National Aeronautics and Space Administration

SUBSONIC VEHICLE TECHNOLOGIES AND TOOLS (SVTT)

Subscale Hardware-In-The-Loop Results for Hybrid Electric Turbofan Controls Use Cases

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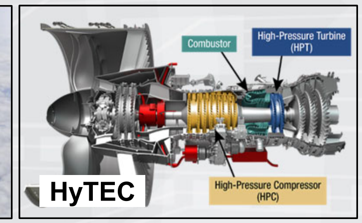
Presentation Overview

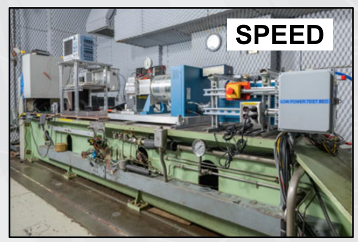
1. NASA Hybrid Electric Research Overview
2. AGTF30-e Engine Model
3. Hybrid-Electric Use Case Demonstrations
4. Hardware-In-The-Loop Testing
5. Conclusions

NASA Electrified Aircraft Propulsion (EAP) Research

- Glenn Research Center (GRC) has been at the forefront of transport aircraft electrification technology development:
  - Developing electrified aircraft propulsion concepts and technologies
  - Testbeds for maturing aircraft electrification technology including component level testing, standards development, hardware-in-the-loop, and integrated systems testing
  - Software modeling tools for analyzing performance, optimization, system dynamics, and control design
  - Turbine Electrified Energy Management (TEEM) is a control strategy for hybrid-electric turbine engines developed at GRC in 2018
- The Hybrid Thermally Efficient Core (HyTEC)[1] project is a partnership between NASA and industry focused on small core engine technologies, including hybrid electric systems

1. Work in the HyTEC project is currently being transferred to the Subsonic Vehicle Technologies and Tools (SVTT) Project





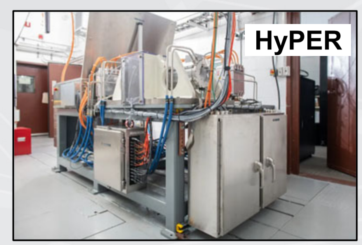


Image credits: nasa.gov/mission/eap

HyTEC Turbofan Power Extraction (PEx) Demonstration

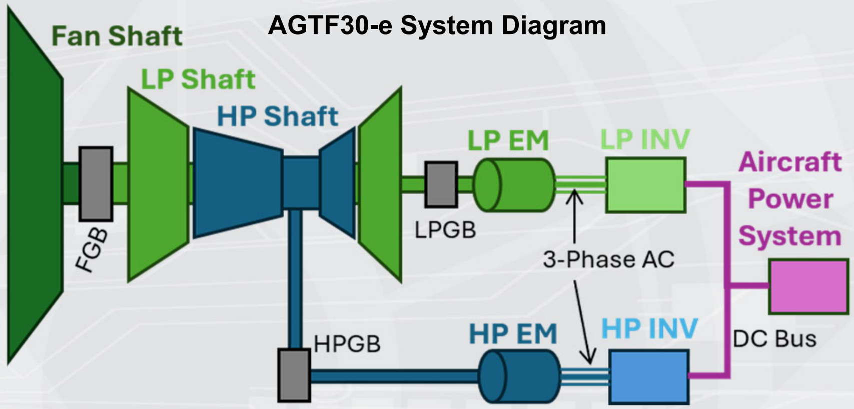
NASA and GE Aerospace completed a ground test of a hybrid electric turbofan engine in 2025

