Thermal Vacuum Testing Lessons Learned for Small Stepper Motors and a CubeSat Translation Mechanism

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Abstract

Near Earth Asteroid (NEA) Scout is a deep space satellite manifested on NASA's ARTEMIS 1 as a secondary payload. The spacecraft meets the CubeSat 6U standard (about 300 x 200 x 100 mm) and is designed to travel 1 AU (150,000,000 km) over a 2-year mission to observe a NEA1. Once dispensed from SLS, the NEA Scout will use an 85-m^2 solar sail to maneuver from lunar orbit to the asteroid. One of the critical mechanisms aboard NEA Scout, the Active Mass Translator (AMT), serves as a trimming and momentum management mechanism for the sail system as it balances the sail center of pressure and the vehicle's center of mass. The AMT produces 150 x 68 mm of translation at sub-millimeter precision and accommodates a shielded wire harness and coax cables during operation. The system has strict power, mass and data budgets and must survive operation in a shaded deep-space environment. The AMT system has recently completed and passed environmental testing. This paper will discuss lessons learned through three consecutive thermal vacuum tests spanning nine months and includes insight from the NASA Marshall Space Flight Center (MSFC) design/test team, NASA MSFC Subject Matter Experts in DC motors and electronics and the NASA Engineering and Safety Center (NESC) Mechanical Systems Discipline Team (MSDT). Important points of discussion will include (1) failure modes of a micro stepper gear motor in vacuum and destructive analysis findings, (2) instrumentation of a TVAC test to determine stepper motor health in near-real time, (3) determination of the duty cycle at a given operational environment, and (4) the design of the TVAC test profile to discover thermal capabilites of the micro stepper motors in vacuum. Papers were previously presented at the 44th Aerospace Mechanisms Symposium entitled "Testing and Maturing a Mass Translating Mechanism for a Deep Space CubeSat" and the 43rd Aerospace Mechanisms Symposium entitled, "Development of a High Performance, Low Profile Translation Table with Wire Feedthrough for a Deep Space CubeSat".

Introduction

The AMT was added to the Near Earth Asteroid Scout project late in the design cycle. So, the volume for the device had to be carved from other subsystems already under design and development. This late addition caused the design team to make design decisions that would not normally be recommended in order to have a chance at meeting volume, cost and schedule targets. One such decision was to use a commercially available space rated stepper/gear motor arrangement. This paper describes the problems encountered in using this motor design in vacuum. and the steps taken to complete qualification testing of the AMT design.

The AMT test phase was originally scoped as a one week activity but grew to nine months due to back-to-back stepper motor failures during TVAC testing. Prior to further discussion, It should be noted that the motors chosen for the AMT design were the smallest motors commercially available, and had been used in a flight design before. However, the previous flight project application was in atmoshere (in cabin) promoting convective heat flow. Since this was a first-time in-vacuum application for these motors, significant design changes (discussed in detail in previous papers cited in the abstract) were made to create a more thermodynamically and mechanically robust design. The mechanical interfaces were revised to include an indium and aluminum clamshell design. This clamshell approach used all surface areas available on the motor and transmission casing as thermally conductive paths. Even so, both failures proved the

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need for even more improvements, both to the hardware and test design. Nine months prior, the Engineering Development Unit (EDU) system demonstrated successful, long-term operation between -50 and 60°C. Needless to say, failures in successive flight TVAC tests at 25 and -35°C were terrible surprises.

During the two failure investigations—the first lasting about 13 weeks and the second about 9 weeks—the design and test team met with subject matter experts from both MSFC and from the NESC MSDT to identify possible causes of the motor overtemperature failures, realistic remediations, and new methods to capture test data. The major events between December 2018 and September 2019 are illustrated in Figure 1. Each of these events will be discussed at greater length.

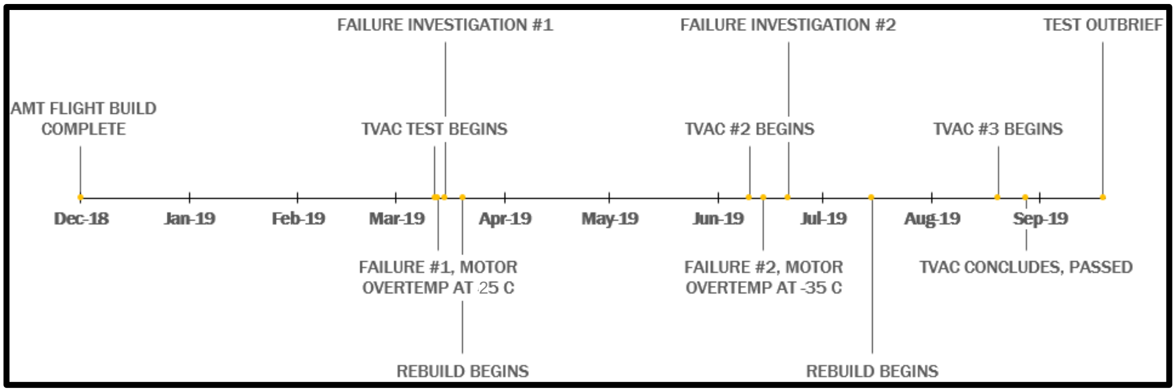

Figure 1. NEA Scout AMT TVAC Test Phase Events

AMT TVAC Test 1, Failure at 25°C

The flight NEA Scout AMT, shown in Figure 2 left, was assembled in December of 2018 to the exact specification represented during the EDU TVAC tesing earlier that year. Notable differences include:

1. Stepper motor manufacturing lot.
2. Use of flight-like mechanical interfaces, shown in Figure 2 right
3. Use of flight spare Motor Controller Board (MCB) instead of a protoboard
4. Different power supply
5. Test chamber setup, including new LED lights, thermocouples and cold plate interface

