Effects of Environmental Exposure on Barium Oxide Cathode Operation

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Hollow cathode assemblies (HCA) are typically designed around a cylindrical emitter for the electron source. Barium oxide (BaO) emitters are one type of emitter commonly used, which consists of a porous tungsten matrix impregnated with a mixture of barium oxide, calcium oxide, and alumina. Barium oxide emitters are susceptible to poisoning by a variety of substances, including oxygen, water vapor, carbon dioxide, and air. Poisoning can occur both during operation and exposure during storage, handling, and transportation. Water vapor is the primary contaminant of concern with ground exposure and has been historically controlled by appropriate storage and handling procedures. Over the past several years, NASA Glenn Research Center (GRC) has been testing BaO cathodes to observe the effects on cathode operation after extended environmental exposures. These observations suggest that controlled exposures to ambient environments for extended periods could have minimal impact to cathode operation following proper cathode conditioning.

I. Introduction

Hollow cathodes are used in electric propulsion (EP) devices as the electron source for both ionizing the propellant in the discharge as well as for neutralizing the ion beam in the thruster plume. Hollow cathode assemblies (HCA) are typically designed around a cylindrical emitter for the electron source. One leading type of emitter used is the barium oxide emitter (BaO), which consists of a porous tungsten matrix impregnated with a mixture of barium oxide, calcium oxide, and alumina [1]. BaO-based emitters have traditionally been used in NASA cathodes and EP devices, particularly those that utilize xenon as the propellant.

Barium oxide emitters are susceptible to damage by a variety of substances, including oxygen, water vapor, carbon dioxide, and air [2–6]. This damage can occur both during operation and from exposure during storage, handling, and transportation. Poisoning of a cathode emitter leads to an increase in work function of the emitter during operation. An increased work function leads to lower emission current at a given operating point [3]. If emission current is held constant, the increased work function leads to a higher operating temperature for the emitter [6].

Poisoning during operation can lead to short-term and long-term effects. Short-term increases to the work function caused by impurities such as oxygen in the feed gas can be quickly reversed by removal of the impurity [6]. Long-term poisoning can promote the formation of tungstates and cause other deleterious chemical reactions on the surface of the emitter [6–8]. These effects are more difficult to reverse and can lead to reduced operating life of the hollow cathode. Operational poisoning is prevented by minimizing impurities of the working gas, controlling the operating environment, and designing and maintaining integrity of the propellant feed system [7].

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Damage from exposure is typically a slower process and can take several forms, including blistering, blooming, and poisoning-like behavior with subsequent operation. During assembly and handling of a hollow cathode assembly, the emitter is exposed to the ambient environment. Certain constituents of the atmosphere, particularly water vapor (H_2O) and carbon dioxide (CO_2), react with the chemistry of BaO emitters. In particular, the barium calcium aluminate impregnate used in the emitters is very hygroscopic. Studies of commonly used impregnate formulations, such as 4 BaO:1 CaO:1 Al_2O_3 (4:1:1), show that exposure to water vapor in the atmosphere drives the critical reactions of concern [9, 10]. These same studies also show that many of these chemical reactions can be reversed by the appropriate application of heating in a vacuum environment. Controlled heating is applied to a cathode assembly after exposure to atmosphere and is referred to as *cathode conditioning*. Though it is thought that conditioning can reverse most of these reactions, ambient exposure on the ground is often controlled in practice through appropriate storage and handling procedures.

Limiting ambient exposures can be generally divided into three approaches:

1) Eliminating contaminating species by storing the emitter in either an inert gas or vacuum environment, or by applying an inert gas purge.
2) Controlling the ambient conditions for storage, i.e. maintaining humidity and temperature within specified limits.
3) Limiting the total time of ambient exposure.

