NASA Hybrid Thermally Efficient Core (HyTEC) Project Overview

Anthony L. Nerone, Joseph M. Haglage, Leah M. Nakley & Robert Tornabene
NASA Glenn Research Center
Cleveland, Ohio 44135

Abstract

The HyTEC Project goal is to mature compact core aircraft engine technologies as part of the NASA-led Sustainable Flight National Partnership (SFNP) that contributes to the United States Aviation Climate Action Plan goal for aviation net zero carbon emissions by 2050. Individual technologies were proposed and defined by industry partners, and then selected technology maturation activities are cost shared. Phase 1 contracts were awarded in 2021, and since then, the project has matured numerous technologies to TRL 4-5. Some of the Phase 1 efforts have been completed with successful results. An initial systems analysis study has been completed to estimate the impact of Phase 1 technologies against project performance metrics, with results indicating significant progress is being made toward meeting those metrics. HyTEC will culminate with an engine core demonstration that will integrate many of the Phase 1 technologies into a large-scale integrated ground demonstration that will achieve TRL 6 to enable industry to transition the technologies into the next single-aisle engine architecture. The goal of the demonstration is to fully meet the project performance metrics that define a compact engine core with substantial improvements in efficiency, durability, performance, hybridization, and sustainability over the baseline established in the year 2020. HyTEC will also incorporate hybrid electric technology into the engine core with the intention to bring the first electrified turbofan engines into production. The core demonstration has been awarded with a cost-share partnership and is planned to occur by the end of 2028.

1. Introduction

The National Aeronautics and Space Administration (NASA) Aeronautics Research Mission Directorate (ARMD) Hybrid Thermally Efficient Core (HyTEC) Project within the Advanced Air Vehicles Program (AAVP) is focused on accelerating the development of small-core turbofan engine technologies. NASA Aeronautics is engaging with industry, academia, and other agencies through the NASA-led Sustainable Flight National Partnership (SFNP) to advance technologies and inform industry decisions for the next entry into service (EIS) single-aisle aircraft expected in the 2030s. HyTEC is a NASA technology development project with the goal of maturing small-core engine technologies to a Technology Readiness Level (TRL) 6 (system/sub-system model or prototype demonstration in a relevant environment) through an advanced core ground demonstration by 2028. This demonstration relies heavily on a cost-sharing partnership with industry to enable effective technology transition. The goal is to accelerate the development of key engine technologies with improvements in efficiency, durability, performance, and hybridization in order to inform decisions on the next EIS single-aisle aircraft expected in the 2030s. The HyTEC Project is focused on technology development in key small-core technology areas such as High Pressure Compressors (HPC), High Pressure Turbines (HPT), Advanced

Materials, Hybrid Electric, and Compact Combustors (including operation with Sustainable Aviation Fuels (SAF)). In partnership with industry, these technologies will enable small-core single-aisle engine development that will significantly reduce fuel consumption, implement engine hybrid electrification, and ensure compatibility with SAF. As part of the propulsion portion of the SFNP, technologies that will be produced by HyTEC will contribute to progress toward reducing carbon emissions from aviation.

2. Goals, Objectives, and Metrics

The HyTEC Project contributes to contributes to the SFNP mission to enable new aircraft to fly safer, faster, cleaner, quieter, and use fuel far more efficiently. The HyTEC Project is aligned with the NASA ARMD 2023 Strategic Implementation Plan (SIP) [1] Strategic Thrust 3 for Ultra-Efficient Subsonic Transports through the realization of revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy.

The HyTEC Project objectives contribute to Thrust 3's Ultra-Efficient Propulsion Research Theme, supporting the research and development of technologies to enable new propulsion systems with high levels of thermal, transmission, and propulsive efficiency, reduced harmful emissions, and innovative approaches to noise reduction and opportunities to transition to alternative energy sources. HyTEC's focus on compact, highly efficient, power dense core technology will provide direct fuel burn benefits to the next single-aisle class aircraft, as well as integrate with other technologies, such as hybrid electric, as they mature to provide substantial continuous fuel burn reductions during the aircraft life cycle. These advances will open the door for cost benefits in commercial aviation while simultaneously reducing adverse impacts on the environment.

