Applied Ion Systems

AIS-TR-005

AIS-gPPT2-1C Gridded Pulsed Plasma Thruster

End of Life Report

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I. OVERVIEW

This report represents the end of life analysis and conclusion of the development phase of the AIS-gPPT2-1C Single-Channel Gridded Pulsed Plasma Thruster. The purpose of this report is to review the thruster after prior testing phases and provide insight on damage mechanisms associated with thruster operation at the nominal tested energy levels, as well as establish reasons for the ultimate lifetime limit of 500 shots found with the thruster design, and provide future recommendations going forward for the next generation thrusters, helping to ultimately expand research information and work on optimizing this unique and relatively unexplored class of sub-Joule micro pulsed plasma thrusters for PocketQube-class satellites.

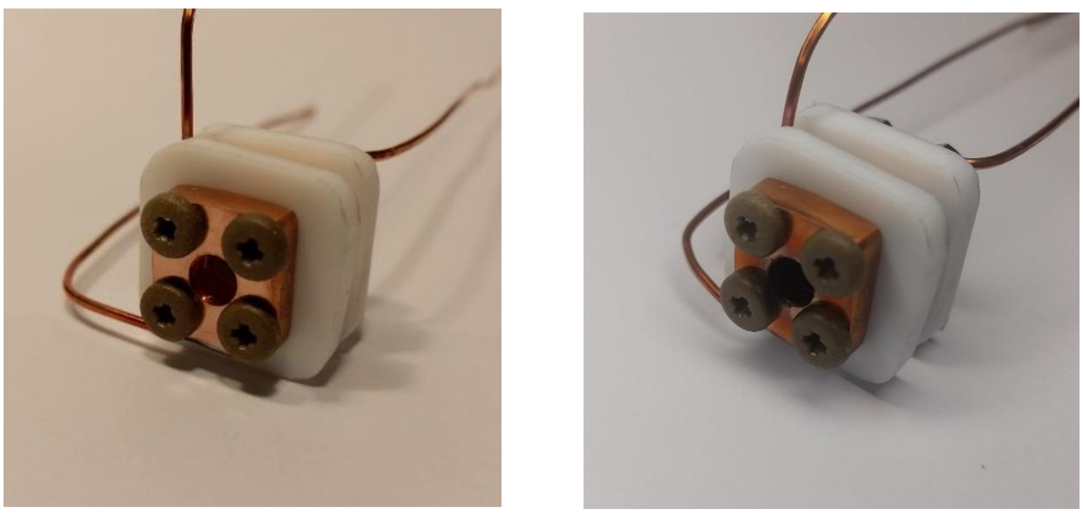

FIGURE 1: *Before testing (left) and after testing (right) of the AIS-gPPT2-1C thruster.*

II. ANODE ANALYSIS

The anode is the top-most electrode of the thruster assembly, charged up to 1.3kV during testing, which allows for the main discharge to occur between it and the bottom cathode electrode after the initial trigger pulse. A picture of the anode after testing can be seen in *Figure 2* below:

