Chapter 6

Hybrid Electric MC-12 Ground Testing Plan Chapter

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Introduction

In the commercial aviation world, hybrid/electric propulsion is a promising technology for fuel, emissions, and noise reduction in support of the challenging goals established by 2050 EU Flightpath/SRIA, NASA ARMD Strategic Implementation Plan, and the US Air Force ATTAM programs. Ongoing results indicate operational benefits are possible in those three technical areas.

Considering military applications, hybrid/electric propulsion may yield further significant improvements by enabling new, unorthodox mission capabilities. Potential benefits are expected in the areas of vehicle signature reduction (lower noise, lower exhaust signature), usage in enhanced flight environments, minimized human-in-the-loop workload by offering a platform compatible with future goals of autonomous operations facilitation, maintenance cost reductions, and performance burst/dash energy. Additional synergies are likely when used in conjunction with energy weapons. Some potential areas of mutual interest could include, dusty operations capability, remote supply capability, extended surveillance, dispatch able power, fuel-flexible vehicles, and autonomous rescue equipment.

Many of the key technologies that have been demonstrated in ground operation must now be qualified for altitude conditions. We expect to have many flight qualified powertrain systems over the next decade for military planners to choose from for new future battlefield capability. This requires new flight-weight and flight-efficient powertrain components, fault tolerant power management, and electromagnetic interference mitigation technologies. Moreover, initial studies indicate some combination of ambient and cryogenic thermal management and relatively high bus voltages when compared to state of practice will be required to achieve a net system benefit. Developing all these powertrain technologies within a realistic aircraft architectural geometry and under realistic operational conditions requires a unique electric aircraft test bed.

The MC-12 surveillance aircraft is an ideal military aircraft for demonstrating some of the benefits of incorporating hybrid electric propulsion. This report details an approach for full-scale ground-based altitude testing the hybrid electric MC-12 powertrain through a full flight profile.

Purpose of the ground testing

The primary purpose of the ground testing is to enable the high-power ambient light-weight power system testing that is required for the development of the following components to Technology Readiness Level (TRL) 6:

- **High voltage bus architecture –**
  - Insulation, geometry, >1kV
- **High power MW Inverters, Rectifiers-**
  - >98% efficient, >10 kw/kg
- **High power MW Motors, Generators-**

- >96% efficient, >6 kw/kg
- **System Communication –**
  - Aircraft CAN, Ethernet, Fiber-optics
- **System EMI Mitigation and Standards –**
  - Shielding, DOD-160, MIL-STD-461
- **System Fault Protection –**
  - Fuse, Circuit Breaker, Current Limiter
- **System Thermal Management –**
  - Active, Ambient, Distributed
- **Turbo-generation-**
  - Single/Double-spool extraction, Parallel turbo-shaft

Electric Aircraft Testbed Capability in the NATO Countries

Historically, turbofan engines were tested in altitude-controlled wind tunnels and engine components such as compressors and turbines were tested with high power electrical motor driven rigs. And now with electric aircraft, the drivetrain power flow has reversed so that the turbines are driving the electric generators and the electric motors are driving the ducted fans. Hence, further technology development requires a new test bed paradigm that supports the testing of flight-weight high power motors and power electronics under flight conditions. In additional, combined altitude testing of turbo-fan/shaft with high voltage machines is also required.

Recently, several new test facilities have become available for testing full-scale hybrid electric powertrains. Notable industry facilities include GE's EPISCENTER, Collins Aerospace's GRID, and Rolls-Royce's Testbed 80, and Airbus's E-Aircraft Systems House. Notable government facilities include Canada's Research Altitude Test facility, Oak Ridge National Laboratory's Technical Testing and Analysis Center, Air Force Research Lab's Integrated Power and Thermal Facility, and NASA's Electric Aircraft Testbed Facility.