NASA Aeronautics is engaging with industry, academia, and other agencies through the SFNP. The goal is to provide technologies for EIS in the 2030s that provide a path to the Climate Action Plan goal of net-zero aviation carbon emissions by 2050. Through collective work in three areas: advanced vehicle technologies, efficient airline operations, and sustainable aviation fuels, NASA is committed to contributing viable solutions for achieving the extreme challenge of aviation decarbonization. This includes enabling up to 30 percent fuel burn reduction in next-generation transports with the capability to utilize 100 percent sustainable aviation fuel and also fly optimal trajectories.

In order to contribute to the ARMD Strategic Thrust 3, the HyTEC Project has the following objectives:

- *Demonstrate increased thermal efficiency with integrated high power-density core engine technologies, achieving a 5- to 10-percent fuel burn benefit, versus 2020 best in class, for 2030s EIS single-aisle aircraft.*
- *Show that 10 to 20% power extraction at altitude from a modern commercial turbofan engine is feasible with the thrust, efficiency, operability, and durability to enable the benefits of electrified aircraft propulsion at a vehicle level via a sea level test and analysis.*
- *Demonstrate the effective and efficient operability of high blend (>80%) SAFs in 2030s EIS combustors.*

These objectives reduce the technical risk associated with the small-core technologies and, through partnerships with industry, accelerate the technologies to enable technology transfer for the next single-aisle aircraft engine. The HyTEC Project developed aggressive goals and objectives that pushed technology forward. The figure below shows how the HyTEC Project is developing technologies to overcome scaling barriers for a compact core. Figure 1 shows the current technology around 2015 and barriers that were limiting turbofan engine technology from meeting the NASA 2030s goals established in 2008. The NASA SFNP has its origins in foundational research both in-house and through contracts initiated with industry and university teams for advanced configurations through studies initiated in 2008, commonly known as the "N+3 studies." NASA solicited ideas for aircraft capable of meeting aggressive environmental goals that could potentially enter service around 2035 (i.e., the N+3 time horizon or three technology generations later than the 2008 state of the art). The N+3 dot indicates an aggressive goal for smaller engines to strive to achieve. The green dots represent larger engines in service with axial high-pressure compressors in 2015, showing their core size and overall pressure ratio (OPR). At the time, an OPR of 25-35 was the norm, with a core size ranging from about 3.5-10 lbm/sec (1.6-4.5 kg/sec). The HyTEC baseline was established in 2020, and at the time, there were two new single-aisle engines that had recently entered into service. These engines were from GE Aerospace and Pratt & Whitney, represented by the green diamonds circled in red and labeled “HyTEC Baseline 2020.” In 2020, the latest technology engines had slightly improved upon the 2015 group, with HPC core flow just above 4 lbm/sec (1.8 kg/sec) and OPRs in the mid-40s. While this was a positive increase, it was still well short of the 2008 NASA N+3 goals. The barriers highlighted in Figure 1 are compressor architecture and materials. The materials were not available for the high temperatures associated with smaller, hotter cores, and the axial HPC was hitting operational limits. HyTEC aims to achieve those aggressive goals by making a large jump in OPR while dramatically decreasing core size. This will be accomplished by developing advanced aerodynamic improvements in both the HPC and HPT, as well as developing advanced materials to withstand the higher core temperatures. If successful, the HyTEC technologies will enable engines that operate at an OPR of 50 with core sizes approaching sub 3.0 lbm/sec (1.36 kg/sec) HPC exit flow. This would be a much more significant jump than from the 2015 in-service engines to the 2020 baseline and approaches the N+3 goal set a decade and a half ago. HyTEC will essentially make the lofty NASA propulsion goals set for the 2030s a reality within the next decade. The engines will still be in the same thrust class of about 25,000 – 35,000 lbf (111-156 kN) for single-aisle aircraft, maintain their axial HPC architecture, yet have much smaller, more efficient cores to dramatically reduce fuel burn and emissions. The HyTEC objective is shown with the large red dot in Figure 1 to illustrate the large increase in OPR with simultaneous reduction in core size.

