NASA/CR-20260001809

Turbofan Engine Power Extraction Demonstration

Final Report

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March 2026

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Prepared under Contract 80GRC020F0188

National Aeronautics and
Space Administration

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March 2026

Acknowledgments

This material is based upon work supported by the National Aeronautics and Space Administration under contract Number 80GRC020F0188 with Joseph Connolly as technical project lead, Kimlan Pham as the project manager, and Linda Nabors as contracting officer. The authors are grateful for the contributions of the following individuals at NASA Glenn Research Center and GE Aerospace who made significant contributions to the project and allowed for the successful execution and completion of the task objectives.

GE Aerospace: The authors would like to thank the over 500 people who supported PEx over the life of this project, with a special acknowledgement to those who contributed over 3,000 hours including Daniel Lang, Ethan O'Connor, Shane Thomas, Joey Klett, Jose Daniel Mendoza, Kathryn Steller, Bennett Snyder, Justin Rothwell, and Juan Barcenas. In addition, the authors would like to recognize the support the team received from GE Aerospace Future of Flight leadership on this project, including from Arjan Hegeman, Alexander Simpson, Kathleen Mondino, Christine Andrews, Nate Roedig, and Brandon Reynolds.

NASA Glenn Research Center: The authors would also like to thank the HyTEC PEx team, including Nateri Madavan, Anthony Nerone, Joseph Haglage, Jonah Sachs-Wetstone, Paul Giel, Santino Bianco, Jonathan Kratz, Jason Nehez, Arman Mirhashemi, Ariel Dimston, Mark Turner, Marcus Horning, Robert Tornabene, Joseph Saus, Ian Park, Amelia Wilson, Nathan Williams, Michael Bennett, Keith Hunker, Nicholas Purpera, David Ashpis, and Jeff Chapman. We'd like to extend a special thank you to the Propulsion Systems Laboratory team including Michael Oliver, Dennis Dicki, Paul Lizanich, Tony Shook, Peter Brown, Jack Kowalewski, Dan Meter, Chris Morris, Clint Shrewsbury, and Kyle Zimmerle.

Finally, the authors also thank numerous other individuals from GE Aerospace and the NASA Glenn Research Center for their technical guidance.

Level of Review: This material has been technically reviewed by expert reviewer(s).

This report is available in electronic form at https://www.sti.nasa.gov/ and https://ntrs.nasa.gov/

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List of Acronyms

AAVP	Advanced Air Vehicles Program
ARMD	Aeronautics Research Mission Directorate
CV	Concurrent Verifier
EAP	Electric Aircraft Propulsion
ECS	Engine Control System
EGT	Exhaust Gas Temperature
EH	Electrical Hazard
EMI	Electromagnetic Interference
EPISCenter	Electrical Power Integrated Systems Center
EPS	Electric Power System
FADEC	Full Authority Digital Engine Control
HPC	High Pressure Compressor
HPFC	High Power Fuel Cut
HP M/G	High Pressure Motor/Generator
HPT	High Pressure Turbine
HVDC	High Voltage Direct Current
HyTEC	Hybrid Thermally Efficiency Core
ISA	International Standard Atmosphere
KPP	Key Performance Parameter
LBF	Pound Force
LOTO	Lock Out/Tag Out
LP M/G	Low Pressure Motor/Generator
LPT	Low Pressure Turbine
M/G	Motor/Generator
NASA	National Aeronautics and Space Administration
NEAT	NASA Electric Aircraft Testbed
NM	Newton-Meter
NPSS	Numerical Propulsion System Simulation
NTRS	NASA Technical Reports Server
OGV	Outlet Guide Vane
PAI	Primary Authorized Individual
PEx	Turbofan Engine Power Extraction Demonstration
PPE	Personal Protective Equipment
PTO	Peebles Test Operation
QRH	Quick Reference Handbook
QWRL	Quick Windmill Relights
RISE	Revolutionary Innovation for Sustainable Engines
RPM	Revolutions Per Minute
SLS	Sea Level Static

STI	Scientific and Technical Information
TPM	Technical Performance Measures
TRL	Technology Readiness Level

Executive Summary

As GE Aerospace advances toward a revolutionary step change in propulsion efficiency, the integration and demonstration of new engine architectures and technology systems are essential. The NASA Turbofan Engine Power Extraction Demonstration (PEx), conducted through the Hybrid Thermally Efficient Core (HyTEC) project, aims to develop and demonstrate megawatt-class hybrid electric capability on a modern commercial turbofan engine. The hybrid electric system is critical to meeting the needs of the U.S. aviation industry for next-generational propulsion systems with greater efficiency, durability, and range. This supports energy independence and helps ensure the security and resilience of one of America's largest export industries.

The PEx project specifically targets three key objectives: mechanically integrating hybrid electric capability into a commercial turbofan engine, integrating electric machine control with turbofan control for advanced power management, and de-risking performance modeling of future hybrid electric architectures.

To mature these technologies to Technology Readiness Level (TRL) 6, a series of electric power system component tests and a baseline engine performance test campaign were conducted. These efforts culminated in an integrated hybrid electric turbofan test campaign demonstrating power extraction, power insertion, and power transfer between spools. Tests of the electric power system were completed at GE Aerospace’s Electrical Power Integrated Systems Center in Dayton, Ohio and engine tests were completed at Peebles Test Operation in Peebles, Ohio.

Hybrid electric trade studies extended the demonstrated capability to altitude using the validated cycle model from the PEx test campaigns, allowing for comments on expanded mission benefits not demonstrated in the ground campaign. The knowledge gained from PEx also supports GE Aerospace’s Compact Core Demonstrator as part of HyTEC Phase 2 and ultimately informs the implementation of hybrid electric systems in the next generation of GE Aerospace commercial engine products.

This report provides a summary of the program background, test campaigns, trade studies, and insights into the technical maturation required to support future commercial products.

1. Introduction

The NASA Aeronautics Research Mission Directorate (ARMD), through its Advanced Air Vehicles Program (AAVP) and the Hybrid Thermally Efficiency Core (HyTEC) project, and GE Aerospace have partnered to develop and demonstrate megawatt-class hybrid electric capability on a modern commercial turbofan engine through the Turbofan Engine Power Extraction Demonstration (PEx). This project focuses on accelerating technology development for next generation single-aisle aircraft, with the objective of meeting the HyTEC hybridization Key Performance Parameter (KPP) and associated PEx Technical Performance Measures (TPMs) shown in Figure 1.

HyTEC KPPs

	Key Performance Parameter (KPP)	Full Success Single Aisle ~2035 EIS	Minimum Success Single Aisle ~ 2035 EIS
KPP-1	Fuel burn reduction attributed to the high power density core of the OEM's vision turbofan engine	10%	5%
KPP-2	Engine Bypass Ratio	> 15	> 12
KPP-3	Engine Overall Pressure Ratio	>50	>45
KPP-4	Durability, measured in operating hours between major refurbishment	Exceed SOA by 5%	Meet SOA of baseline
KPP-5	Degree of hybridization measured by level of power extraction from the turbine engine	20%	10%
KPP-6	HPC Exit Corrected Flow	< 3 lbm/s	<3.5 lbm/s

PEX TPMs

	Technical Performance Measures (TPM)
TPM-1	MW-Class Power Extraction (SLS Demonstration, Cruise by Analysis)
TPM-2	EGT Reduction (Takeoff Demonstration)
TPM–3	Electric Taxi (Corrected Fan Speed Demonstration)
TPM–4	Power Transfer (G/I Demonstration, % Core power injected)

All PEx TPMs are Aligned to KPP-5

Figure 1: HyTEC KPPs and PEx TPMs

2. Technology Background

The PEx program combines small core engine technology with a history of electric power system component development to demonstrate hybrid electric capability on a modern state-of-the-art commercial turbofan.

2.1 Hybrid Technology Roadmap

The PEx demonstrator is part of the CFM Revolutionary Innovation for Sustainable Engines (RISE) program. Through the RISE program, GE Aerospace and its CFM partners are advancing a suite of new aviation engine architectures and technologies aimed at achieving at least 20% improved fuel efficiency and 20% fewer CO_2 emissions compared to today's engines. The RISE program features four complementary technology pillars as shown in Figure 2.

