Applied Ion Systems

AIS-TR-008

AIS-gPPT3-1C Integrated Propulsion Module V3
Phase III - Lifetime Testing - 09/30/2019-10/03/2019
Testing Report and Summary

Michael Bretti – 03/04/2020

I. TEST PARAMETERS

- **System:** AIS-gPPT3-1C Integrated Propulsion Module V3
- **Main Bank Capacitor:** 0.136uF C0G ceramic capacitor
- **Main Bank Charging Voltage:** 944-2000V
- **Shot Energy:** 0.06-0.27J
- **Pulse Repetition Rate:** 0.25-0.33 Hz
- **Total Number of Shots:** 1968
- **Maximum Chamber Pressure During Testing:** 1 x 10^-5 Torr
- **Testing Status:** COMPLETE

II. OVERVIEW

This test represents Phase III of testing and development for the AIS-gPPT3-1C Integrated Propulsion Module. The purpose of the test was to establish thruster lifetime and operational performance under extended periods. This test also served as the preliminary qualification runs for the two AIS-gPPT3-1C thrusters currently being prepared to be fabricated and integrated with AMSAT-Spain's two GENESIS 1.5P PocketQubes.

Due to premature bank failure of 130 shots from the prior two testing phases, the V1 thruster underwent several redesign iterations to accommodate new higher performance pulse capacitors. Several new changes and features were added to the board as a result. For Phase III testing, V3 of the AIS-gPPT3-1C thruster module was used.

The first major change of the thruster includes the use of Kemet high voltage pulse rated MLCC C0G SMT capacitors. The bank consists of two 0.068uF pulse capacitors in parallel, soldered vertically to accommodate for spacing with the limited area on the board for their larger size. The total bank size from V1 to V3 therefore decreased from 0.2uF to 0.136uF, and at the same charge voltage of 944V, also sees a reduction in bank energy from 0.09J to 0.06J.

In addition to the main capacitor bank change, the igniter bank was also upgraded to the same Kemet MLCC pulse capacitor. While no issues have occurred with the ignition capacitor due to the significantly lower stresses seen during operation, it was decided to factor in higher performance capacitors during the overall upgrade to mitigate possible issues in the ignition circuitry should they arise from extended operation. *Figure 1* shows a comparison of V1 and V3.