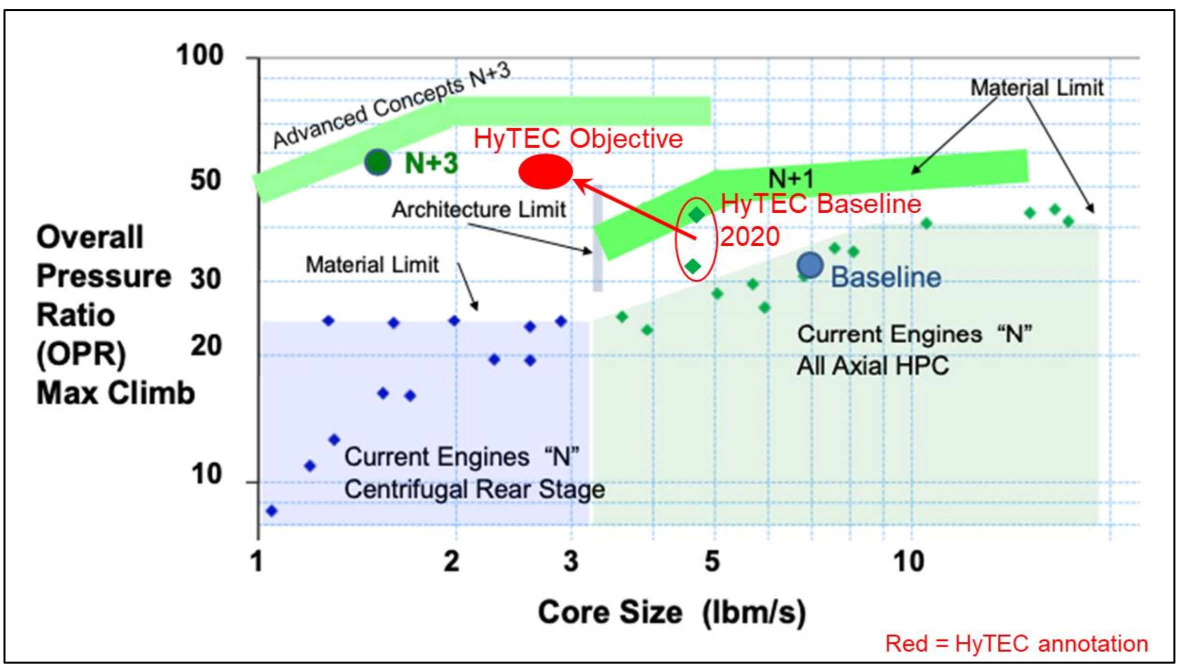

Figure 1: OPR versus core size for generation N, N+1, N+3 AIAA 2015-00071 [2]

The HyTEC Project has identified several technical performance metrics. These metrics are defined as a set of measures based on the expectations and requirements that are tracked and assessed to determine overall system effectiveness and meeting stakeholder expectations. The Key Performance Parameters (KPPs) shown below define the full and minimum success criteria for the HyTEC Project. Table 1 below shows the HyTEC KPPs that have been defined to be applicable to the small engine core technologies, power extraction ground demonstration, and the HyTEC advanced engine core ground demonstration. The values specified are intended to be achieved for successful technology development.

KPP #	Key Performance Parameter	Full Success Single-Aisle ~2030s EIS	Minimum Success Single-Aisle ~2030s EIS
KPP-1	Fuel burn reduction attributed to the high-power density engine core of the original equipment manufacturer's (OEM) 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 established at altitude by level of power extraction from the turbofan engine via sea level demonstration and analysis.	20%	10%
KPP-6	HPC Exit Corrected Flow	< 3 lbm/s	< 3.5 lbm/s
KPP-7	Combustor operability using SAF is comparable to its performance using Jet-A/A-1 fuel, as measured by lean blowout and ignition performance.	Combustor operability demonstrated with 100% SAF	Combustor operability demonstrated with >80% SAF
KPP-8	Degree of hybridization measured by level of power extraction/insertion from the engine core	10%	5%

Table 1: HyTEC key performance parameters

3. HyTEC Project Description

HyTEC is divided into two phases: the first phase, in which technologies are developed at the component or subsystem level, and the second phase, in which technologies are integrated into engine core ground demonstrations. In Phase 1 the research focuses on addressing technology challenges through component or subsystem testing to advance a suite of small-core technologies to TRL 4-5. NASA TRL 4 is defined as "Component and/or breadboard validation in a laboratory environment" and TRL 5 is defined as "Component and/or brassboard validated in a relevant environment." These technologies are being developed in collaboration with U.S. aircraft engine manufacturers in a cost-sharing arrangement wherein industry partners show direct traceability to HyTEC goals, a path to a core demonstration, and a link to an eventual production engine. In Phase 2, aggressive, impactful small-core turbofan technologies with development risk will be integrated into engine core ground demonstrations to raise TRLs to 6 no later than 2028.