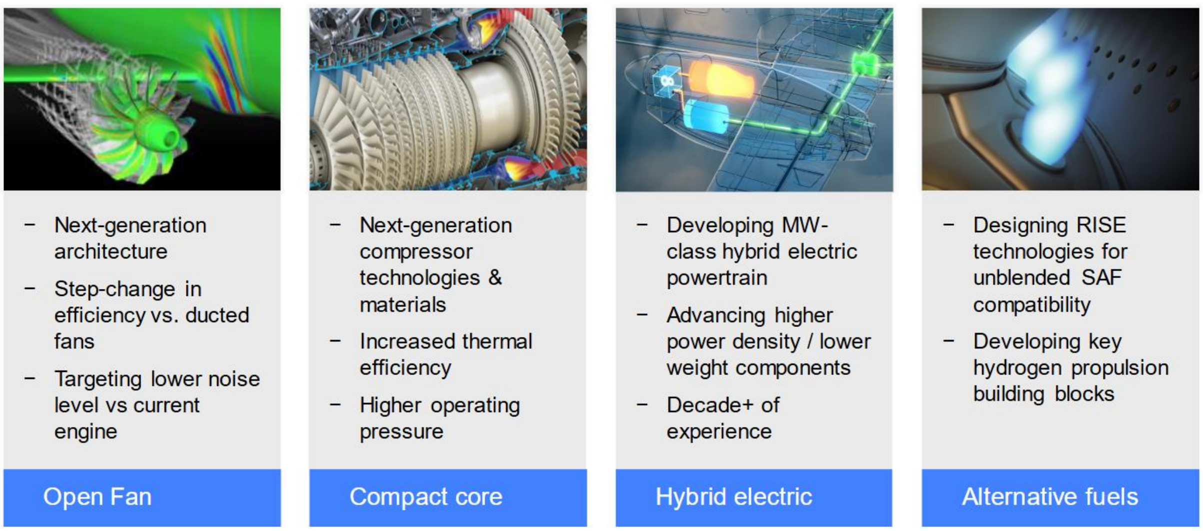

Figure 2: RISE Technology Pillars

The first foundational pillar in the RISE program is the open fan. The open fan strives to achieve the ultimate in propulsive efficiency at the flight speeds of traditional turbofan engines by overcoming the fundamental limitations of traditional ducted systems. The high efficiency fan system naturally drives down the required core power and size. Paired with the open fan, the compact core system addresses challenges of small turbomachinery, while preparing technology for the next generational step in thermal efficiency and enabling additional low emissions technologies within the engine system.

The hybrid electric pillar, within which PEx is a key demonstration, complements the other technologies through an additional step change in system efficiency and emissions through optimization of engine operation and power offtakes, and assists in managing the operation and design challenges of the small turbomachinery in the compact core. This pillar features a step-wise approach to component development, engine integration, and validation tests to mature technologies for turbofan hybrid electric capabilities to TRL 6.

Prior to the PEx hybrid electric turbofan test, the electrical system components were advanced through a series of activities at the NASA Electric Aircraft Testbed (NEAT) facility and through campaigns at GE Aerospace's Electrical Power Integrated Systems Center (EPISCenter). These activities burned down key risks by demonstrating component capabilities and understanding component performance. In parallel to electrical system development, the baseline Passport turbofan engine was tested at Peebles Test Operation (PTO). Summaries of these test campaigns are contained in this report.

The learnings from the PEx demonstrator will inform the implementation of hybrid electric in the RISE product vision. Beyond PEx, this will first be tested on the Core Demonstrator which is a partnership between NASA and GE Aerospace through the HyTEC Phase 2 Project.

2.2 Program Objectives

The objectives of the PEx program were to mechanically integrate hybrid electric capability into a commercial turbofan engine, to integrate electric machine control with turbofan control for the use of advanced power management, and to de-risk performance modeling of future hybrid electric architectures. This section contains a summary of the desired research areas, contractual program objectives, and deliverables that support those objectives.

2.2.1 Summary of Research Areas

Six categories and nine research areas, summarized in Figure 3, were identified to support the overall program objectives. These inform specific use cases explored in the Numerical Propulsion System Simulation (NPSS) model studies (see Section 7) and informed component testing and engine demonstration.

Category		Research Areas	Analysis	SL Test
Dual Spool PEx / Augmentation	(a)	Power Balance Optimization	✓	✓
	(b)	Transient Performance	✓	✓
	(c)	Takeoff and Climb Assist	✓	✓
	(d)	Start and Relight Assist	✓	✓
Augmented Engine Idle Conditions	(a)	Idle power sharing / augmentation	✓	✓
Turbine Electric Energy Management	(a)	Supervisory Control and Power Management	✓	✓
Electric Fan Assist	(a)	Power Extraction at Part Power (Cruise)	✓	✓
In-flight battery recharge	(a)	Battery Recharge	✓	✓
Electric Taxi	(a)	Electric Machine Powered Taxi	✓	✓

Figure 3: Research Areas

2.2.2 Contract Objectives and Deliverables

To support the research areas, specific objectives and deliverables were defined in the PEx contract. A summary is provided here, and further details can be found in Contract No. 80GRC020F0188.

- GE Aerospace shall detail design, build, and assemble motor/generators and power electronics necessary to include on an engine test of a two-spool turbofan.
- GE Aerospace shall define the mechanical, electrical systems, and layout to integrate hybrid electric capability into a modern commercial two spool turbofan engine, and ensure availability of test enabling hardware required for the planned testing. Testing will include adequate instrumentation to understand engine operation and overall performance.

- GE Aerospace shall develop and execute a pre-test model capable of predicting engine and component efficiency, performance, and operability for pre-test predictions, and, in a single aisle flight envelope for conceptual studies.
- GE Aerospace shall perform a variety of ground demonstrations of the integrated electrical and turbofan engine, to both reduce operational risk and understand engine performance in both steady state and transient operation. Testing aims to include operating modes of power extraction, power insertion and transfers between spools.
- GE Aerospace shall provide sufficient information for independent NASA controls and systems analysis assessment/validation.

3. Demonstrator Design

3.1 Summary of System Design

The PEx demonstrator integrated two electric M/Gs with a Passport turbofan. The alternating current M/Gs were individually linked with the HP and LP drivetrains via test enabling hardware, allowing each electric machine to inject or extract power from its corresponding engine spool. Gearing was implemented to align the design spaces of the turbofan engine and M/Gs.

Each electric machine was controlled by a dedicated power converter connected to a High-Voltage DC (HVDC) bus. The power converters invert DC voltage to AC voltage while injecting power into the engine, or rectify (convert) AC voltage into DC voltage when extracting power from the engine. A set of DC power supplies and a load bank were also connected to the HVDC bus to supply or dissipate energy. The Passport Full Authority Digital Engine Controller (FADEC) was equipped with a PEx specific software (leveraging a history of Passport turbofan controls) and coordinates electric machine demand inputs passed to the power converters. More detail on each of these components is included in the following sections.

3.2 Passport Turbofan

The Passport turbofan is a 20,000 lbf thrust class engine designed to power a high altitude, high Mach number, long range business jet. The PEx engine was a repurposed Passport development engine, reassembled in Evendale, Ohio.

The Passport turbomachinery architecture was unchanged from the development engine. The engine turbomachinery consists of:

- Single stage fan blisk with a composite case and composite outlet guide vanes (OGV's)
- Three stage low pressure compressor (booster)
- Ten stage high pressure compressor, with five stages of variable vanes
- Annular rich burn combustor
- Two stage high pressure turbine with active clearance control
- Four stage low pressure turbine with active clearance control
- Long duct mixed flow exhaust

3.3 HP System

The PEx HP system contained the HP M/G connected to the Passport high-pressure spool (HPC and HPT) through the accessory gearbox and located at the 6 o'clock position. The PEx HP M/G was a GE Aerospace MW-Class M/G design

3.4 LP System

The PEx LP System contained the LP M/G connected to the Passport low-pressure spool (Fan, Booster and LPT) on the aft side of the LPT via a series of shafts and a gearbox. A mount extension provided the structural connection for the LP System, the extended flowpath exhaust duct around the M/G assembly, and the air, oil, and electrical services. The PEx LP M/G was a GE Aerospace MW-Class M/G design.

