Capacitor Failure Investigation Results for the NEXT Ion Thruster Power Processing Unit (PPU)

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April 17, 2012
Discussion Topics

- PPU background
- Failure #3 Investigation
- Key Findings
  - Beam module testing and analysis
  - Capacitor testing and analysis
- Electrical Testing to Mimic in Circuit Phenomena
- Failure Conclusions and Corrective Actions
- Summary
NASA’s Evolutionary Xenon Thruster (NEXT) Background

- 7.0 kW ion propulsion system
- Leverages elements from NSTAR (DEEP Space I)
- Designed to meet propulsion requirements of Jupiter/Saturn DRMs
- PPU was constructed with the objective of flight-like form/fit/function
- Multiple functional test cycles conducted in ambient/vacuum with resistive load/thruster
- Environmental qualification-level testing planned until string of failures occurred
NEXT Power Processing Unit

- Modular design featuring 7 power supplies
  - Discharge supply
  - Quad supply containing
    - Accelerator
    - Neutralizer keeper
    - Discharge cathode heater
    - Neutralizer heater
  - Housekeeping power
  - Beam supply
    - Processes 93% total power
    - Up to 96% efficient
    - Contains 6 parallel modules
    - Input Voltage: 80 to 160 V
    - Output voltage: 275 to 1800 V
Background MLC Capacitor Failures

1st failure
Module #1
March 2008

2nd failure
Module #6
Feb 2009

3rd failure
Module #4
April 2010
Failure #3 Investigation
Module #4 failure
- Top capacitor
- 50°C baseplate temp.
- Operating at 3.5kW
- 4 modules @ 820 W/module
- Failed during forced recycle
- 160 V input
- < 136 hrs operating in vacuum
PPU Capacitor Failure Tree

1.0 Intrinsic defects
2.0 Assembly & Handling
3.0 Mechanical design
4.0 Operating Environment
5.0 Electrical design & operation

Color Code:
- Very Likely: Red
- Likely: Yellow
- Not Likely: Green
- Clear: Blue
Key Findings

Beam module testing and analysis
Beam Supply
Simplified Schematic

Circulating Current
16A p-p @ 200kHz

Ripple Current
20A p-p @ 200kHz

Failures #1 & #2
Failure #3

Circulating Current between Two Capacitors
In Phase Shift Mode
Cap Current and Circulating Current

- **Gate Drive**
- **Capacitor Ripple Current** is 20 A p-p @ 200 kHz
- **Capacitor Circulating Current** is 16 A p-p @ 200 kHz
- **Transformer Current**
Capacitor Current and Voltage During a Fault

- Voltage Hump
- Transformer Current 50 amps / div
- Cap Voltage 50 Volts/ div
- Current Spikes
- Cap Current 50 amps / div
Key Findings

Capacitor testing and analysis
A ceramic capacitor is constructed of alternating layers of metal and ceramic, with the ceramic material acting as the dielectric.

A typical dielectric material is X7R – a form of Barium Titanate

- Minor Dopants change the electrical and mechanical properties

Barium Titanate can be highly piezoelectric based on the additives used
Ceramic Capacitor Used in the Beam Supply

• Custom Part – 9uf; 300 Volt ceramic capacitor; case code #3

• This custom dielectric formulation is highly piezoelectric
  – Easily polarized by applied voltage at elevated temperature
  – Internal mechanical resonances a function of case dimensions
    • Frequency = (Velocity of Sound in Dielectric) / 2* (Length Dimension)
  – Electrical behavior is a strong function of frequency near resonances
  – Capacitance drops with applied voltage
Piezoelectricity

Piezoelectricity is a form of electricity created when certain crystals are bent or otherwise deformed. These same crystals can also be made to bend slightly when a small current is run through them.

Barium Titanate (the capacitor dielectric) is piezoelectric

Displacement = $f$ (Electric Field)

GRC Measured Data on Custom Capacitor
New Custom Caps from Stock

Not subjected to temperature or voltage

Custom Caps Burned-In @ 125°C and 600 V\textsubscript{DC}

- Temperature and voltage polarizes the dielectric creating the piezoelectric effect.
- Spike in the impedance indicate piezoelectric resonant frequencies.
- Resonant frequencies are function of ceramic slab dimensions and material.
Electrical Testing to Mimic in Circuit Phenomena
Test Circuits

Growler
- Provides 7.5 amps rms of sinusoidal circulating current @ 170 to 220 kHz

Growler / V-Thumper
- Augment the growler circuit with a 75 volt transient 3 times / second to simulate recycle conclusion

- 200kHz
- 5.47 degree phase lag
FRB Cap Failure #3

Failure Specifics
- 345 total hours
- In Vacuum & Air
- Exercised at 192-205 kHZ (90sec sweep)
Failure Conclusions and Corrective Action
Summary of Failure Mechanism

The confluence of 3 independent design elements is responsible for the capacitor failure.
Replacement 5.6µF/500V

0 volt Bias

Custom 9µF/300V
Reduce Circulating Current

Before

Added MPP* Core Differential Mode Choke

After

* Molybdenum Permalloy Powder
Summary

- Piezo-electric characteristics of the custom capacitor at the operating frequency of the beam power supply led to its failure in this application.
- Circulating currents at the operating frequency within the bridge aggravated the problem.
- Recycle of the beam supply may be final trigger of the failure but is not the primary cause.
- Replace capacitors with a non-piezoelectric capacitor.
- Add MPP Core to eliminate circulating current.

Capacitor problem has been solved.