4. HyTEC Phase 1 Overview

The HyTEC Project is part of NASA's overall subsonic transport technology strategy that focuses on the development and demonstration of high-power density, small-core gas turbine engine technologies. HyTEC's focus on small-core technologies will provide direct benefits and inform industry decisions for the next single-aisle class aircraft in terms of thermal efficiency, as well as integration with other technologies, through increased hybridization, as they mature to provide substantial continuous fuel burn and emission reductions during the aircraft lifecycle. Under the SFNP, NASA ARMD has partnered with U.S. industry and regulators to advance small-core engine technologies that will enable the highest likelihood of adoption and resulting fleet impact. NASA is using model-based systems analysis and engineering to assess the impacts of the technologies individually and as an integrated system. Each technology development and demonstration effort will encourage the use of model-based engineering approaches for execution efficiencies, data transfer, and technology validation. To align with the next-generation single-aisle aircraft, any technologies developed under HyTEC must have a direct path to an engine for that aircraft class. Therefore, the technologies have a direct path to informing a future industry product, which is assumed to have the following characteristics: ~180 passengers, with a minimum range of 1,500 nautical miles (2400km) and requiring a thrust of 25,000 – 35,000 lbf. (111-156 kN).

Under Phase 1, NASA awarded eight cost-share contracts to GE Aerospace of Cincinnati, Ohio, and Pratt & Whitney, a division of RTX Corporation, of East Hartford, Connecticut, as shown in Table 2. Both GE and Pratt & Whitney are matching or exceeding NASA's investment during the contract period. HyTEC is accelerating these technologies through the following partnerships with industry to enable technology transfer and inform industry decisions for the next single-aisle aircraft engine.

GE Aerospace	High Pressure Compressor
	High Pressure Turbine Advanced Aerodynamics
	High Temperature Environmental Barrier Coatings (EBCs)
	Ceramic Matrix Composite Combustor Liner
	Turbofan Engine Power Extraction Demonstration
Pratt & Whitney	High Pressure Turbine Advanced Aerodynamics
	Ceramic Matrix Composite (CMCs) and EBCs
	Sustainable Aviation Fuel (SAF) Combustion Technologies

Table 2: HyTEC Phase 1 contracts

Under these contracts, GE Aerospace and Pratt & Whitney address specific technical challenges associated with reducing engine core size and increasing fuel efficiency and reducing emissions. Table 3 summarizes the work under Phase 1.

Technology	Technical Challenges
Advanced high-pressure compressor	Develop casing treatments and advanced designs with smaller parts and tighter clearances to enable small-core compressors that maintain operability while optimizing performance and efficiency.
Advanced high-pressure turbine	Demonstrate efficient and durable turbine operation by minimizing turbine cooling penalties incorporating advanced airfoils, aerodynamic features, and effective cooling. Demonstrate ceramic matrix composite (CMCs) and environmental barrier coatings (EBCs) for turbine components to increase temperatures and efficiency of turbines.
Enhanced combustor materials	Demonstrate CMCs and EBCs applied to combustor components to increase performance and durability.
Turbofan Power Extraction (PEx)/Insertion	Integrate electric machines with a modern commercial turbofan engine to address the interaction and integration of the turbine engine with the motor/generators.
Small-Core Combustion and SAF Compatibility	Develop small-core combustor designs with reliable ignition and lean blowout performance when using 80% or greater SAF.

Table 3: HyTEC Phase 1 technologies and technical challenges

Several of these contracts have been completed with successful outcomes, meeting all or nearly all of the performance metrics set at the award. The remaining Phase 1 contracts will be completed by the end of 2025, at which time NASA will conduct an assessment to determine the overall progress of Phase 1 at the TRL 4-5 development stage.