3.5 Electric Power System Components

HP and LP Power Converters: The PEx HP and LP power converters were a GE Aerospace MW-Class power converter design. The power converters were bi-directional DC-AC and AC-DC converters which utilized DC bus voltage to control AC current in the M/Gs.

AC Power Feeders: The AC power feeders provide the electrical connection between each power converter and M/G. The connection was formed by two three-phase power feeders in parallel. Both the HP and LP type design cables were routed from the on-engine M/Gs to the off-engine power converters.

3.6 Key Test Electrical Enabling Hardware

Power Supplies: The DC power supply system utilized for PEx testing at PTO consists of multiple power supplies interconnected to provide power in excess of 1 MW.

Load Bank: A DC resistive load bank was set based on the operating mode of the electric power system and the needs of the test plan.

Thermal Management: Cooling and lubrication to the electric power system components was provided via an external cart.

3.7 Site Design

Engine testing of both the baseline and hybrid electric engines was completed at PTO Site 3B, a test cell capable of performing development and certification test campaigns. For the PEx hybrid test, additional test systems were integrated into the facility, including external generators, the DC power supplies and load bank, power converter test enabling thermal management system, and mounting structures. Figure 4 shows the primary thrust stand surrounded by test enabling hardware, while the control room is out of view.

Figure 4: Hybrid Electric Turbofan Testing at PTO

3.8 Control Systems

The PEx Demonstrator control system integrated existing Passport FADEC components, power converters, and the PTO facility control system.

Full Authority Digital Engine Control: The FADEC performed the role of hybrid supervisor for the PEx hybrid vehicle, managing the operation of each electric machine within the limitations of the entire control system. The FADEC directly controlled engine behavior (fuel schedules, actuator commands, etc.) in a closed loop manner, and controlled the power converters through open loop demands. The FADEC also enforced magnitude constraints and ramp rates on the power converter load demands. The state of the electric machines was always selected by a facility operator and transmitted by the FADEC; the PEx demonstrator is neither configured, nor is it an objective of the PEx demonstrator to have power controllers that are configured, to select the configurations of the electrical machines. Additionally, the PEx demonstrator did not use sensed parameters of the engine during the test to stop the generation of electrical power and then supply power to the other electric machine.

Power Converter: The two power converters (one for the LP M/G, one for the HP M/G) control their respective M/G operation. The power converters each received their mode commands, setpoint demands, and other inputs from the FADEC, and sent operational status and faults back to the FADEC.

Programmable Logic Controller: A series of programmable logic controllers (PLCs) enabled operators to interface with the test system, including controlling test-enabling systems, FADEC inputs, and the electric power system set points.

3.9 Operating Modes

During motoring (power injection) test conditions one or both M/Gs positively applied torque to the drive train and the engine system's corresponding spool. This can impact engine operation by increasing the turbine or fan speed, or by reducing the required fuel demand while maintaining turbine or fan speed. Excess power required for these test conditions is supplied by the power supplies.

Conversely, generating (power extraction) occurs when the M/Gs pull torque from the engine system. This has the opposite effect of superficially slowing down engine speeds or requiring more fuel burn to maintain the operating condition of the engine. Excess power pulled from the engine during extraction testing is dissipated into the load bank.

The PEx electrical system utilized two M/Gs and two respective power converters that each function in independent operating modes, therefore combinations of injection, extraction, or standby operation were possible. Hybrid operation was demonstrated with and without the use of external energy sources.

A simplified drawing of the PEx electric power system is shown in Figure 5, with elements of the control system highlighted in blue.

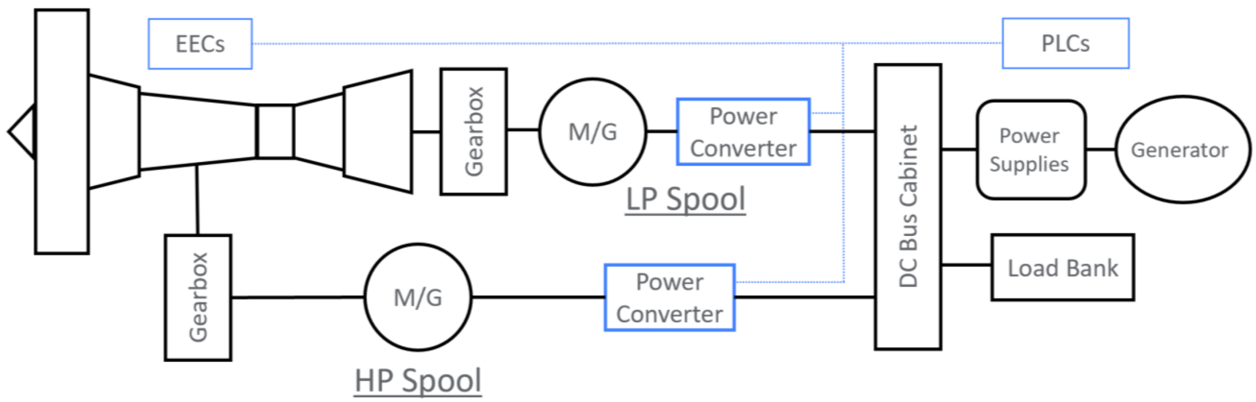

Figure 5: Simplified PEx Diagram

3.10 Safety Measures

The complexity of the PEx engine test introduced several novel risks and safety challenges to manage and mitigate for the personnel responsible for operating, testing, and maintaining the engine. These risks necessitated new safety measures not traditionally used in engine testing at GE Aerospace. The measures used were derived from several sources, including industry best practices, previous GE Aerospace engine and rig tests, and PEx-specific component testing. Examples of expanded safety measures include site access controls, an expanded Lockout/Tagout plan, test-specific training, and specialized Personal Protective Equipment.

Site Access and Lockout/Tagout (LOTO): The PEx engine introduced significant electrical operations and hazards not historically present at PTO. Mitigating these risks was accomplished through the clear definition of roles and responsibilities, dividing the site into colored zones reflecting the level of risk, and concise LOTO procedures.

The PEx risk mitigation plan characterizes participants into two categories: (1) Authorized and (2) Affected Personnel. An individual's role category is used to determine site access and training requirements. The primary difference between Authorized and Affected personnel is that Authorized personnel have a need to physically interact with potentially hazardous equipment, whereas Affected do not. Therefore, Authorized personnel have a higher training requirement than Affected personnel. These roles also directly impact site access permissions.

Access to the site was restricted and dependent on the level of risk. The site was divided into colored zones that were each defined by specific criteria and training for personnel to access. The highest level of risk was defined by the "Red Zone", and access to this zone was restricted to the Primary Authorized Individual (PAI) and Concurrent Verifier (CV) for the sole purpose of performing Primary LOTO. Once Primary LOTO was complete, the site transitioned to the "Yellow Zone", increasing the level of access to include those authorized and affected individuals with a demonstrable need. Special procedures for visitors were developed, including required training and an escort.

Emergency Response: The design of the PEx engine presented a unique challenge to the engine operators in the form of multiple control systems: the traditional turbine engine fuel control, and the Electric Power Systems (EPS). This made management of actions and communication during emergency situations an essential safety consideration. The PEx team developed a Quick Reference Handbook (QRH) to address this challenge.

The QRH is a procedures guide modeled after an aircraft emergency procedure checklist and is intended to be used as a training tool pre-test, and for reference in an actual emergency. The contents of the QRH reflect the most likely emergencies operators may encounter with the engine and test enabling systems (e.g., engine fire, compressor stall, or generator fire). In addition, the QRH contains facility-specific procedures to ensure the proper response to multiple emergency situations.

