Experimental Performance Evaluations of Mo and ZrC-Coated Mo Field Emission Array Cathodes in Oxygen Environments

Colleen Marrese-Reading and Jay Polk
Jet Propulsion Laboratory (JPL), California Institute of Technology
M/S 125-109, 4800 Oak Grove Drive, Pasadena, CA 91106
818-354-8179, colleen.m.marrese@jpl.nasa.gov
818-354-9275, james.e.polk@jpl.nasa.gov

Kevin L. Jensen
Naval Research Laboratory, Code 6841, ESTD
Washington, DC 20375-5347,
202-767-3114, kevin.jensen@nrl.navy.mil

IEPC-01-278

This performance of Mo and ZrC-coated Mo field emission array cathodes in oxygen environments is discussed in this article. These results were obtained in the first year of a program to develop field emission cathodes to operate in low Earth orbit (LEO) environments for electrodynamic tether systems. A model is described that enables the comparison of the self-generated atomic oxygen fluxes in a molecular oxygen environment to the flux of atomic oxygen in LEO. The results of this model for experiments performed are presented. This report describes the experimental results obtained from evaluating the performance of Mo and ZrC/Mo cathodes in oxygen environments. The results show that the performance of ZrC-coated Mo field emission array cathodes is more stable than Mo field emission array cathodes, but they suggest that neither material has acceptable stability in atomic oxygen environments.

Introduction
Field emission cathodes are under development to be compatible with the performance and lifetime requirements of several space-based applications to replace hollow and thermionic cathodes conventionally used to improve power, efficiency, mass and system complexity. Electrodynamic tethers, colloid thrusters, FEEP thrusters, micro ion engines and Hall thrusters should significantly benefit from field emission cathodes compatible with their current and lifetime requirements in the spacecraft and laboratory environments. These applications will require field emission cathode materials with a high resistance to oxidation and sputtering by ion bombardment. The cathode architecture must provide control over the electron energy independent of the electron extraction voltage to satisfy the lifetime requirements and improve the space charge current limits. [1] The cathode architecture should also provide current limitations to protect them against catastrophic performance degradation from arcing and debris impact to meet the demands on cathode lifetime in the space environment.

The current requirements for the tether and thruster applications range from 10 mA/cm² to 200 mA/cm² at <10 mW/mA for thousands of hours. The operating environments can differ significantly and depend on the laboratory and spacecraft environments. During ground testing in simulated application environments, the cathodes must operate in oxygen partial pressures greater than 10⁻⁹ Torr, and even this environment can affect the performance of these cathodes. Most contaminants can cause changes in the work function of the tip material and/or the electric field distribution on the tips.

The field emission cathode current is exponentially dependent on the work function and electric field on the emitting tips. [2] Therefore the performance of the cathode is very sensitive to its operating environment because it can cause changes in its work function and tip radius of curvature. Chemisorption or physisorption of oxygen in these environments can increase the cathode work function and decrease the surface conductivity, causing temporary and permanent performance degradation. Ambient ions or ions generated between the tips and gate electrode can sputter the tips to increase the tip radii and decrease the geometrically enhanced electric field at the tips. This environmental effect results in permanent cathode performance degradation.

The cathodes must be compatible with atomic oxygen environments for operation with electrodynamic tethers in LEO. Some cathode performance degradation in atomic oxygen may be acceptable if the required current can be maintained by operating at higher voltages or turning on additional cathodes. However, the operating voltage will be limited so that the energy of the ions created between the tips and gate and downstream of the cathode will not exceed the threshold for sputtering the cathode material. The performance degradation rates depend on the cathode material, operating voltage, cathode geometry, constituents of the environment and contamination rate. Mo is the most common field emission array cathode material with the most well developed and reliable fabrication processes. Therefore, we characterized its stability in oxygen even though previously reported results were not promising. [3,4] ZrC was identified as potentially more stable material in oxygen because of promising results obtained at Linfield Research Institute. [5,6]

Evaluating the performance of various cathode materials in simulated LEO environments is challenging because atomic oxygen is much more reactive than molecular oxygen and much more expensive to supply for contamination studies. The simplest cathode stability experiments have been performed by operating the cathode in molecular oxygen environments. Concerns about the applicability of these results to understanding the performance of the cathodes in a LEO environment motivated the development of the model presented in this article. This model is used to estimate the flux of atomic oxygen to the cathodes which is self-generated by the interactions of the electron beams with the molecular oxygen environment.

This article presents the model developed to characterize the laboratory environment, a comparison of the laboratory environment to the LEO environment, and the results from experimental cathode performance evaluations in oxygen environments.

**Laboratory Environment**

The LEO environment is described in the Table 1. The most dangerous constituent of this environment is currently believed to be atomic oxygen (AO). AO is extremely reactive, capable of changing the work function and conductivity of the cathode surface if the material is not resistant to oxidation.

<table>
<thead>
<tr>
<th>n (cm⁻³)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>10⁹</td>
</tr>
<tr>
<td>O₂</td>
<td>2x10⁷</td>
</tr>
<tr>
<td>O⁺</td>
<td>10⁶</td>
</tr>
<tr>
<td>N₂</td>
<td>10⁸</td>
</tr>
<tr>
<td>He</td>
<td>10⁴</td>
</tr>
<tr>
<td>H</td>
<td>10⁴</td>
</tr>
</tbody>
</table>

To evaluate the compatibility of the cathode with this environment, either the cathodes need to be tested in the LEO environment or tested in an environment with a comparable flux of AO to the emitting area of the tips. AO sources in vacuum systems can simulate the fluxes and energies of AO which the cathodes would experience in LEO. A unique aspect of testing FEA cathodes in molecular oxygen environments is that they self-generate a substantial population of AO and ionized molecular oxygen by electron bombardment of molecular oxygen and collisions of ionized oxygen with the field emission cathode surface. This unique aspect of these experiments is exploited to perform relatively low cost and quick cathode sensitivity tests.