5. Phase 1 Preliminary Systems Analyses and Integration Results

When all of the Phase 1 contracts are complete, an assessment is planned to determine the progress toward the HyTEC KPPs when TRL 4-5 is reached. The goal is for HyTEC to meet at least minimum success for all of the KPPs by the end of the project when TRL 6 is achieved. The Phase 1 assessment serves as a project mid-point check to see what progress has been made versus the 2020 baseline engines. The KPPs are not expected to be met at the mid-point due to the technology maturation stage (TRL 4/5 versus 6) but meaningful progress should be made toward that goal. The NASA systems analysis team has developed baseline models for both GE and Pratt & Whitney baseline engines with corresponding aircraft to perform this assessment. For GE, the CFM LEAP-1B28 turbofan (LEAP) and Boeing 737 (B737) MAX 8 were used as the reference baseline state-of-the-art (SOA) systems. For Pratt & Whitney, the PW1127G was the baseline engine, and the aircraft was an Airbus A320neo. All the models were developed using only publicly sourced information and data. Table 4 shows the baseline engine parameters used for the model.

	GE Baseline	P&W Baseline
Parameter	**LEAP-1B28**	**PW1127G**
Type	**Turbofan**	**Geared Turbofan**
Net Thrust (lb)	**29,317**	**27,075**
Bypass Ratio	**8.6**	**12.28**
Overall Pressure Ratio (Top of Climb)*	**44.6**	**46.0**
HPC Exit Corrected Flow (lbm/s)*	**4.23**	**4.41**
TSFC (lbm/hr/lbf)*	**0.56**	**0.52**
Engine Weight (lb)	**6,130**	**6,300**
Fan Diameter (in)	**69.3**	**81.0**

*** Model-based estimate**

Table 4: HyTEC Phase 1 assessment baseline engines

Since all of the Phase 1 contracts are not yet completed, the initial projections of the models will be the best-case scenario where all contracts produce fully successful technology maturation. This means that each technology is assumed to have met all technical performance metrics, so the projected benefits will be the maximum level attainable. The way the models are built, the Phase 1 HyTEC technologies are being implemented into the current 2020 baseline engines. At the conclusion of the core demonstration in Phase 2, the final assessment will be representative of a vision system in which all of the technologies will be implemented into a new engine that takes maximum advantage of them all working in tandem. However, without this vision system in Phase 1, the HyTEC team was limited to making them backwards compatible into current product models. While that limits the impact of each technology, it is a representative data point to show how the first phase of the project would improve 2020 engines. In some cases these models include technology efforts outside of HyTEC that industry partners are pursuing alone, that are being incorporated to capture the full scope of engine benefits.

This data and the process that generated the following analyses were obtained from Bennett, et al [3]. Figure 2 illustrates a hypothetical scenario where the HyTEC technologies at the end of Phase 1, assumed to all be completed to a high degree of success, are implemented into a NASA-developed propulsion model calibrated to simulate the performance of a CFM LEAP-1B28. The colors indicate separate components, such as HPC and HPT, with their corresponding technologies and impacts to the engine. By inserting the new technologies from Phase 1, the effect on the LEAP is dramatic. These technologies, when added to a 2020 baseline engine, meet or nearly meet all of the HyTEC KPPs at minimum success. The most dramatic improvements were the fuel burn reduction of 5.2% and the HPC exit corrected flow reduction from 4.23 to 3.25 lbm/s (1.9 to 1.47 kg/sec). Even without implementing these technologies into a vision system where they can perform synergistically, the effect on a current product is nonetheless quite impactful, with 2 of the 3 KPPs assessed meeting minimum success goal targeted for the end of Phase 2.