Personal Protective Equipment (PPE): Numerous overhead lines running to the engine posed a hazard requiring the use of safety glasses to prevent eye injuries caused by falling hazardous liquids. In addition, the electrical hazards associated with the PEx engine warranted the use of electrical hazard (EH) rated footwear. Both PPE requirements exceed what is required for traditional engine testing.

4. Test Program

The PEx program consisted of a hybrid electric turbofan test, supported by additional GE Aerospace test campaigns: the turbofan Baseline Test, and EPS module checkouts.

4.1 Turbofan Baseline Test

Figure 6: Turbofan Baseline Engine Test

A Passport development engine was selected for use as the base turbofan engine for the PEx campaign. The engine was disassembled, inspected, re-instrumented, and reassembled. A baseline engine test of the turbofan asset was successfully completed to verify the functionality of the reassembled engine and to collect performance data for an NPSS data match specific to the PEx turbomachinery.

4.2 Electric Power System Module Checkouts

The electric power system modules including the power converters, AC power feeders, and M/Gs were tested at GE Aerospace's EPISCenter in Dayton, Ohio prior to integration with the engine. Testing included functional checkouts and demonstrations of steady state and transient capabilities and performance across the intended engine operating range. The results also informed an NPSS data match specific to the PEx hardware.

4.3 Hybrid Electric Turbofan Testing

4.3.1 Objectives

The hybrid electric turbofan engine was tested in 2025 with the following objectives:

- Conduct ground demonstrations of the integrated electrical and turbofan engine to reduce operational risk and understand engine performance in both steady state and transient operation.
- Include operating modes of power extraction, power insertion and transfers between spools. Demonstrate relative performance, changes in capabilities, and transient effects of each mode.
- Evaluate the research areas as outlined in Section 2.2. while targeting the trade space levels shown in Figure 7. Altitude demonstrated via analysis.

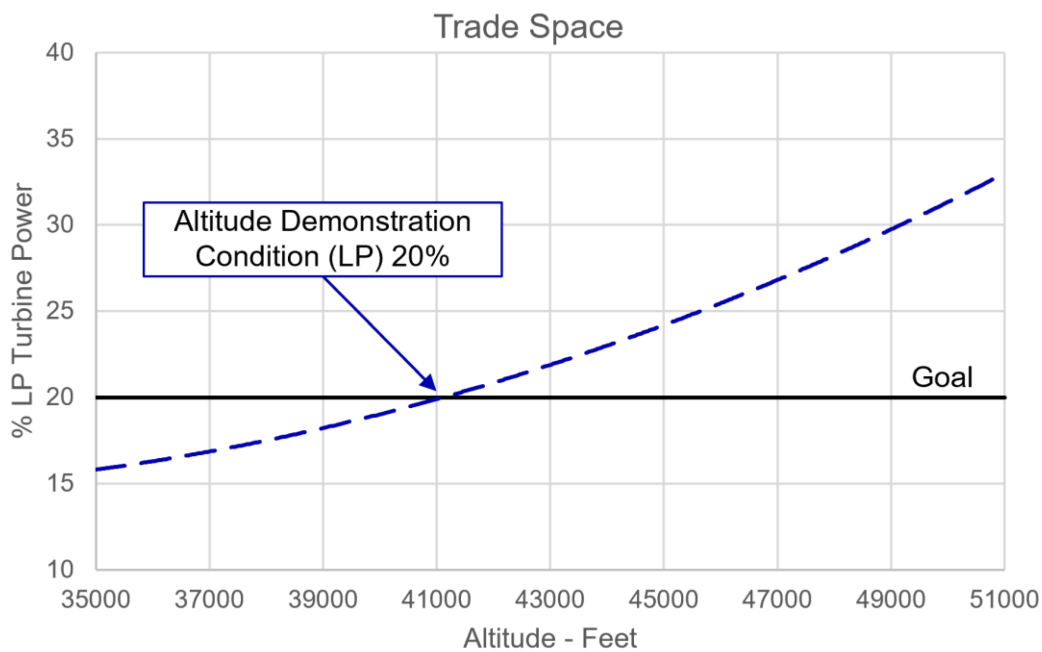

Figure 7: Target Trade Space Levels

4.3.2 Assembly and Test Configuration

After the completion of the Baseline Test, the new PEx drive shaft was installed to the rear of the LPT and a new sump and bearing assembly was constructed inside the Passport tail cone. The LP Module assembly was then built, consisting of the LP M/G, a planetary gearbox, and a drive shaft and bearing assembly. A structural case and two struts surrounded the LP M/G and gearbox to connect to the test enabling mount hardware. A significant quantity of air and oil services were routed through the struts to supply the LP M/G gearbox, and LP sumps. All components were heavily instrumented.

The engine was secured to the PEx engine mount assembly, and the forward sections of the engine (HP gearbox, HP M/G, Bellmouth) were installed. The LP Module was connected to the mount system and aligned to the Passport engine. The inner and outer flowpaths were installed, and final instrumentation routing was completed. Final assembly is shown in Figure 8. Finally, the engine was transported to PTO Site 3B for installation and testing.

Figure 8: Final Hybrid Electric Turbofan Engine Assembly

4.3.3 Instrumentation

The hybrid electric turbofan engine retained all instrumentation that was present on the Baseline Test. The M/G instrumentation was preserved from the EPISCenter campaigns. The new PEx turbomachinery was equipped with extensive instrumentation including pressures and temperatures on all air/oil services, bearing temperatures, stator accelerometers, and more.

4.3.4 Data Acquisition and Reduction

Data acquisition of the baseline turbofan engine used for the PEx program consisted of GE Aerospace's standard suite of data acquisition systems used for a development engine. With the addition of the hybrid electric system of the PEx demonstrator, additional data acquisition systems were also required for increased engineering monitor capability.

4.3.5 Test

The overall PEx test sequence was designed to achieve the PEx Program Objectives summarized in Section 4.3.1. The objectives were divided into five categories which are summarized below. Procedures were developed to ensure data was collected to support each category, these are referred to as test cards.

1. TPMs
2. Steady State testing to inform the NPSS model match
3. Transient testing to inform the NPSS model match
4. Engine controls technical maturation
5. Product vision demonstrations

The engine successfully started on its first attempt. Checkouts were completed for the engine operation while the electrical system was not active, these included high power runs, controls validation, and inbound power calibrations to compare to engine performance on the Baseline Test. Hybrid electric engine operation followed, with LP only, HP only, and dual M/G operation through the end of the campaign. For all testing except electric-taxi demonstrations, the engine fuel control was still active. Testing was completed with Jet-A fuel as well as a drop-in SAF blend. The following sections summarize key data captured throughout the campaign.

5. Technical Performance Measures and Key Performance Parameters

5.1 TPM Results

The PEx program assessed capability against four TPMs, each aligned to HyTEC KPP-5 'Degree of hybridization measured by level of power extraction from the turbine engine'. The TPMs are designed to demonstrate capability with different engine operating conditions representative of different phases of flight.

- TPM #1 was a MW-class power extraction demonstration at sea level static conditions with a projection to cruise conditions
- TPM #2 was a demonstration of EGT reduction at takeoff
- TPM #3 validated electric taxi capability
- TPM #4 was a ground idle representative power transfer demonstration

For each TPM, a dedicated test procedure referred to as a test card was developed for validating both a representative baseline condition (without use of the electric machines) as well as the demonstration of the TPM objective.

TPMs use as-measured data with appropriate corrections as required to inform success. Additionally, TPM #1 uses an NPSS model projection to altitude to assess against the success criteria. Test cards were performed multiple times to ensure repeatability.

TPM #1: Ground demonstrations of maximum LP extraction on PEx were performed at an engine setting representative of cruise (targeting a cruise corrected fan speed from altitude). The ground results were projected to cruise conditions using the as-measured PEx data, the validated Passport altitude lapse, and NEAT altitude test results for the electric power system. It was confirmed that TPM #1 exceeded the full success of 20% LP extraction at cruise.

TPM #2: Demonstrations of maximum LP injection on PEx were performed at takeoff engine power. This TPM exceeded the full success criteria, achieving a significant EGT reduction.