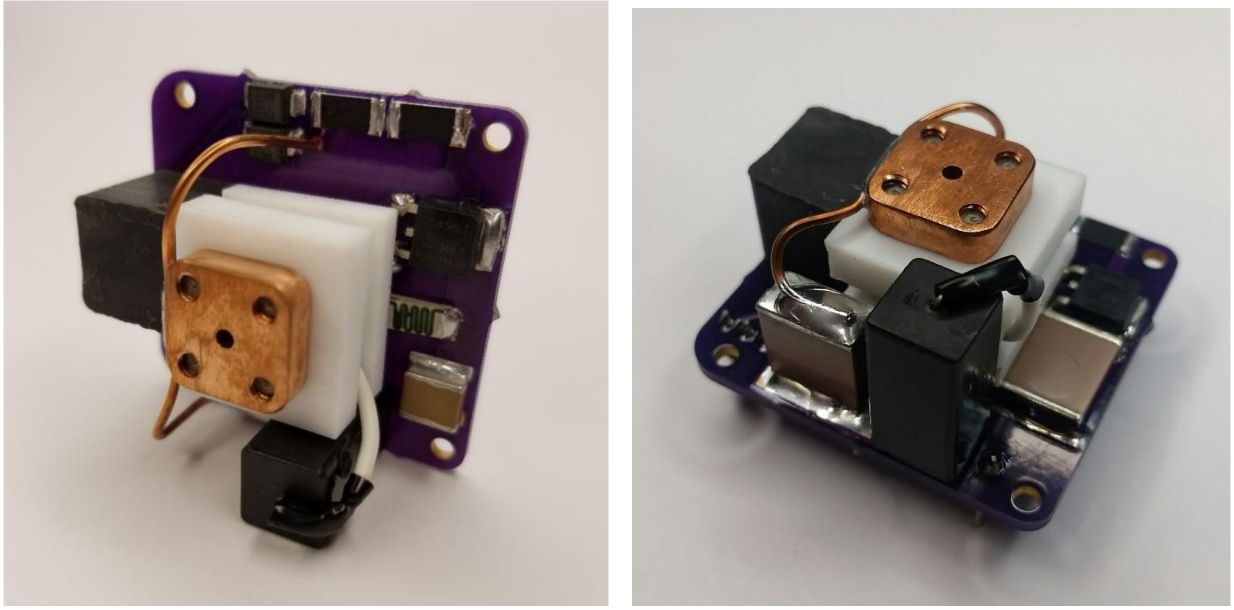

FIGURE 1: *AIS-gPPT3-1C Thruster Module - V1 (left), V3 (right)*

The high voltage charge circuitry remained the same from V1 to V3, with only slight changes in layout to accommodate the above mentioned upgraded capacitors. *Figure 2* shows the PCB changes from V1 to V3 on the top of the boards where the charging circuitry is located.

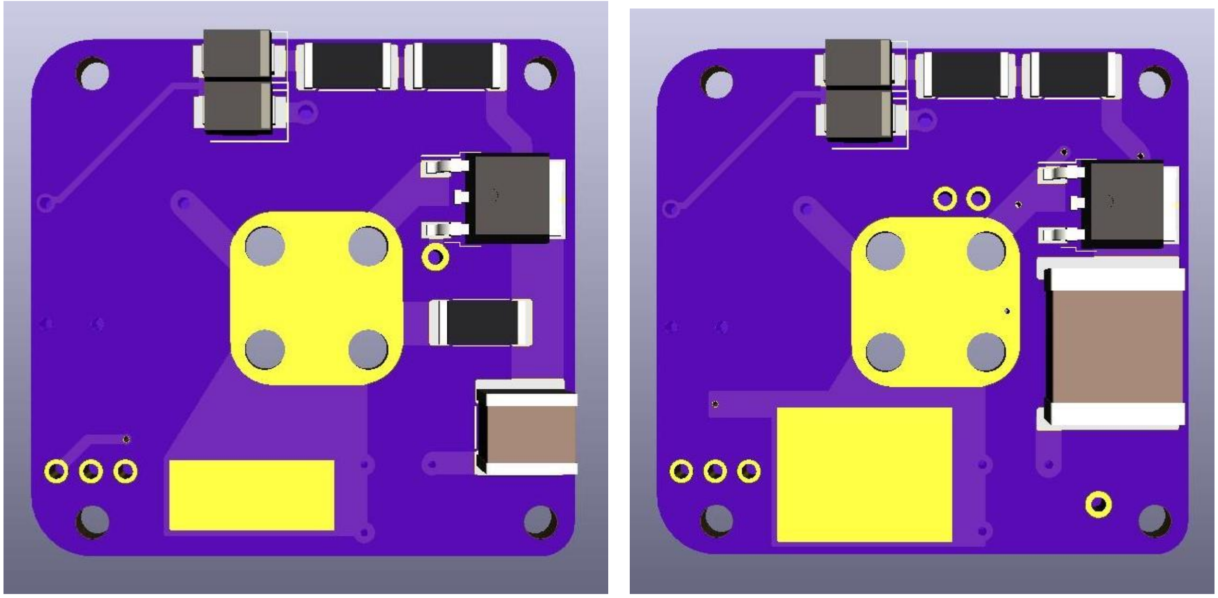

FIGURE 2: *AIS-gPPT3-1C Thruster Module PCB Front - V1 (left), V3 (right)*

Finally, high-value resistive divider readouts were included to view the voltages on the main pulse bank and the ignition bank. Each of the readouts drop the bank voltages from hundreds of volts down to a safe level of around 2.5V for max charge conditions for each bank. This simple solution provides critical diagnostic feedback during operation and troubleshooting of the thruster, and serves as a way to validate thruster operation in space. In addition, on the input side, an output filter and shunt resistor were removed from the load switch circuitry due to observed failures of these components during prior preliminary testing. *Figure 3* shows a comparison between the V1 and V3 boards with the circuitry changes.