It is important to note that these testbeds are key to understanding how actual individual research hardware components contribute to the overall aircraft net performance. For example, a cryogenic motor located next to an ambient inverter may suffer thermal losses not identified from motor testing alone. Or, a high dv/dt from a high PWM switching rate in the inverter may damage a low impedance motor-especially as the cable length increases. These system interactions can only be identified in a full-scale powertrain testing environment under controlled flight profile scenarios.

Required Capability

- **Facility and Testbed Interfaces**

The hybrid electric MC-12 utilizes two PT6-60A turboshaft engines that are rated at 780kW, 8.5 OPR, 48cm X 1.84 m, and 1,700 RPM and is shown in Fig. 1. Note that the clutch can be implemented with an AviAero Dual Pac Gearbox that naturally adjusts dual power source input. The powertrain will have a 2 kVdc bus with 350kW motor and generator operating at up to 35,000 feet. Overall system will achieve about a 15% reduction in fuel burn if operated at maximum range cruise at 14,000 feet, ISA conditions for about 3 hours with battery providing about 12% of required cruising power. Added electrical system weighs 120 lbs. and is assumed overall 94% efficient.

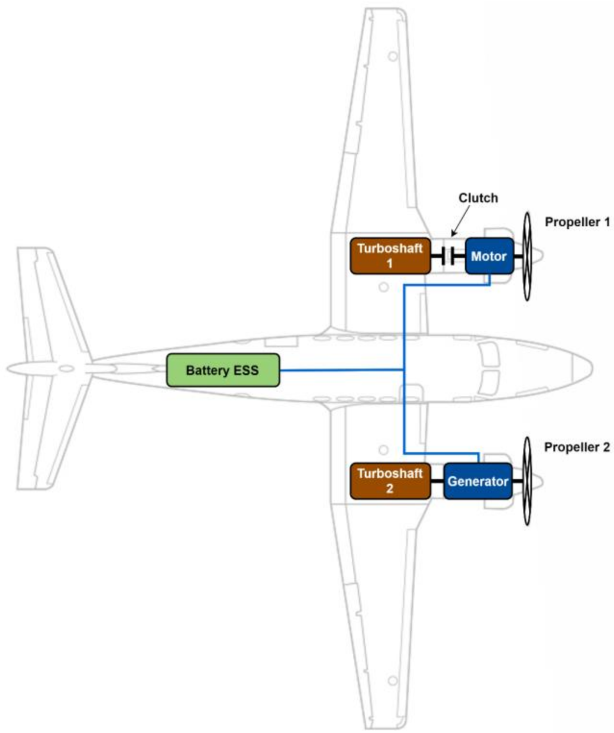

Figure 1. MC-12 Hybrid Electric Configuration

The electric powertrain test configuration is shown in Fig. 2. The facility and research hardware will have the following interfaces:

Power Interfaces

The simulated aircraft DC bus, control, and instrumentation will be supplied with:

- 4160 VAC/480VAC 3 Phase 3MVA facility service (Exterior)
- 220VAC, ±10%, 1 Phase (Interior)
- 120VAC, 1 Phase (Interior)

Aircraft onboard power Interfaces

The onboard aircraft generators and hybrid battery are configured as:

- 350kW generator outputs
- Three series connected 100kW battery simulators

Facility regenerative load side power Interfaces

The fan load dynamometers are used to simulate in-flight ducted fans and feedback thrust power to the facility power supply that in turn powers the simulated turbines that drive the generators:

- 2MW turbine power
- 3 Series Connected 275KW bidirectional 2000VDC power supply

Facility Command and Data Management System (CDMS) Interfaces

Remote control of the facility and test bed is with:

- Ethernet, PLC

Aircraft Onboard Command and Data Management System (CDMS) Interface

The aircraft components utilize the following standards that enable multiple node control/feedback across a single bus:

- CAN, RS-485, ARINC-664

Power Protection Devices and EMC

Initially standard protections are utilized in both the aircraft and facility including:

- Fuses, power relays, pre-charge circuits
- 480Vac 3 phase circuit breakers (At inputs of battery simulators and 2000VDC bidirectional power supply)
- Grounding and Bonding

Video

Due to the hazards associated with high energy and voltage, a remote user room will be used. The user room includes computers, monitors, voice links, and operator station. Due to the distance between the test facility and use room, fiber links are used. There are provisions for standard NTSC video over fiber and Ethernet over fiber.