TPM #3: Demonstrations of dual spool injection for an electric taxi operating condition were successfully completed. This TPM exceeded the criteria maintaining ground idle fan speed operation following a fuel cut while powered by the M/Gs only.

TPM #4: Demonstrations of ground idle power transfer via injection into the HP were completed. This TPM exceeded the full success criteria for a representative product vision level of power injected into the HP spool.

5.2 KPP Results

As noted in Section 1, all PEx TPMs were aligned to HyTEC KPP-5. All TPMs exceeded full success criteria, confirming that 10-20% power extraction from a next generation single aisle engine as defined in KPP-5 is achievable.

6. Additional Test Results

6.1 System Performance Validation

After the completion of initial engine testing, two sets of inbound power calibrations were performed. These power calibrations gathered baseline performance data with both the LP and HP electric machines in standby for comparison to data with the hybrid system active. The high-level performance parameters of the engine matched pre-test predictions. These results demonstrate that the engine was in good condition and operating similarly to its performance during the Baseline Test.

The electric power system operation was evaluated through a combination of steady state and transient test cards. Steady state mapping served both as a controls validation exercise and provided initial insights into the electrical system performance and hybrid electric engine derivatives. The high-level performance parameters of the electrical system also matched pre-test predictions.

6.2 Steady State Performance Mapping

The objective of steady state performance test cards was to collect high quality and repeatable data to inform multiple research areas including power balance optimization, as well as inform the post-test model match effort. In addition to demonstrating capability, data collected in this campaign informs model match efforts that validate the modeling of electrical systems and their impact to the engine cycle. The steady state performance matched model is a deliverable under the PEx contract to further support NASA's hybrid electric studies.

Two types of test cards were developed: test cards that explored detailed variation in load derivatives at select engine speeds, and test cards that held constant load setpoints on the electric machines but collected data in detail along the engine operating line.

Derivatives were collected with the electric machines in LP extraction/HP standby, LP injection/HP standby, LP standby/HP injection, and LP extraction/HP injection configurations, at takeoff, multiple part-power, and idle engine speeds.

High level performance parameters such as thrust, EGT, fuel flow, fan airflow, and corrected core speed were compared against model predictions across different LP and HP load setpoints. Trends in high level parameters generally are well matched between model predictions and test data. Figure 9 and Figure 10 below are examples of the model trends compared to as-measured trends of thrust and fuel flow versus load at takeoff power.

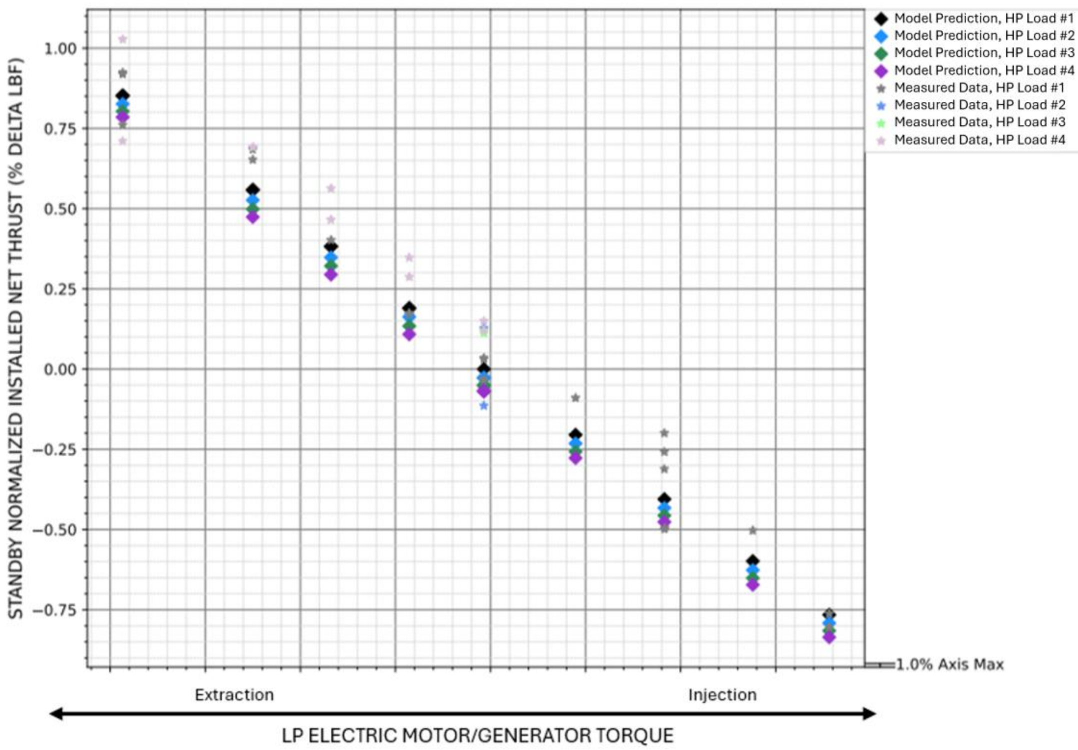

Figure 9: Normalized Thrust Trends at Takeoff

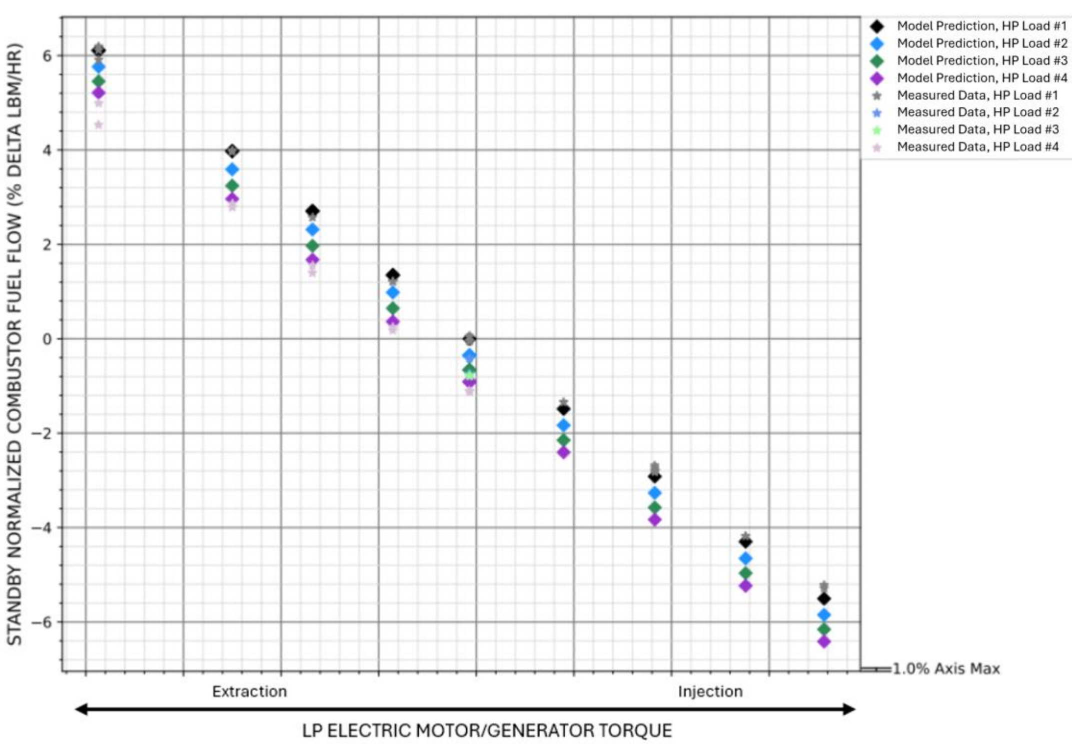

Figure 10: Normalized Fuel Flow Trends at Takeoff

6.3 Transient Performance Mapping

Similar to steady state performance mapping, the objective of transient performance test cards was to collect high quality and repeatable data informing multiple research areas, that will be used to improve transient modeling of the hybrid electric system's impact on engine transient response.

Baseline transient testing included operation with the hybrid electric system in standby at multiple acceleration and deceleration rates to characterize the baseline transient performance of the PEx engine. Loaded data was then collected with varied levels and configurations of the electric power system, including with HP injection, HP extraction, LP extraction, LP to HP power transfer, as well as dual extraction.

