X-57 Cruise Motor and Inverter Failure Modes

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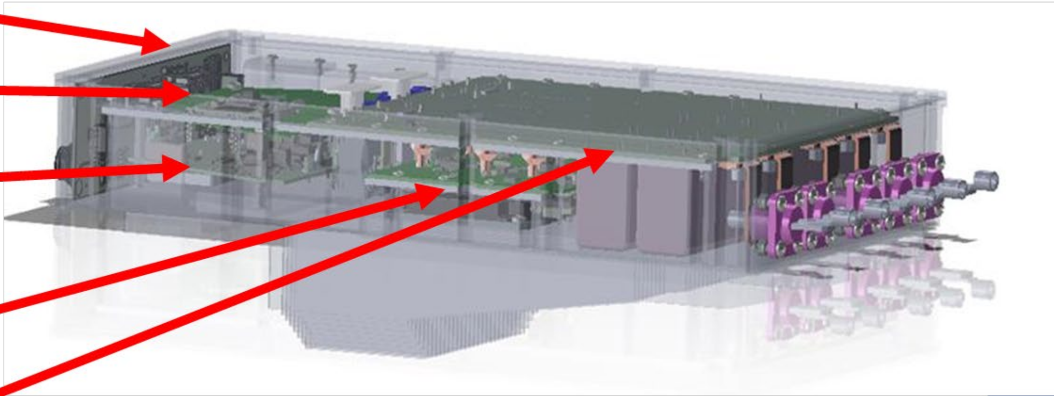
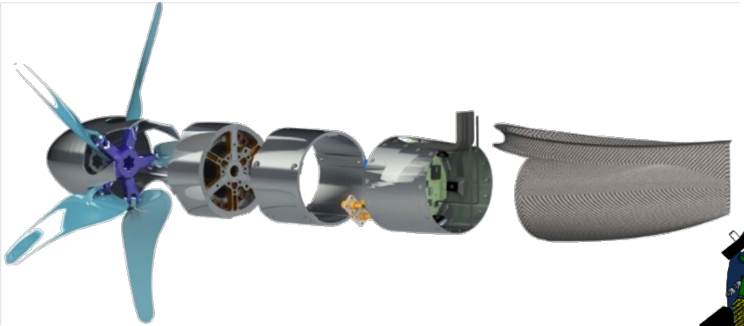
XM3 Cruise Motor Controller Layout

- Connector Board
  - Reused on XM3 CMC
- CPU
  - Reused on XM3 CMC
- Power Board
  - Auxiliary Power Distribution
  - Supporting Circuitry
  - Fault Circuitry
- Driver Board
  - Gate Drive Circuitry
- AC-DC Board
  - Voltage/Current Sense Circuitry
  - DC Bus filter
  - High Power Connections

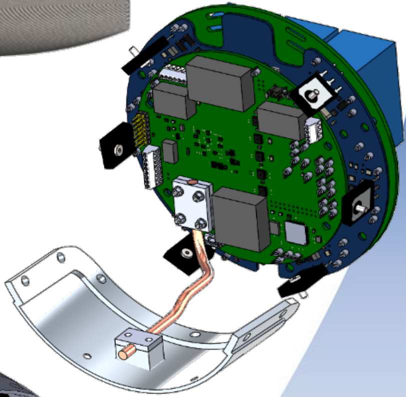


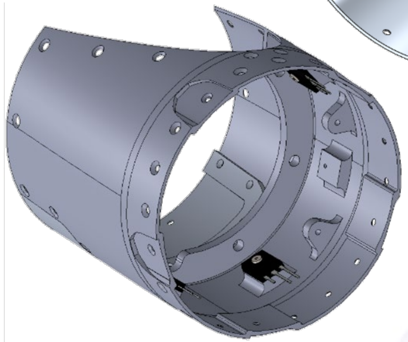
- 39kW Nominal Output with 55kW Overdrive
- Nominal Voltage 320-538 VDC
- 97% Efficient
- Sensorless Current/Torque “Field Oriented” control
- Passive Air Cooling

High Lift Motor Controller (HLMC) Overview



- 11 – 14 kW AC Output
- 538 V DC Bus
- Less than 330 W loss (> 97% Efficiency)
- Mass ≤ 1 kg
- Passive, Outer Mold Line Cooling
- Sensorless Motor Control