The first approach prevents undesirable reactions from ever happening, while the other approaches limit the overall magnitude of reactions, with the presumption that they are cumulative in nature [10]. Some combination of the above three approaches is often chosen. It becomes more difficult to apply approach #1 as assembly, test, and integration progresses, particularly once the thruster has been integrated onto the spacecraft. Eventually, the total time for ambient exposure (#3) can also be difficult to limit in a practical manner; while spacecraft and launch vehicle fairing environmental conditions are controlled, accommodating complex spacecraft integration and testing, and extensive launch windows in particular, can put serious strain on low total exposure durations.

To this end, over the past several years, NASA Glenn Research Center (GRC) has been testing BaO cathodes to observe the effects on cathode operation after extended environmental exposures. Ambient environments tested have targeted launch vehicle processing and fairing conditions.

II. Approach

The high-level test plan for the extended exposure cathodes consisted of the following steps:

1) Brief operation and characterization of performance prior to exposure.
2) Exposure to nominal ambient environment.
3) Post-exposure operation and characterization.
4) Longer duration operation and characterization.

A. Test articles

Two populations of hardware were used for the tests. The first set of cathodes was existing hardware from prior GRC activities. Four cathodes were constructed in the late 1990's and subjected to similar environmental exposure testing in 1998. The cathodes were exposed to an environment of 26.7 °C and 50% relative humidity, corresponding to a dew point of 15 °C, for a duration of 480 h. At the conclusion of this testing, the cathodes were stored in dry nitrogen storage boxes until 2018, at which point steps #1–3 in the above test plan were executed. The cathodes were returned to dry nitrogen storage until 2021, when step #4 was undertaken. This set of hardware will be referred to as the group A cathodes, enumerated A1–4.

A second population of four cathodes was constructed in 2020. The emitters used in these cathodes are from the same manufacturing batch as group A. Three of the emitters, which will be labelled as the group B cathodes (B1–3), were previously used in the testing described in [11]. The testing performed was analogous to steps #1-3, though it occurred in custom glass test vehicles and not in traditional hollow cathode assemblies. A final emitter, labeled C1, was installed in a cathode assembly at the same time as the group B cathodes were built. This emitter was fresh from factory packaging and served as a control with no ambient exposure. The group B and C1 cathodes then went through the step #4 testing, noting that cathode C1 never had any significant ambient exposure.

All test articles were 1/4"-class cathodes, with nominal operating currents of 3 A and xenon flow rates of 6 sccm. The cathode assemblies did not have keepers; ignition was performed by applying a voltage between the cathode and an

Table 1 Launch vehicle processing environments.

Launch Vehicle	Temperature (°C)	Relative Humidity	Dew point (°C)
Ariane 5	21–25	60 %	13–17
Atlas V	21–27	55 %	12–17
Falcon	18–24	60 %	10–16

Table 2 Ambient exposures for the test cathodes.

Cathode	Exposure duration (h)	Relative Humidity	Temperature (°C)	Dew point (°C)
A1	2117	49.5 %	27.6	16.0
A2	4033	49.4 %	27.6	16.0
A3	6002	49.4 %	27.6	16.0
A4	7990	49.4 %	27.6	16.0
B1	1268	44.3 %	25.6	12.5
B2	4030	44.3 %	25.6	12.5
B3	7531	44.3 %	25.6	12.5
C1	0	–	–	–

anode placed 1" downstream. Each cathode assembly was instrumented with a thermocouple attached to the orifice plate.

Due to the nature of the prior testing on group B, the cathode assemblies used for the B and C emitters differed slightly from the group A cathodes; the main difference was the emitter retention scheme. The group B and C assemblies used a spring to push the emitter against the orifice plate, while the group A emitters had wire "legs" that performed the same role.

B. Pre-exposure operation

Prior to atmospheric exposure, cathodes from group A were placed in a vacuum facility and had their operation characterized. Cathodes were allowed to vacuum soak before conditioning. Conditioning consisted of running the cathode heater for several hours in a controlled fashion without a plasma discharge. After conditioning was completed, the test articles were ignited and characterized.