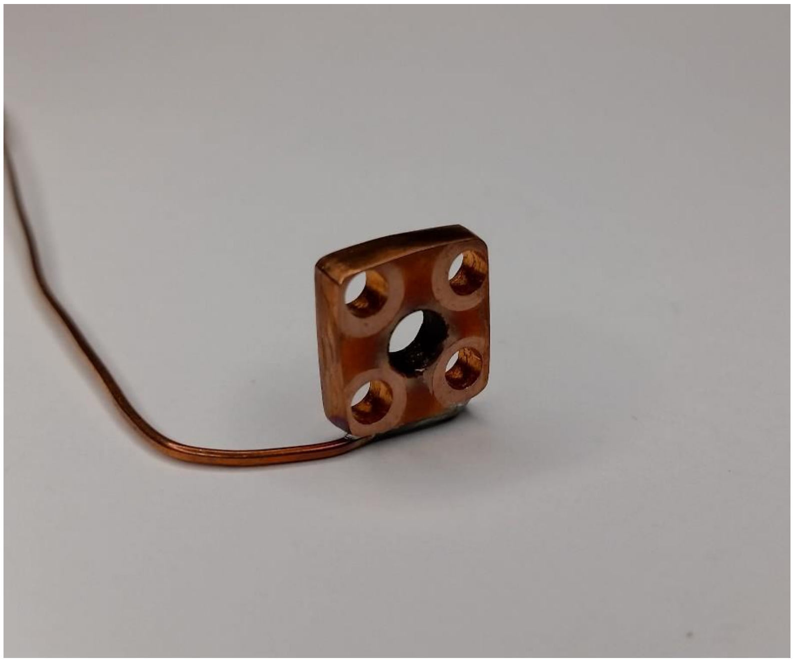

FIGURE 2: *Post testing anode*

Clear indication of fuel deposition both on the surface of the anode, as well as inside the anode bore can be observed. The areas where the PEEK bolt heads were located over the mounting holes can be seen to be deposit free compared to the rest of the surface. A close-up view of the bore can be seen in *Figure 3* below under a low-intensity optical microscope:

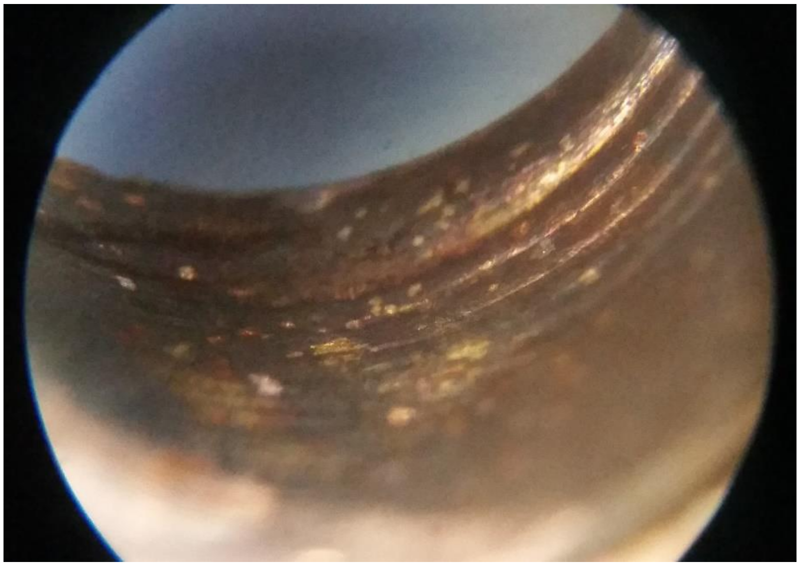

FIGURE 3: *Microscopic view of the anode surface*

There is again clear indication of fuel deposition buildup on the surface of the anode, which indicates carbon charring of the Teflon fuel. However, there appears to be minimal physical wear or erosion of the anode surface despite the main discharge and plasma interaction with the anode bore. The grooves around the face of the anode are from machining, and are not actual erosion. Around the surface, tiny lighter specs can be seen against the darkened surface, indicating arc attachment points from the main discharge. Overall, distribution looks fairly even and random in nature. There is currently no indication of measureable electrode wear for the anode over the course of 500 shots for the varying shot energies from 0.24J to 0.84J.

III. IGNITER ANALYSIS

The second electrode of the thruster assembly, located in the center of the thruster stack, is the igniter. Initial visual inspection of the igniter bore surface indicates carbon deposition around the area of the bore directly under the Teflon fuel plate, with less discoloration towards the back. This carbonized ring around the upper part of the bore also coincides with the cathode pin edge where ignition would most likely occur.