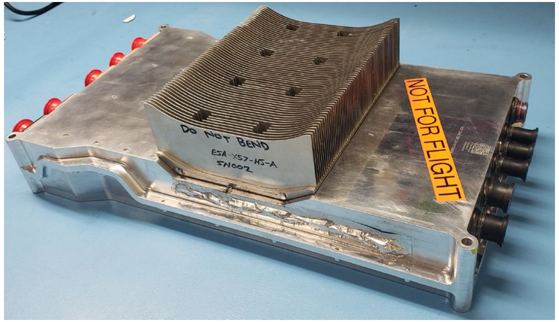


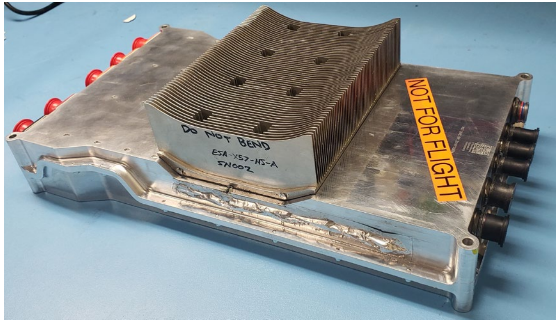


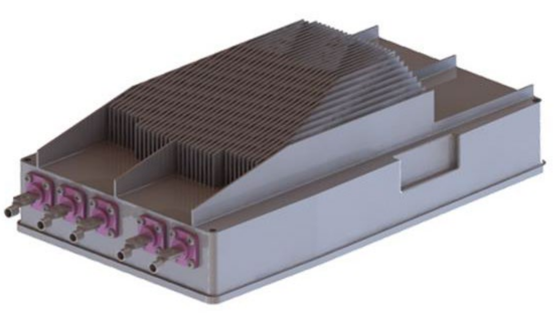
Inverter Failure Modes

- Design
  - Electrical (Isolation, gate drive quality, DC bus filtering, sense circuit accuracy (voltage/current/thermal), fault circuits, EMI mitigations, etc)
  - Thermal (Isolation, component limits, heat rejection, etc)
  - Mechanical (Vibration/Shock)
  - Component Selection (part ratings, tolerances/sensitivity/accuracy, environmental limits)
- Assembly
  - One loose washer can cause catastrophic failure!
- Tuning/Powered Testing
  - Test Setup
  - Software/control law
  - HW/SW Fault Protection

CMC Development Timeline







BM2 CMC

- Original CMC developed by Joby and QDESYS

Microsemi CMC

- Same as BM2 but with a different MOSFET Module

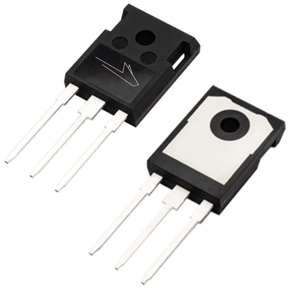
XM3 CMC

- Flight Qualified CMC

X-57 MOSFET Failures

- MOSFETs are utilized to convert battery power (DC) to 3-phase (AC) power to control the speed and torque of the motor
- X-57 utilized SiC MOSFETs in both inverter designs (CMC and HLMC)
- High power density (The CMC could switch at 538 VDC and output 200 Apk per phase)
- Typical Failure Causes: Over-temp/current/voltage, poor gate voltage quality, vibration
- Typical Failure Mode: Short circuit with potential for material ejection. Often results in destruction of drive circuit and PCB

Half Bridge MOSFET Modules



Discrete MOSFET

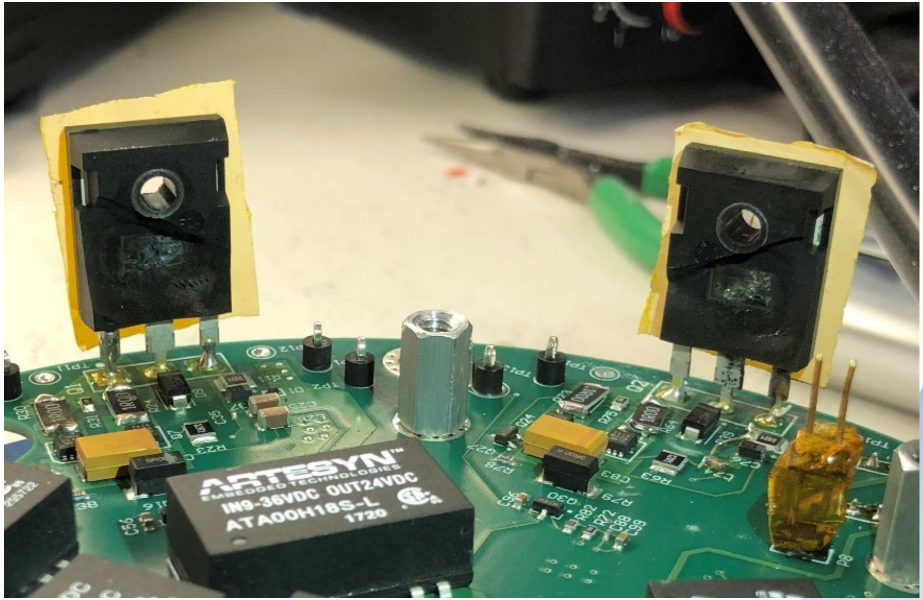
X-57 MOSFET Failures (Vibration)

- Initial CMC MOSFET module could not survive vibration tests
- Typical failure mode: short circuit across DC bus resulting in module failure
- Tests conducted at ≤ 10 kW
- Module case stayed intact, but material ejection probable at higher power levels
- Initial Vibe Level: Random Vibe, 7.7 Grms, 20 min/axis

BM2 MOSFET Catastrophic Failure from Vibe

X-57 MOSFET Failures (Thermal)

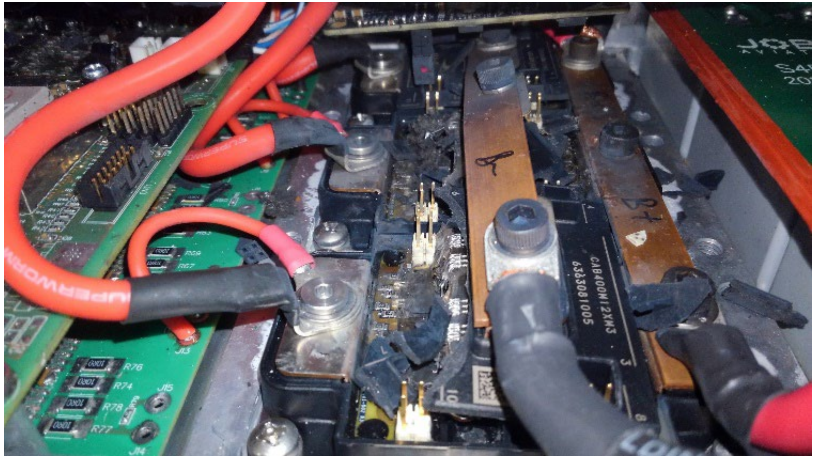
- Thermal gap pad between HLMC discreet MOSFET case and heat sink was too thin
- Imperfections in MOSFET case wore through gap pad resulting in over-temperature of the MOSFET junction
- MOSFET internals were ejected out of the MOSFET case