Notable demonstrations included reductions in transient times on a rapid engine acceleration as shown in Figure 11, booster pinch point avoidance on a rapid engine decelerations, demonstrating load drops during dual max extraction, and demonstrations that target steady state operating lines during a rapid engine acceleration or deceleration. Variations of applied load were performed to better understand the impact of hybrid electric transient behavior on engine transients, enabling development of transient hybrid electric use cases for a future product.

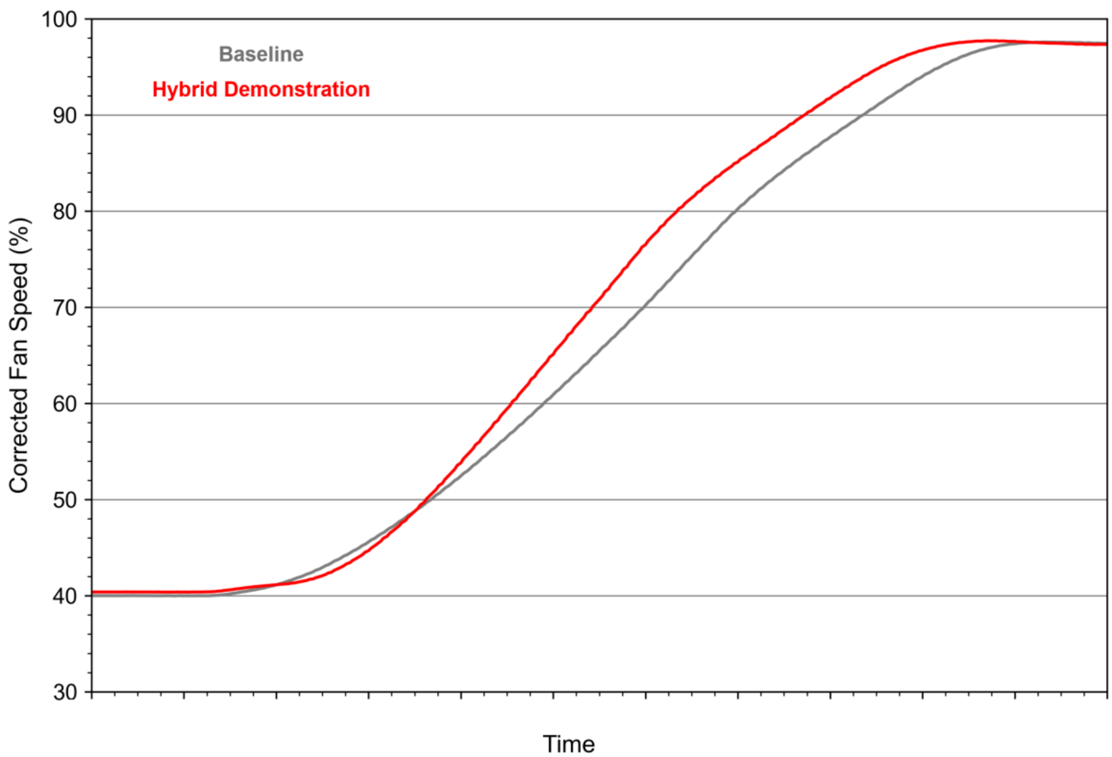

Figure 11: Reduction in Transient Time with Hybrid System

6.4 Test Conclusions

Data collected from this campaign validated PEx engine health, validated safe operation of the electrical system, and completed research objectives for NASA and GE Aerospace.

Key test accomplishments include:

- Safely completed the test in accordance with the issued safety plan, achieving zero incidents.
- Demonstrated and exceeded full success criteria for all TPMs.
- Mapped steady state performance across the planned operating space on both LP and HP spools, including demonstrating all combinations of LP injection, extraction, and standby with HP injection, extraction and standby configurations.
- Performed transient testing with electric machines in several configurations, introducing load at multiple times throughout the throttle movement to demonstrate measurable performance benefits of the hybrid electric system.
- Conducted load drop testing on both the LP and HP spools.

7. Mathematical Model and Electrified Aircraft Propulsion Trade Studies

This section provides an analysis of electrified aircraft propulsion (EAP) studies conducted using the PEx NPSS model, developed as part of the PEx program. This section explores the integration of hybrid electric technologies into single-aisle aircraft, focusing on steady state and transient performance, trade studies, and system-level impacts. Key areas of investigation include the effects of electric machine loading on engine components, fuel burn reduction strategies, and transient operability improvements. Additionally, the section examines advanced hybrid electric capabilities such as start and relight assist, thermal management, and expanded mission profiles, highlighting the potential benefits of hybrid electric systems in improving efficiency, operability, and engine life. The findings are supported by detailed simulations, test results, and conceptual studies, offering valuable insights into the future of electrified propulsion systems.

7.1 Mathematical Model

The content contained within this section was generated utilizing a PEx NPSS steady state model previously delivered to NASA as part of the PEx program.

An engine specific match of the Baseline Test results was applied to a validated Passport engine model to customize the model output to the unique asset used for the hybrid electric test campaign. Additionally, the results of the individual HP and LP EPISCenter tests were incorporated into the model through component level model matching.

7.2 Steady State Analysis

The PEx model was used to calculate predicted performance for multiple altitude conditions at the same corrected fan speeds and electric machine loading as tested at PTO. Figure 12 and Figure 13 illustrate the explored load envelope as a function of shaft speeds. Engine performance and operability were evaluated for these conditions, allowing for cycle and system level conclusions to be drawn.