Ethernet

Four Ethernet links will be used. The first link is dedicated for facility use. The facility uses Programmable Logic Controllers (PLCs) to provide overall monitoring and control. Additionally, this interface would be used for safety critical functions. The second link is used for motor control of the powertrain systems. This would handle the normal communications between the operator, turbine generator, and propulsion motors. The third link would be used for project specific data. This includes transfer of high frequency data, control and monitoring of simulated motors, and control and monitoring of power distribution systems. The fourth link is reserved for hardware developers that have needs due to proprietary or confidential data. Since the control interfaces are Ethernet, the interface can be reconfigured to allow operating the system locally (either co-located or in a user room at the facility).

Power

A high power 4160VAC power feed is standard at the facility. The test bed will regenerate the load-produced power. The high-power feed will be used to start the motors and to replace power due to inefficiencies in the test bed.

Cooling Water

Cooling water is standard via remote cooling towers and/or chillers. Due to the power levels, many of the test bed components are water cooled.

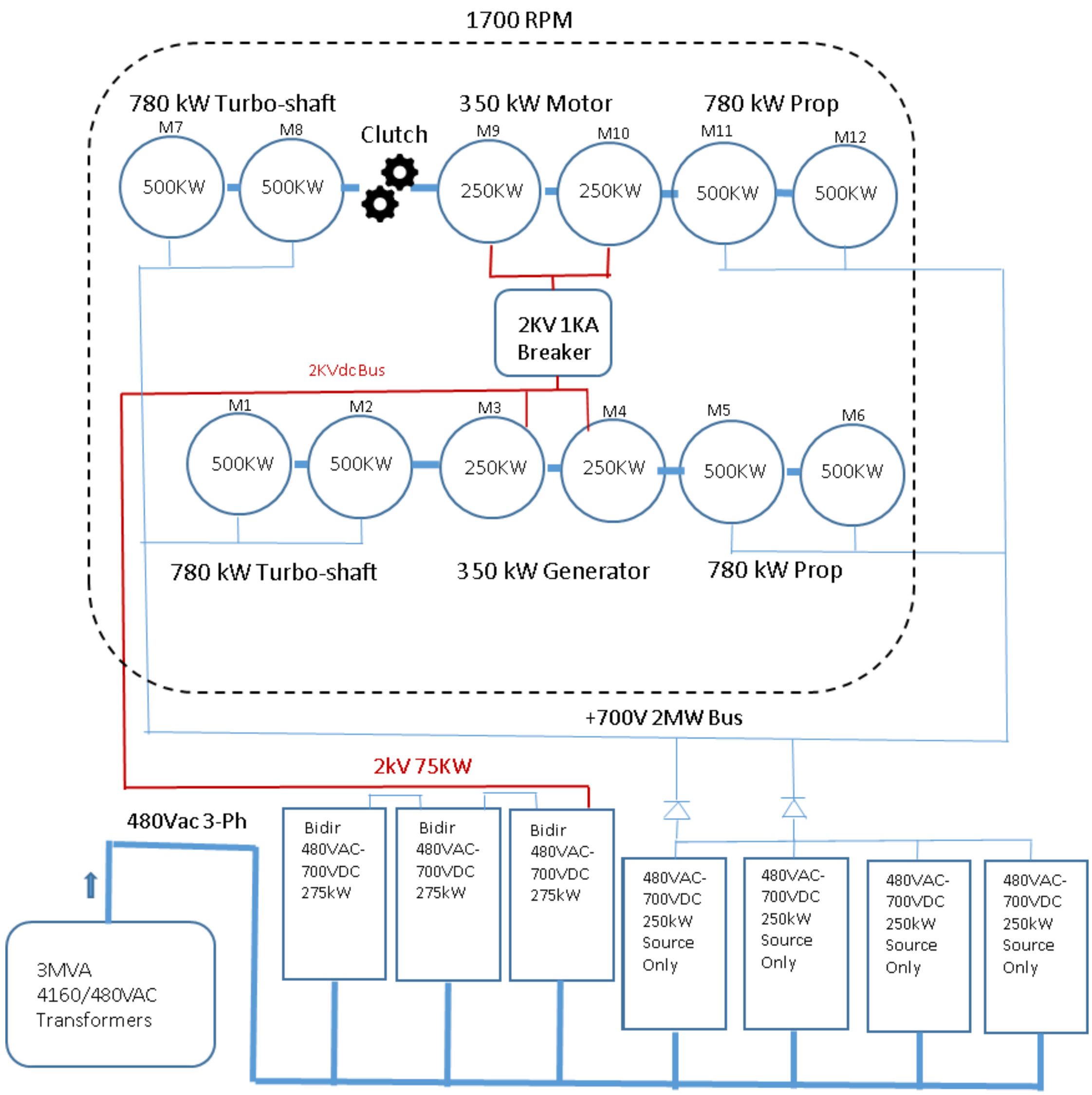

Figure 2. MC-12 Hybrid Electric Powertrain Test Configuration

Development Steps for Advancing MC-12 Powertrain Testing

The scientific goals for developing this test bed may be summarized as finding a way to construct a hybrid electric MC-12 Beechcraft powertrain that provides a significant range benefit relative to standard P6-60A turbo-shaft propulsion systems currently in use. Initially, the goal is to demonstrate that the full complexity of the powertrain system is manageable and safe to use with the best commercially available components. Next, with the performance and control of the powertrain COTS system demonstrated under simulated flight scenarios, the individual commercial components are replaced with ambient flight-weight research hardware. And finally, the most advanced flight certified hardware will be incorporated and tested as they become available. This plan of steady scientific progress minimizes development risk and provides the fastest return on investment.