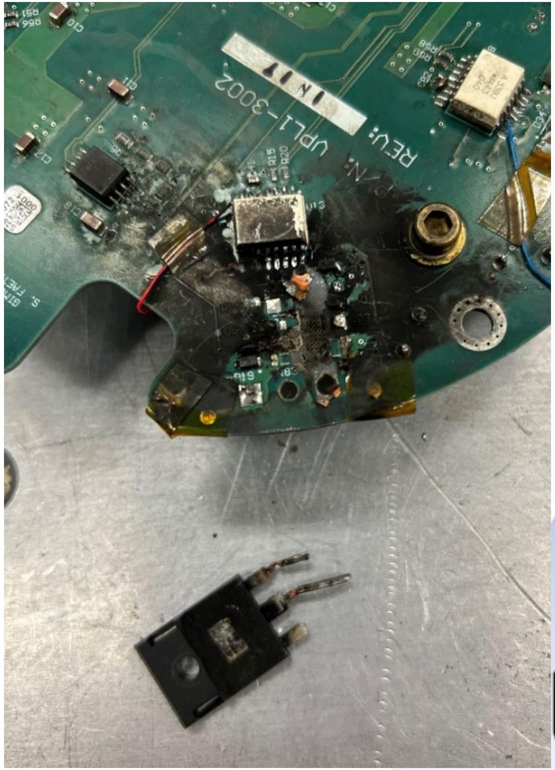


HLMC MOSFET Catastrophic Failure from Overheating

X-57 MOSFET Failures (Drive Quality and Software)

- Inadequate gate drive signal (excess or insufficient drive signal can result in degradation and catastrophic failure)
- Left Image: CMC improper control law tuning resulted in failure of all 3 phases
- Right image: Early HLMC SW version commanded shoot through (resulting in catastrophic MOSFET and PCB failure)





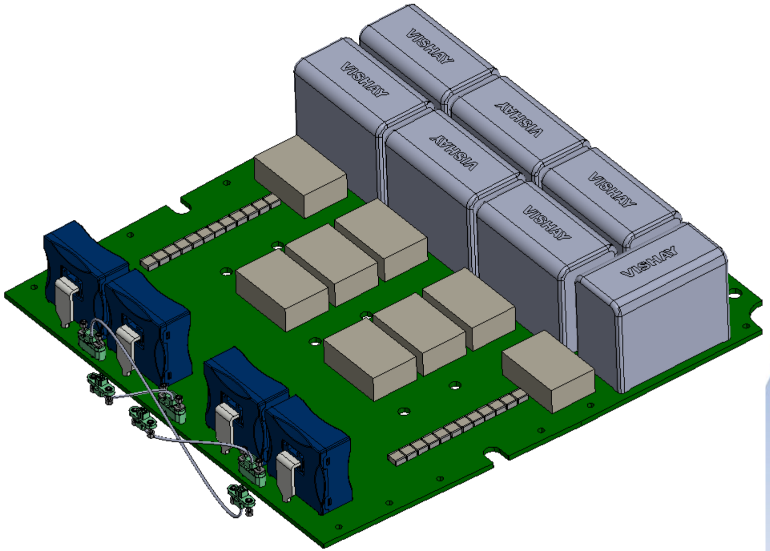
MOSFET Catastrophic Failure from Software Faults

X-57 MOSFET Failure Takeaways/Recommendations

- MOSFETs utilized in inverters have high power density and can short circuit the DC Bus, rapidly heat, and explode/eject material
  - Enclosure/mechanical design should take this failure mode into consideration
- Incorporate overcurrent and shoot-through protection in software and hardware
- Ensure that the thermal management system is robust enough to reject required heat from power MOSFETs
- Measure MOSFET temperature as close to the junction as possible
- Test critical components individually, if possible, and powered
- Perform MOSFET health/degradation checks if possible (blocking voltage, reverse diode voltage/current, Rds measurements)
  - A curve tracer is extremely helpful for this type of testing
- Gather temperature data over time to detect signs of degradation

X-57 DC Link Capacitor Failure

- The DC Link filter is an energy dense circuit within the inverter
- The filter is a capacitor bank that mitigates voltage/current ripple on the DC Bus
- Typical Failure Causes: Over voltage/current/temp, mechanical stress
- Typical Failure Modes: Open or short circuit depending on cause and type of capacitor
    - Shorts can often lead to explosive failures



XM3 CMC AC/DC Board with DC Link Filter Capacitors

X-57 DC Link Capacitor Failure

- Failure in isolation between the DC bus and enclosure led to an explosive failure of multiple ceramic DC Link capacitors within the CMC
- Failure of one capacitor may further degrade others and cause cascade failures