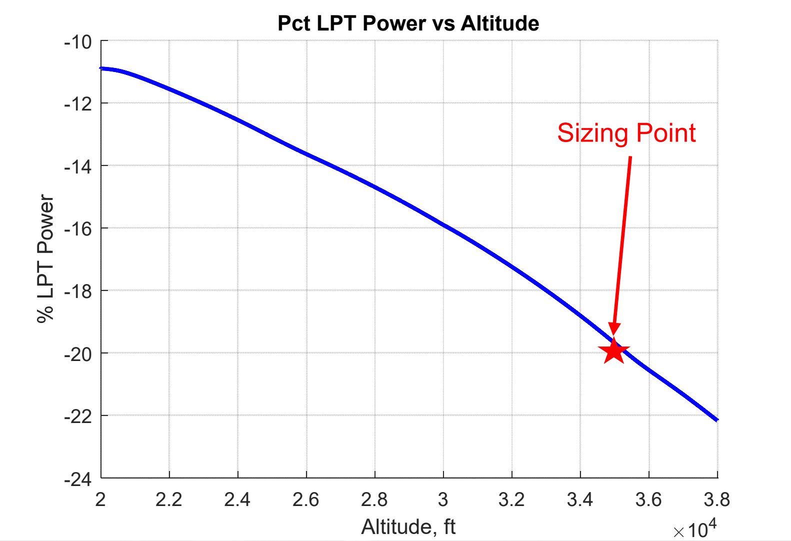
- Demonstrated feasibility of >20% power extraction from a modern commercial turbofan
- Advanced the Technology Readiness Level (TRL) of the hybrid turbofan configuration
- Results used to validate NASA software tools and modeling approaches for hybrid electric turbine engines

Image credits: GE Aerospace

System Under Study – NASA's AGTF30-e

- A public reference hybrid turbofan model is used to evaluate hybrid system applications studied during the PEx Demonstration
- Advanced Geared Turbofan 30,000 lbf – electrified (AGTF30-e) [1, 2]
  - 30,000 lbf thrust class N+3 reference engine design
  - Geared turbofan with variable bleed valve and variable area fan nozzle
  - Bypass ratio of 24, overall pressure ratio of 55, and turbine inlet temperature of 3360 °R (1600 °C) at 35,000 ft, Mach 0.8 thermodynamic design point
  - Hybrid electric system:
    - Electric Machines (EMs) connected to Low-Pressure (LP) and High-Pressure (HP) Shafts via gearboxes
    - EM Efficiency = 96%
    - Inverter (INV) Efficiency = 98%
    - Hybrid system resized to match HyTEC PEx hybridization target (20% LP Extraction at design cruise, maximum core extraction at idle)
      - Maximum LP EM power = +/- 1850 hp
      - Maximum HP EM power = +/- 600 hp