Phased Powertrain Development

We plan to build up the test bed in steps of increasing complexity along three key areas: regenerative power feedback with full COTS configuration, add ambient research components, add jet fueled turbo-shaft. Initially our powertrain will verify full functionality using COTS equipment only with simulated turbines and ducted propulsors. After full flight profile and regeneration functionality is confirmed, the next step is replacing the COTS generator and motor with flight-weight equivalents operating at full bus voltage. And in the final configuration the simulated turbo-shafts are replaced with the actual P6-60A jet fueled turbo-shafts in an altitude environment.

The high-level development plan is dependent upon project funding, but a representative outlook is provided herein as a guideline. It is divided into three phases:

1. State of the art testing (FY23)
2. Full aircraft bus ambient research hardware testing (FY24)
3. Integrated turbo-shaft, ambient flight-ready powertrain, and thermal management research hardware testing under altitude (FY25)

Phase 1: State of the art testing at sea level (FY23)

During this phase, state of the art (commercially available) power system components are used to simulate an electrically powered hybrid electric MC-12 aircraft. This will demonstrate the facility and test hardware are successfully integrated and enables the use of more advanced power system components in the next phase.

FY23 Scientific Development Goals

Install and demonstrate a complete two propulsor system operating on a single bus at the 350kW total power level. At this power level, both the propulsor and generator portions of the hybrid electric MC-12 configuration can be separately tested. In addition, the 350kW ULI or other NATO research hardware can be added to the test bed as it becomes available. The scientific value of this activity is the identification of methods and processes for stable bus system performance under a variety of fault conditions and for confirming the research inverters perform as predicted.