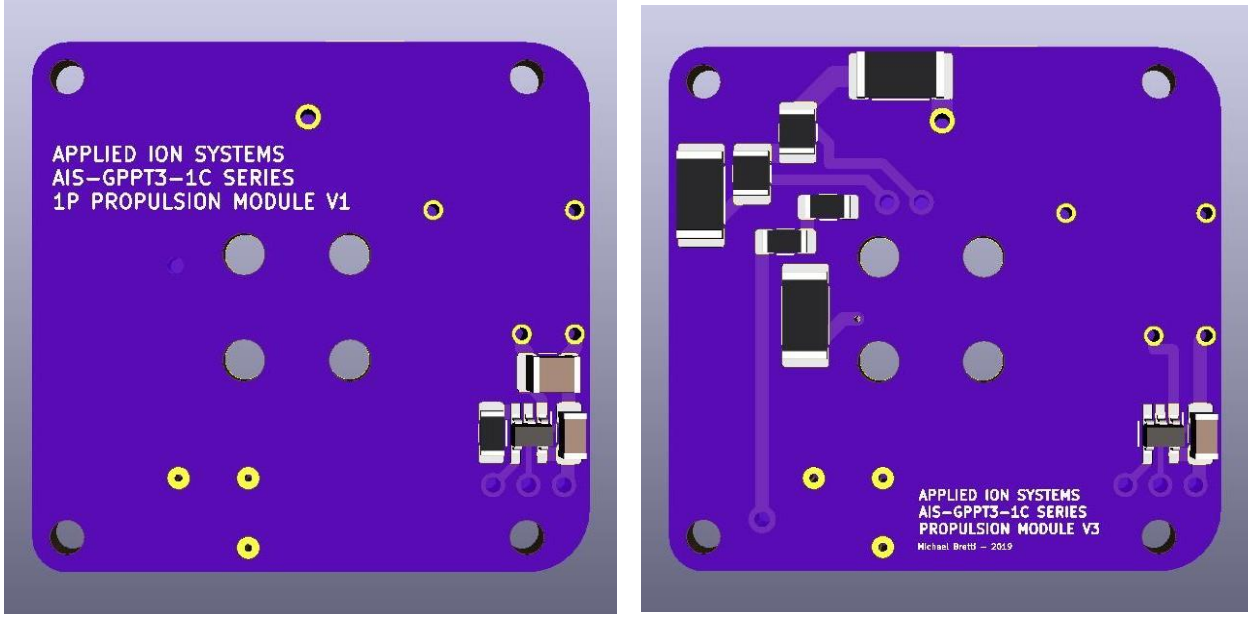

FIGURE 3: *AIS-gPPT3-1C Thruster Module PCB Back - V1 (left), V3 (right)*

III. TEST SETUP SUMMARY

The AIS-gPPT3-1C thruster was mounted to a conflat feedthrough adapter utilizing a simplified direct feedthrough connection from the high voltage conflat feedthrough to a zero-clearance reducer on the micro propulsion testing chamber. 0.25”OD x 0.1875”ID Teflon tubes were used to secure and support the thruster to the feedthrough. 18 AWG bare copper wire with pin sockets soldered to the wire ends were used for all power and control inputs. Connection pins were soldered to the thruster to interface with the wire connections.

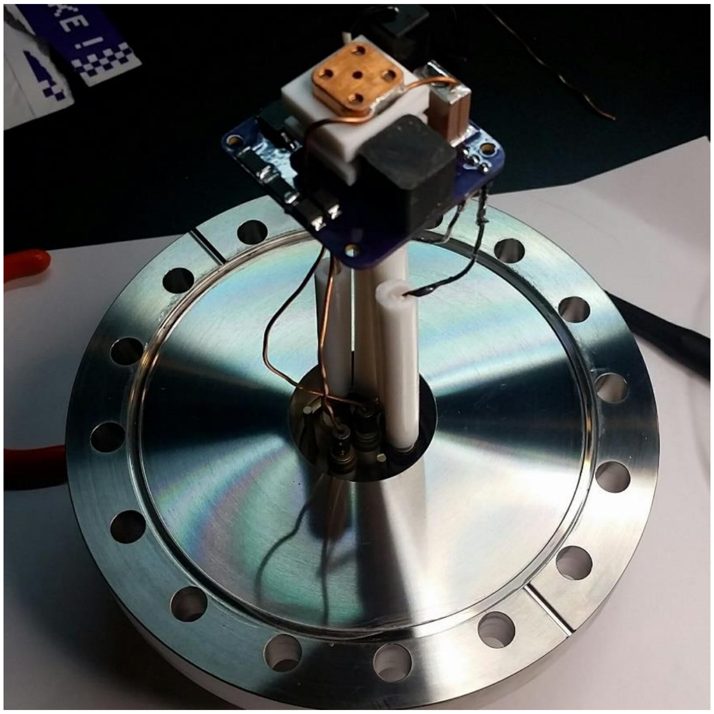

FIGURE 4: *AIS-gPPT3-1C thruster mounted to conflat feedthrough.*

Thruster mounting lengths were determined based on the length required to center the thruster in the adjacent 6” conflat viewport.