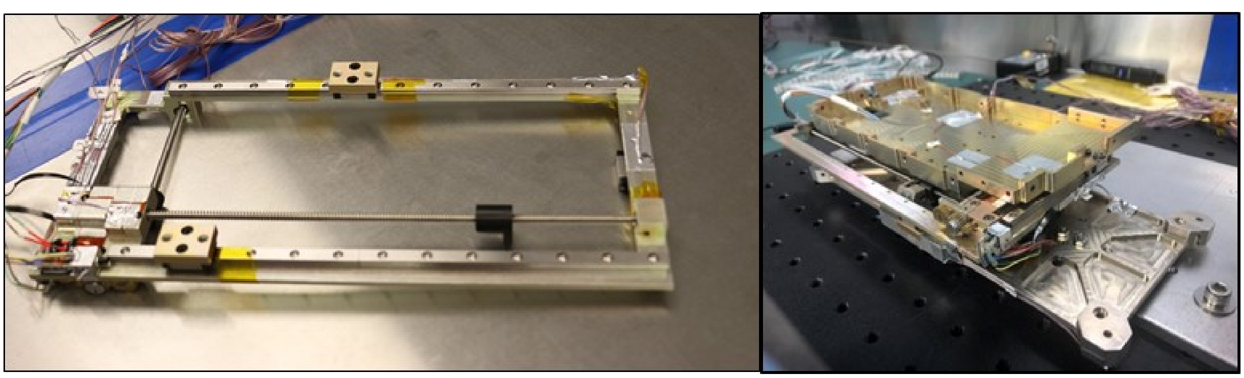
Figure 2. NEA Scout AMT and Test Configuration

Following a functional test verifying the electrical, mechanical and test chamber set up, the TVAC chamber was controlled to 25°C, given time to dwell and depressurized to <1.0E-5 Torr. The AMT motors were powered to begin the first functional test at ambient temperature (25°C). About a minute later, the team noted temperature spikes from TCs mounted near the motor housings. After pausing the operation and reading the motor coil impedances, it was clear that the motors had begun the process of a cascading short failure. Given the previous TVAC tests for the EDU, the team had a natural inclination to suspect overheating of the motor coils, but the root cause was unsure. Previously, it had been a poor thermal conductive path, which had been addressed for this mechanism. The next 13 weeks would revisit and uncover a few new contributers that were not discovered during the EDU tests.

Investigation Method, Failure Mode and Destructive Investigation

The team chose to maintain the test configuration for a time until a detailed plan was developed in order to preserve any contributions from the test facility and set up. The plan included (1) collection of all data, compiled and reviewed to hint at a "smoking gun", (2) a controlled return to ambient, (3) detailed documentation of test configuration tear down, (4) return hardware to cleanroom for non-destructive evaluation, (5) removal of stepper motors from hardware, (6) precision x-ray of steppers, (7) destructive evaluation of stepper motor internals. Data logs were compiled and compared to previous temperature and chamber pressure data. A compiled temperature and pressure data set is shown in Figure 3. The data did show a temperature spike and a pressure rise in the test chamber correlating perfectly with a current spike from the power supply. The small pressure rise is indicative that the lacquers on the motor windings reached an overtemped state and began to offgas. Hundreds of pictures were taken throughout the process, the most valuable of which would come during the destructive evaluation of the failed stepper motors.