FY23 Key Task List

Task	Q1	Q2	Q3	Q4
Operate Single-String as Generator	X			
Single-Bus Design	X			
Single-Bus Hardware Purchased	X			
Safety and Hazard Review		X		
Install single-bus test hardware			X	
Operational Readiness Review			X	
Test Single-Bus Propulsor/Generator			X	
Validate controls, protections, performance				X
Validate Simpowersystems modeling				X
Operate as a fan/turbine-mapped propulsor				X
Characterize power quality standards				X

Phase 2: Ambient research hardware testing at altitude (FY24)

As new higher performing research hardware is developed under NRA, SBIR, ULI, NATO, industry, and in-house efforts such as the MW-class motor/generator and rectifier/inverter, these new technologies will be inserted into the existing test bed. They will be operated at standard temperature and pressure but will provide the high efficiency and less total mass that is required for improved electric aircraft propulsion systems.

FY24 Scientific Development Goals

Install and demonstrate a complete MC-12 hybrid electric aircraft powertrain at the 2MW power level. The system will utilize a single bus and include both the turbine-generator machine and the propulsion-fan machine. In addition, the 1MW ambient research hardware can be added to the test bed to validate performance. The research hardware includes motor, inverter, and cooler technologies currently under development.

At this level of development, the project can determine the true feasibility of a flight-weight powertrain for the MC-12 hybrid electric aircraft. The scientific challenges being addressed at this level include maintaining system stability, addressing power quality constraints, confirming system weight and efficiency goals are met, addressing electromagnetic interference, flight control response, higher bus voltages, high power protection schemes, and health monitoring.

Note that at 2kV that the machine, inverter, thermal management, and fault management technology does not yet exist and will need to be developed now to be able to support this FY24 testing schedule.

FY24 Key Task List

Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Add 350kW research hardware	X							
NEAT Multi-Bus Design	X							
High voltage bus Hardware Purchased	X							
Safety and Hazard Review		X						
Install high voltage bus test hardware			X					
Operational Readiness Review			X					
Test high voltage Propulsor with Generators			X	X				
Validate controls, protections, performance				X				
Validate Simpowersystems modeling					X	X		
Operate full fan/turbine-mapped as system						X		
Characterize power quality standards							X	
Incorporate flight control scheme								X

Phase 3: Integrated MC-12 Powertrain research hardware testing at sea level (FY25)

Next, the fully integrated jet fueled hybrid electric MC-12 powertrain is tested at full altitude of up to 35,000 feet (14,000 feet in 2-hour cruise) in a vacuum chamber that simulates correct pressure, humidity, and temperature (1% cold-day, 1% hot-day, typical day) with simulated propulsor fans.

FY25 Scientific Development Goals

Install and demonstrate a complete MC-12 aircraft powertrain at the 2MW propulsive power level incorporating flight-ready P6A-60A turbo-shaft and 2kV machine components. The system will utilize a single bus and include both the turbine-generator motors and the propulsion-fan motors. Recently developed research hardware including a 350-kW motor, 350kW inverter, and solid-state protection systems will be incorporated as they become available. The key scientific questions addressed at this stage will be identifying methods and processes for maximizing powertrain metrics and for identifying what combination of ambient electric and jet fueled components work best together. This level of testing will utilize facility full altitude combustion environment to determine maximum potential benefit that can be derived from this class of powertrain.

As shown in the following key task list below, that at this stage of technical development the full powertrain is integrated together for the first time and is likely tested at a location that can support both altitude combustion/exhaust and partial discharge testing. The only publicly available facility for this testing is the Canadian NRC Research Altitude Facility. FY23 and FY24 tasks require MW-scale power that is not available at this facility. Some consideration should be given to leveraging new industry-developed test facilities that may now incorporate both these requirements (combustion and partial discharge) into a single facility to minimize the complexity of testing this system in stages at multiple locations.