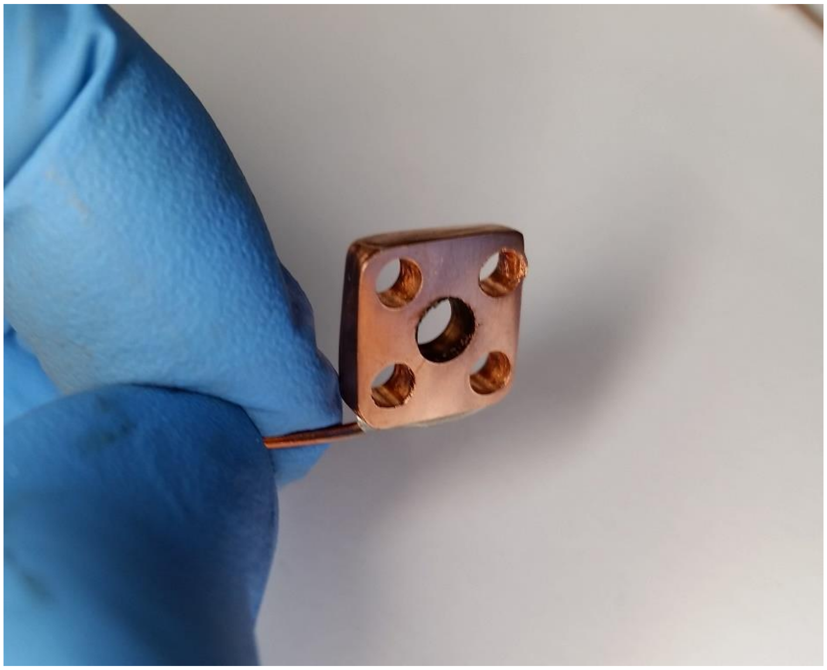

FIGURE 4: *Igniter electrode post-testing*

Inspection under the microscope confirms this, with much more carbon deposit and arcing spots towards the front of the bore. These arc spots are due to the ignition pulse between the igniter and cathode pin. The lack of arcs or carbon deposit towards the back half of the bore indicates little to no damage, arcing, or ablation around the Teflon cathode insulator plate.