The fluxes of ionized and atomic oxygen to the emitting areas of the tips were calculated using the model included in Appendix A. The following three reactions take place in this environment to contribute to an effective flux of atomic oxygen to the cathode:
Critical to this model is a statistical representation of the cathode emission distribution in an array of tips. The Jensen performance model uses the cathode geometric and material characteristics with experimentally acquired I-V data to determine the number of tips carrying the current load, the current per tip, the effective tip radius of curvature, and the distribution of tip radii in an array. [7,8] The flux model provides first order estimates of the fluxes of various oxygen species. It was assumed that oxygen atoms participate in only one reaction, therefore, once molecular oxygen is dissociated into 2O, those oxygen atoms could not later be ionized also. The majority of the oxygen bombarding the tips is ionized because these ions are accelerated to the emitting area of the tips by the local radial electric field. Within approximately 1 μm from the tips, all ions generated bombard the emitting tip area while little of the neutral molecular and atomic oxygen reach it. [9] Because ionized oxygen molecules are bombarding the tips with significant energies, they are highly reactive with the surface. With molecular oxygen energies exceeding a few eV, they will dissociate on impact and provide highly reactive atomic oxygen to the surface. [10]

LEO and laboratory environments are described in Table 2. A cathode could be positioned in the ram, wake, or somewhere between these regions on a spacecraft. The cathode will not be positioned intentionally in the spacecraft ram because of the hostile environment with the highest probability of debris impact. This environment is described in Table 2 as LEO RAM. The extremely low pressure in the wake of a spacecraft will prohibitively limit the space-charge current density. [11] The LEO environment described in columns 2 & 3 of Table 2 is the most likely environment for the FEA cathodes on a spacecraft in LEO. The fluxes of AO to the emitting area of the tips was calculated with the neutral particle number densities, thermal energies, kinetic energies, and the emitting area of the tips.

We have used the model with experimental data to show that operating FE cathodes in molecular oxygen environments in our laboratory produces AO fluxes that are comparable to the flux of AO in LEO or in a laboratory facility with an AO source. The caveat is that the cathode has to have decent performance with 100 μA at ~50 V. If much higher voltages are required the cathode could be sputter damaged during the exposures. The modeling results show that the self-generated flux of AO to the emitting area of the tips is comparable to the flux of AO in LEO with the right combination of current per tip emitting and oxygen pressure. The biggest difference is the energy of the impinging oxygen. This approach to simulating LEO is effective because the only environmental effect in LEO that will impact the cathode performance are the changes that occur in the emitting area of the tip. These changes include work function, geometry, tip radius of curvature, and conductivity. The self-generated flux to the emitting area of the tip is comparable to the AO flux in LEO because of the radial electric field focusing ions near the tips. Only the emitting tips self-generate this environment, but this scenario is sufficient for our investigations.

Experiments have been conducted with the Lab Ia and Ia pressure and conditions, as described in Table 2. These experiments will be discussed later in the article. The cathode characteristics defined by the Lab Ia scenario describe the Mo cathode with the initial performance shown in Figure 7. The cathode characteristics defined by the Lab Ia scenario describe the ZrC coated Mo cathode before oxygen exposures, with performance shown in Figure 16. Lab Ia and Ila environments have the same molecular oxygen pressures. In each environment, the cathodes are operating at 50 V with the total current, I_{tot}, the current per emitting tip, I_{tip}, number of tips emitting, N_{tipemitting}, determined using Jensen’s model. The flux of atomic oxygen to the emitting tips (2Φ_{O2}+Φ_{O}) is also described in these columns as determined with the model developed and described in Appendix A. N_{tipemitting} identifies the number of tips which are carrying the majority of the current in the arrays. In the Mo cathode test conditions described in the Lab Ia environment, only 120 of the 50,000 tips in the array are carrying the current. In 10^{-7} Torr of oxygen, the flux of atomic oxygen to those tips is 0.361 /s. With the effective tip radius identified for this cathode as 2.28 nm, the flux of atomic oxygen in LEO is 1.5 /s as shown in Table 2. Data in Lab Ib column show that the flux of atomic oxygen to the tips can be increased to 3.61 /s by increasing the pressure from 10^{-7} to 10^{-6} Torr. This flux in the laboratory environment exceeds the flux in LEO. The effect of oxygen ion energies on these results should also be determined.

1) O₂ + e -> O₂⁺ + 2e
2) O₂ + e -> 2O + e
3) O₂ + e -> O⁺ + O + 2e
The same result is shown in for the cathode described in LEO II, Lab IIa and Lab IIb. This ZrC/Mo cathode has significantly different operating characteristics and tip radius as identified with the Jensen model while operating at the same voltage and the same number of total tips in the array-50,000. In $10^{-7}$ Torr the atomic oxygen flux is 0.4 in the Lab Iia scenario. The flux to a tip with the same radius of curvature will be 5.5 /s in LEO. The flux of atomic oxygen in the laboratory environment is linearly dependent on $I$/tip and pressure of molecular oxygen, as shown in Eqn 13. Therefore, increasing the pressure to $10^{-6}$ Torr increases the flux of atomic oxygen by one order of magnitude so that the flux of atomic oxygen in the laboratory environment is much closer than the flux in LEO. With slight increases in pressure and/or $I_{tip}$, the flux in the laboratory will exceed the flux of atomic oxygen in LEO. These results could be presented more easily as flux densities, showing that the tip radius of curvature only slightly affects the results of the model; it influences the maximum radial distance from which an ion created will impact the emitting area of the cathode tips.