FY25 Key Task List

Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Add jet fueled turbo-shaft hardware	■							
Low impedance fault protected bus design	■							
2kV Fault Protection Hardware Purchased	■							
Safety and Hazard Review		■						
Install all 2kV bus test hardware			■					
Operational Readiness Review			■					
Test 2kV Bus System			■					
Validate controls, protections, performance				■				
Validate Simpowersystems modeling					■			
Operate full fan-mapped/turbine as system						■		
Characterize power quality standards								■
Add 0.1MW thermal research hardware				■	■	■	■	■

System Geometry and Network Topology

It is important to test all the powertrain components within a physical layout that is consistent with the actual aircraft geometry and network topology. The primary reasons for this are:

- field effects such as EMI and thermal management are sensitive to component proximity,
- wave effects such as power line reflections are sensitive to cabling length
- circuit topology effects such as inverter switching cogging or sparking the motor are sensitive to inverter and motor connections

- system mass is sensitive to number of power distribution cables and their voltage
- latency effects such as communication rates are sensitive to number of nodes per topology

Clearly, it is important to have the testbed look and operate like an MC-12 aircraft for those reasons and many others. And moreover, operating the testbed over a full flight profile such as shown in Fig. 3 is required to confirm all systems integrate well over a range of altitude and operational scenarios.

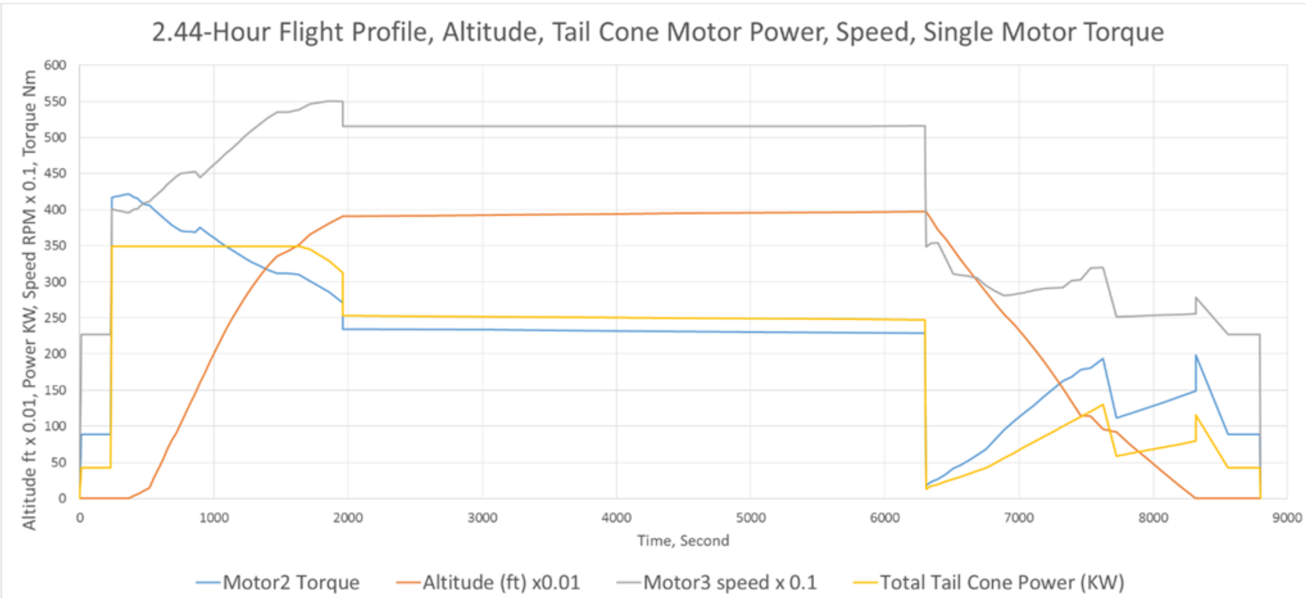

Figure 3. Example full flight profile for MC-12

Conclusion

Ground-based simulated altitude testing is a key enabler of flight-weight powertrain development. The combination of high voltage, high power, distributed low temperature heat sources, combustion, and altitude requires unique testing capabilities that have only recently become available within NATO countries. Moreover, a staged approach of adding powertrain complexity allows for safely testing the hybrid electric MC-12 powertrain under full-scale conditions. And this is best accomplished with a collaboration of government, industrial, and academic test facilities. The proposed development approach and test plan provides an important next step in the path towards electrification of future NATO aircraft.

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