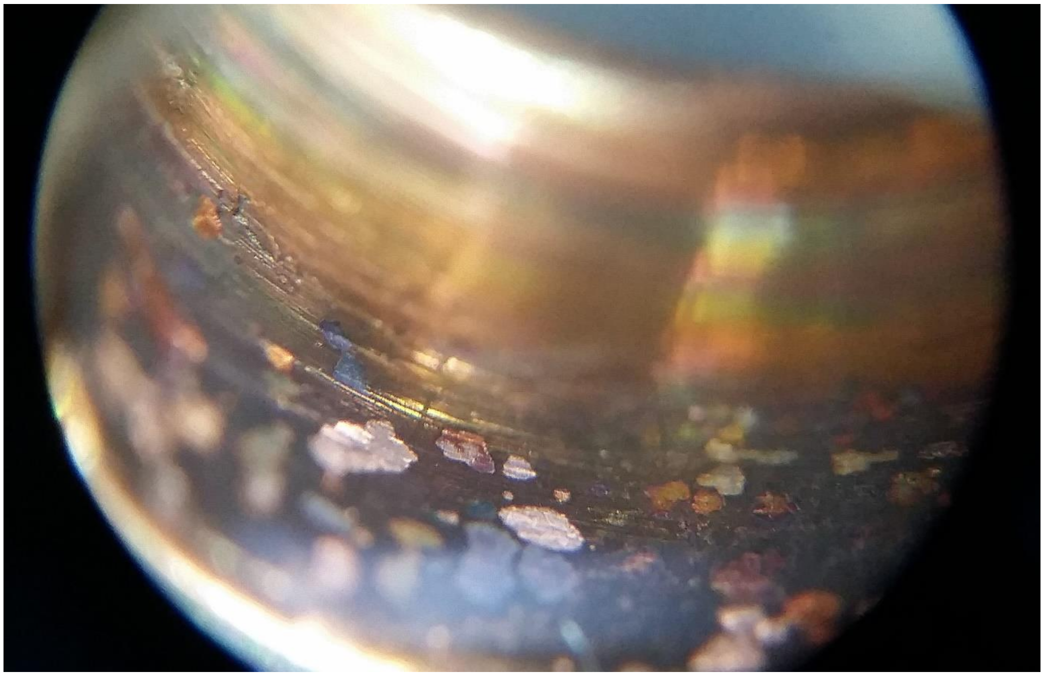

FIGURE 5: *Microscopic view of the igniter surface*

Despite the arcing and carbon deposit, there is little indication of significant damage or erosion to the igniter bore that would impede performance.

IV. CATHODE AND CATHODE INSULATOR ANALYSIS

The third and final electrode of the thruster assembly is the cathode plate, and is located at the bottom of the stack. The cathode connects to ground, and serves as the major electrode where both the igniter and anode discharge to during the ignition pulse and main discharge respectively. Due to this, the cathode will be under higher erosion and wear than the other two electrodes.

In this thruster configuration, the cathode extends out with a 0.125” diameter flat-ended pin, protruding fully into the igniter bore, and separated from the anode with the Teflon fuel plate. In addition, between the cathode and igniter plates, there is a Teflon insulator plate. The insulator plate connected to the cathode can be observed below in *Figure 6*.

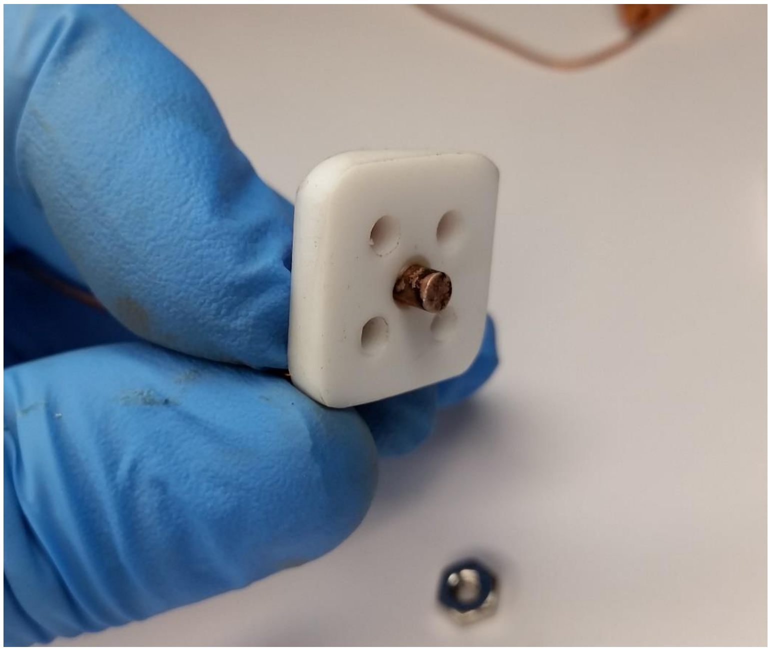

FIGURE 6: *Cathode pin and Teflon cathode insulator after testing*

While there is some evidence of wear and ablation on the Teflon insulating plate, damage is minimal, indicating that shorting failure at this stage of the thruster lifetime is not due to cathode-igniter insulation failure or charring.

FIGURE 7: *Teflon insulator after testing*

In Figure 8, the cathode electrode is separated from the insulator. A very clear ring of wear and carbon deposit can be observed around the circumference at the end of the cathode pin. Wear appears to be uniform around the cathode pin.