The results of the atomic oxygen flux model show that the environment that is generated in the laboratory can be identified and used to interpret results from the oxygen exposure experiments. The oxygen exposures can be compared to the application environment to identify how the cathodes responded to an environment which is more or less damaging than the LEO environment. This tool is useful at this stage in our program when many cathode materials are under investigation to identify the most appropriate material. The laboratory experiments in which AO is self-generated in the molecular oxygen environment can present a slightly more hostile environment than LEO. In this case the cathode is forced to perform in a worst case scenario, but not extremely different than the LEO environment. Stable performance demonstrated in these experiments ensures stable performance in the LEO environment, which can be subsequently demonstrated in a vacuum system with a 5 eV atomic oxygen beam bombarding the cathode. Conversely, some experiments will generate a flux lower than the flux in LEO. A cathode demonstrating unacceptable stability in this environment will probably demonstrate even worse performance in LEO. This result depends on the sensitivity of the sticking coefficient of oxygen to the cathode material at energies up to 50 eV.

Table 2. A comparison of the LEO (300 km) and laboratory environments.

<table>
<thead>
<tr>
<th></th>
<th>LEO Ram (300 km)</th>
<th>LEO I (300 km)</th>
<th>LEO II (300 km)</th>
<th>Lab Ia</th>
<th>Lab IIa</th>
<th>Lab IIb</th>
<th>Lab IIb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_0$ (/cm$^3$)</td>
<td>$10^9$</td>
<td>$10^9$</td>
<td>$10^9$</td>
<td>$10^9$</td>
<td>$10^9$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$P_0$ (Torr)</td>
<td>$10^{-7}$</td>
<td>$10^{-7}$</td>
<td>$10^{-7}$</td>
<td>$10^{-7}$</td>
<td>$10^{-7}$</td>
<td>$10^{-6}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$n_{O_2}$ (/cm$^3$)</td>
<td>$2x10^7$</td>
<td>$2x10^7$</td>
<td>$2x10^7$</td>
<td>$10^9$</td>
<td>$10^9$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$P_{O_2}$ (Torr)</td>
<td>$2x10^{-9}$</td>
<td>$2x10^{-9}$</td>
<td>$2x10^{-9}$</td>
<td>$10^{-7}$</td>
<td>$10^{-7}$</td>
<td>$10^{-6}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$n_{O+}$ (/cm$^3$)</td>
<td>$10^6$</td>
<td>$10^6$</td>
<td>$10^6$</td>
<td>$10^6$</td>
<td>$10^6$</td>
<td>$10^6$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$T_e$(eV)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$KE$(eV)</td>
<td>5</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td>$T_i$(eV)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\Phi_{O_2}$ (#/s)</td>
<td>0.52</td>
<td>0.02</td>
<td>0.07</td>
<td>1.64</td>
<td>1.85</td>
<td>16.4</td>
<td>18.5</td>
</tr>
<tr>
<td>$\Phi_O$ (#/s)</td>
<td>36.2</td>
<td>1.5</td>
<td>5.42</td>
<td>0.33</td>
<td>0.37</td>
<td>3.3</td>
<td>3.7</td>
</tr>
<tr>
<td>$2\Phi_{O_2} + \Phi_O$ (#/s)</td>
<td>37.24</td>
<td>1.54</td>
<td>5.56</td>
<td>3.61</td>
<td>4.07</td>
<td>36.1</td>
<td>40.7</td>
</tr>
<tr>
<td>$r_{tip}$ (cm)</td>
<td>$2.28x10^{-7}$</td>
<td>$2.28x10^{-7}$</td>
<td>$4.39x10^{-7}$</td>
<td>$2.28x10^{-7}$</td>
<td>$4.39x10^{-7}$</td>
<td>$2.28x10^{-7}$</td>
<td>$4.39x10^{-7}$</td>
</tr>
<tr>
<td>$I_{tip}$ (A)</td>
<td>$9.2x10^{-8}$</td>
<td>$2.8x10^{-8}$</td>
<td>$9.2x10^{-8}$</td>
<td>$9.2x10^{-8}$</td>
<td>$2.8x10^{-8}$</td>
<td>$9.2x10^{-8}$</td>
<td>$2.8x10^{-8}$</td>
</tr>
<tr>
<td>$N_{emitting}$</td>
<td>120</td>
<td>6000</td>
<td>120</td>
<td>6000</td>
<td>120</td>
<td>6000</td>
<td>120</td>
</tr>
<tr>
<td>$I_{em}$ (A)</td>
<td>$1.1x10^{-3}$</td>
<td>$1.67x10^{-4}$</td>
<td>$1.1x10^{-3}$</td>
<td>$1.67x10^{-4}$</td>
<td>$1.1x10^{-3}$</td>
<td>$1.67x10^{-4}$</td>
<td>$1.1x10^{-3}$</td>
</tr>
<tr>
<td>$V_g$</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$\angle$ (°)</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
</tr>
</tbody>
</table>
Cathode Experiments: Performance Sensitivity to Oxygen Environments

Experimental Apparatus

Cathodes

The field emission array cathodes were fabricated at SRI Int. and Aptech. The cathode configuration is shown in Figure 1a. A single element of a field emission array (FEA) cathode is shown in Figure 1b. The Mo FEA cathode was developed at SRI Int. ZrC films were deposited on the FEA cathode at Aptech. The thickness of the films is approximately 20Å. The height of the tips is ~1 µm and the gate aperture radius is 0.45 µm. The tip-to-tip spacing on the cathodes tested was 4 µm. The resistivity of the Si wafer was 2000 Ohm-cm. The arrays of tips consisted of 50,000 tips in a 0.78 mm² circular pattern area.