FIGURE 5: *AIS-gPPT3-1C thruster centered in high vacuum chamber viewport.*

Testing was performed in the Micro Propulsion Testing Chamber using the Integrated High Vacuum Test Stand. Ignition testing vacuum levels were first verified at 1 x 10^-5 Torr before attempting ignition. During testing vacuum levels were unaffected from the thruster firing.

A new feature of this testing was also livestreaming of the test via webcam on the Applied Ion Systems YouTube channel. This marked the first attempt at livestreaming a propulsion test for Applied Ion Systems, and is the anticipated direction going forward for future propulsion tests. This allows anyone to view advanced electric propulsion testing live as it is happening, as well as actively engage in discussion during testing. This also provides others a unique look at raw testing, including everything from successful testing to troubleshooting, and introduces a new level of accessibility and transparency to advanced electric propulsion research and development in the field.

IV. TEST RESULTS – ROUND 1 LIFETIME TEST

The first round of lifetime testing aimed at qualifying the total lifetime of the system. The thruster was fired at nominal conditions until operation ceased. The total test ran about 2 hours. For the first 1.5 hours, ignition was very erratic. While each successful firing corresponded with a trigger command, most shots were misfires with the thruster failing to ignite. After the first hour of testing, a total of 200 shots were confirmed. Various rep rates from 0.5Hz to 0.25Hz, and trigger widths from 0.1s to 0.5s were tried.

During the last half an hour of the test, stable and repeated ignition was achieved. The repetition rate was set to 0.25 Hz, lower than the nominal anticipated frequency of 0.33 Hz. The cause of the stable ignition however was due to increasing the input voltage from 3.3V to the maximum of 5V, which simultaneously boosted the primary voltage, bank energy, and ignition voltage. During the half an hour period, almost no misfires occurred. *Figure 6* shows the captured plume from testing from the webcam during the livestream.

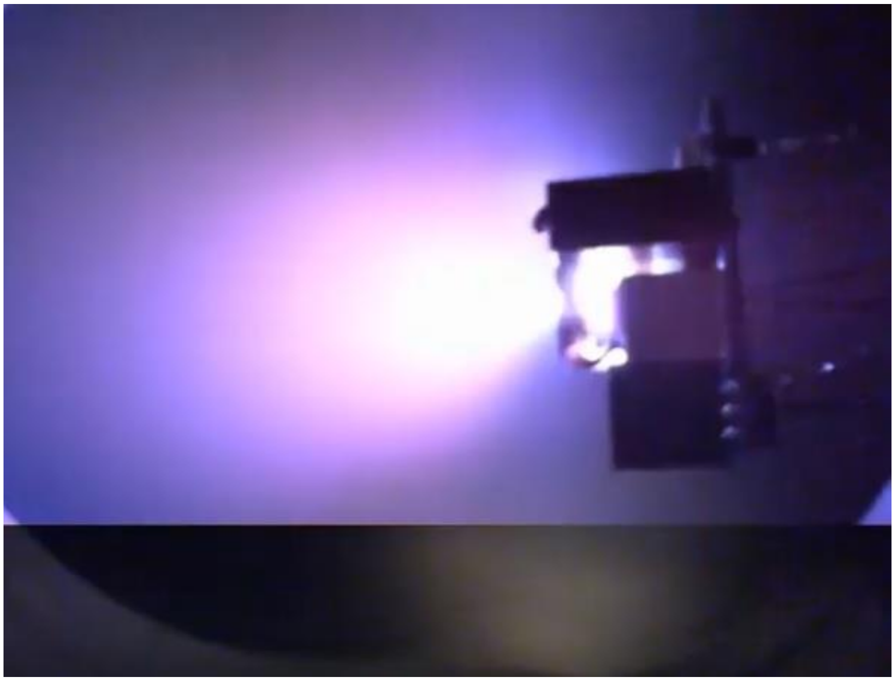

FIGURE 6: *AIS-gPPT3-1C plasma plume recorded from webcam during livestream of round 1 lifetime testing.*

Unfortunately, this increase in output voltage resulted in overdriving the pulse caps, despite very stable operation. Peak pulse capacitor voltage was at 2kV, resulting in a total bank energy of 0.27J. The test was terminated when one of the main pulse caps failed catastrophically, blowing out debris from the side of the casing. Although the capacitors are rated for a peak of 2kV, nominal operation is only around 1kV. *Figure 7* shows the captured failure during the end of testing. *Figure 8* shows close-up analysis of the failed pulse capacitor.