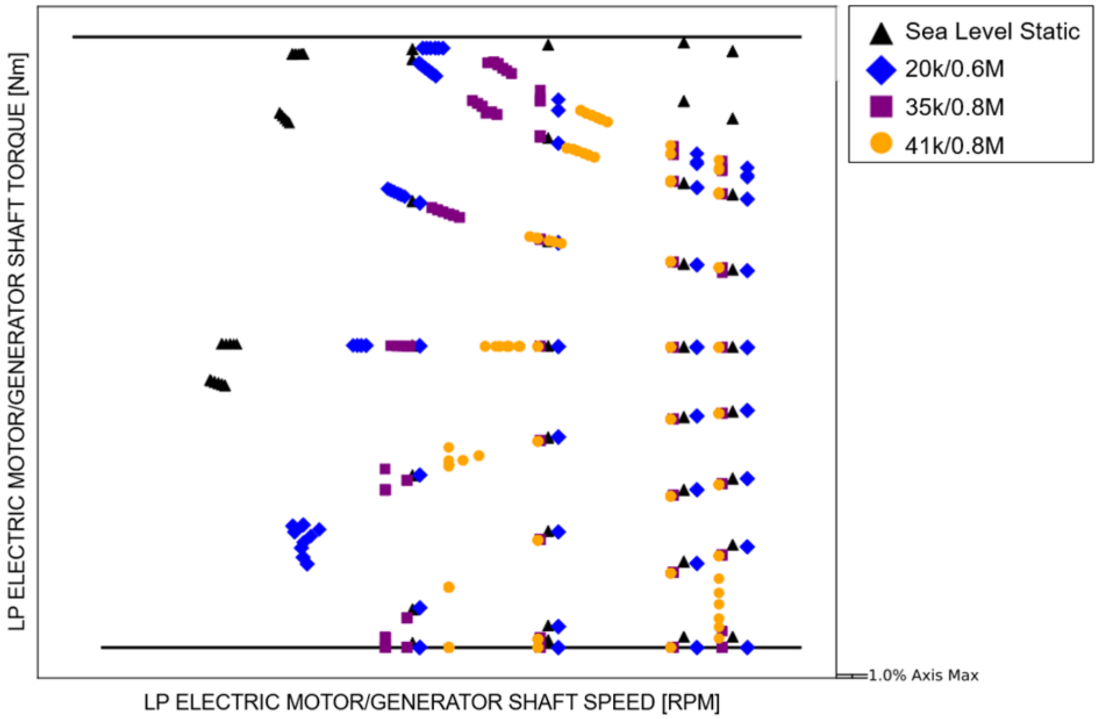

Figure 12: LP M/G Torque Envelope at Evaluated Altitudes

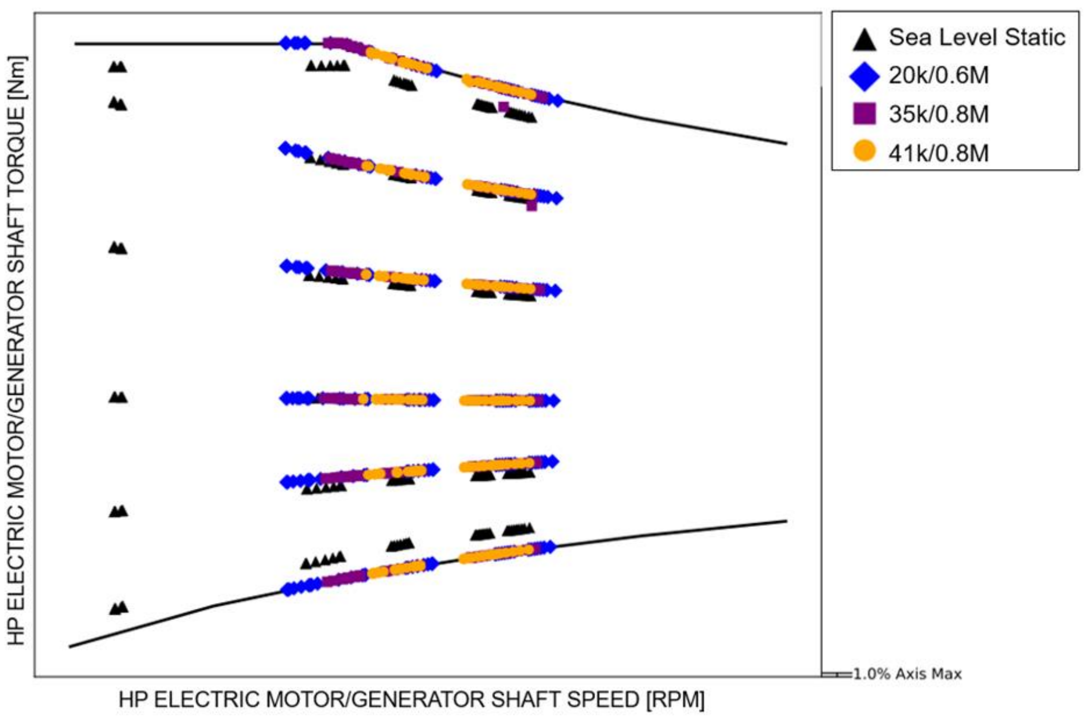

Figure 13: HP M/G Torque Envelope at Evaluated Altitudes

To evaluate how electric machine loading affects engine component performance, steady state derivatives were explored for electric machine operations on each spool, including all combinations of maximum injection, maximum extraction, and standby conditions. Component performance was evaluated both at sea level static and altitude. Studies show similar impacts on component behavior at sea level and at altitude. In the description of resulting effects the term operating line refers to a compression component's (fan, booster, or compressor) natural progression in pressure ratio and flow as engine speed is increased or decreased.

Some notable observations from the studies include:

- The correlation between corrected core speed and corrected fan speed varies with electric machine operation. On PEx, the core speed is highest at maximum LP extraction and lowest at maximum LP injection.
- There is minimal impact to fan component behavior off-idle with changes in electric machine loading, operating line movement is small.
- Booster operating line is dependent on the LP electric machine loading. Increasing LP extraction lowers the booster operating line, while decreasing LP extraction increases it. The effect of HP loading on booster operating line is less significant than LP loading.
- As LP extraction is increased, engine operation shifts the HPC operating line up, and as LP injection is increased it moves engine operation down the HPC operating line. There is little movement along the operating line relative to HP loading.
- Shifts in compressor operating line resulted in variation in compressor efficiency as operation was moved closer to or further from peak efficiency. As power is extracted from the LP shaft corrected core speed is increased, which in turn drives the HPT further down the high speed roll off characteristic and decreases overall efficiency on PEx. HP injection generally decreases HPT efficiency, with a stronger correlation at idle.
- At high fan speeds electric machine loading has minimal impact on LPT efficiency. At idle, LPT efficiency increases with HP and LP injection. LP injection moves the engine operation up in corrected LPT speed associated with reduction in EGT.

7.3 EAP Trade Studies

A study was completed that defined a notional flight profile for the PEx engine. The objective of the mission profile is to reduce total fuel burn relative to the generic mission that includes traditional customer bleed.

7.3.1 Reference Missions

The reference mission utilized is comprised of the following elements:

- A 2 hour and 800-nautical-mile mission flight profile and associated segment times consistent with typical narrow-body applications
- Engine thrust settings developed from a generic engine rating

This mission is consistent with a representative thrust rating and current fleet utilization, but is not specific to any current or proposed application. The study is focused on derivative changes in mission fuel burn between traditional pneumatic engine compressor bleed air environmental control system (ECS) supply configurations and hybrid "all-electric" ECS systems.

The reference mission was exercised for an ISA temperature day for four different configurations targeting the same engine thrust, shown in Figure 14. These are summarized below:

1. Baseline Bled Mission: A traditional pneumatic ECS application.

2. Mission A: A derivative case where the traditional pneumatic system is replaced by an “all electric ECS” system representative of the PEx demonstrator vehicle capabilities. In this case, the electrical power demand was biased towards the motor-generator connected to the HP spool.
3. Mission B: A derivative case similar to Mission A, except that the electrical load was biased to the LP spool.
4. Optimized Mission: A derivative case combining the best fuel burn from Mission A and Mission B to represent the optimal selection of HP versus LP M/G supply for each phase of flight.

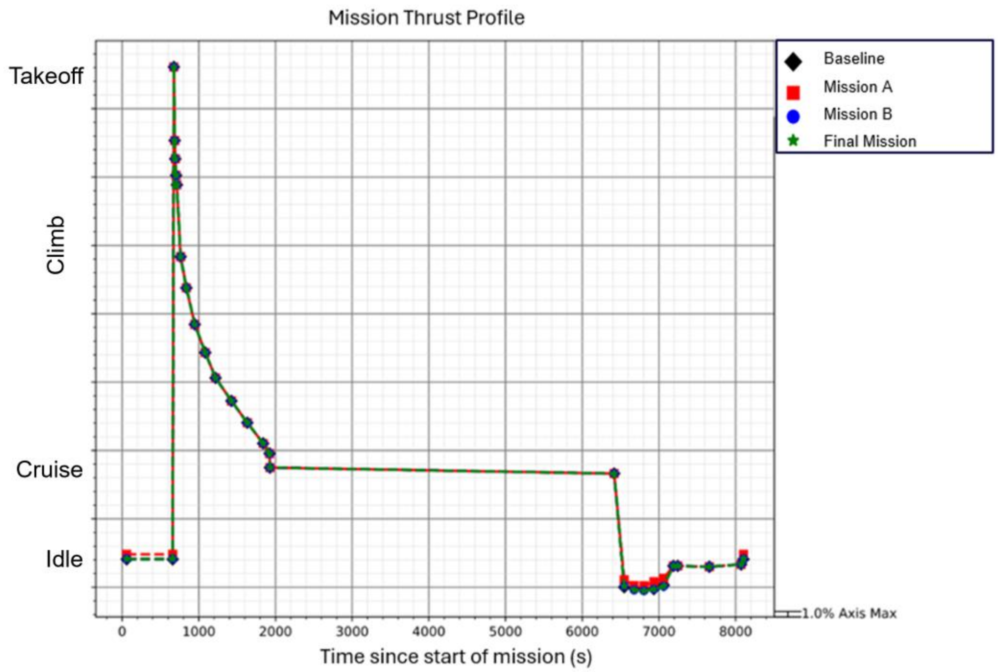

Figure 14: Mission Profile

7.3.2 Results

To minimize mission fuel consumption, percent change in fuel flow against a baseline mission with a traditional pneumatic ECS was calculated for Mission A and Mission B. Takeoff, climb, cruise, and flight idle conditions were all evaluated with the most impactful benefits at idle. The change in EGT for each mission profile compared to the Baseline Bled Mission was also assessed as an indicator for the impact hybrid electric technologies can have on engine life. For fan speeds above idle, the hybrid electric configurations provide significant EGT reduction due to flow being maintained when pneumatic bleed is eliminated from the system.