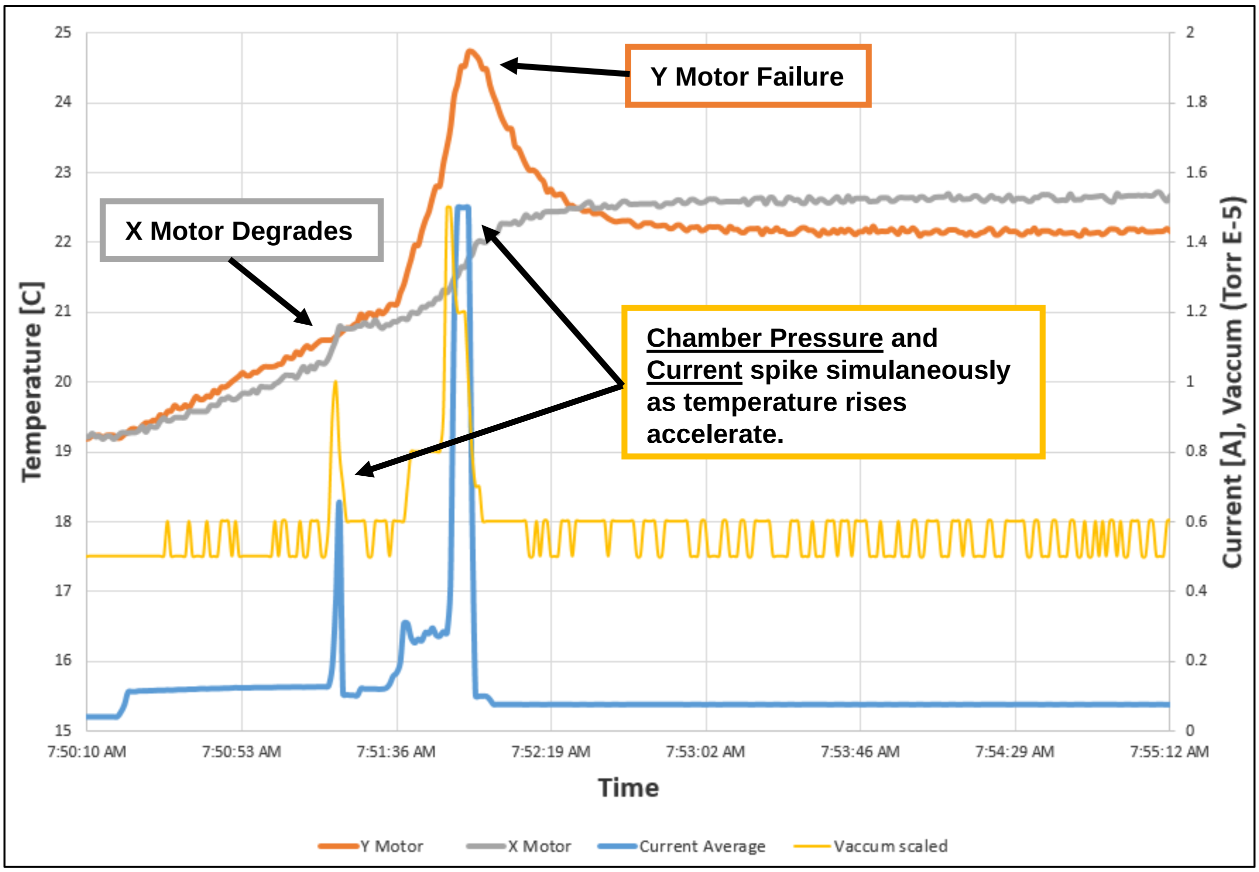

Figure 3. NEA Scout AMT Ambient Failure Temperature, Current and Pressure Data

NASA MSFC has a team and facillity devoted to failure investigation and these resources were vital to the stepper motor destructive evaluation process. Figure 4 shows some of the sample images of the failed stepper motor. These motors, which are about 6 mm in diameter, showed clear signs of overheating at first glance. The discolored (reference the coil at 10 o'clock in the right image of Figure 4) and deformed (same coil shown in the right image at the top) exhibited tell-tale signs of the coils overheating. The overheating was a two-fold failure. First, the lacquer break down emitted material causing the noticable pressure spikes. Second, the rapid temperature rise causes the copper wire to lengthen, creating the wavy, deformed coil.

Electrical testing would also show that the deformed coil was indeed the coil that failed, rendering the motor useless. The motor vendor, which was gracious to participate in these efforts, agreed to these conclusions.

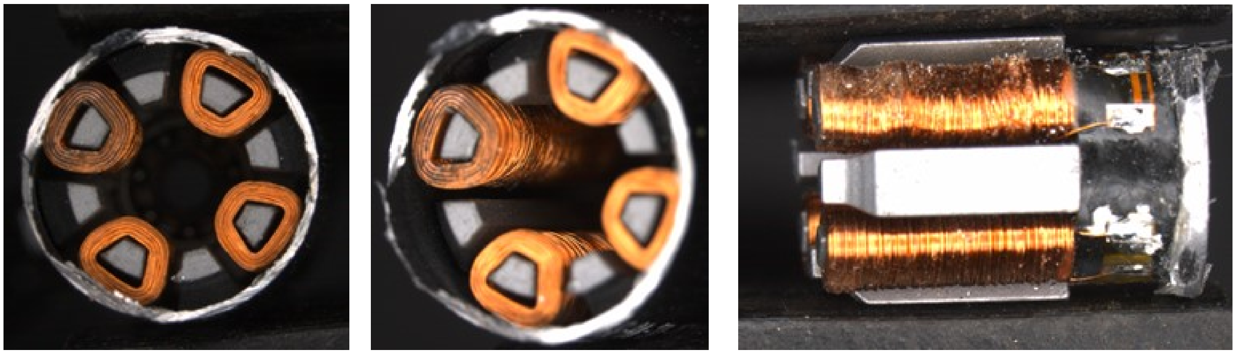

Figure 4. Motor Coil Images post Destructive investigation. Note waviness to coil in 3rd image, top coil

Though the symptom of the failure was obviously coil overtemp, the investigation team was unsure why these motors would fail at 25°C in a minute when motors of identical design were used on the EDU and lasted for up to an hour at 60°C without issue. Unfortunately, due to scheduling constraints, the program required the rebuild the AMT before the fundamental cause could be determined. The team chose to protect the motors from future failure by creating a “duty cycle” for the motors at 25°C and above. This duty cycle would be determined by the rebuilt hardware in the TVAC facility at vacuum. A sequence of increasingly long run times followed by coil impedance measurements would determine when the coils would reach a maxiumum allowable temperature. The impedance would then be monitored until it returned to a near-ambient temperature, allowing for the motor to be cycled again. Each motor coil was monitored, and the performance ranges between coils and motors were larger than expected. The first lot of duty cycle discovery gave a maximum of 40 seconds on, 25 seconds off. This duty cycle would keep the motors from reaching a “red line” test limit of 110°C maximum coil temperature. The team chose to use the duty cycle operation at the 25°C and 45°C functional tests.

Lessons Learned from AMT TVAC Test Failure 1

1. Pressure, temperature and current data should be collected at a much faster rate than we previously thought during TVAC testing involving DC motors. These motors weigh less than 4 grams, and the coils may be a few tenths of a gram each. Their overheating still produced a measurable pressure spike of nearly 200% above the ambient pressure at 0.5E-5 Torr. One second data rate was chosen for further testing.
2. Thermocouples should be placed on available motor surfaces and a nearby heat sink to estimate thermal conductance. Close correlation of the two temperatures are a great sanity check that the system’s heat is conducting as expected.
3. This motor coils’ performance has a wide range of variability. You cannot base performance of a system on a previous motor set. (The team would later discover that within a single motor, one coil would require a hefty duty cycle of 50% while the other didn’t need one at all. The team believed this to be largely because the motors were not originally designed for a vacuum application.)

AMT TVAC Test 2, Failure at -35°C

The Flight AMT was rebuilt with new flight motors and returned to the TVAC facility in June of 2019. Using the newly employed duty cycles at ambient and hot temperature ranges, the team felt confident that the issue was resolved using the operational change. The ambient and hot functional tests went without issue. The hardware then was tested at the cold extreme of -35°C. After a 20-minute continuous operation, the motor current spiked—indicative of a short in the windings due to overtemperature—and the test was aborted. The failure at the second protoflight TVAC test was completely unexpected and gave more insight into the motors' sensitivity to thermal environments and conductive paths. Prior to the second test, the team determined a duty cycle for the motors at the ambient and hot extreme.

Failure Mode, Preliminary Findings and Destructive Investigation

Since the first failure, the test plan was updated to use a data logging power supply to monitor current and voltage levels across the motor driver circuits. Analyzing these log files, the team found some peculiar current behavior which resembled a motor failure on the Tethered Satellite mission. (The motor on the TSS mission was determined to have failed due to a phenonmenon called Paschen Discharge.) This current behavior is shown in Figure 5. Since the faliure occurred at such a low temperature, the team—believing the causes of failure may have been different than before—spent weeks investigating Paschen Discharge. This effort was never fully realized due to schedule constraints, but the team could never rule out the possibility completely. The concluded hypothesis was that the heated coils offgassed small amounts of lacquer which filled the small cavity inside the motor. The motor vent paths, sealed by kapton tape and/or indium, disallowed any free molecules to escape and possibly raised the pressure into the critical 10^{-4} to 10^{-3} Torr range. This pressure, coupled with the local magnetic field may have provided a "sweet spot" for the discharge to occur across particular lengths of winding. This hypothetical event could have caused the currrent to rise to 0.7 amp, hold for a moment, and once winding temperatures exceeded a failure temperature, create a short.