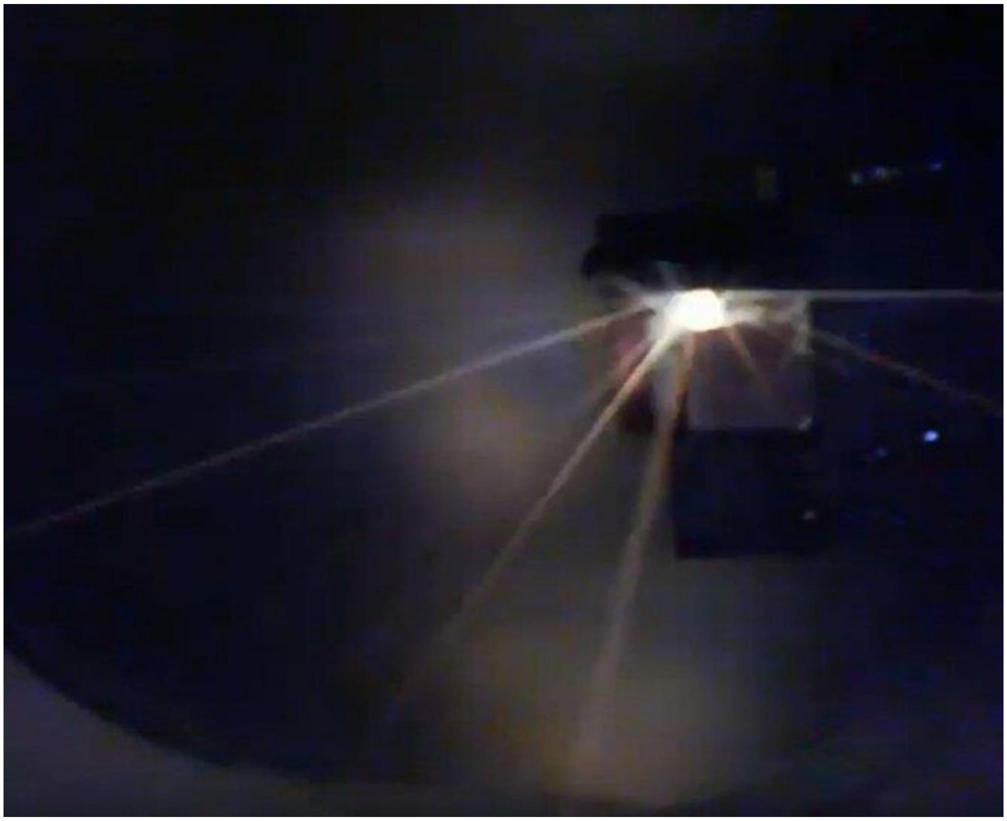

FIGURE 7: *Catastrophic failure of the primary pulse capacitor bank during round 1 lifetime testing.*