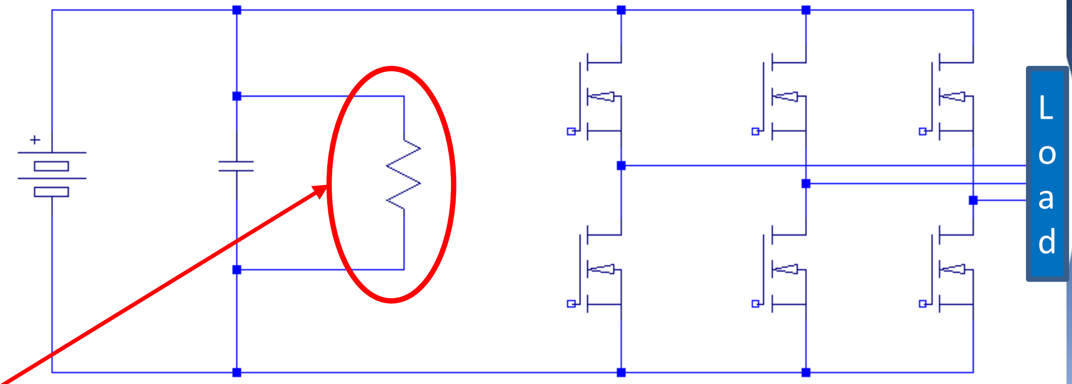
Flight XM3 CMC Row of Capacitors Failed due to Error in Assembly Process to Properly Isolate DC Bus and Gnd

X-57 DC Link Capacitor Failure Takeaways/Recommendations

- DC Link capacitor failure has multiple sources including vibration, electrical stress, temperature, PCB placement, reflow temperature, component quality, etc
- Mechanical stress should be mitigated as much as possible, especially when using ceramic capacitors
- Inverter enclosure design should take explosive failures into account
- Internal (PCB) and external (connector) Hi-pot tests should be conducted regularly to confirm isolation between the DC bus positive and negative planes, as well as to the enclosure

DC Link Bleed Resistor

- Discharges DC Link Capacitors to safe voltage
- Time to discharge can be tuned



DC Link Bleed Resistors

Inverter Maintenance Recommendations

- Document all testing, discrepancies, etc. and create traveler for each inverter
- Periodic inspections and health tests:
  - Low power or unloaded tests can provide insight into MOSFET health and ensure proper control functionality (externally measure phase voltage/current, load banks are helpful here)
  - High power dynamometer or loaded motor tests with power analyzer
  - Perform external Hi-pot tests at the connectors and between enclosure and/or vehicle chassis
  - Monitor/log temperatures of critical components (MOSFETs, converters, PCBs, etc.) for signs of component degradation over time

Lessons Learned/Recommendations (1/3)

Create a Comprehensive Tuning and Airworthiness Qualification Program

- Define the test
  - Is it acceptance/qualification? Workmanship screening? Do you just need it to survive the environment?
  - E.g., X-57 redefined our vibration curves multiple times to attempt to better replicate the actual environment on the plane. Your initial guess may not reflect reality when it comes to vibe/thermal levels
- Ensure testing envelopes all nominal and corner cases
  - Power, Efficiency, Thermal, Vibration, etc

CMC Test Program

Assembly at OCf
- Detailed assembly instructions have been iteratively improved between Techs and Designer
- Mandatory inspection points
- Hi-pot isolation checks

HW Checkout
- Hi-pot: 500-1000 V component to case
- Proc-CEPT-162 functional test. (no-load motor at 100-550 VDC)

Dyno functional Acceptance
- Current and voltage sensor gains characterized
- Tests all interfaces and full power envelope

High Power Vibration Environment
- 20 minutes on each axis, 60 minutes total
- Does not fully screen for workmanship defects (each axis 37% effective per MIL-HDBK-344A)

High Power Thermal Environment
- 7 thermal cycles incl. op & non-op limits.
- Does not fully screen for workmanship (18% effective per MIL-HDBK-344A)

Aircraft V&V
- Exercises the entire powertrain with static propeller loads in single, dual, and quad CMC modes.
- Exercises flight interfaces in relevant EMI and power quality environment.

Flight Operations Tests
- Combined Systems Test (CST) demonstrates compatibility between all systems
- Taxi Test demonstrates vehicle operation in dynamic environment

- CMCs demonstrate full performance on dyno and operate at high power in prescribed environments.
- Workmanship screening not fully complete solely from Env. Testing, but runtime from each of stage of ground testing accumulates stress screening from incidental thermal/vibe cycles

Lessons Learned/Recommendations (2/3)

Design and Assembly:

- Internal isolation between LV and HV components (separate ground planes with single-point interfaces)
- Design controller with sufficient dead time and desat/shoot-through protection (hardware and software)
- Design for high EMI environments; consider physically isolating high and low power electronics, using differential PWM signals with appropriate RC filtering, and proper grounding techniques
- Size current sensors for the highest resolution and accuracy attainable
- Design dedicated heat rejection paths using rigid heat distribution parts
- Utilize thermal isolation for LV and HV components; use separate ground planes with single-point interfaces
- Choose high precision parts for applicable circuits (desat, current sensing, voltage sensing, temp sensing, etc.)