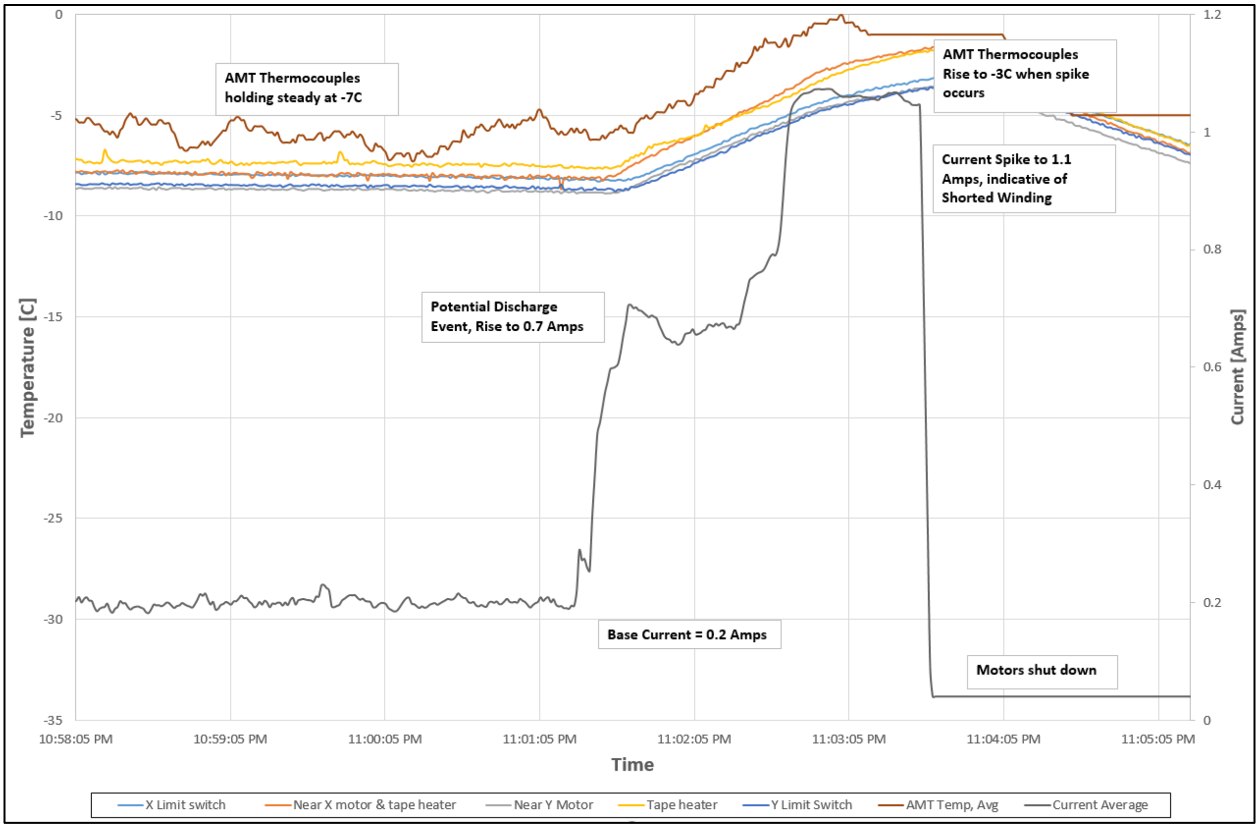

Figure 5. Potential current rise and pause could be Paschen Discharge

The failed motors from the second TVAC test were also taken to the MSFC failure analysis team. This second investigation yielded some helpful data in regards to the manufacuring variations in the motors, coils, magnet wire and potting. The motors underwent a typical round of X-ray imaging, which plainly showed deformed coils, as shown in Figure 6. The destructive evaluation showed a few new irregularities. One of which showed that the ball bearings inside the motor were single shielded and were installed with no regard to the shield direction. The next irregularity was with the laquer. A special instrument allowing metals and polymers to be clearly distinguished under microscope showed that the laquer was producing very large bubbles/voids in random areas. Figure 7 shows an image of a few bubbles or voids formed in the lacquer, either due to testing or remnant of manufacturing processes. This image, amongst others collected, also gave insight that the coil/stator design was not suitable for sustained use in vacuum. The most prominent detail noticed at this investigation was with the potting and mounting of the coils to the stator. The team assumed the coils were potted to the stator, but a coil was accidentally damaged and became detached from the stator. Upon further analysis, it became clear that each coil was potted to the stator in a single location, with a single dab of adhesive which was not especially thermally conductive. An example of this potting location is shown in Figure 8.