FIGURE 8: *Cathode pin surface erosion after testing*

Upon closer inspection under the optical microscope, discoloration of the copper and evidence of arc spots is noticeable. However, like the previous two electrodes, actual erosion from thruster operation is minimal, and does not appear to play any factor in thruster lifetime at this stage of testing. In *Figure 9*, a portion of the igniter pin around the circumference at the end of the electrode is observed. Due to the low energy of the igniter pulse, erosion is kept minimal. In *Figure 10*, the end of the cathode pin is viewed. This portion of the pin is more directly exposed to the main discharge between the cathode and the anode, and is evident with the larger area of discoloration. Scratches on the surface are due to machining and are not part of the erosion process. Despite the main discharge and exposure to the plasma, no perceptible or measurable change in electrode dimensions were observed. Overall, uniform erosion around the edge for ignition, as well as at the flat tip has been confirmed for the limited shot lifetime of the thruster during prior phases of testing.

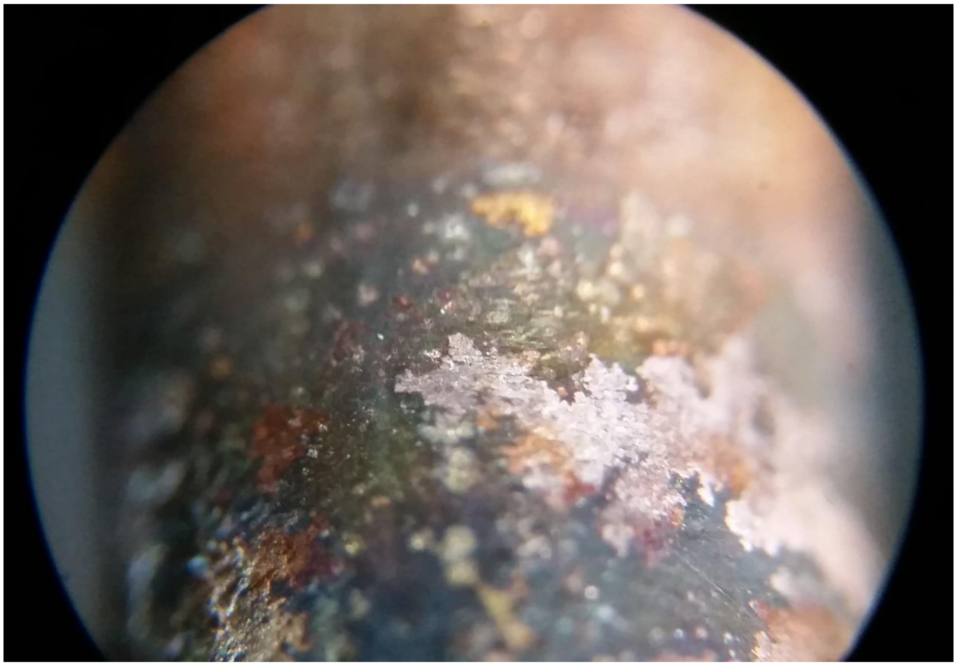

FIGURE 9: *Microscopic view of the circumference of the cathode pin surface erosion after testing*

FIGURE 10: *Microscopic view of the end of the cathode pin surface after testing*

V. TEFLON FUEL BORE ANALYSIS

The final component of the thruster, and main area of interest, is the Teflon fuel plate. This plate is located between the middle igniter plate and the upper anode plate, and provides the source of fuel for the thruster. Upon disassembly, it was immediately evident that the fuel bore suffered severe charring at the surface. This can explain the carbon deposits on the various other electrodes prior discussed. *Figure 11* depicts the Teflon fuel bore after 500 shots in the thruster.