Vacuum Facility

An ultra high vacuum (UHV) facility is employed in these experiments. The facility is pumped by a turbomolecular pump, a sublimation pump, and an ionization pump to attain base pressures as low as 7x10⁻¹¹ Torr. Two UHV-compatible leak valves feed in oxygen and xenon for elevated pressure exposure tests. The cathode test flange is shown in Figure 2. The electrical schematic is shown in Figure 3. Cathode current through the base, gate and anode are measured with picoameters. A 1 MOhm resistor on the gate electrode regulates gate voltage if the gate current is excessive and helps to prevent arcing between the tip and gate electrode. A data acquisition system is employed to record and store the experimental data.

Experimental Results: Effect of the Oxygen Environment on Cathode Performance

Mo and ZrC-coated Mo cathodes were tested in UHV and oxygen-rich environments at JPL to determine the
effect of oxygen on their performance. Specific objectives included determining the emission stability of the cathodes while operating in oxygen environments and the upper limit on operating voltages to avoid sputtering the tips by oxygen ion bombardment. The results of experiments performed earlier at Linfield Research Institute showed that single crystal ZrC tips were not easily damaged during operation in oxygen environments at voltages >1kV. Those results motivated the investigations discussed in this article. The data obtained from many experiments with Mo and ZrC/Mo cathodes in oxygen environments are included in Appendix B.
10⁻⁷ Torr for 1 hour. It was shown that the cathode current decayed only when it was operating during the exposures. The cathode performance was not affected by exposure to 10⁻⁵ Torr of oxygen during 1 hour when it was not operating. The cathode I-V characteristics were identical before and after the exposure. It is believed that the performance of the cathode is only noticeably affected by the oxygen environment while operating because the electron emission into this environment after being accelerated through the gate potential generates an much more reactive environment with ionized and atomic oxygen as shown with the model described in Appendix A.

During the exposures to oxygen while the cathode was operating, the current always decayed with an exponential behavior. When the oxygen was removed from the environment and it returned to ~10⁻⁷ Torr, the Mo cathode performance recovered to the pre-exposure performance if the operating voltages and exposure doses of oxygen were low enough. Operating with gate electrode voltages ≤90 V at 10⁻⁷ Torr, the Mo FEA cathodes were not permanently affected by these exposures as shown in Figure 8-Figure 12 in Appendix B. Table 3 in Appendix B summarizes the results from all of the experiments. Data is presented in the graphs and table in the order that it was acquired. The results suggest that no sputtering damage was done to the cathodes during the experiments; only the work function was changed by the oxygen adsorption. These results are very promising in comparison to the operating voltage limitations of ~36 V for the same cathodes in 10⁻⁵ Torr of xenon. [1]

Experiments performed on ZrC/Mo cathodes showed that these cathodes were slightly more stable than the Mo cathodes, the performance responses to increased oxygen pressure was very repeatable and that total dose of oxygen during the exposures had a more significant impact on the performance response to increased oxygen pressure than operating voltage. These cathodes also demonstrated that they would not be sputter-damaged by ion bombardment while operating at 50 V during a dose of 1.1x10⁻⁷ Torr-hour of oxygen, as shown in Figure 15. Figure 16 shows an I-V trace taken in UHV after experiment #100400. Repeatability in current degradation rate in the same oxygen environment was demonstrated in two 50 V exposures. The cathode recovered during a 50 V exposure to 4.85x10⁻⁷ Torr-hours (Exp. #101100) as shown in Figure 17; however, it did not recover within 120 hours in UHV from an exposure to 7.64x10⁻⁷ Torr-hours (Exp. #101700), as shown in the same figure. The cathode did recover later during a facility bake-out. Figure 17 also shows that the performance response to the oxygen exposure was totally repeatable for the same dose and initial operating current. Figure 17 shows the results from an exposure to an even greater dose of oxygen, 10⁻⁶ Torr-hours (Exp. #103100). The cathode never demonstrated a full recovery from this exposure. Figure 17 shows that partial performance recovery will occur while the cathode is not operating in UHV. These results suggest that some of the oxygen adsorbed by the cathode will desorb in UHV. Physisorbed oxygen is expected to quickly desorb in UHV. Performance improvements observed during operation in UHV after exposures with cathodes operating can be attributed to electron induced desorption also.

ZrC/Mo cathode 1096D was used in an oxygen exposure experiment to determine the cathode current and work function when it was in equilibrium with a relatively high pressure environment and to determine if it was possible to maintain a constant current by regulating the voltage in this environment. Figure 19 shows current and voltage data taken in UHV after the cathode demonstrated stable performance in the UHV environment at 10⁻⁹ Torr. Table 3 shows the experimental conditions and response of the cathode to exposure to oxygen in this experiment, #032701, and in previous experiments. Data in Figure 20 show the stable cathode current observed in UHV before the cathode was exposed to elevated oxygen pressures. Figure 20 also shows the cathode current response to the increased oxygen pressure. It was anticipated that the current would stabilize in this environment after approximately 1 hour. Instead, the current continued to decay after more than 7 hours in this environment. Figure 20 can be misleading because it appears that 6 hours into the exposure, the current had stabilized. Figure 21 shows some of the same data on a different scale. With this scale it is obvious that the current continues to decay after an exposure of 8.9x10⁻⁶ Torr-hours; oxygen continued to react with the cathode material changing its work function, conductivity or both.