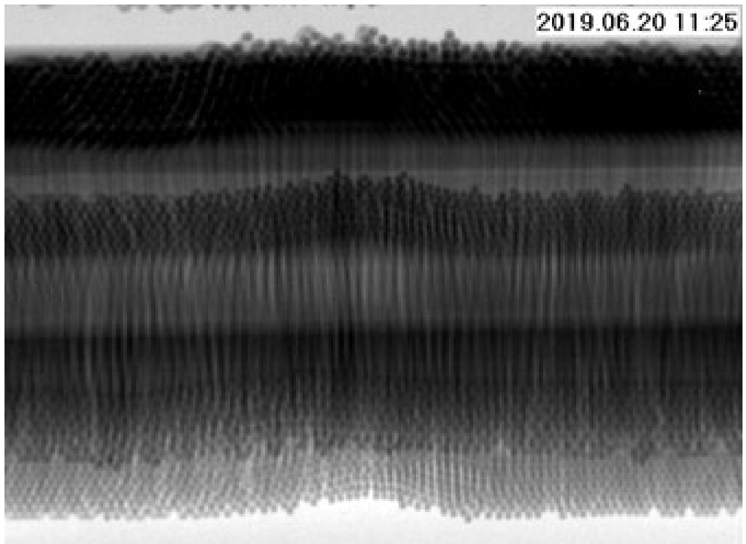

Figure 6. Deformed Stepper Motor Coil under X-ray

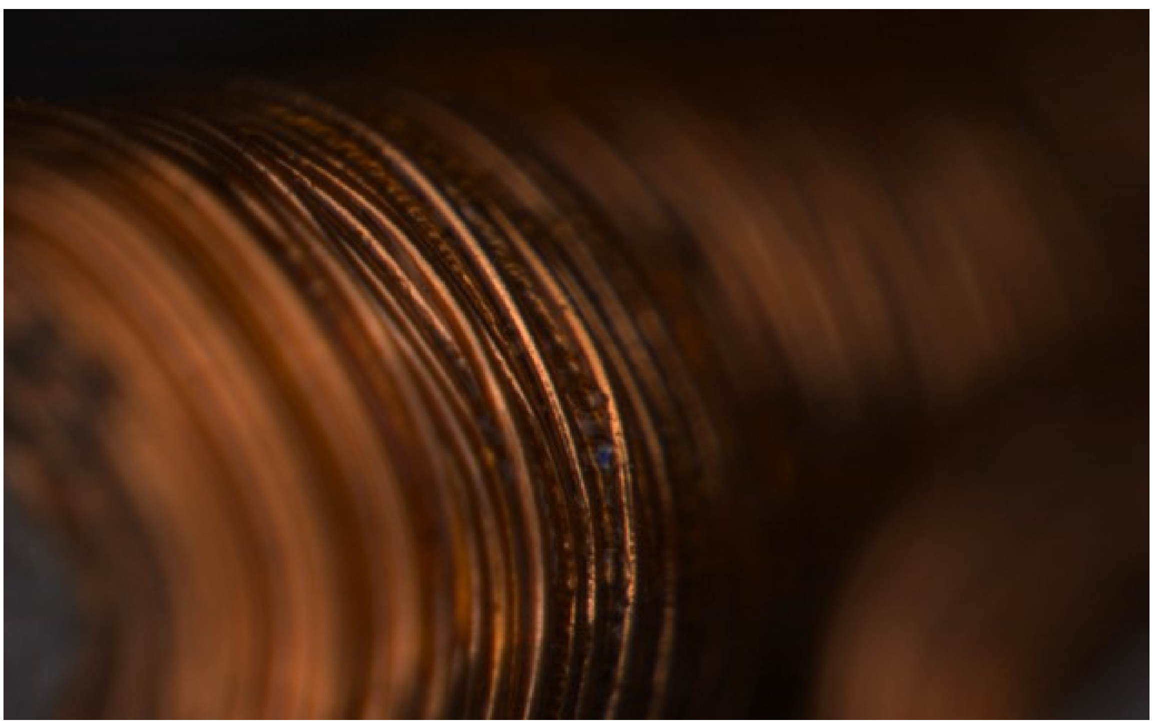

Figure 7. Coils under high magnification showing some evidence of voids in insulation

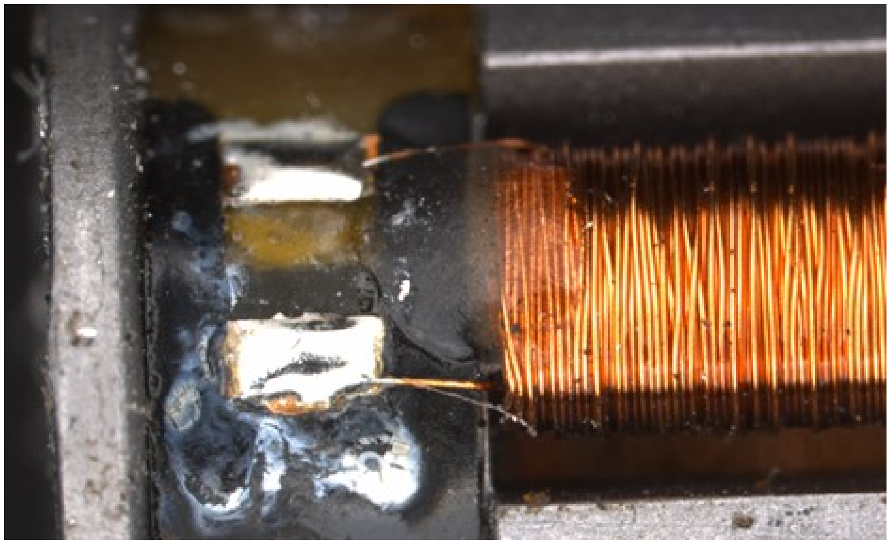

Figure 8. Potting location for coil to stator

The potting underdesign and presence of voids in wire insulation were clear signs that these motors were not well suited for a vacuum environment operation. The conductive paths from the windings to the motor casing were undersized, and the magnet wire had thin insulation. These findings paired with the manufacturing variance of the potting and insulation thickness made it clear that the motors would have to complete a more enhanced thermal acceptance testing to choose the more robust motors from a particular lot. Only after completing these tests could the motors be integrated into the flight hardware for an AMT subsystem TVAC test. The details of the acceptance and burn-in testing will be covered in the next section.

Lessons Learned from AMT TVAC Test Failure 2

1. Motors intended for vacuum use should use coilwire with thicker vacuum compatible insualtion. Some vendors will twice or thrice dip their products for vacuum application.
2. Magnet wire defects such as thin insulation and voids/bubbles can be susceptible to first time-wide temperature swings (such as a first time run in vacuum).
3. Motor coils should be potted on all available surfaces to maximize thermal conduction. These motors, though advertised as vacuum rated, were contacting the stator in a single, potted location. This potting was analyzed and had little to no thermal conductive properties. The team's thermal analyst would have assumed these coils to be relying on radiative cooling alone.
4. When using small (<15 mm) DC motors, or any motor from a non-flight rated vendor, a detailed motor thermal model should be developed to estimate a steady state temperature or a first cut duty cycle. Buy some motors, break them open, and figure out how the heat is conducting to the surface.
5. Acceptance testing in vacuum at the motor level is a must. Again, buy extra motors in case of failures.
6. Motors may be susceptible to discharge-related failures if the insulation offgasses due to rising temperatures.