Lessons Learned/Recommendations (3/3)

Design and Assembly Continued:

- Perform hi-pot isolation checks throughout the assembly process
- Perform HW functional checks at intermediate stages during the assembly process

Programmatic:

Take the time to perform acceptance/qualification tests of hardware before using them to complete other project milestones

Testing:

- Use low voltage tests to baseline inverter performance before and after acceptance/qualification tests
- Test DC bus filter quality with full powertrain and avionics to avoid future EMI troubleshooting
- Test critical components in flight-like environment under power; individually if possible

X-57 Cruise Motor (CM) Background

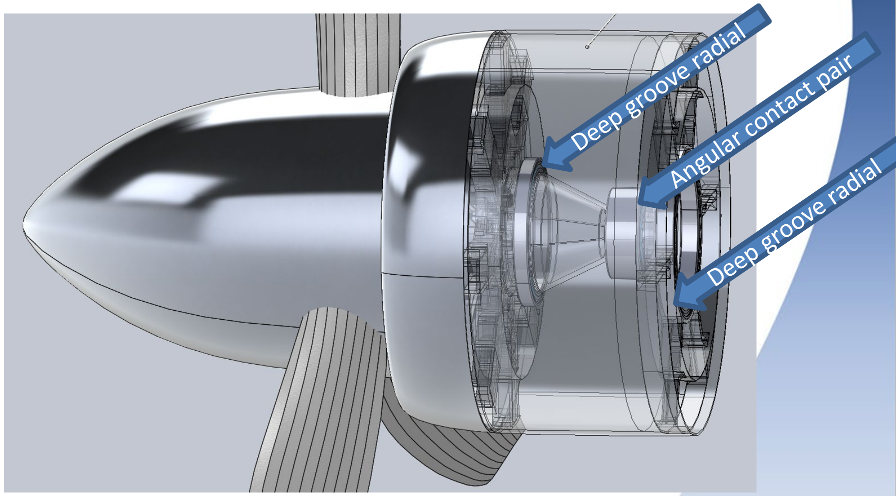
- **Manufacturer**: Designed and built by Joby Aviation under contract to ESAero to meet NASA specification
- **Model**: JM-X57 Rev K, build 2
- **Function**: Provides up to 72 kW of propellor shaft power at 255 Nm of torque at a speed of 2700 RPM
  - Air-cooled out-runner design
- **Subsystem Testing**: Proto-qual and Acceptance performed by ESAero

Additional Background:

- X-57 Cruise Motor design developed solely for NASA
- Joby Aviation's current motor design is significantly different and more advanced than the X-57 CM design

X-57 Cruise Motor (CM) Background

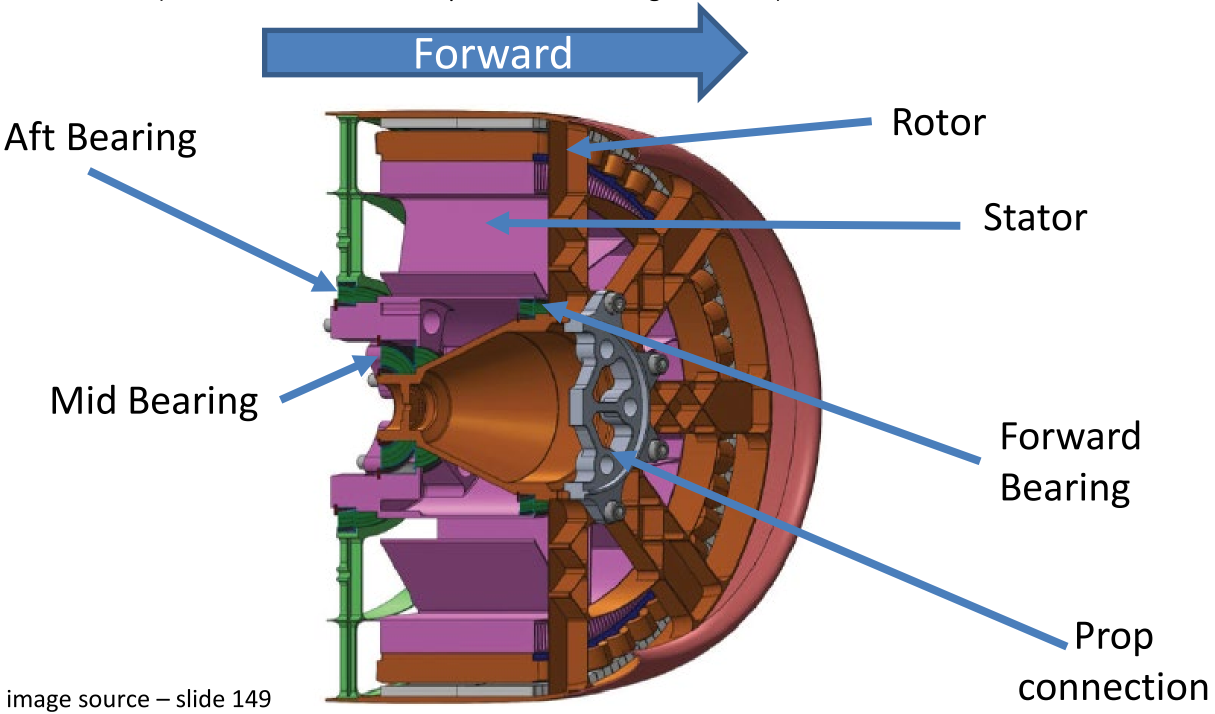
- Provides up to 72 kW of propellor shaft power at 255 Nm of torque at a speed of 2700 RPM
- Powered by the Cruise Motor Controller (CMC)/Inverter that converts DC input from battery to 3-phase AC
- Two independent sets of windings (Two CMCs per motor for redundancy)
- Normal flight operational range of 538V – 340V
- Air-cooled design
- Cruise motor design includes a slip-ring interface for the prop pitch control and position sensing feedback
- Cruise motor temperatures collected and placed on the Aircraft CANBus



Rotor with Bearings

Cruise Motor Bearings

JMX57J
(Earlier iteration that is representative of flight version)



JMX57J image source – slide 149
https://cms.nasa.gov/sites/default/files/atoms/files/sceptor_cdr_day_1_package.pdf

Forward & Aft Bearing Type
(Not to scale)