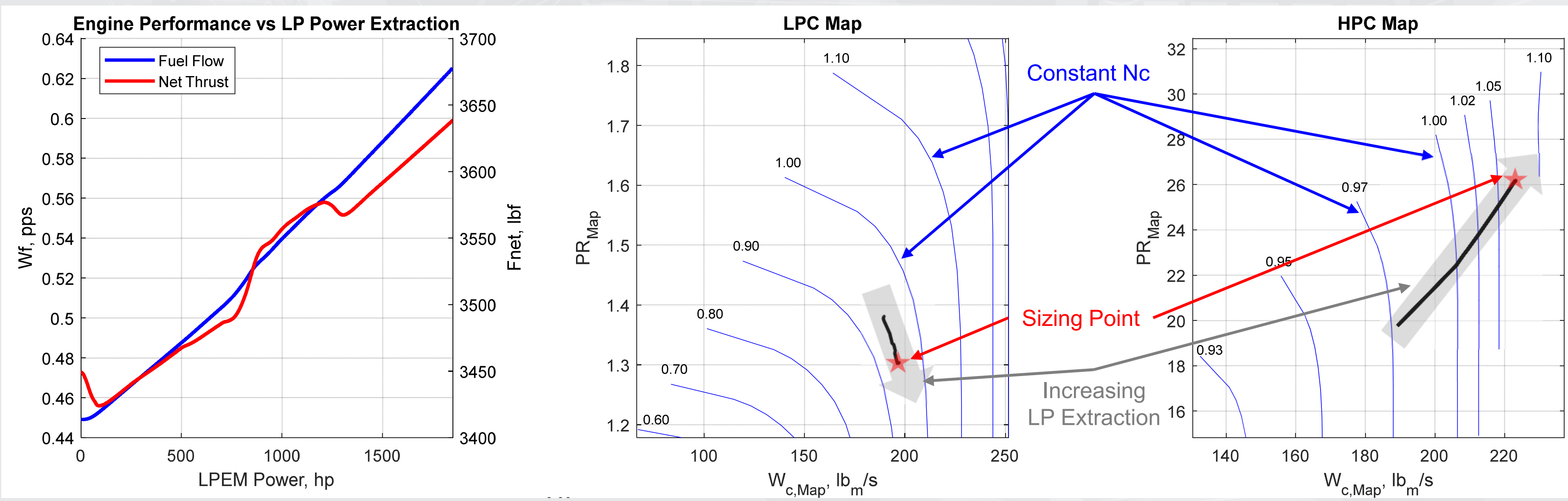




[1] J. L. Kratz, "The Advanced Geared Turbofan 30,000 lbf – electrified (AGTF30-e): A Virtual Testbed for Electrified Aircraft Propulsion Research," in *AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, Las Vegas, NV, 2024.
[2] NASA, "Advanced Geared Turbofan 30,000lbf – Electrified (AGTF30-e) Dynamic Engine Model and Controller", (LEW-20614-1), Accessed 8/10/2026, https://software.nasa.gov/software/LEW-20614-1

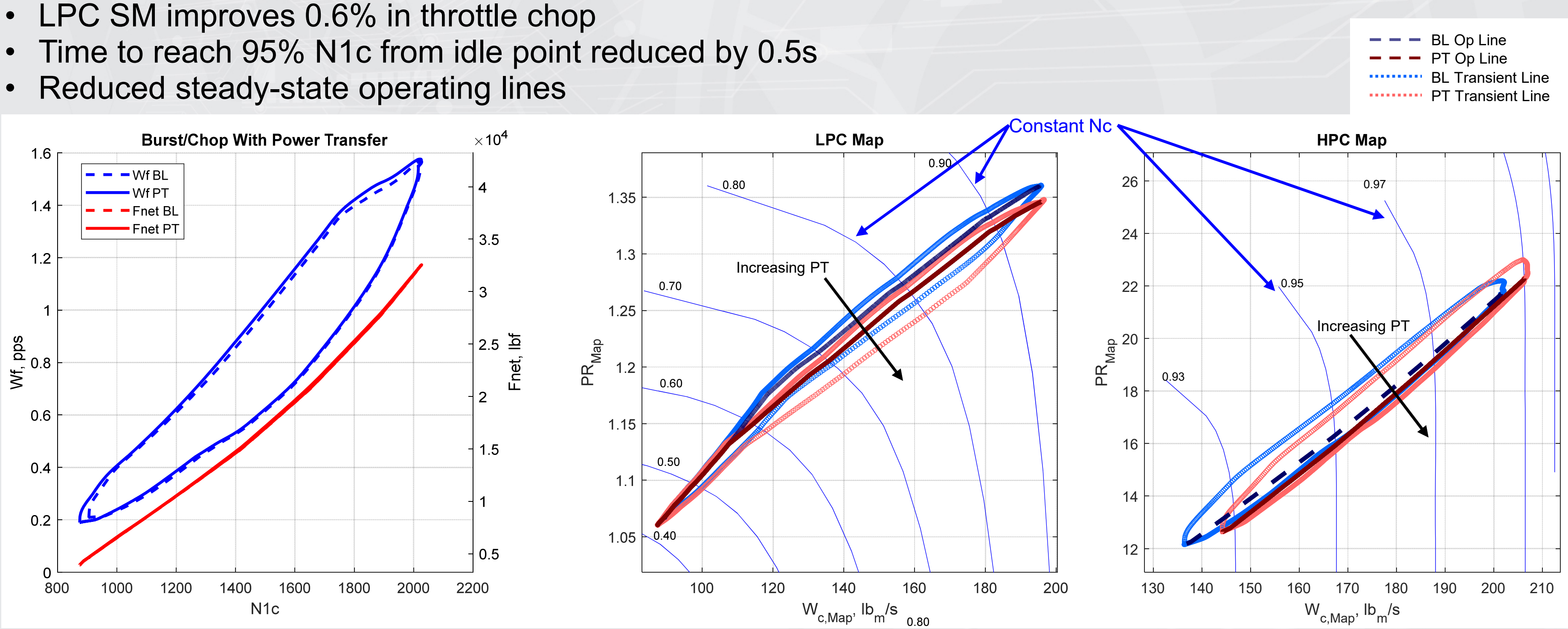
AGTF30-e Use Case Demonstration – LP Power Extraction