Characterization consisted of operation at discharge currents of 2.75 A and 3 A and flow rates between 4.5–9 sccm. Telemetry was collected for discharge current and voltage, flow rate, orifice plate temperature, and peak-to-peak and RMS measurements of both discharge current and voltage. Group A cathodes were characterized in Vacuum Facility 61 (VF-61) at NASA GRC.

The group B emitters were characterized pre- and post-exposure as detailed in [11]. Characterization and operation occurred in custom glass test vehicles, and the emitters were not installed in traditional hollow cathode assemblies.

C. Ambient exposure

The exposures targeted were chosen to approximate the sea-level exposure a cathode might experience during launch base operations and after being encapsulated in a launch vehicle fairing. Table 1 lists environments from several launch vehicle user guides that spaceflight hardware would be exposed to during processing and encapsulation [12–14]. A dew point range of 10–17 °C spans these environments, with the nominal value being approximately 14 °C.

All cathode assemblies were exposed in an environmental chamber to simulate an environment representative of those listed in Table 1. Exposure was monitored throughout the duration. Group A cathodes were exposed to an average temperature of 27.6 °C, a relative humidity of 49.4 %, and a dew point of 16 °C. Group B cathodes were exposed to an average temperature of 25.6 °C, a relative humidity of 44.3 %, and a dew point of 12.5 °C. Exposure durations varied by cathode and ranged from 1268–7990 h. Specific exposures conditions and durations are listed in Table 2.

While relative humidity is often used to denote the water vapor content in the atmosphere, its definition is dependent

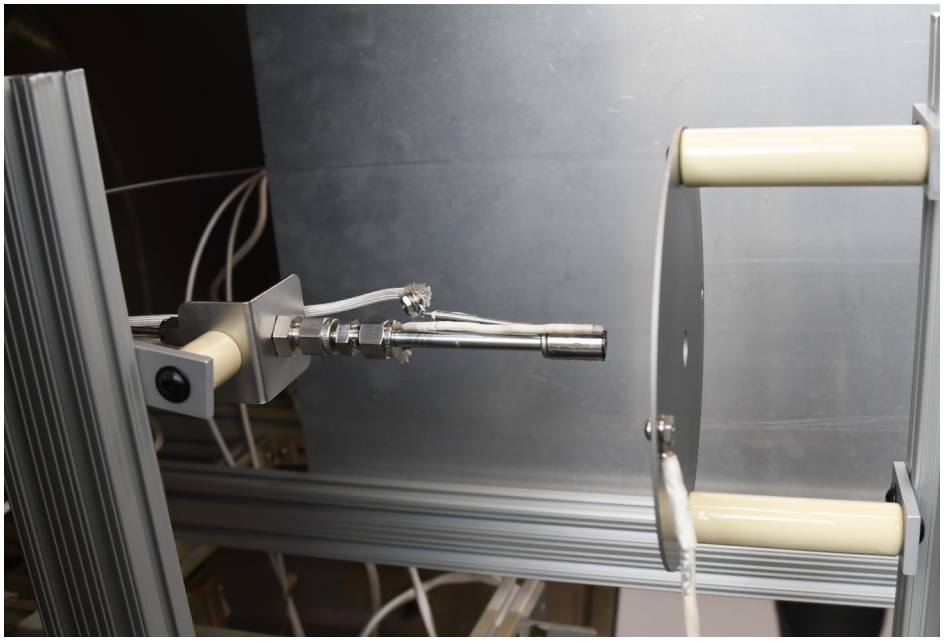

Fig. 1 A test cathode installed in VF-67. The plate anode is on the right. The second cathode is located behind the metal divider.

on the temperature. For the purposes of cathode exposure, the absolute water vapor content (or water vapor partial pressure) in the atmosphere is what drives the chemical reactions in the cathode emitter. Using dew point can make comparisons of water content over a range of temperatures easier as it is directly correlated to water vapor partial pressure.

D. Post-exposure operation

After ambient exposure, cathodes were again placed in a vacuum facility and characterized. The process was identical to the pre-exposure characterization and operation for each group of cathodes.