Motor Conditioning and Burn-in Test Method

An initial effort was made to determine a method to recreate a Paschen Discharge. Exploring the variables that factor into achieving this effect led to the realization that the conditions could not be duplicated. Focus turned instead to preventive tactics. Ultimately every motor failure traced back to coil temperature, either by causing off-gassing that created an atmosphere to carry a discharge, or by outright melting the wire coatings, resulting in a short. This points to the wire coatings as the weakest link, and coating inconsistency between batches as one of the hurdles. A two-part approach was planned. First, develop a conditioning and vetting test series. Second, determine duty cycles to prevent coil overheating.

The conditioning tests were designed to gradually “burn in” the motors by incrementally heating and allowing to cool in vacuum. Coil temperatures would gradually approach but be kept below manufacturer’s rated value. This would theoretically allow “bubbles” in the wire coatings to work their way out gradually through softened coating material without leaving permanent damage.

A duty cycle is determined as the amount of time the motor is allowed to run in a specific environment before forcing a rest/recovery period. The run and rest times were, in this case, selected to limit the coil maximum temperature, and cool to a minimum temperature selected by the team before running again. Determining duty cycles were actually a by-product of the conditioning test series, and were established and recorded along the way. This testing would also demonstrate each motor’s individual capability to survive operation in a vacuum environment. Overall performance during the test series would be used as a basis for ranking flight motor candidates. A sample of the motors final duty cycle is shown in Figure 9.

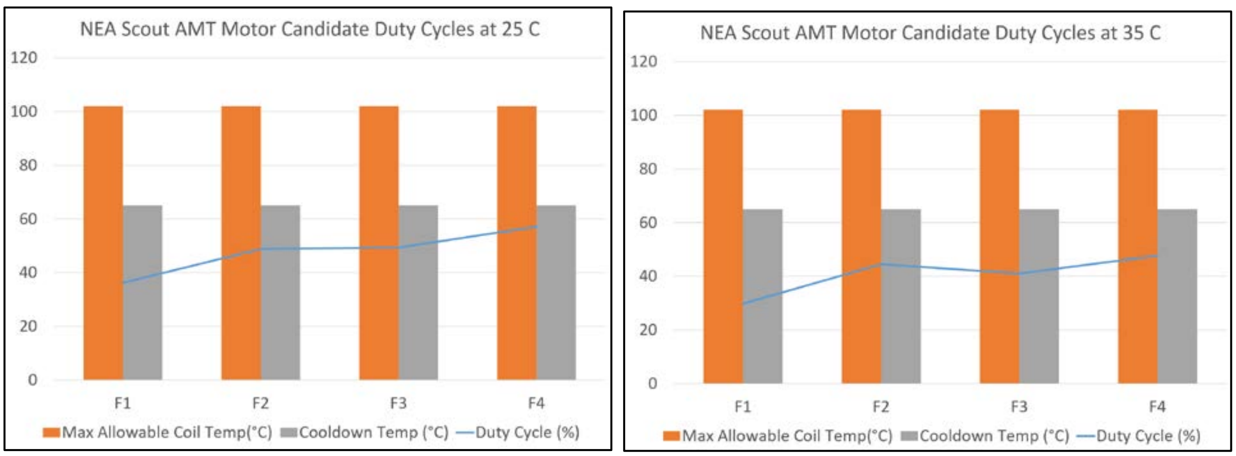

Figure 9. Duty cycles for AMT flight motor candidates at 25°C and 35°C.

The four motor candidates shown above were from the exact same vendor lot and were run with the same max allowable coil temps and cool down targets, but the duty cycles ranged from 36% to 57% at 25°C and 30% to 48% at 35°C.

The previous use of thermocouples to monitor coil temperature was insufficient for closely monitoring the coil temperature due to the thermal lag through the motor casing, indium, and clamshell bracket to the thermocouple. Instead, the team turned to resistance measurements. Coil temperature correlates to motor impedance. Resistance of the coils was measured while the motor was off, and immediately being energized. Resistance-based temperature measurement was calculated for each coil, and verified against the chamber temperature prior to start of testing. More on this method is discussed in “Testing and Maturing a Mass Translating Mechanism for a Deep Space CubeSat” from the 44th Aerospace Mechanisms Symposium.

For all motors not previously used in a vacuum, a standard vacuum bake-out was performed to reduce the amount of material that would offgas during the duty cycle and burn in testing.

<u>Test plan</u>

Three vacuum chamber temperatures were selected for duty cycle determination: room temperature (25°C), max operational tempature (45°C), and a mid value (35°C). Motors were mounted in a flight-like manner, wrapped in indium and installed in EDU chassis; no drive train hardware was included, allowing the motors to freely rotate. Maximum coil temperature and minimum cool-down temperatures were selected, and resistance was determined corresponding to each temperature. Two voltages were selected, the first being at the low-end of controller capability, the second at expected mission level. In this mission case, it was 9.8-12.0 V. Multiple voltages were selected to test the sensitivity of the coil maximum temperatures to voltage supply. During testing, the team noticed that the motors actually ran hotter at a lower voltage. This was because the motor driver would send a higher current at the lower voltage, which was counter to intial assumptions.

The assumed most favorable conditions were selected for the initial test, being lower voltage and coolest temperature. A duty cycle was determined, and then a total of 15 minutes of run time was performed at that duty cycle. The voltage was increased and the test repeated. Then chamber temperature was increased, and the test repeated for both voltages, and the entire series run again at the third chamber temperature. A duty cycle was recorded for each specific motor at the given voltage and chamber temperature in which it was determined, so that each motor had six duty cycles established. At the end of this series, the motor was considered “conditioned”.