- At design point cruise conditions (35,000 ft, MN 0.8), holding Fan Speed (*N1c)* setpoint at 2000 rpm
- Extracting up to 1.3 MW of electrical power from the LP shaft
  - Increases fuel flow (*Wf)* by 0.18 lb/s
  - Moves LP compressor (LPC) to lower pressure ratio at constant *N2c*
  - HP Compressor (HPC) driven to higher operating line
  - Net thrust increases due to changing core thrust contribution
  - Results align with trends reported from HyTEC PEx Demonstration



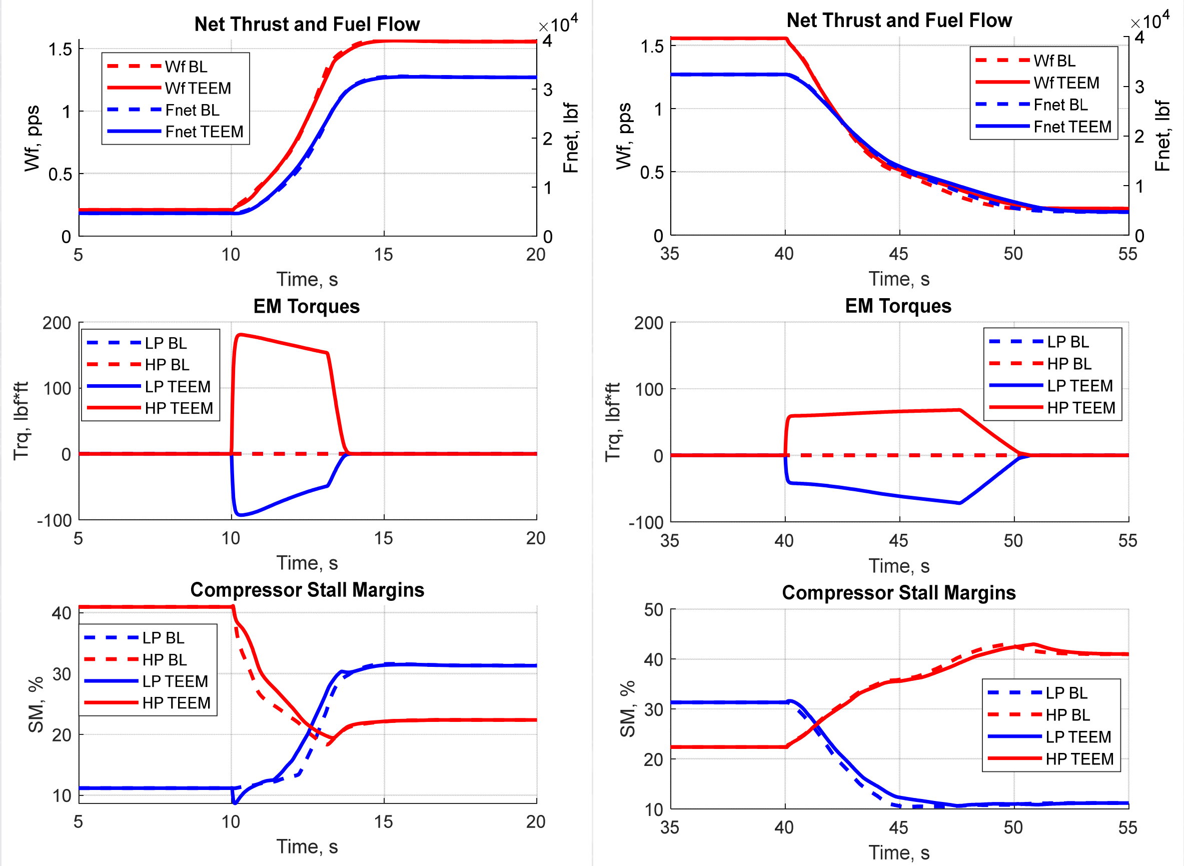
AGTF30-e Use Case Demonstration – Burst-Chop with Power Transfer