Figure 22 shows the ZrC/Mo cathode 1096D current response to increased operating voltage in 10⁻⁶ Torr of oxygen. Voltage increases were employed in an
attempt to demonstrate that the current density required, \( \sim 10 \, \text{mA/cm}^2 \), could be maintained in this environment, albeit at higher operating voltages. The initial cathode operating voltage was 50 V to supply 19.9 mA/cm\(^2\) with 156 \( \mu \text{A} \) from 0.78 mm\(^2\). The data in Figure 22 shows that, in this environment, the cathode operating voltage could not be increased to compensate for the change in work function and conductivity and maintain a stable 19.9 mA/cm\(^2\). The cathode operating voltage was increased up to 90 V in this experiment. Each increase in gate voltage was accompanied by an initial increase in current and subsequent current decay. The current decay rate seemed to increase with gate voltage. In subsequent cathode testing gate voltages up to 110 V in UHV were employed to accelerate the recovery process, but the cathode never fully recovered from the exposure; it continued to decay during operation, and demonstrated significantly reduced efficiency. The efficiency change is characteristic of a sputter damaged cathode.

Figure 23 shows the normalized current degradation as a function of pressure and exposure time for this experiment and three experiments performed previously on this same cathode. Each of the experiments was conducted with a gate voltage of 50 V, however the initial current levels and oxygen pressures during the exposures were significantly different as shown in Table 3. The experimental results were remarkably repeatable.

A second ZrC/Mo cathode, 1098F, was also tested in oxygen-rich environments. The performance of this cathode was inferior to cathode 1096 D; however the experimental results in response to the oxygen environment were similar. This cathode required much higher operating voltages for significant current levels with lower efficiency. Three experiments (Exp. #121100, 122100, 010501) were performed on this cathode with the same exposure doses. The current decay in all three experiments differed by only 9%, demonstrating acceptable repeatability. These data are shown in Figure 24, Figure 26, and Figure 27. The current-voltage characteristics of this cathode are shown in Figure 25.

The performance responses of Mo and ZrC/Mo cathodes are shown in Figure 28 and Figure 29. The ZrC/Mo cathodes behaved similarly to the oxygen environment demonstrating repeatability. The superior stability of these cathodes could be responsible for this repeatable performance. Mo and ZrC/Mo cathode responses to the oxygen environment clearly vary. The cathode performance should be characterized from Jensen’s model and the I-V traces taken before each exposure for comparison. Different performance responses may be attributable to these differences.

In all of the experiments conducted, the cathode current never reached an equilibrium surface state in the environments. In each of the experiments, the environment and cathode operating conditions generated a flux of AO to the tips which is lower than would be expected in LEO, therefore, the performance decay rates expected in LEO would be even higher. Future experiments will help to identify how the energy of the impinging oxygen affects the adsorption rate.

**Conclusions**

The results of this investigation include a better understanding of the environment near the tips and the effect of the environment on the performance of the Mo and ZrC/Mo cathodes. The modeling results showed that we can self-generate a flux of AO to the tips that is comparable to the flux of AO in LEO by scaling the emission current and oxygen pressure. It was shown that the cathodes are more sensitive to the oxygen environment than expected.

In the oxygen environment, both the work function and conductivity seemed to be affected. The immediate physical adsorption of oxygen increases the work function to decrease the emission current. The oxygen then diffuses its way into the bulk, eventually forming a oxide that decreases the conductivity of the cathode and degrades its performance further. Once this film is thick enough it can charge up and further degrade the cathode performance. If the film is thin enough, the cathode can self-recover by electron induced desorption of the oxygen in UHV. We believe that in some of our experiments, the oxide film became too thick to self-remove by electron induced desorption, therefore we observed some irreversible performance damage. In all experiments, the oxide film formed never passivated itself. The surface state of the cathode continued to degrade after significant exposures in which the cathodes were exposed to a lower flux of AO than is expected from the LEO environment.
The tolerable operating voltages demonstrated were very promising. The Mo cathode performance recovered from temporary performance degradation at 50-90 V in oxygen. The ZrC/Mo cathodes were tolerant of the environment when operating at 50 V, but suffered from irreversible damage when operating at 90 V. The upper limit has not yet been identified and may depend on environmental pressure, but is between 50 V and 90 V and possibly ~66 V.

Further experimentation is required to determine whether the operating voltage and pressure together define operational limitations of the cathode. The experimental results showed that the Mo cathode could be operated up to 90 V for $1.1 \times 10^{-7}$ Torr-hours of oxygen without irreversible performance degradation. 66 V seemed to be the operating voltage limitation at $10^{-6}$ Torr. Larger dose experiments should also be conducted at 50 V to demonstrate that this operating voltage is an upper limit which is independent of oxygen dose.

**Acknowledgements**

The authors would also like to gratefully acknowledge NASA MSFC (John Cole, Dr. Kai Hwang, Randy Bagget, Les Johnson) and Tethers Unlimited Inc. (Dr. Rob Hoyt) for funding the development of field emission cathodes for space-based applications and Drs. Capp Spindt and Bill Mackie for their advice on cathode testing. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
APPENDIX A: Flux of Atomic Oxygen in Laboratory Environment