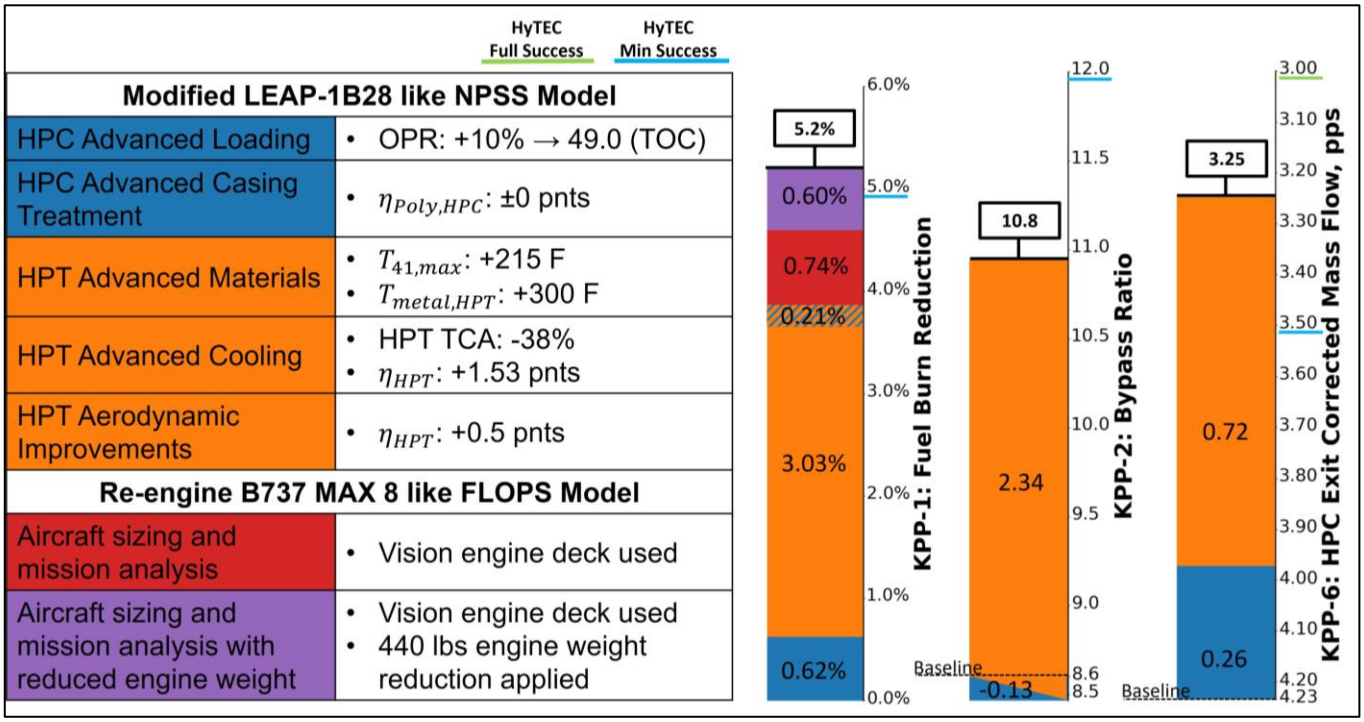

Figure 2: CFM LEAP-1B assessment with HyTEC Phase 1 technologies

The same analysis was carried out considering technologies being developed with the other HyTEC partner, Pratt & Whitney, as shown in Figure 3. Similar technology advancement assumptions were applied to a NASA-generated model of the PW1127G, including technologies that Pratt & Whitney is funding outside of HyTEC. Again, without the benefit of integrating in a new, cohesive vision system, inserting these technology improvements into a current product model yields impressive results. The fuel burn reduction is 6.2%, which again meets HyTEC minimum success, and the bypass ratio jumps from 12 to 15.8, which meets the full success of the HyTEC KPP. The core size also drops dramatically, with the exit corrected flow of the HPC reducing from 4.41 to 3.33 lbm/sec (2 to 1.5 kg/sec).