The Optimized Mission results demonstrate the potential for a multiple percent reduction in fuel burn as compared to the traditional bled Baseline Bled Mission.

7.4 Transient Analysis

The PEx hybrid electric system has many potential impacts on transient performance and operability. The following studies were completed to target transient performance characteristics of interest, each was included as a demonstration in the test plan for PEx.

Steady State Booster Operating Line Transient Simulation: Hybrid electric integration offers the opportunity to reduce or eliminate the operability margin consumption arising from engine transients. Reduced transient consumption may allow for more efficient steady state operation at off-design conditions.

Steady State HPC Operating Line Transient Simulation: Similar to booster transient operating line migration, it is also desirable to minimize the transient migration of the HPC operating line during a burst from ground idle to max fan speed.

Transient Time Reduction: Hybrid schedules can be developed to augment the engine response during throttle maneuvers, designed to inject power into the HP spool and extract power from the LP spool. For all cases evaluated, the time required to reach demanded fan speed was reduced.

Core Speed Overshoot Reduction: Hybrid schedules can be developed to reduce core speed overshoot during accelerations while targeting a common fan speed, by modifying HP load for core speeds approaching the demanded endpoint speed.

Core Speed Undershoot Reduction: Similarly, hybrid schedules can be developed to reduce core speed undershoot during a rapid deceleration maneuver, by modifying torque into the HP spool near the desired ending speed.

HPC Operating Line Pinch Margin: Hybrid schedules can be developed to demonstrate HPC stall margin improvement during a transient maneuver, by increasing HP injection around the pinch point to reduce the transient operating line.

Booster Operating Line Pinch Margin: Hybrid schedules can be developed to demonstrate booster stall margin improvement during a transient maneuver, by increasing LP extraction around the pinch point to reduce the transient operating line.

Motor/Generator Load Drop Scenarios: Simulations of load drops were performed to understand the engine response in the event of a faults or electric machine failures.

Studies were completed at sea level static as well as at a cruise altitude condition, and informed test card definition prior to the test campaign.

7.5 Start and Relight Assist

One area specifically studied within the contract were the benefits of a hybrid electric system for start and relight assist. The addition of electric machines to the engine system allows for torque injection during engine starting and relight attempts.

With the availability of an aircraft power source such as another engine providing electrical power or an energy storage source, air start envelopes could be expanded to lower airspeeds and/or higher altitudes, assuming these power sources provide more torque than traditional air turbine starters.

Additionally, supplying electric machine torque during High Power Fuel Cuts (HPFC) or Quick Windmill Relights (QWRL) could improve engine recovery performance. HPFCs and QWRLs are instances where the engine is shutdown in flight due to either an inadvertent pilot input or an unintended interrupt of fuel to the engine. In these scenarios, it is required that the engine is capable of relighting quickly and returning to power. During either scenario, torque injection to both the LP and HP spools results in slower deceleration and higher turnaround shaft speeds.

This would allow for successful engine recovery after longer fuel-off durations compared to traditional architectures, and less severe thrust loss would occur during the event due to slower spool decelerations. These benefits allow for longer pilot reaction times to restore fuel to the engine. Additionally, relights would occur from a higher HP spool speed compared to traditional architectures, allowing for quicker relights and a potentially expanded QWRL envelope.

Power injection in the HP spool during engine starting also provides a potential operability benefit through lowering the HPC operating line and therefore increasing stall margin. This injected power provides additional stall margin and HP spool acceleration during starts when compared to a start with an identical fuel schedule without injected power.

Additionally, the increased stall margin from HP injection allows for the option of trading the increased stall margin for a more aggressive fuel schedule, yielding a faster engine start time with a similar amount of stall margin as starts without torque injection. There is also the potential to tailor HP torque injection schedules around the stall margin pinch points for specific compressor designs, allowing for further optimization of the sub-idle design space.

8. Technology Readiness Assessment

8.1 Current state of the art technology readiness level

The PEx program represents a significant step forward in support of a notional product. While electric M/Gs have been integrated with engines in the past, the integration of the electric power system with the engine control system and the ability to both share and transfer power between the high and low pressure engine spools provide key information to the value story for such architectures going forward.

One of the primary purposes of the PEx program is to demonstrate at an engine level the efficiency gains envisioned by integrating large, controllable electric motors with an engine power plant. This test burns down several narrowbody product vision risks allowing the PEx architecture to progress to **TRL 6**:

- **Integration of large electric machines with a production engine control system**: The hybrid electric turbofan test campaign demonstrates large scale energy extraction, injection, and power transfer with integrated power converter and FADEC control systems, leveraging a modern commercial turbofan engine. Notable demonstrations include TPM1, a megawatt class extraction demonstration at sea level that is projected to cruise, and TPM2 an injection demonstration targeting reduced EGT at takeoff.
- **Demonstrating transient benefits of hybrid electric technologies, examples include improving operability margin and managing acceleration/deceleration times**: The PEx test campaign contains extensive transient performance demonstrations, including baseline testing, derivative testing with constant torque inputs, and product-like demonstrations. These test cards capture measurable performance differences as compared to their baseline demonstrations and represent a key step in technology maturation for future applications.
- **All electric taxi demonstrations**: TPM3 demonstrates the control systems ability to maintain a target fan speed with no fuel and power injection. This demonstration showcases a key benefit of a future hybrid system.
- **Demonstrates capability for optimal power balance between the HP and LP spools:** The extensive steady state mapping campaign on PEx and TPM4 confirm performance derivatives on each of the components as the hybrid electric system moves operating lines. The data captured here enables power management to be developed on future applications, further integrating the engine and electric system controls.
- **Demonstrates operation with multiple power converters on HVDC bus:** PEx successfully demonstrates both steady state and transient operation of multiple power converters, including demonstrating power transfer from the LP to HP, dual extraction, and load-drop fault scenarios, while maintaining power quality.

In addition, the PEx program provides significant learnings and risk reduction towards **TRL 4,** on how to design and execute a large scale aerospace hybrid electric engine.

- The PEx engine configuration takes significant steps in understanding how to design an engine architecture with an embedded motor/generator, including demonstrating a mechanical integration of the LP M/G and required services in the PEx exhaust flowpath. Electrically, the design also demonstrated the M/G EMI emissions compatibility with the engine control system.
- The control system for PEx demonstrates the FADEC's ability to perform the role of hybrid supervisor, managing the operation of the electric power system within the limitations of the system.

The HyTEC Phase 2 through the Compact Core will take lessons from the PEx program to further mature hybrid electric technologies towards a future product.

8.2 Key technology maturation that remains for a notional product

While the PEx program retires several product vision hybrid electric risks, technical areas remain that require continued technology maturation and demonstration. Areas include continuing to mature electrical component design, further maturing control system design and fault mitigation within an aircraft system, and building on mechanical integration, packaging, and thermal management for a product.

9. Conclusion

The Turbofan Power Extraction Demonstration was a successful multi-year partnership between NASA’s Glenn Research Center and GE Aerospace, supporting the technical maturation of physically integrating hybrid electric capability into a commercial turbofan engine. This effort included integration of electric machine control with turbofan control for the use of advanced power management and de-risking performance modeling of future hybrid electric architectures.

All Technical Performance Measures and Key Performance Parameters were not only met but exceeded during engine testing conducted at PTO. Additionally, data collected from component level and engine testing enabled comprehensive performance modeling of both the electrical and integrated engine system, facilitating product-like studies and mission assessments.

As the aerospace industry moves towards more electric flight, the Turbofan Power Extraction Demonstration is a key milestone in GE Aerospace's stepwise technology maturation towards the next-generation commercial engine products.