Mid-Bearing

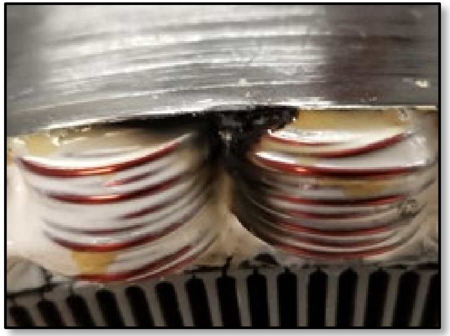
X-57 Cruise Motor (CM) Hardware Background

- **CMs 001-005 (2017 – late 2018)**
  - ~130 hours on Airvolt Test stand across CMs 001-003
  - < 10 hours on aircraft at Scaled Composites
  - Bearing damage/rotor wear noted at teardown and assessed to be the result of not following manufacturer's recommendations to bond bearings in place
  - Stator build for CMs 001-005 was assessed to be non-flightworthy due to stator potting issue resulting in loss of isolation
- **CMs 006-010 (late 2019 – late 2022)**
  - Contains new build stators, which address the previous potting issues, and original rotors
    - Intent and assumption was no mechanical difference from old stators
  - ~200 hours on dyno as part of CM acceptance & proto-qual testing and CMC development and acceptance efforts
    - CM acceptance & proto-qual testing intended to confirm performance
  - ~27 hours on-aircraft
  - Bearing damage and rotor wear noted during pre-planned bearing replacement
- **Team identified concerns with CMs 007-010 and attempted to address with two approaches**
  - Slightly modified configuration to resume ground testing and assess for flight (Mod 0)
  - Additional minor modifications to improve bearing operation (Mod B)

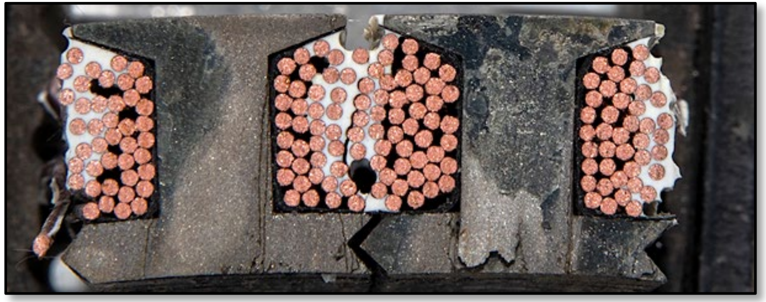
Dynamometer Image Source
https://www.esaero.com/products

Summary of CM Technical Issues: Stator Potting

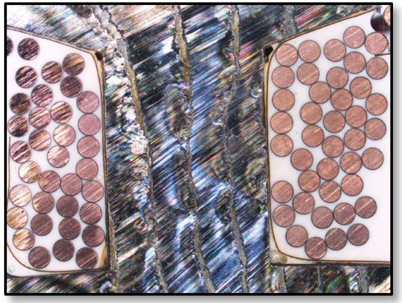
- Fabricated new stators in 2019/2020 to correct winding isolation defects
- Stator laminate stack up design introduced high-stress at end-turn areas
  Phase-to-structure isolation faults after prolonged operation
- Potting process control did not ensure sufficient penetration into winding bundle. New fabrication run improved from ~20% to ~90% penetration, but void pockets still existed and were accounted for in thermal analysis
- Performance/thermal void analysis of updated potting reduces stator thermal margin, but still positive in the ICPT model



Isolation failure of original design during HV vehicle test produced internal arc fault



Original motor winding poor epoxy penetration (typical throughout)



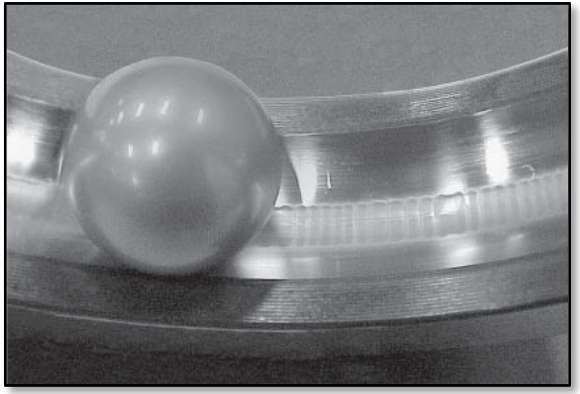
Improved fabrication process (typical for 80% of samples)

Improved fabrication process still exhibits some voids

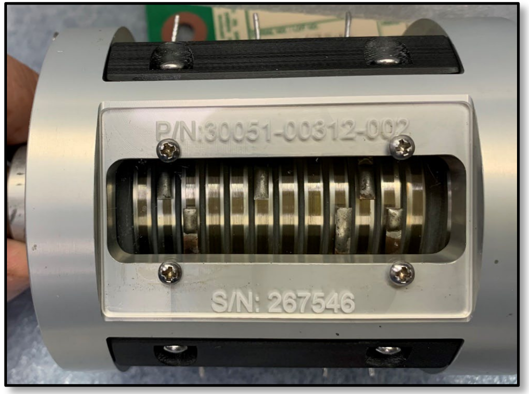
https://ntrs.nasa.gov/citations/20210025904

Summary of CM Technical Issues: Bearing EDM Damage

- Electrical Discharge Machining: rapid switching in modern AC drive systems may generate high frequency (HF) current pulses through the bearings
- If the energy of these pulses is sufficiently high, metal transfers from the ball and the races to the lubricant and is manifested as pitting
- Recommend creating a rotor to chassis drain path (grounding pin) through slip ring