In contrast to the group A cathodes, the group B emitters were operated after post-exposure characterization for an extended duration, as described in [11]. Cathode B1 was operated for 1128 h, B2 for 2256 h, and B3 for 1992 h. This operation was *not* in a traditional hollow cathode assembly like the rest of the testing presented here.

E. Long-duration operation

For all cathodes except for the control unit C1, the prior steps occurred in 2018. From 2018 to 2021, the cathodes were either stored in dry nitrogen storage boxes (group A cathodes) or in evacuated glass test vehicles (group B cathodes). Group B and C emitters were installed in hollow cathode assemblies prior to the long-duration operation test; the group A cathodes were tested in their existing assemblies.

All cathodes were characterized again at the beginning of the long-duration operation phase. Characterization consisted of operation at discharge currents of 2.75 A and 3 A and flow rates between 4.5–9 sccm. Cathodes were then operated at a nominal discharge current of 3 A and a flow rate of 6 sccm for 500 h. Following the 500 h operating segment, the cathodes were again characterized.

Cathodes were tested two at a time in Vacuum Facility 67 (VF-67) at GRC. Each cathode had a plate anode positioned 1" from the orifice plate. The anode had a 0.5" diameter hole about which the cathode was axially centered. The hole provided a sightline for a disappearing filament pyrometer. The two cathodes were separated by a metal divider and were operated at the same time. See Fig. 1 for a photo of a cathode installed in the facility.

After all 8 cathodes were operated for 500 h each, two of the cathodes, A2 and B2, were reinstalled into the facility and operated for an additional 2630 h for a total of 3130 h of operation post-exposure. The cathodes were removed at the end of the initial 500 h segment and put in dry N_2 storage for several months, before being reinstalled for the

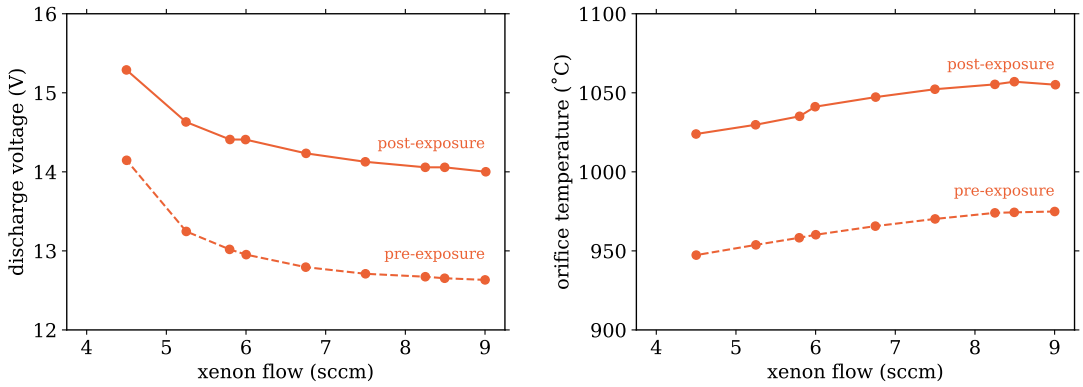

Fig. 2 Cathode A4 characterization at 3 A comparing pre- and post-exposure discharge voltage and orifice temperature.

Table 3 Averaged operating changes before and after exposure.

Cathode	Discharge voltage change (V)	Orifice temperature change (°C)
A1	1.7	154
A2	2.6	161
A3	1.3	110
A4	1.4	80

additional testing.

III. Results

A. Pre- and post-exposure characterization

Group A cathodes were characterized before and after controlled ambient exposure. All four cathodes exhibited an increase in discharge voltage on the order of 1.5 V immediately following exposure. Some portion of this could potentially be from slight variations in test setup as the test facility was used for other purposes during the environmental exposure. None of the operating voltages were deemed unacceptably high or out of family. Plume mode transition was also examined, and no change was observed post-exposure.