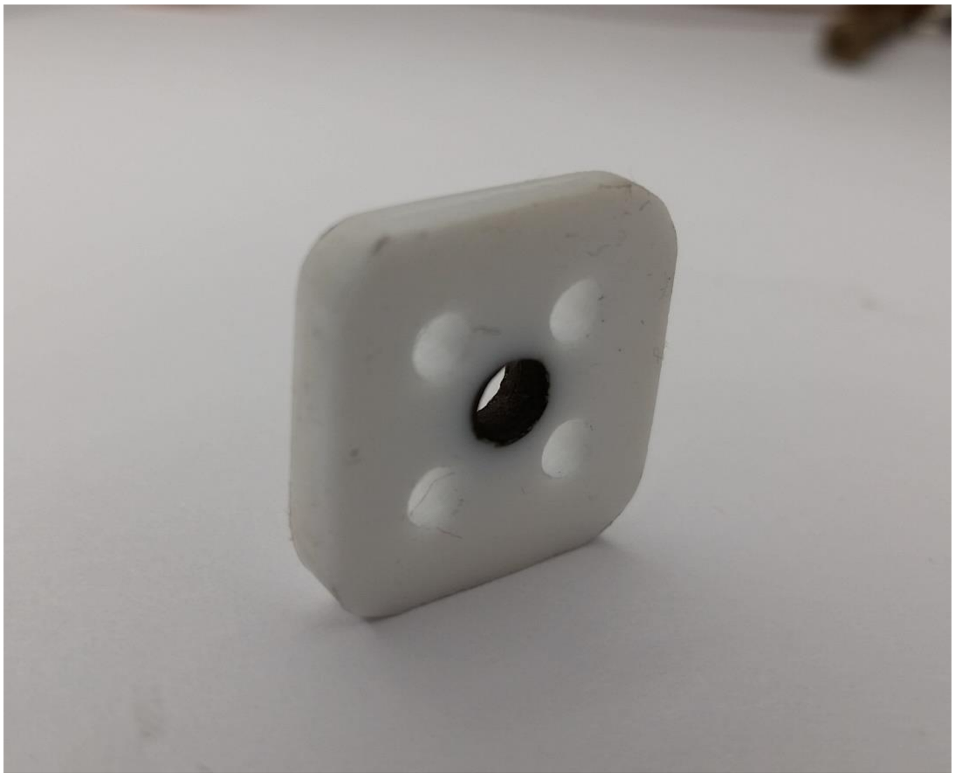

FIGURE 11: *Teflon fuel with severely charred bore after testing*

Upon further inspection under the microscope, a clear picture of very uniform charring and wear is evident along the surface of the fuel bore. Measuring the bore with calipers, there appeared to be no measurable deviation in bore diameter from the original starting diameter of 0.15”. During testing, towards the end of life of the thruster, it was observed that the thruster would break down randomly regardless of the ignition pulse. It can therefore be inferred that the cause of failure of the thruster over its 500 shot lifetime is due purely to charring of the Teflon fuel, causing the thruster to eventually short, as opposed to any electrode erosion or fuel depletion.