Fluting caused by bearing currents
Figure from ABB drives Technical guide No. 5: Bearing currents in modern AC drive systems



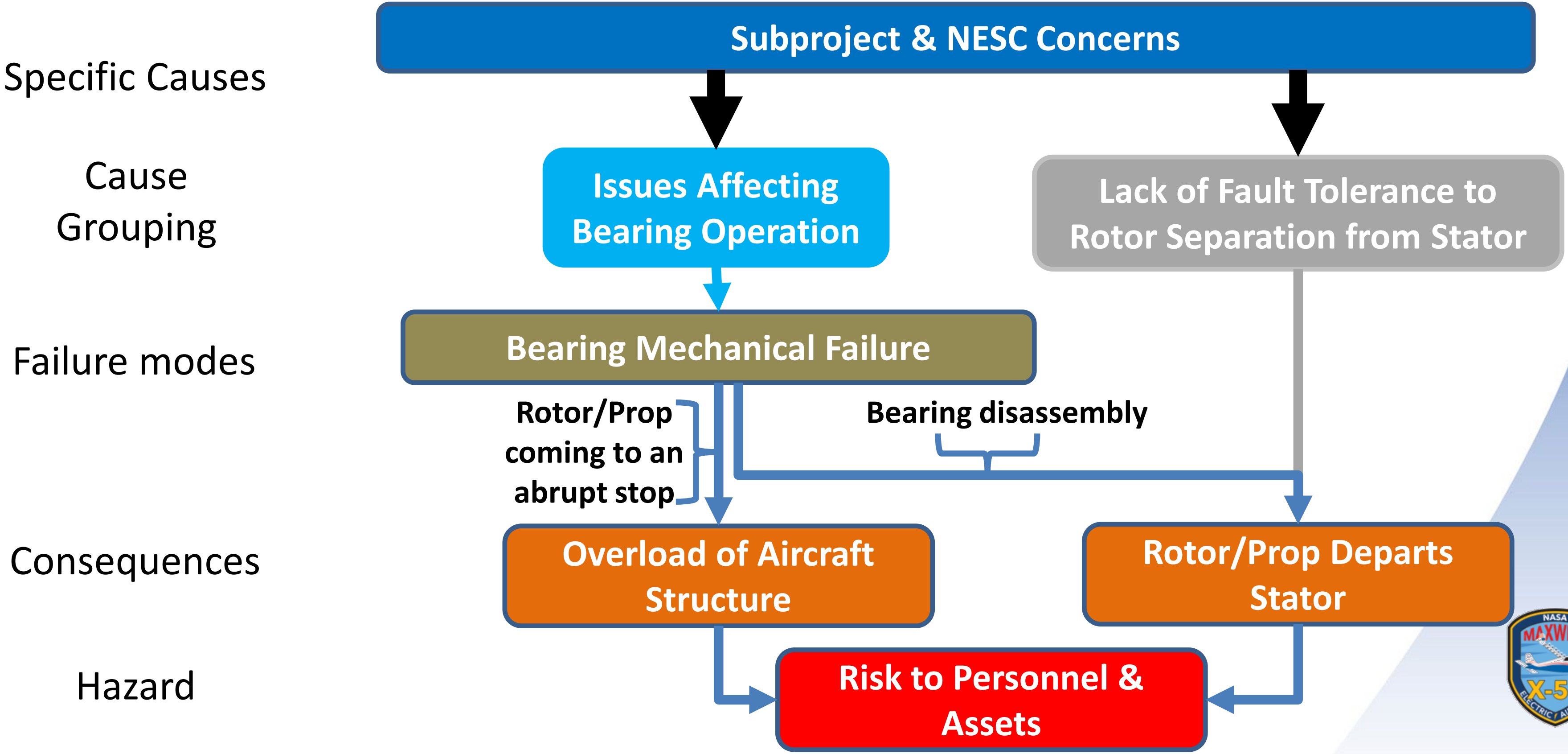
Slip Ring brush arms and rotor rings via inspection window
Also visible: pins not in use after channel reassignment
("guard channels" providing extra clearance)

Summary of the X-57 Cruise Motor Technical Issues

- X-57 Subproject and the NASA Engineering and Safety Center (NESC)* identified several issues with the CM design that affect airworthiness
  - NESC input was requested by the project following concerns raised by X-57 team members
- Subproject and NESC CM Design Issues Fall into 2 Overarching Categories:
  - Issues affecting bearing operation
  - Lack of fault tolerance to rotor separation from the stator
    - Project had not previously considered this to be a credible failure mode

* NESC's mission is to perform value-added independent testing, analysis, and assessments of NASA's high-risk projects to ensure safety and mission success. The NESC engages proactively to help NASA avoid future problems.