Discharge voltage and orifice temperature characterization for the 8000 h exposure cathode (A4) can be seen in Fig. 2. The other three cathodes showed similar behavior.

Changes in operating voltage and orifice temperature differences pre- and post-exposure are summarized in Table 3. Values are averaged over the flow rates tested. As can be seen, operating temperature rose significantly immediately after exposure. Operating temperature appeared to drop with continued operation, but the group A cathodes were operated for less than 10 h after exposure. The A2 cathode's out-of-family discharge voltage increase is likely due to a change in the test setup.

The emitters used in the group B cathodes underwent an analogous characterization before and after exposure, as detailed in [11].

B. 500 h test segment

Cathodes showed similar behavior when comparing characterizations made at the beginning and the end of the 500 h test segment, with each group exhibiting like behavior. An example of the 8000 h exposure cathode (A4) can be seen in Fig. 3. Discharge voltage dropped over the course of the 500 h test segment on the group A cathodes, while orifice temperature showed a large decrease at the 500 h characterization. On the other hand, group B cathodes exhibited

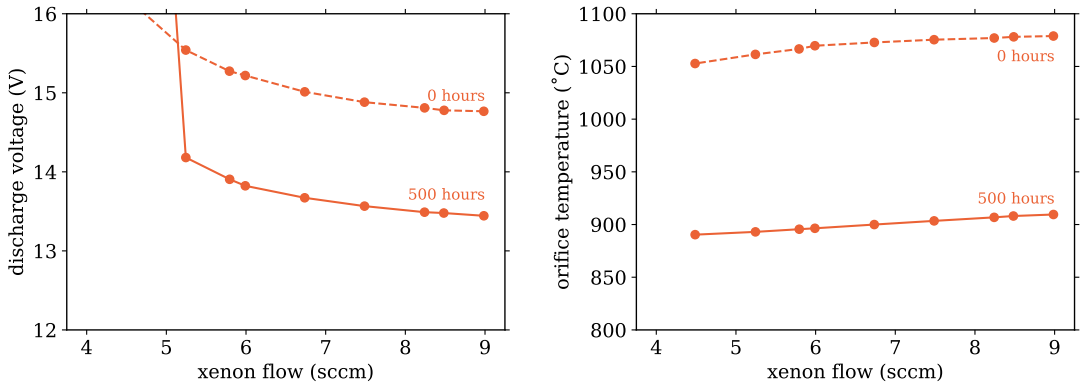

Fig. 3 Cathode A4 characterization at 3 A comparing discharge voltage and orifice temperature at 0 h and 500 h of operation.

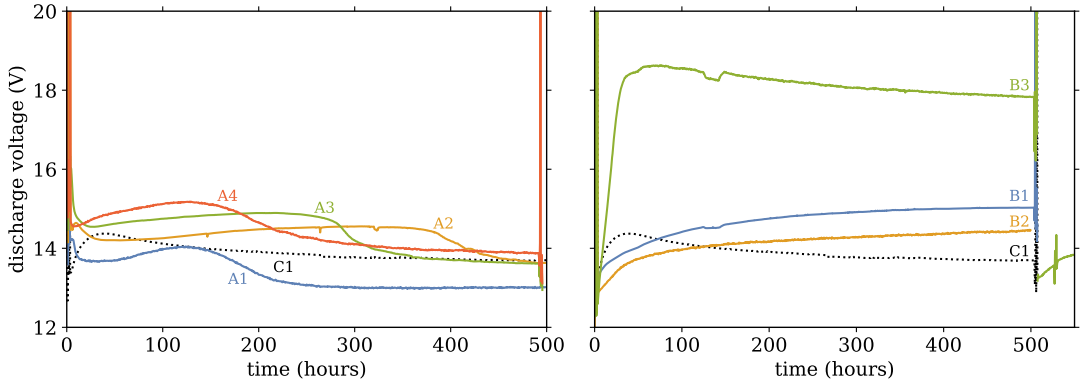

Fig. 4 Discharge voltage for the cathodes during the 500 h wear test.

an increase in discharge voltage on the order of 1 V, while orifice temperatures were either slightly lower (B2, B3) or slightly higher (B1) at the 500 h characterization.