- AGTF30-e throttle burst/chop at sea level static conditions
- Constant direct 250hp power transfer between spools (LP to HP)
- Power transfer (PT) reduces fuel burn at idle, steady-state operating line and improves throttle response and minimum stall margins (SMs) when compared to baseline (BL)
  - Lowered idle point reduces fuel burn by 9.5%
  - LPC SM improves 0.6% in throttle chop
  - Time to reach 95% N1c from idle point reduced by 0.5s
  - Reduced steady-state operating lines



AGTF30-e Use Case Demonstration – TEEM

- Turbine Electrified Energy Management (TEEM) [1] uses EMs on the engine spools as actuators to actively reduce excursions from compressor steady-state operating lines
- TEEM controller determines EM command via lookup table based on *N1c* Error
  - Using existing TEEM controller in AGTF30-e public release
- Improves HPC SM by 1.1% during burst
- Improves HPC SM by 0.2% during chop



[1] D. E. Culley, J. L. Kratz, and G. L. Thomas, "Turbine Electrified Energy Management (TEEM) For Enabling More Efficient Engine Designs," in AIAA Joint Propulsion Conference, Cincinnati, OH, 2018.

Hardware-In-The-Loop (HIL) Testing – HyPER Lab

- Results are shown here for a previous (2023) test of a hybrid-electric AGTF30 in NASA's Hybrid Propulsion Emulation Rig (HyPER)
  - HyPER is a subscale (100 kW) electrified aircraft controls testbed [1]
  - Turbomachinery emulation and dynamic scaling is handled with a sliding mode impedance controller [2]
  - Engine model and controller are compiled to target hardware and run in real time using feedback from HyPER sensors
- HIL testing in HyPER shows that full-scale model results hold when run in real-time on representative subscale electromechanical hardware