Cruise Motor Issues & Consequences



Rotor/Prop Departs Stator Consequence

- Bearing mechanical failure resulting in bearing disassembly concern
  - Difficult to assess likelihood of bearing failure due to non-standard design implementation
  - Bearings will deform under flight loads and deformation will impact bearing operation, which increases the probability of a failure

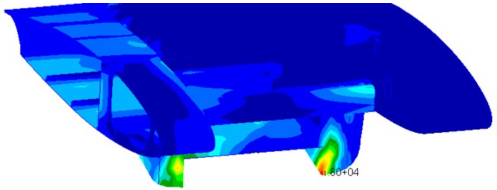
Mid-Bearing

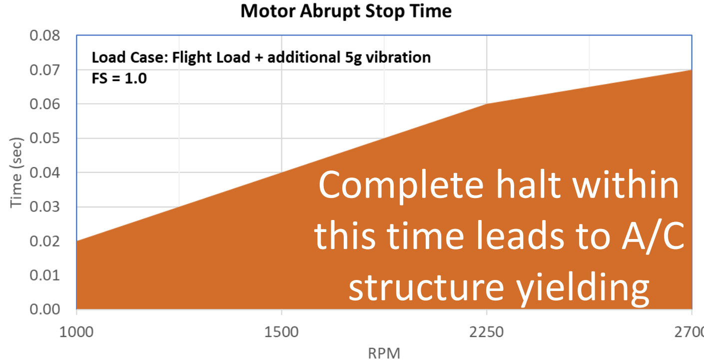
Consequence – Rotor/Prop departs the Stator in event of a bearing disassembly

- Lack of Fault Tolerance and adequate retainment method increases the probability of this consequence occurring

Overload of Aircraft Structure Consequence

- Abrupt stop of the motor caused by a seized bearing can overload the structures and cause structural damage
  - The critical area is Wing and Truss attachment
  - Load case: flight load + assumed additional 5g motor vibration due to bearing failure
  - For example, Structural damage may occur if the motor comes to a halt in less than 0.06 seconds while running at 2250 rpm.
- In the scenario where the motor does not seize, an imbalance load of ~750 lb total as a result of bearing operation failure will exceed the structural limits
  - Design requirements sets 255 lb as max. allowable imbalance load





Consequence – Overload of Aircraft Structure
- Overload of Aircraft Structure is an increased concern due to bearing operation issues.
  - Analysis indicates that a bearing failure that rapidly halts rotor/prop rotation will overload the aircraft interface structure

Technology Development Process Recommendations

- Conduct Technology Readiness Assessments (TRAs) throughout project lifecycle
  - Required to develop a properly scaled and resourced (personnel & skillsets) technology maturation plan
  - Independent Review scope is tailored to match the technology maturation plan (Defined entry/exit criteria, Identification of key subject matter experts)
  - For X-57, pausing to complete a full TRA and redesign the hardware was not practical with competing technical challenges, limited resources for unplanned development, and approaching aircraft integration and flight milestones
- Listen to the hardware
  - Investigate any signs of wear during development; identify and address the root causes
  - Don't be fooled by good results early in a lifecycle. "But it didn't fail…" doesn't mean there aren't more defects
  - There is no substitute for hands-on hardware inspections; especially after tests
  - Establish explicit pass/fail criteria for disassembly inspections and integrate multiple inspection points into development and qual plan

Cruise Motor Testing Considerations

- The X-57 Subproject developed an Airworthiness Acceptance Test Program to qualify the Cruise Motors for flight based primarily on dynamometer operations and previous Airvolt Endurance testing
  - The Cruise Motors technically passed all required tests yet were later found to be unfit for flight
  - The X-57 plan had only one qual inspection on a single motor. More inspection points throughout the development cycle would have helped
  - Acceptance Test Program was focused on verifying and validating the electrical system performance since the mechanical design was thought to have been validated on Airvolt
    - Subproject assumed that the mechanical design was at a higher TRL with COTS heritage, which would have made this a valid assumption
  - There were instances during the acceptance testing campaign (e.g., multiple discrepancies related to bearing health) where these major discrepancies could have been identified

In hindsight, the Cruise Motor Airworthiness Test Approach was more appropriate for screening of mature systems, not for proving out a new design

Proposed Updates to Cruise Motor Acceptance Test Program

Manufacture
- Stators and rotors manufactured
- *More frequent inspection points**

Assembly
- Bearing installs, rotor mated with stator, slip ring, sensor wiring, prop pitch, etc.
- *More frequent inspection points**

HW Checkout
- TP101 Stator winding resistance/inductance tests
- TP102 DC injection tests screen for defects in winding/tooth assembly
- TP103 Periodic Hipot tests check for insulation resistance between windings and CM chassis
- TP104 Rotor magnet health checks for BEMF waveform amplitude and quality

Enviro*
- *Standard Vibration test per DO-160 Section 8.2.1.1*
- *Operating High Temperature Thermal Test per DO-160. Section 4.5.4, fig. 4-4*

Dyno Acceptance
- TP106 Overspeed Test
- TP107 Partial Operational Envelope
- TP108/109 Single/Dual CMC High Torque/Power
- TP110 Hot Steady State

Qual / Protoqual

Protoqual:
- TP111 Partial Operational Envelope

Qual:
- TP113 High Voltage
- TP114 Thermal Envelope Expansion
- I.X57-003-REVB Destructive Teardown

Endurance (on Dyno)*
- *100 cycles, 50 hours of 30-minute mission profiles on Dyno*
- *5x spot checks (every 25 cycles) includes Hi-Pot testing*

Endurance (on Prop)*
- *200 cycles, 100 hours of 30-minute mission on prop test stand*
- *9x spot checks (every 25 cycles) includes Hi-Pot testing*

Proposed updates were in-work and not fully defined prior to Subproject closeout

Bottom Line

- X-57's Cruise motor issues are unique to the X-57 Subproject specifications and Subproject implementation
- The X-57 cruise motor experience is NOT an indication of the state of the electric aircraft motor technology or industry capabilities
- The X-57 cruise motor experience is NOT an indication of the viability of air-cooled electric aircraft motor technology
  – The X-57 Subproject demonstrated an extended ground run with the air-cooled system
- X-57 is discussing the challenges with the X-57 Cruise Motor design with the community so others can hopefully avoid similar mis-steps

Questions?