Data from the continuous operation during the 500 h are shown in Figs. 4 and 5. Fig. 4 shows the discharge voltages from the cathodes. Group A cathodes showed a slight increase in discharge voltage in the first several hundred hours of operation before decreasing. Orifice temperature showed a rapid decrease in the first 24 h, followed by period of stability, and finally a drop of roughly 75 °C. The temperature drop was correlated with the timing of the voltage drop.

Group B cathodes showed a slowly increasing discharge voltage. Temperature dropped steeply in the first few tens of hours and slowly increased for the rest of the test segment. This trend was not apparent looking only at the 0 h and 500 h characterization data. Of note is the B3 cathode. During conditioning, it was suspected that the anode became contaminated. After initial characterization, the discharge voltage rose roughly 4 V over the course of 25 h of operation, but the 500 h test segment was allowed to continue. After the segment, it was confirmed that the contaminated anode was responsible for the rise in discharge voltage, and the cathode was recharacterized with a clean anode, where the discharge voltage returned to ~14 V. Data for B3 with the clean anode is shown in Figs. 4 and 5, after the 500 h mark.

The discharge voltage and orifice temperature of the C1 control cathode both peaked after approximately 39 h of operation, before decreasing for the rest of the test segment to values similar to the final values of the group A cathodes.

With respect to plume mode transition, the cathodes operating in VF-67 were able to transition to plume mode at slightly higher flow rates compared to the prior data obtained in VF-61. This was true for group A, B, and C cathodes. Presumably this is attributed to the difference in test setups, particularly the hole in the anode. There was no significant difference in transitional behavior between the beginning and the end of the 500 h test segment.

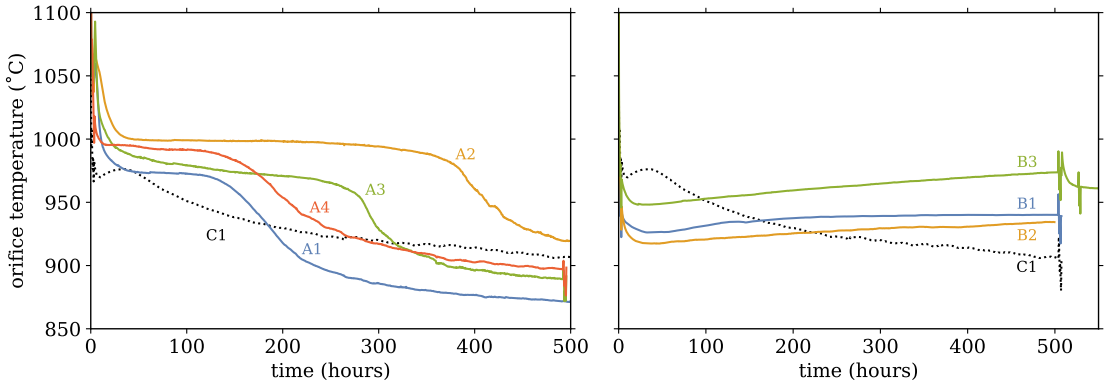

Fig. 5 Orifice temperature for the cathodes during the 500 h wear test.