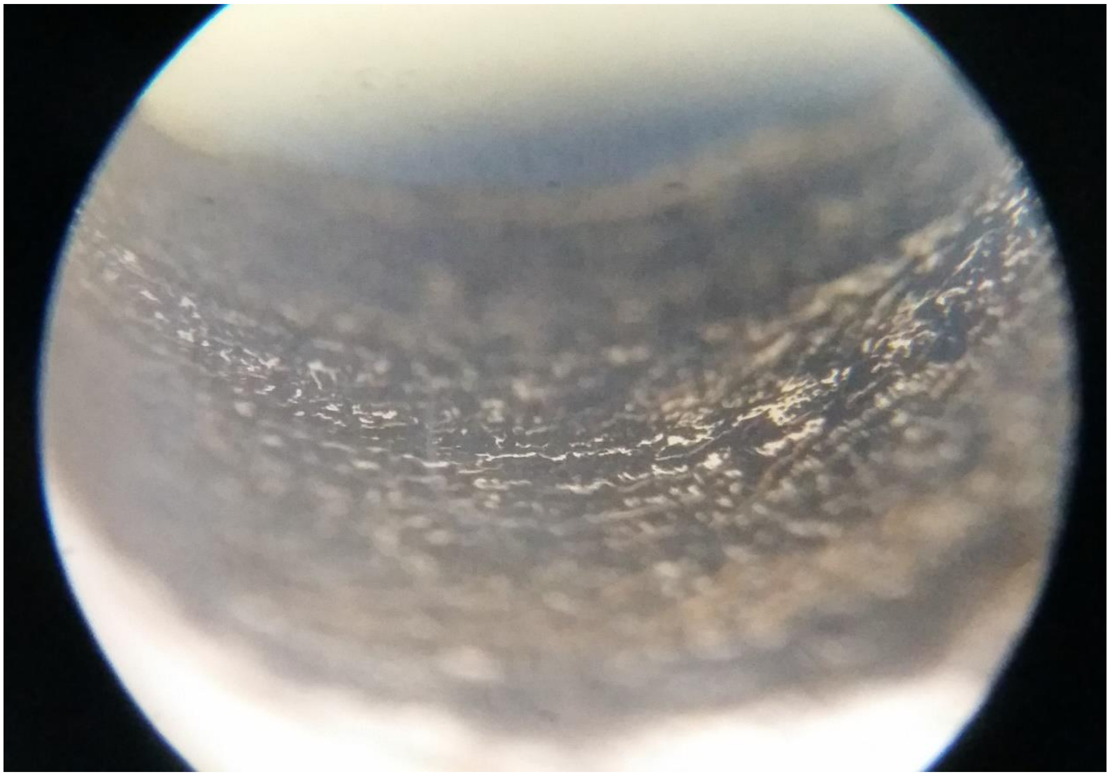

FIGURE 12: *Microscopic view of the Teflon fuel bore after testing*

VI. CONCLUSION AND FUTURE RECOMMENDATIONS

The AIS-gPPT2-1C thruster has been disassembled and studied at the end of its operating lifetime of 500 shots. Over the course of testing, various discharge energies, ranging from 0.24J up to 0.84J were used. Ignition testing, impulse bit, and lifetime tests have been successfully completed and documented on this thruster configuration. Based on the analysis presented above, the following conclusions can be made:

- The cause of failure of the thruster, ultimately limiting its lifetime to 500 shots, was a result of charring of the Teflon fuel, causing eventual misfires and shorting of the thruster.
- Uniform wear and charring of the Teflon fuel bore was observed, with no measurable changes in diameter over its lifetime. Therefore, it can be inferred that lifetime based on fuel usage is significantly higher than lifetime limits from charring.
- Uniform distribution of arc spots were observed on all three electrodes, showing good evidence that wear over extended use should be fairly uniform.
- While discoloration and arc spots were evident on all three electrodes, no noticeable erosion due to arcing or plasma was observed that would indicate any reduction in lifetime or failure modes at this number of thruster firings.
- Minimal wear on the Teflon cathode insulator plate was observed, along with the rear portion of the cathode pin and igniter bore, indicating that breakdown for the ignition

pulse, and subsequent plasma blow-back, is limited to the front of the cathode pin and kept away from the insulator.

Going forward, the key issue to be addressed is charring of the Teflon fuel. Based on the Teflon fuel bore starting surface area of 0.38 cm^2, and a maximum tested discharge energy of 0.84J, the maximum energy density on the fuel surface is 2.22 J/cm^2. Due to operation of this low-energy, sub-joule, coaxial pulsed plasma thruster in electrothermal mode, it is expected that the energy density on the Teflon fuel was excessive, causing significant charring of the fuel, resulting in radically shortened lifetime. This may be further exacerbated by the unusually short discharge length and aspect ratio of this particular thruster, due to space constraints for use with PocketQube-class satellites for which this thruster was designed for. Areas to explore to mitigate these effects include changing the fuel bore aspect ratio, decreasing the energy per shot for this configuration, exploring other fuels, and ultimately optimizing the energy density on the fuel surface to provide enough ablation for reasonable thrust while being low enough to prevent carbon charring of the Teflon.