A. Nomenclature

\[ A_1 = \text{electron emitting area of tip (cm}^2) \]
\[ A_{\text{tip}} = \text{area of the tip emitting (cm}^2) \]
\[ d_{cc} = \text{center-to-center tip distance on array(cm)} \]
\[ E_e = \text{electron energy (eV)} \]
\[ I_{\text{tip}} = \text{single tip current (A)} \]
\[ I_{\text{tot}} = \text{total cathode current (A)} \]
\[ J_e = \text{cathode electron current density (A/cm}^2) \]
\[ k = 1.38 \times 10^{-23} \text{ J/K} \]
\[ m_0 = 2.179 \times 10^{-25} \text{ kg} \]
\[ m_{O_2} = 4.358 \times 10^{-25} \text{ kg} \]
\[ n = \text{number density (/cm}^3) \]
\[ \angle = \text{half-cone emission angle (°)} \]
\[ r_{bo} = \text{radial position of beamlet overlap (cm)} \]
\[ r_{cea} = \text{radius of cathode emitting area (cm)} \]
\[ r_{\text{tip}} = \text{radius of curvature of the tip (cm)} \]
\[ r_m = \text{maximum radial distance from which an ion formed will impact the emitting area of the tips} \]
\[ v = \text{velocity (cm/s)} \]
\[ V_g = \text{gate electrode voltage (V)} \]
\[ V_2 = \text{volume element contributing to the generation of AO (cm}^3) \]
\[ Q = \text{collision cross-section (cm}^2) \]
\[ \phi = \text{flux hitting the emitting area of the tip (/s)} \]
\[ \Phi = \text{flux of molecular oxygen (/cm}^2\text{s)} \]
\[ \psi = \text{angle in volume integral (radians)} \]
\[ \nu = \text{velocity (cm/s)} \]
\[ \Theta = \text{angle between the atomic oxygen source volume element and the tip surface normal (radians)} \]

B. Reaction cross-sections

The reaction cross-sections for electron collisions with molecular oxygen used in the model are shown in Figure 4. Only cross-sections for collisions creating oxygen capable of bombarding the tips are shown and considered in the model. These data show that the most probable collisions result in O_2^+ and O^+. 

![Figure 4. Reaction cross-sections for electron collisions with molecular oxygen.](image-url)
C. Flux of oxygen to FEA cathode tips

C.1 Flux of Molecular Oxygen

C.1.1 Random

\[ A_{tip} = \frac{2 \angle \theta}{360} 4 \pi r_{tip}^2 \]  

\[ \Phi \theta = \frac{1}{4} n_{O_2} v_{O_2} \text{(/cm}^2\text{s)} \]  

\[ v_{O_2} = \sqrt{\frac{8kT}{m_{O_2}}} \text{(cm/s)} \]  

\[ \phi = \Phi \theta A_{tip} \text{(/s)} \]  

C.1.2 Directed with 5 eV

\[ \phi = \Phi \theta A_{tip} \text{(/s)} \]  

C.2 Flux of Atomic Oxygen

\[ \phi_{O_2} = n_{O_2} I_{tip} \int_{r_{tip}}^{r_{tot}} Q_{O_2}(E(r))dr \]  

C.3 Flux of Atomic Oxygen

C.3.1 Near-tip contribution

Atomic oxygen production rate

\[ \frac{dn_{O_2}}{dt} = n_{O_2} n_e v_e Q_{O_2/O_2} = n_{O_2} \frac{J_e}{e} Q_{O_2/O_2} \]  

Flux of atomic oxygen leaving dV2 and arriving at A1

\[ \Phi = \frac{dn_{O_2}}{dt} \frac{A_1 \cos \theta}{r^2 4 \pi} dV_2 \]  

where \( \frac{A_1 \cos \theta}{r^2 4 \pi} \) is the fraction of AO that reaches the tip, A1.

\[ \frac{d\phi}{dt} = \frac{A_1 \cos \theta}{r^2 4 \pi} n_{O_2} \frac{J_e}{e} Q_{O_2/O_2} \frac{dV}{dV_2} \]  

\[ A_1 = \frac{2 \angle \theta}{360} 4 \pi r_{tot}^2 \text{and } J_e = \frac{I_e}{4 \pi r_{tot}^2} \]  

It is assumed here that \( I_e \) is not a function of \( \theta \). While this is not true, it will not affect our results since we are interested in the total flux to the emitting area of the tip only.

\[ \Phi = \frac{n_{O_2} I_{tip} r_{tip}}{4 \pi} \int_{r_{tip}}^{r_{tot}} \int_0^{2 \pi} Q_{O_2/O_2} E(r) \cos \theta \sin \theta \frac{dV}{dV_2} \]  

\[ \phi = n_{O_2} I_{tip} r_{tip} \frac{2 \angle \theta}{360} \int_0^{2 \pi} Q_{O_2/O_2} E(r) \sin \theta \frac{dV}{dV_2} \]  

C.3.2 Far-field Contribution (after the individual beamlets overlap)

The initial beam radius is \( r_{esa} \) which includes all 50,000 beamlets in the array. It is assumed that the beam is uniform in current density for this calculation. It is assumed that a single beamlet half-cone emission angle is 37o and that the combination of all of the beams expands at this angle also so that the current density varies as a function of radial distance from the source as

\[ J_{tot} = \frac{I_{tot}}{\pi (r_{esa} + r \tan \angle)^2} \]

Then contribution to the flux of atomic oxygen to the tips from this far-field population is

\[ \phi_{O_2} = n_{O_2} I_{tip} \frac{2 \angle \theta}{360} r_{tip}^2 \sin^2 \angle \int_0^{r_{tot}} Q_{O_2/O_2} E(r) dr \]

where \( r_{bo} \) represents radial position of beamlet overlap and

\[ r_{bo} = \frac{d_{esa}}{\tan \angle} \]

In this calculation it is assumed that the energy of the electrons does not exceed the gate electrode potential. In reality, the electrons will be accelerated between the gate and anode; however, the potential distribution in that region has not yet been included in this model.