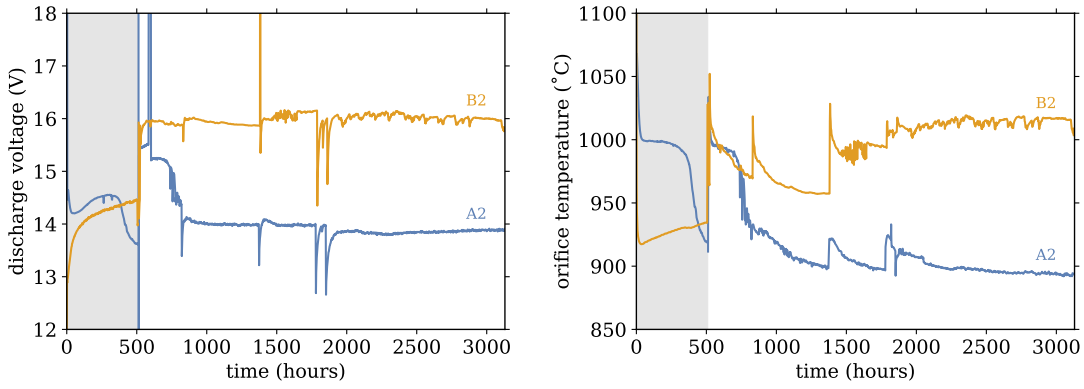

Fig. 6 Discharge voltage and orifice temperature for cathodes A2 and B2 during the 3130 h wear test.

Table 4 Summary of orifice temperatures.

Cathode	Exposure duration (h)	Characterization test - 2018 (°C)		Wear test - 2021 (°C)			
		Pre-exposure	Post-exposure	4 h	24 h	500 h	3130 h
A1	2117	960	1063	1060	981	871	–
A2	4033	960	1052	1068	1010	919	895
A3	6002	1000	1077	1093	995	889	–
A4	7990	985	1012	1018	995	897	–
B1	1268	–	–	940	928	940	–
B2	4030	–	–	943	918	934	1007
B3	7531	–	–	974	949	961*	–
C1	0	982†	–	980	975	906	–

* The temperature for cathode B3 at 500 h was taken after it was tested with the new cleaned anode.

† C1 was characterized in the 2021 wear test.

C. 3130 h extended segment

Fig. 6 shows the discharge voltage and orifice temperature of the A2 and B2 cathodes during the full 3130 h wear test with the first 500 h test segment shaded gray. Discontinuities at 500 h, 825 h, 1375 h, 1785 h and 1860 h were due to vacuum facility venting. The cathodes were not removed, and the configuration was unchanged for all of these except the 500 h venting. The A2 and B2 cathodes showed clearly different behavior during this test. Discharge voltage on the A2 cathode started high but settled down after a few hundred hours of operation where it remained. Upon reinstallation, the B2 cathode's voltage was higher than at the end of the 500 h segment, but it remained relatively stable for the rest of the testing.

Likewise, the orifice temperatures of the two cathodes showed different behavior. The A2 cathode temperature had dropped during the 500 h segment. Upon reinstallation, it returned to its previous higher value of ~1000 °C, before dropping to an even lower temperature after continued operation. The B2 cathode had showed a slightly rising temperature during the 500 h segment. During the next 900 h, the temperature started out high but exhibited a steady drop until the venting at 1375 h, where the temperature rose again and hovered around 1000 °C.

After the 500 h segment, the B2 cathode assembly did need to be adjusted. During this first wear segment, the emitter-retaining spring relaxed and needed to be adjusted to ensure good contact between the emitter and the orifice plate. It is possible that some of the behavior the B2 cathode exhibited during the full 3130 h wear test is due to degradation of this retaining mechanism.

Despite the differences in voltage and temperature observed in the A2 and B2 cathodes, the operating parameters of both cathodes were within the bounds of nominal operation.

IV. Discussion

Table 4 shows the orifice temperature summary data of all eight cathodes. Presented are group A cathode pre- and post-exposure orifice temperatures, taken from the 2018 characterization test as well as temperatures at 4 h[a], 24 h, and 500 h of the 500 h wear test for all cathodes performed in 2021. Additionally, orifice temperatures of cathodes A2 and B2 at the end of the 3130 h of operation are tabulated.

As stated previously, the group A cathodes saw a significant increase in operating temperature following exposure. This increased temperature was maintained after the cathodes were removed from 3 years of storage and operated again. After 24 h of operation, temperatures dropped significantly, nearing the pre-exposure operating temperatures. This trend continued, and by the end of the 500 h test, the orifice temperatures had dropped well below the pre-exposure temperatures.

