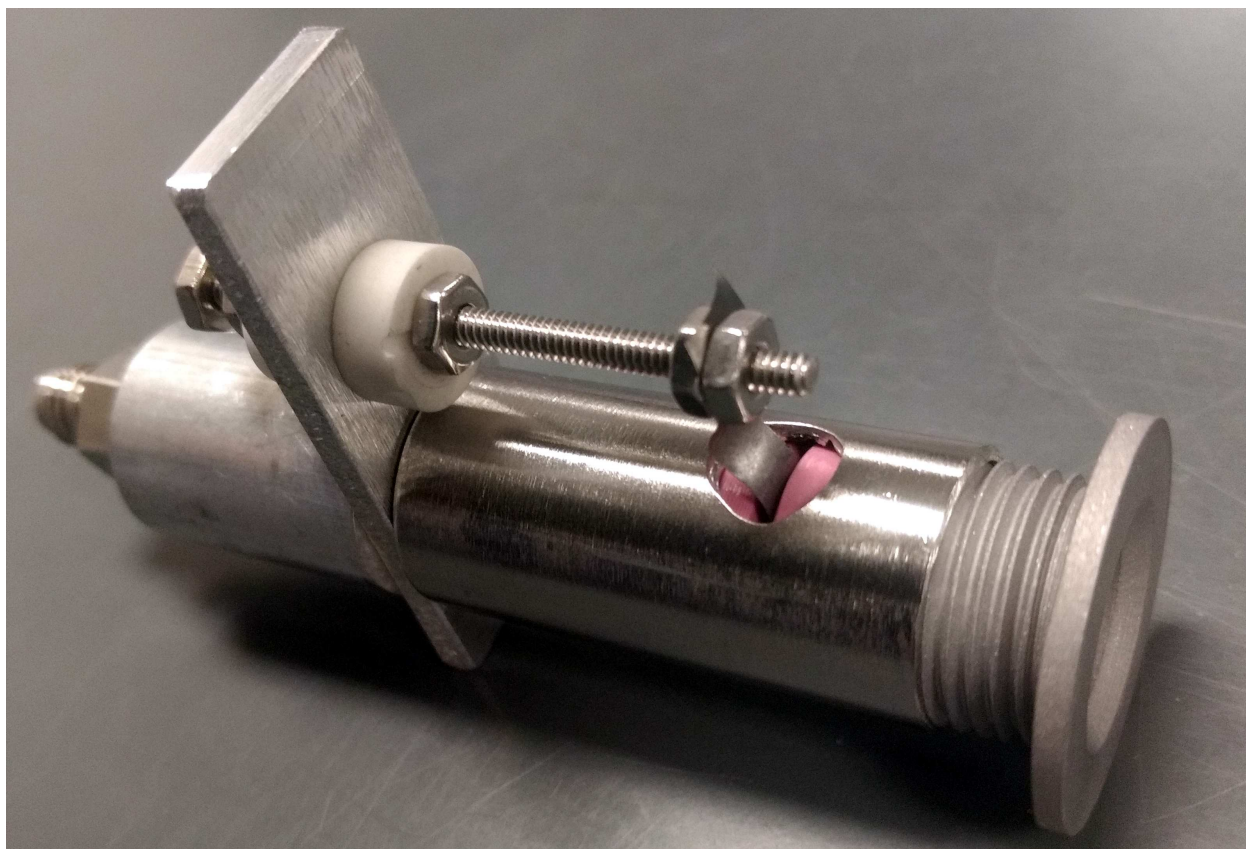
(a) Modified oil drain plug used to secure internal components within the assembly.



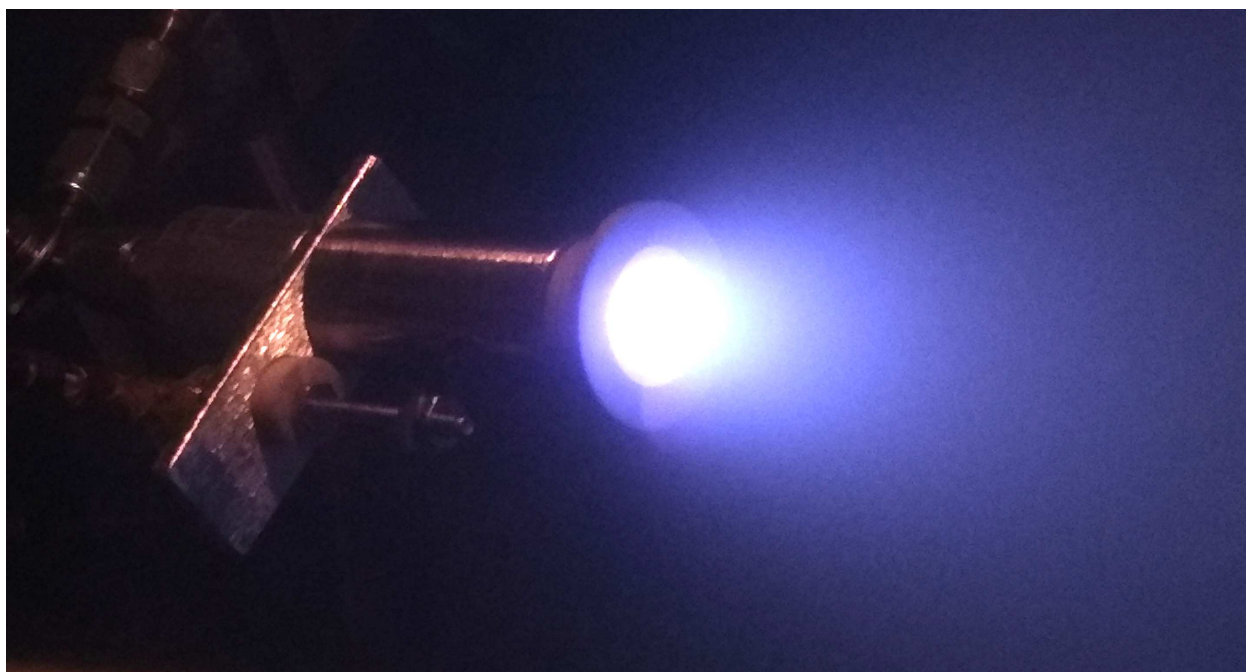
(b) Internal components of the cathode assembly.

Figure C.2: Photos of the components that make up this unique cathode assembly.

While the cathode operated stably when several amperes of discharge current were coupled to an external anode, the device did not exhibit optimal performance characteristics. While this cathode design is not practical in many applications, its development serves as a demonstration of the noteworthy design freedoms that are afforded by heaterless cathode technology.



(a) Fully assembled device



(b) Photo of the cathode emitting several amperes of discharge current to an external anode.

Figure C.3: Photos of the completed cathode assembly.