C.4 Flux of Ionized Atomic Oxygen

\[ \phi_{O_2} = n_{O_2} I_{tip} r_{tip} \frac{2 \angle \theta}{360} \]  

D. Collision-induced Electron Beam Attenuation

As the electron beamlets participate in ionization and dissociation reactions, the supply of electrons in the beam is depleted. This model did not take into account electron beam depletion; therefore, significant depletion will introduce errors in the results. Collision-induced electron beam depletion rate was determined to assess its significance on the results of this model with the relationships

\[ \frac{dl}{dr} = -n_{O_2} Q(E(r)) \]  

which is evaluated as

\[ \frac{l}{I_{tip}} = \exp \left( -n_{O_2} \int_{r_{tip}}^{r_{tot}} Q(E(r)) dr \right) \]  

The results from this analysis are shown in Figure 5. The depletion rate is shown for one type of reaction only-total ionization by electron bombardment forming O2+. This reaction is primarily responsible for depleting the electron beam as shown by the reaction cross-section data in Figure 4. The O2 pressure must be \( \sim 10^3 \) Torr before 0.25% of the beam...
is depleted within 1 cm of the tip. The experiments discussed in this study were conducted at ~10^7 Torr, therefore, an insignificant number of electrons are being depleted within 1 cm of the tip. Beyond this distance, an insignificant number of ionized and atomic oxygen generated hit the emitting area of the tip.

![Graph](image.png)

Figure 5. The variation in current with position downstream of the tip due to reaction collisions at various environment pressures.

**D. Modeling Results**

The results of the model using the reaction cross-sections shown in Figure 4 are shown in Figure 6. The results in the figure show the fluxes to the tips expected in the LEO environment with the conditions shown on the graph. Two scenarios were considered: the ambient environment and in the spacecraft ram where the oxygen will be impacting the spacecraft and cathodes with 5 eV. Figure 6 also shows the flux of various oxygen species generated by a field emission cathode operating in a molecular oxygen environment. The results show that the flux of oxygen to the emitting tips is primarily O\(_2^+\) in a molecular oxygen environment with the tips emitting electrons with energies that exceed oxygen ionization potentials. The O\(^+\) population represents the second largest population of oxygen bombarding the emitting tips. The high ion fluxes to the tips is attributed to the radial focusing of the trajectories by the electric field near the tips. The fluxes of AO to the tips from the dissociation reactions are orders of magnitude lower than the ion fluxes. The O\(_2^+\) ions bombard the tips with >12 eV of energy, therefore they dissociate on impact, providing two oxygen atoms for each O\(_2^+\) impact. This source of atomic oxygen is the most significant. To simulate the flux of atomic oxygen in LEO during the laboratory experiments, Figure 6 shows that the current per tip should be increased by 10000x or the P\(_{O_2}\) should be increased by 10000x or some combination of these changes like a cathode emitting 100 nA/tip in 2x10^{-7} Torr of O\(_2\). These results show that it is possible to self-create an AO flux to the tips that is very similar to the AO flux to spacecraft in LEO. To determine how the self-generated flux of AO oxygen compares to the LEO environment, Jensen’s cathode performance model and experimental data are required. Many of the results of this modeling are presented in Table 2. The results can easily be scaled from the data given for changes in number of tips emitting, pressure, tip radius of curvature, or current per tip.
Figure 6. Fluxes of ionized and neutral atomic and molecular oxygen to tips as generated in the laboratory and expected in LEO.

APPENDIX B: Experimental Data

A compilation of experimental data is presented in Table 3. Data acquired from each experiment is included in the following figures. The data in each figure are identified by the experiment numbers. The details of the operating conditions of the experiments are given in Table 3.
Table 3. Summary of cathode performance responses to exposure to oxygen.