The group B cathodes behaved differently from the group A cathodes. The orifice temperatures measured at the beginning of the wear test were not as high as the group A post-exposure temperatures; they were more in line with the group A pre-exposure temperatures. Temperatures dropped for the first 30–45 h of operation by 15–25 °C. The values

[a]Data was taken at 4 h, after the characterization was completed.

listed in Table 4 at the 24 h point are close to the minimum temperatures measured. After this period, the temperatures slowly recovered close to values measured at 4 h.

The C1 control cathode displayed a reduction in operating temperature over the course of the test segment, starting near the pre-exposure temperatures of the group A cathodes and ending around the same temperatures that the group A cathodes ended at.

It is unknown why the group A and B cathodes showed different behavior after exposure. It is possible that during the extended post-exposure operation as described in [11] that the B cathodes went through prior to the 500 h test segment, the emitter temperature evolved significantly in an unobserved manner. It is also possible that the difference in the controlled exposure environments may have had an impact, as the dew point of the group B cathodes was 3.5 °C lower. Another potential factor is that the environmental chamber that the group A cathodes were exposed in lost power at one point; it is possible that an unrecorded excursion in dew point occurred during this outage, which may have affected the emitters.

Regardless of this difference, the group A cathodes 'recovered', exhibiting relatively normal orifice temperatures with minimal operation (less than 24 h). Even during the period where elevated orifice temperatures were observed, the cathodes were well behaved and showed no difficulties in starting. The elevated temperatures, while high, were not so high as to cause significant concern. Emitter temperatures are assumed to be higher than the observed orifice temperatures by ~125 °C, as shown in [15]. While prior studies of emitter temperatures in operating cathodes found that orifice plate temperatures were ~75 °C *higher* than peak emitter temperatures [6], it is unlikely that the cathodes described here had emitter temperatures as low as 800 °C.

Barium depletion models [16–18] suggest that the expected impact to cathode lifetime is minimal. The likely emitter temperatures were not high enough to cause barium depletion to become the life-limiting factor of the cathode assembly. In addition, the time at the elevated temperature was relatively short, measured in hours. The rapid reduction to lower temperatures within 24 h means that any excess barium depletion from elevated emitter temperature is limited to just a few hours, not occurring over the tens of thousands of hours of the full cathode lifetime. This assumes a cathode design that is appropriate for the needed discharge current. As shown in [15], peak emitter temperature can vary over a wide range depending on the operating condition. Cathodes that are operated near their design capability could be pushed into sub-optimal emitter temperatures if exposure induced effects increased operating temperatures even more.

The rapid recovery of operating temperatures from the post-exposure increase in the group A cathodes is encouraging, implying that detrimental effects from atmospheric exposure can be short lived. The group B cathodes displayed no anomalous increase in operating temperature after exposure, and they exhibited relatively nominal behavior throughout the wear testing. These observations, coupled with the encouraging activity curves before and after exposure presented in [11], suggest that controlled exposures to ambient environments for extended periods of time appears to have minimal impact, assuming proper cathode conditioning is performed before operation. Impacts on end-of-life behavior are unknown at this time.

V. Future Work

Due to the varied prior histories of the hardware used for testing, a final set of cathodes is being constructed and will undergo testing similar to the work presented here. Testing will be augmented with extended operation prior to environmental exposure, meant to simulate operation hours accumulated during acceptance testing. This extended operation prior to ambient atmospheric exposure could make the emitter chemistry more susceptible to detrimental effects from the exposure.

VI. Conclusion

Multiple BaO hollow cathode assemblies have been operated following extended exposure to environmental conditions. Two sets of cathodes have been successfully operated for 500–3130 h following exposures of up to 8000 h to ambient conditions simulating launch processing and fairing environments. Some cathodes did exhibit increased operating temperatures following exposure; however, operating temperature in these cathodes quickly recovered. These observations suggest that controlled exposures to ambient environments for extended periods could have minimal impact to cathode operation following proper cathode conditioning.

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