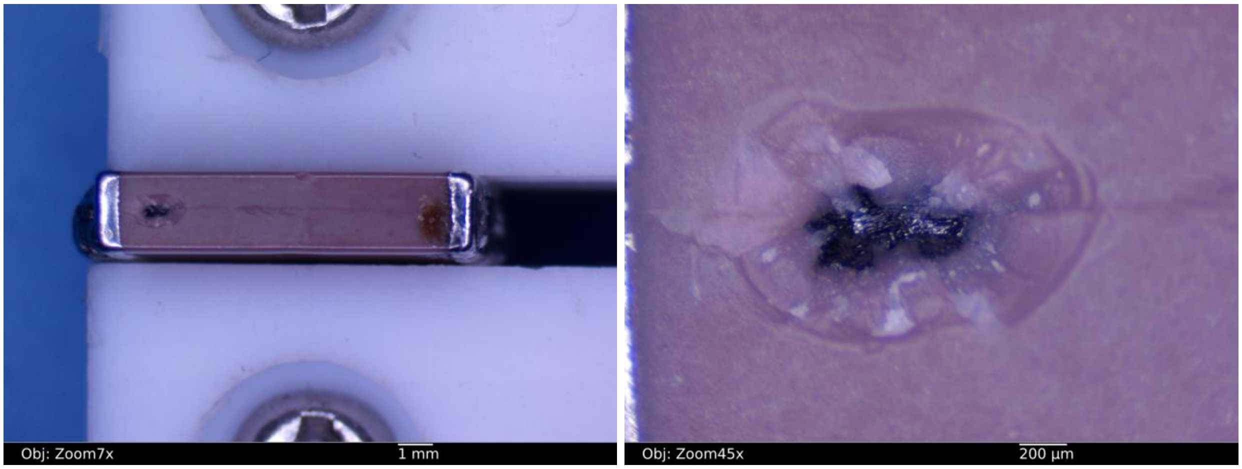

FIGURE 8: *Close-up analysis of the failed pulse capacitor. Photographs and analysis courtesy of Andrew Zonenberg.*

The total recorded pulses for the V3 module for Round 1 testing counted to 736 successful shots. The prior V1 survived 130, marking a significant improvement in performance, however still orders of magnitude off from the final goal of several tens of thousands of shots. After the Round 1 testing, the copper/Teflon thruster stack had clocked a total of 866 pulses, showing no charring or wear in the fuel bore, and minimal electrode erosion.

TEST RESULTS – ROUND 2 LIFETIME TEST

After the capacitor bank was repaired with new capacitors, round 2 of lifetime testing could begin. During this test, the operating parameters of the thruster were modified. It was first decided to operate the thruster at a voltage of 4V as opposed to the original nominal operating conditions of 3.3V, and lower than the max input of 5V. This was thought to be a good balance between lifetime and ignition reliability. Second, the test was performed to mimic operating cycles in orbit onboard the GENESIS PocketQubes. The thruster would fire for 15 minutes straight, with a 5 minute cooldown between each firing period. Normally in orbit, the thruster would fire for 15 minutes straight, and rest for the remaining 75 minutes of the complete 90 minute orbital cycle. However, 5 minute cooldowns were decided upon to speed up testing to reasonable time frames.

The thruster successfully completed 5.33 15 minute orbital firing cycles with 5 minute cooldowns in between, before the main bank shorted and failed. The repetition rate was between 0.29-0.33 Hz for each 15 minute cycle duration. The input voltage was kept at 4V for the duration of the test. Figure 9 shows an example of the captured plasma plume during round 2 of lifetime testing from the webcam livestream.