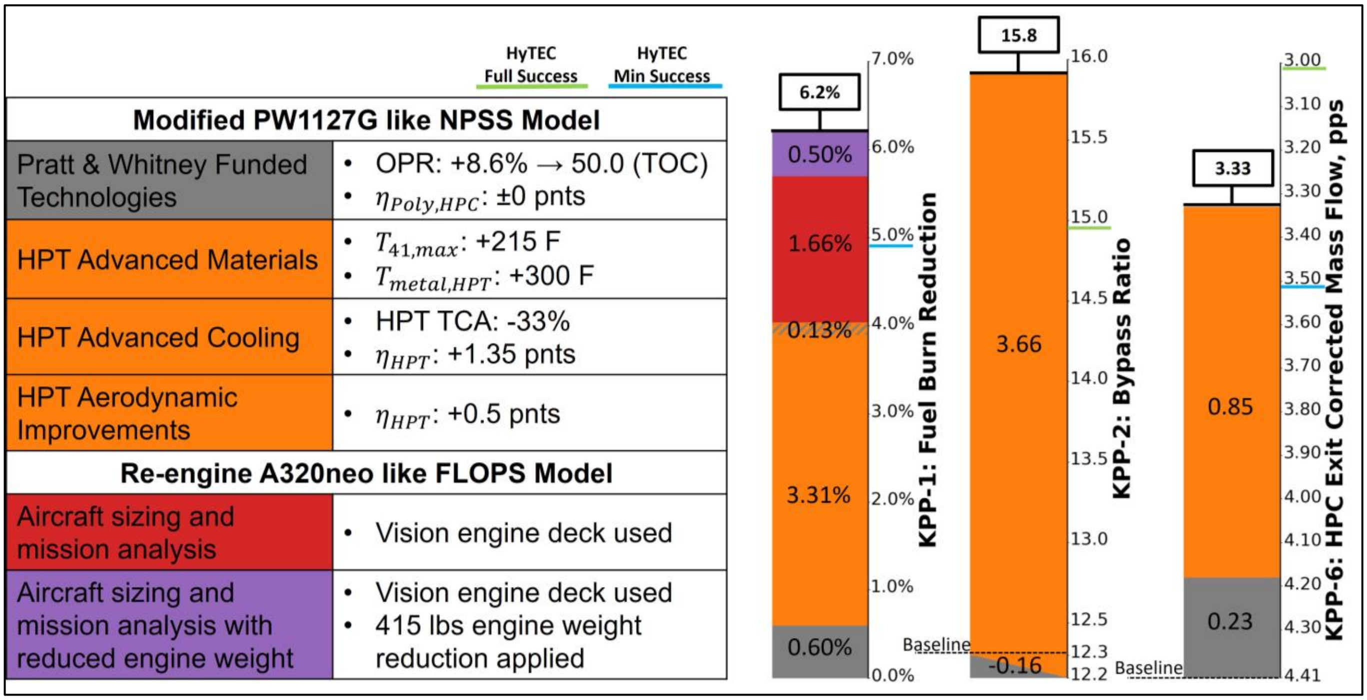

Figure 3: P&W 1127G assessment with HyTEC Phase 1 technologies

If all of the HyTEC Phase 1 technologies are successful, the progress of the project will be, by all measures, in excess of expectations. When the technologies are implemented in a backwards compatible fashion into current engines, every measured key KPP is met with at least minimum success except for one by the CFM LEAP. The substantial improvement in both engines shows the impact of all of the small-core technologies under development by the project. If the potential improvement in current product models is this dramatic, this gives a good indication that when the vision system model is developed and the core demonstration is completed, the project expects to meet all of its KPPs at minimum success, with many reaching full success. When Phase 1 is complete, and the data is available for every technology development effort, these analyses will be performed again using these models with the actual test results. While the expectation is that some of the technologies will not meet full success, substantial progress has been made under Phase 1, putting the project on track to meet at least minimum success for all KPPs by the end of the project.

6. HyTEC Phase 2 Advanced Core Demonstration (ACD)

The ACD has entered into a collaborative effort with industry for the purposes of integrating targeted technologies into a ground core demonstration to meet the TRL target and the HyTEC Project technical metrics. The ACD will execute the technology demonstration to ensure that the hardware development, testing, and performance assessments are all completed successfully. The technologies demonstrated will show direct traceability to the HyTEC objectives, and technical performance metrics and measures. Data from the ACD will be utilized for the final determination of the technology's success against the metrics. The process will be similar to the Phase 1 systems analysis approach except that for Phase 2, a vision system engine and aircraft models will be developed to assess the performance of the technologies in an integrated fashion to maximize the system benefits. The data from the core demonstration will be directly used in this process to measure the overall progress towards the KPPs at the end of the project. Learnings on technology integration challenges and benefits will inform decisions on engine systems to power next generation single aisle aircraft.

NASA has selected GE Aerospace for HyTEC's Phase 2 Integrated Technology Advanced Core Demonstration cost-share contract with a maximum government value of approximately $68.1 million with a minimum 50% cost match from industry over a five-year performance period that began in February 2024. To meet the Phase 2 goal, GE is integrating a suite of technologies, many of which were developed in HyTEC Phase 1, and will perform core demonstration tests to bring these selected technologies to TRL 6 by the end of September 2028.