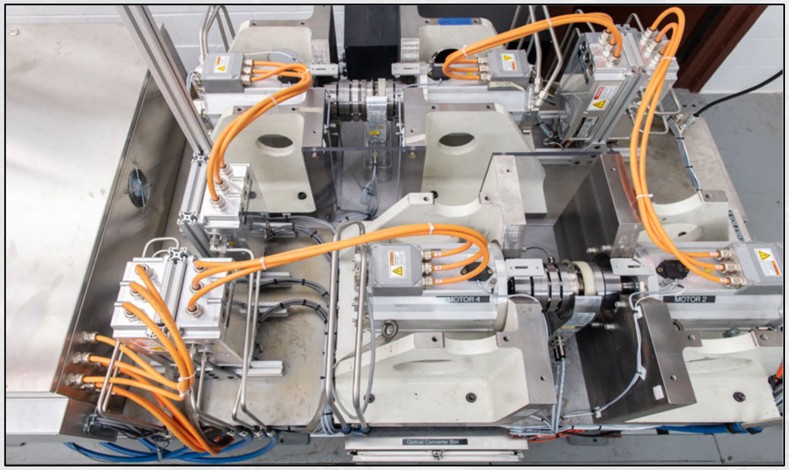
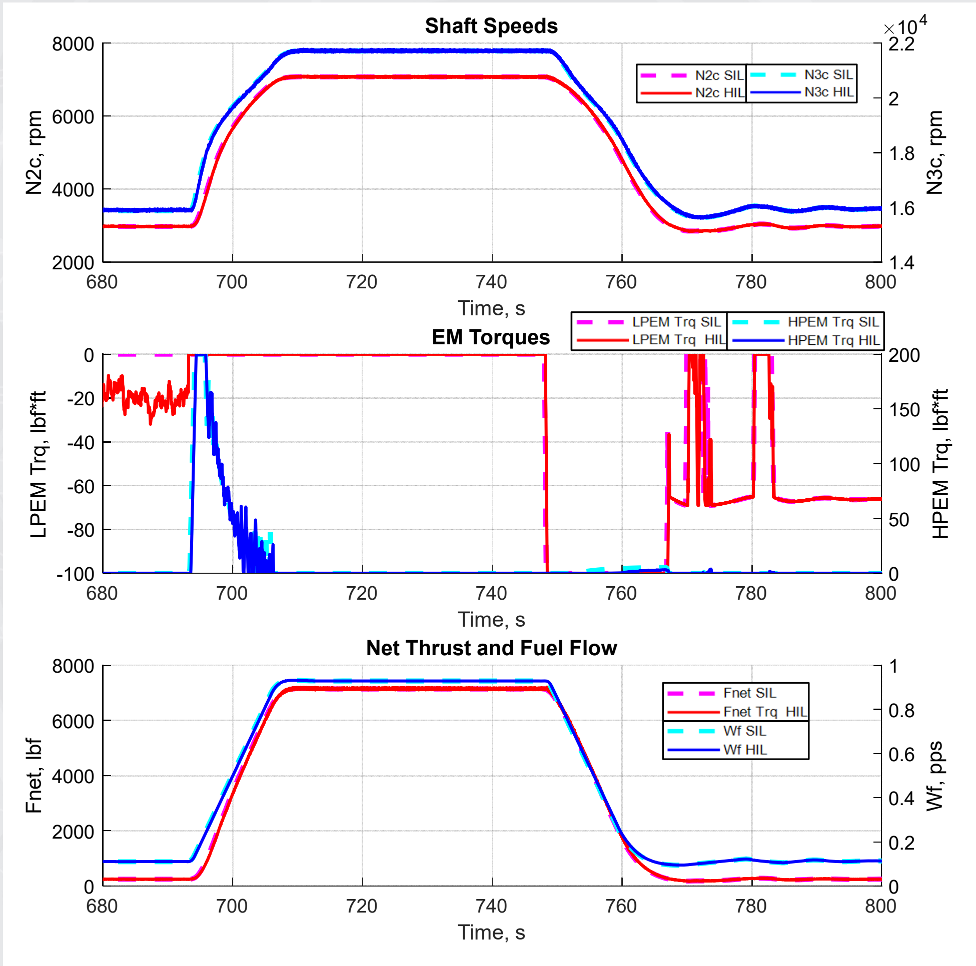


Image credits: nasa.gov/eap-labs-and-testbeds/hyper/

[1] S. J. Bianco, et. al., "Hybrid-Electric Aero-Propulsion Controls Testbed Results with Energy Storage," in *AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, San Diego, CA, 2023.
[2] S. J. Bianco and D. L. Simon, "Sliding mode transient scaling controller for gas turbine engine emulation on an electric machine," in AIAA Propulsion and Energy Forum, Virtual Event, 2020

Hardware-In-The-Loop (HIL) Testing – AGTF30-e Results

- Test results are shown for a series of throttle movements, utilizing TEEM control
- HIL testing in HyPER shows the AGTF30-e full-scale model results hold when run in real-time on representative subscale hardware
  - Engine model performance is captured in HIL
  - Hybrid controller implementation performs when run on target hardware
  - Validates model assumptions about turbomachinery and electrical system interaction



Conclusions

- NASA's AGTF30-e model is used to demonstrate hybrid electric use cases explored as part of the HyTEC Turbofan Power Extraction (PEx) Demonstration
- NASA has high confidence in the T-MATS and EMTAT modeling tools to capture the steady-state and transient performance of hybrid-electric turbomachinery systems
- Mild hybrid electric turbine engine configurations offer significant fuel burn reduction and operational flexibility without the use of massive batteries
- **The benefits of hybrid systems cannot be fully realized without an engine designed from the ground up to take advantage of the hybrid capabilities**

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