<table>
<thead>
<tr>
<th>EXP #</th>
<th>FEAC #</th>
<th>$V_s$(V)</th>
<th>$V_a$(V)</th>
<th>$I_t$(µA)</th>
<th>$J_t$ (mA/cm²)</th>
<th>$P_o2$ (Torr)</th>
<th>$t_{exp}$ (hr)</th>
<th>$\Theta$ (Torr-hr)</th>
<th>$I_r$ (uA)</th>
<th>$I_f/I_i$</th>
<th>%ΔI</th>
<th>Recovery time in UHV (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>091300 A</td>
<td>Mo 1100C</td>
<td>50</td>
<td>100</td>
<td>11</td>
<td>1.4</td>
<td>~10⁻⁸</td>
<td>1</td>
<td>1.26x10⁻⁷</td>
<td>11</td>
<td>1</td>
<td></td>
<td>64</td>
</tr>
<tr>
<td>091300 B</td>
<td>Mo 1100C</td>
<td>60</td>
<td>100</td>
<td>34</td>
<td>4.4</td>
<td>~10⁻⁷</td>
<td>1</td>
<td>1.08x10⁻⁷</td>
<td>30</td>
<td>0.88</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>091500</td>
<td>Mo 1100C</td>
<td>70</td>
<td>100</td>
<td>72</td>
<td>9.2</td>
<td>~10⁻⁷</td>
<td>1</td>
<td>1.35x10⁻⁷</td>
<td>66</td>
<td>0.92</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>091700</td>
<td>Mo 1100C</td>
<td>80</td>
<td>130</td>
<td>170</td>
<td>21.8</td>
<td>~10⁻⁷</td>
<td>1</td>
<td>1.42x10⁻⁷</td>
<td>150</td>
<td>0.88</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>091900</td>
<td>Mo 1100C</td>
<td>90</td>
<td>160</td>
<td>425</td>
<td>5.0</td>
<td>~10⁻⁷</td>
<td>1</td>
<td>1.23x10⁻⁷</td>
<td>390</td>
<td>0.92</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>092100</td>
<td>Mo 1100C</td>
<td>100</td>
<td>300</td>
<td>850</td>
<td>109.0</td>
<td>~10⁻⁷</td>
<td>1</td>
<td>1.36x10⁻⁷</td>
<td>700</td>
<td>0.83</td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>100400</td>
<td>ZrC/Mo 1096D</td>
<td>50</td>
<td>130</td>
<td>188</td>
<td>24.1</td>
<td>~10⁻⁷</td>
<td>1</td>
<td>1.16x10⁻⁷</td>
<td>149</td>
<td>0.79</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>101100</td>
<td>ZrC/Mo 1096D</td>
<td>50</td>
<td>130</td>
<td>167</td>
<td>21.4</td>
<td>~10⁻⁷</td>
<td>4.9</td>
<td>4.85x10⁻⁷</td>
<td>15.5</td>
<td>0.09</td>
<td></td>
<td>91</td>
</tr>
<tr>
<td>101700</td>
<td>ZrC/Mo 1096D</td>
<td>50</td>
<td>130</td>
<td>170</td>
<td>21.8</td>
<td>~10⁻⁷</td>
<td>7.7</td>
<td>7.64x10⁻⁷</td>
<td>13</td>
<td>0.08</td>
<td></td>
<td>92</td>
</tr>
<tr>
<td>103100</td>
<td>ZrC/Mo 1096D</td>
<td>50</td>
<td>130</td>
<td>276</td>
<td>35.4</td>
<td>~10⁻⁷ to ~10⁻⁶</td>
<td>~3.7</td>
<td>1.00x10⁻⁶</td>
<td>5</td>
<td>0.02</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>121100</td>
<td>ZrC/Mo 1089F</td>
<td>90</td>
<td>200</td>
<td>88</td>
<td>11.2</td>
<td>~10⁻⁸</td>
<td>1</td>
<td>~1.1x10⁻⁷</td>
<td>69</td>
<td>0.78</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>122100</td>
<td>ZrC/Mo 1089F</td>
<td>90</td>
<td>160</td>
<td>68</td>
<td>8.7</td>
<td>~10⁻⁷</td>
<td>1</td>
<td>~1.1x10⁻⁷</td>
<td>60</td>
<td>0.88</td>
<td></td>
<td>46</td>
</tr>
<tr>
<td>010501</td>
<td>ZrC/Mo 1089F</td>
<td>90</td>
<td>160</td>
<td>48</td>
<td>6.1</td>
<td>~10⁻⁸</td>
<td>1</td>
<td>~1.1x10⁻⁷</td>
<td>41</td>
<td>0.85</td>
<td></td>
<td>52</td>
</tr>
<tr>
<td>032701</td>
<td>ZrC/Mo 1096D</td>
<td>50</td>
<td>130</td>
<td>276</td>
<td>19.9</td>
<td>10⁻⁶</td>
<td>7.6</td>
<td>8.9x10⁻⁶</td>
<td>0.43</td>
<td>0.0027</td>
<td></td>
<td>99.7</td>
</tr>
</tbody>
</table>

Note: %ΔI represents the percentage change in current, and recovery time in UHV (hr) indicates the time taken for recovery in ultra-high vacuum conditions.
Figure 7. I-V data taken with cathode Mo-1100C before Exp. #91300.

Figure 8. Current and Pressure data from Exp. #91300A with cathode Mo-1100C.

Figure 9. Current and pressure data from Exp. #91300B with cathode Mo-1100C.
Figure 10. Current and pressure data from Exp. #91500 with cathode Mo-1100C.

Figure 11. Current and pressure data from Exp. #91700 with cathode Mo-1100C.

Figure 12. Current and pressure data from Exp. #91900 with cathode Mo-1100C.
Figure 13. Fowler-Nordheim plot and I-V data taken with cathode Mo-1100C before Exp. #91900.

Figure 14. Current and pressure data from Exp. #92100 with cathode Mo-1100C.

Figure 15. Current and pressure data from Exp. #100400 with cathode ZrC/Mo-1096D.
Figure 16. Cathode ZrC/Mo-1096D characteristics before Exp. #101100.

Figure 17. Current and pressure data from Exp. #101100 and 101700 with cathode ZrC/Mo-1096D.

Figure 18. Current and pressure data from Exp. #103100 with cathode ZrC/Mo-1096D.
Figure 19. I-V characteristics of cathode 1096D before Exp.#032701 with an anode voltage of 100 V.

Figure 20. ZrC/Mo 1096D cathode current response to increase in oxygen pressure in Exp.# 032701.

Figure 21. Data from Figure 20 shown on a different scale.
Figure 22. Cathode current response to operation at increased voltages in $10^{-6}$ Torr of oxygen in Exp. #032701.

Figure 23. Normalized current vs. pressure and time from Exp. #032701 and previous experiments #101100, 101700, 103100.
Figure 24. Current and pressure from Exp. #121100 with cathode ZrC/Mo-1089F

Figure 25. I-V data taken after the Exp. #121100 with cathode ZrC/Mo-1089F and an anode voltage at 260 V.
Figure 26a,b. Current and pressure from Exp. #122100 with cathode ZrC/Mo-1089F.

Figure 27a,b. Current and pressure from Exp. #010501 with cathode ZrC/Mo-1089F.
Figure 28. Comparison of performance decay rates of both ZrC/Mo cathodes in oxygen.

Figure 29. Comparison of performance decay rates of ZrC/Mo and Mo cathodes in oxygen.

References