Duty Cycle Discovery Method

- Run motor for a few seconds
- Measure and record all coil resistances immediately after operation ends. Recommend to have a multimeter in the loop of the driver circuit.
- Continue to monitor resistance until reading is below the cool-down value.
    - Note that cooling in vacuum is asymptotic in nature.
    - Cooling to within 5-10°C of ambient gives a good restart point for the following cycles
- Run motor a few seconds longer than the previous run, depending on motor performance trends.
    - If the motor max coil temp is below maximum allowable, the following cycle can be longer
    - If the motor max temp is met or exceeded, either reduce the run time or extend the cool down time. Again, note that extending the cool down time is more time expensive than reducing the on time.
- Continue until three runs are made with the same runtime, cool-down, and resistance values. This indicates a steady state duty cycle.

A sample of the Duty cycle discovery data is shown in Figure 10.

The data shown in Figure 10 is extensive, but still reduced from the total data set (a sample of which is shown in Figure 11) the team used to finalize a duty cycle for flight operations. The most pertinent data is the red and green boxes, which show the increasing run and cool down times as the approach a final value. For the left sample, this time was about 20 second run time, followed by a 55 second cool down. The right sample had a 35 second run time and a 70 second cool down. The teal line shows the duty cycle as a percentage of run vs. cool down time. Note the differences between the two identical motors, further indicating some thermal differences resulting from manufacturing variance. A final data point of note is the light green line, showing the current draw during a duty cycle. The upward sloping nature during each on cycle is indicative of the heating coil. As the coil temp rises, the resistance does as well. The motor driver hardware sends more current as a response. The peaks of the green line during a cycle could be charted to give a maximum coil temp trend. The peaks remained horizontal for this data set, hinting that the coil temperature maximums were holding constant across the cycles. If the peaks were rising gradually, the coil temp could be assumed to be rising as well and the duty cycle could be adjusted accordingly. The same is true if the peaks were falling, except the coil temps would be decreasing and the duty cycle could be adjusted in kind.

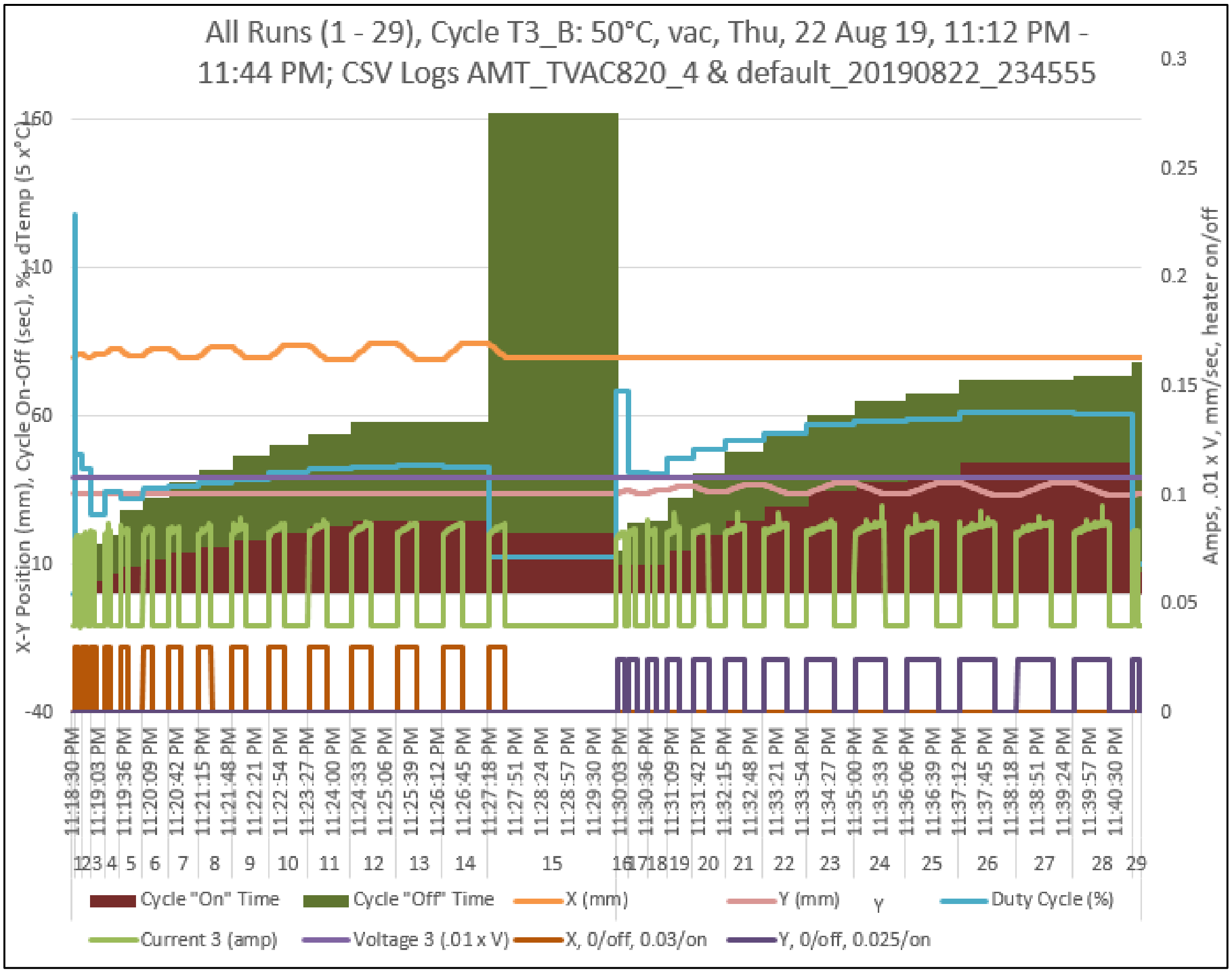

Figure 10. Duty Cycle Data for two Stepper Motors

<u>Motor Burn-in</u>

Following a duty cycle discovery run in a vacuum environment, the motors were run per the discovered duty cycle until 15 minutes of motor run time had occurred. Resistances and times for run and cool-down were recorded to verify that a long duration cycling would not overtemp the motor coils. This burn in time was used to help coil insulation material offgas at a slower, more controlled rate, and reduce any opportunity for an arcing event to occur. Further, the burn in time would reduce the thermal shock to the insualtion and reduce the risk of voids forming in the insulation.