The technologies for Phase 2 were intended to be within the same categories as those awarded in Phase 1. A previous award in Phase 1 was not required to be considered for Phase 2 as long as the technology had reached a minimum of TRL 4 through relevant testing regardless of the funding source and each technology was related to the focus categories. As previously mentioned, only one award was made for Phase 2 to GE Aerospace, and this collaborative research contains all of the technology portfolio for the core demonstration. Table 5 contains the Phase 2 technologies and technical challenges that will be integrated and matured to TRL 6 via ground tested engine core test in partnership with GE Aerospace.

Technology	Technical Challenges
Advanced high-pressure compressor	Demonstrate advanced HPC design with smaller parts and tighter clearances for high OPR, small-core compressors that maintain operability while optimizing performance and efficiency.
Advanced high-pressure turbine	Demonstrate efficient and durable turbine operation by minimizing turbine cooling penalties incorporating advanced airfoils, aerodynamic features, and effective cooling.
Combustion Technologies	Demonstrate ceramic matrix composite (CMCs) and environmental barrier coatings (EBCs) applied to combustor components to increase performance and durability. Demonstrate compatibility of near drop-in sustainable aviation fuels (SAF) without blending with Jet-A/A-1 in small-core combustor designs.
Core Engine Hybridization	Demonstrate a configuration to achieve power extraction and/or insertion at relevant operating conditions from the proposed next-generation engine core to enable the benefits of electrified aircraft propulsion at a vehicle level. Demonstrate progress toward practical electric machine and engine spool integration solutions that achieve significant power transmission at high efficiency.

Table 5: HyTEC Phase 2 Technologies and Technical Challenges for the ACD

7. Summary and Conclusions

HyTEC is in its 4th year and has made significant progress to date. The project was formulated, the objectives set, and the overall metrics of the project established. A Phase 1 solicitation led to technology development showing significant progress thus far. Several technology contracts have been completed, with the rest set to be completed by the end of 2025, at which time an updated NASA assessment of overall progress toward the project metrics will be conducted to measure the technology impact at the TRL 4-5 maturation level; this update will build on the preliminary evaluation discussed herein that shows significant promise. Phase 2 solicited and awarded an ACD in collaboration with GE Aerospace, and this effort is currently underway. As Phase 1 winds down, Phase 2 will accelerate, culminating in a TRL 6 integrated technology engine core ground demonstration by 2028. This demonstration will show the effect of all the technology maturation conducted in HyTEC operating at a system level to serve as the basis for the final assessment against the project metrics and to inform industry decisions on next generation systems for single aisle aircraft. Given the projected progress shown with the preliminary Phase 1 assessment and the promising technology development plans for Phase 2, all indications are that HyTEC will accomplish all of the project goals. HyTEC is making significant progress toward demonstrating integrated advanced technology to inform decisions on a future single-aisle engine. The new engine core will be more efficient, produce less emissions, be the first production engine with hybrid electric technology, and run on sustainable fuel. The future single-aisle airplanes will greatly benefit from this new propulsion system, and it will make significant progress toward the SFNP goals that include up to 30% fuel burn at the aircraft level as compared to the 2020 best in class airplanes. Ultimately, the results will have a sizeable impact toward achieving the US Aviation Climate Action Plan goal for net zero carbon emissions by 2050.

Acknowledgements

The authors acknowledge the NASA Advanced Air Vehicles Program, GE Aerospace, and Pratt & Whitney for supporting HyTEC, as well as the NASA System Analysis & Integration team and Glenn Research Center test facilities for their support. We want to recognize Douglas Wells from NASA Langley Research Center and Michael Bennett from NASA Glenn Research Center for their system analysis efforts and support to generate the engine assessment Figures. A special thanks to Ashley Marshall of Consolidated Program Support Services from NASA Langley Research Center as well for her contributions to this publication.

References

[1] National Aeronautics and Space Administration, "NASA Aeronautics Strategic Implementation Plan," NASA Aeronautics Research Mission Directorate, Washington D.C., 2023

[2] Lord, W.K. et al.: “Engine Architecture for High Efficiency at Small Core Size,” AIAA 2015-00071. https://arc.aiaa.org/doi/10.2514/6.2015-0071

[3] Bennett, M; Chapman, J.W.; Wells, D.P.; “An Approach to Evaluating the Impact of Small-Core Turbofan Technologies on Engine and Aircraft Performance”, AIAA 2024-1372.

Copyright Statement