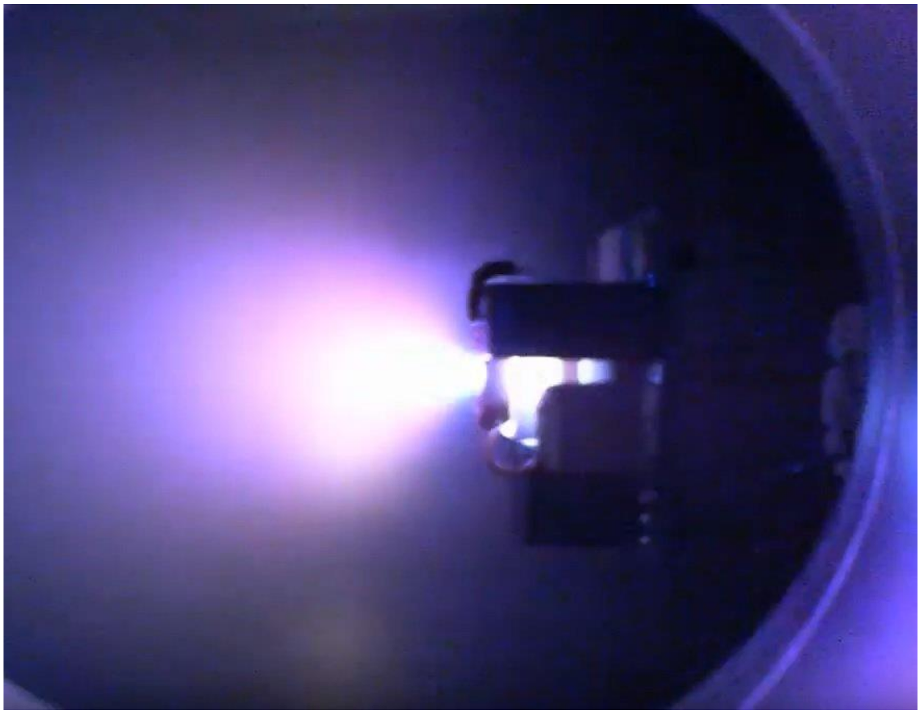

FIGURE 9: *AIS-gPPT3-1C plasma plume recorded from webcam during livestream of round 2 lifetime testing.*

During this second lifetime test, a total of 1232 shots were counted, the highest shot number yet for a test for the gPPT series thrusters. Lower and upper bounds for successful ignitions was between 78-91%. For the 15 minute firing cycles, total ignitions were very repeatable, at around 220-240 per cycle.

In addition to lifetime qualification, operating parameters of the power supply were also verified. At 4V in, the peak current draw during the start of each charging cycle was 150mA, for a peak module power of 600mW. Standby current draw was around 90mA, for a standby power of 360mW. Shot energy was around 0.15J per shot.

Although the main bank died, it was confirmed that reasonably reliable ignition can be achieved with the designated 4V bus input from the battery supply, even after several thousand shots. Upon inspection of the thruster, no noticeable change in electrode buildup was observed. In addition, the Teflon fuel still had no charring or wear in the bore, and no measurable change in diameter. Total shots to date on the board (minus the main pulse capacitor) and thruster stack is at 2098 shots.

V. CONCLUSION

The AIS-gPPT3-1C Integrated Propulsion Module V3 has been successfully characterized and tested to establish nominal operating conditions, limiting factors, and ultimate lifetime. Two lifetime tests were conducted to gauge overall system reliability, as well as system viability for integration and use with AMSAT-Spain’s GENESIS PocketQubes. Steady state and peak power during nominal operation was confirmed during round 2 of lifetime testing. Over the course of the two lifetime tests, the thruster was fired a total of 1968 times. It was found that the thruster must be operated at higher input voltages than ideal and originally anticipated. While 3.3V direct from PocketQube buses is the simplest and ideal solution, ignition reliability suffers too greatly to be practical. At 5V in, the thruster has very high ignition reliability, but extremely short lifetimes. It is recommended that 4V operation in its current form is used for balance between functionality and lifetime. While the thruster should work in orbit, its lifetime is severely restricted, limited to only about 5 orbital cycles firing continuously for 15 minutes each cycle. This limits the AIS-gPPT3-1C as an educational lab unit or experimental demo payload in its current form. Nevertheless, it is a powerful learning tool, and provides anyone in the field a means of exploring electric propulsion at extremely low costs.

It has been established that the key issue going forward remains the main pulse capacitor lifetime that ultimately limits the total thruster lifetime. To date, the thruster stack assembly has been fired over 2000 times with no measurable indication of wear, charring, or fuel depletion. However, every tested has been terminated early due to main bank failures. It has been shown that bank lifetime is directly related to charging voltage, however ignition reliability is inversely related. As a result, both ignition geometry, ignition drive, and main bank capacitors must be addressed for future iterations and improvements towards a high-reliability propulsion system.

First, high reliability pulse capacitors must be found. In addition, these capacitors must be high enough in rated voltage to be significantly under-driven, while still having high enough voltage and stored energy for successful ignition of the thruster. Potential solutions include larger arrays of capacitors to distribute the load during the pulse, restricting peak pulse current, or looking at larger, more conventional through-hole capacitors. In either of these cases, new thruster topologies may need to be explored, which will naturally result in increased package size.

Second, ignition reliability needs to be improved. This includes the use of higher ignition voltage, higher ignition current, sharpened igniter surfaces to enhance breakdown, and/or exploring new materials for the igniter itself. Of the two major problems presented with the current thruster design, ignition reliability is less of a challenge to overcome than limits with current miniaturized pulse capacitor technology.

Going forward, V4 of the AIS-gPPT3-1C is already in the works, aiming to push the limits of ignition at lower energies, under-driving the main bank to increase lifetime, and increasing the ignition voltage to improve ignition repeatability at this further reduced operational energy.