AMT TVAC Test 3, Passed

The final flight TVAC test plan included even more data capturing requirements: (1) Local temperatures on AMT logged at 1 Hz, (2) Chamber control temperature taken logged at 1 Hz, (3) Chamber pressure logged at 1 Hz, (4) Motor circuit current and voltage data logged at 5 Hz, (5) Control Board Memory and Commands logged at 1 Hz and (6) Motor Winding impedances taken immediately after operation termination. These data sets were combined into a master data set where temperature, current, pressure, and operation speeds could be compared at each thermal cycle. An example of the combined sets is shown in Figure 11.

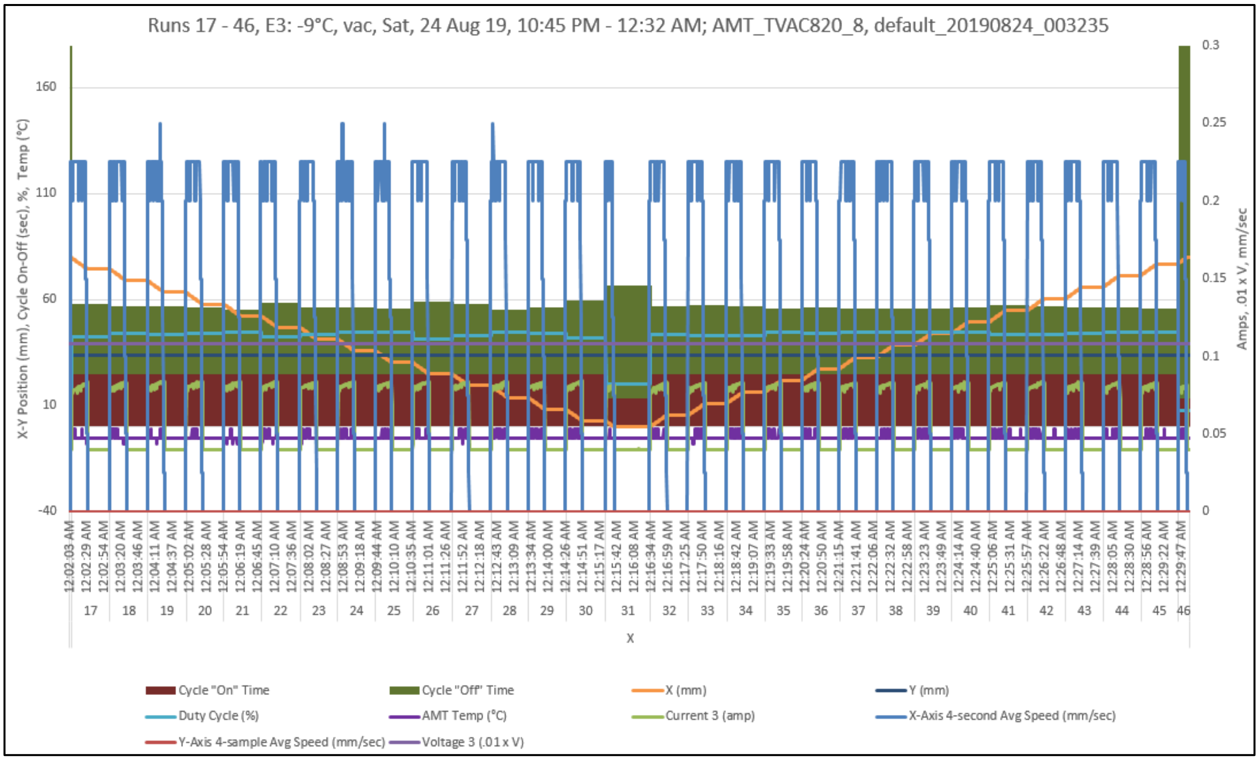

Figure 11. Combined data set. Note orange line documents X axis change in position. Duty cycle = 40%.

The extensive measures taken to understand the details of the motors' internal design paired with the meticulous process of duty cycle determination and burn in testing yielded a long-awaited succesful test. The third iteration of the NEA Scout AMT test passed with flying colors. The motors, though unable to perform in vacuum under typical operation, showed an ability to operate in vacuum for thousands of duty cycles and an acculculative run time of over 10 hours.

All data points were reviewed in detail following the conclusion of test 3. A single engineer took a few weeks to align time signatures across each data source and compile the data to create tables and charts similar to Figure 10 and 11. The data was reviewed and compared with the thermal environments in the test chamber to inform the final control parameters for the flight motor controller boards. These data sets will also be valuable to compare with flight data in the event AMT operation telemetry is reviewed or modified.

Conclusion

In conclusion, the AMT system TVAC test failures caused the team to develop new processes to determine a motor's duty cycle prior to environmental test with limited risk to flight hardware, instrument and collect data for post-test analysis, and perform destructive analysis on failed micro gear motors. The motors used on the NEA Scout AMT were determined not to be suitable for 100% duty cycle in vacuum, but a conservative duty cycle enabled the AMT to operate and meet long-term mission requirements. The AMT motors were instrumented to determine motor health in near real time. Previous failures during NEA Scout AMT TVAC test always pointed back to an unfit thermal conductive path, most likely due to under-insulated magnet wire and poor thermal conduction from motor coils to a larger heat sink. It was hypothesized that Paschen discharges could occur in a small stepper motor such as these if the coil temperatures rises and offgasses enough material, though this hypothesis could not be recreated or confirmed through further testing.

Major Lessons Learned

1. A Commercial off the Shelf (COTS) non space-qualified motor *could* be used for flight purposes if proper motor conditioning and duty cycling is determined in a comparable space environment
2. Any COTS non space-qualified motor *should* be destructively analyzed prior to use to accurately create a thermal model.
3. TVAC tests including DC motors *should* log motor temperature, power supply current, power supply voltage and chamber pressure at 1 second resolution, at minimum.
4. Motor internal pressure could increase to a pressure range suitable for arcing, discharging or ionizing if magnet wire insualtion breaks down due to overtemperature conditions, leading to failure.

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