NASA/CR-20250006263

NASA Hybrid Thermally Efficient Core (HyTEC) Phase 2 Q2’GFY24 to Q2’GFY25 Unlimited Rights Annual Report for CLIN 1 and 2

Brian Weber
GE Aerospace, Cincinnati, Ohio

June 2025

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION.
  Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM.
  Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT.
  Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION.
  Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION.
  Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION.
  English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

NASA/CR-20250006263

NASA Hybrid Thermally Efficient Core (HyTEC) Phase 2 Q2’GFY24 to Q2’GFY25 Unlimited Rights Annual Report for CLIN 1 and 2

Brian Weber
GE Aerospace, Cincinnati, Ohio

Prepared under Contract 80GRC024CA001

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

June 2025

This work was sponsored by the Advanced Air Vehicles Program
at the NASA Glenn Research Center.

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

NASA STI Program/Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Table of Contents

List of Acronyms and Abbreviations

ACC	Active Clearance Control
BWM	Bow Wave Mitigation
CDR	Critical Design Review (NASA)
CoDR	Conceptual Design Review (GE Aerospace)
CFD	Computational Fluid Dynamics
CLIN	Contract Line Item Number
CMC	Ceramic Matrix Composite
DCR	Design Consensus Review
DDR	Detailed Design Review
D-TDR	Detailed Test Design Review
EBC	Environmental Barrier Coating
EPIS	Electrical Power Integrated Systems Center
ERM	Engineering Requirements Management
FAR	Full Annular Rig
GEA	GE Aerospace
HP	High Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine
HSRC	High Speed Research Compressor
HT	High Temperature
HTP	High Temperature and Pressure
HyTEC	Hybrid Thermally Efficient Core
ICD	Interface Control Document
KPPs	Key Performance Parameters
MISTICC	Mixer Swirl Turbine Interaction Clocking Cascade
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
OPR	Overall Pressure Ratio
PD	Preliminary Design
PDR	Preliminary Design Review
RISE	Revolutionary Innovation for Sustainable Engines
SA&I	Systems Analysis and Integration
S1N	Stage 1 Nozzle
SAF	Sustainable Aviation Fuel
SiC-SiC	Silicon Carbide – Silicon Carbide
SLIN	Sub Contract Line Item Number
SoA	State-of-the-Art

TCA	Tunable Combustion Acoustics
TDR	Testing Design Review
TEH	Test Enabling Hardware
TG	Tollgate
TPMs	Technical Performance Measures
TRA	Technology Readiness Assessments
TRL	Technology Readiness Level
TRT	Notre Dame Transonic Research Turbine
TTF	Target to Fire
TVF	Turbine Vane Frame
UND	University of Notre Dame
VDR	Validation Design Review
VEN	Variable Exhaust Nozzle

1.0 Introduction

The HyTEC Phase 2 Project focuses on the development and demonstration of high-power density, small engine core gas turbine engine technologies. The focus of HyTEC on these small engine core technologies will provide direct benefits to the next single-aisle class aircraft in terms of thermal efficiency, as well as integrate with other technologies, through increased hybridization, as they mature to provide substantial continuous fuel burn reductions during the aircraft lifecycle. These advances will strengthen the US position in the commercial aviation engine market and enable cost benefits in commercial aviation.

GE Aerospace is executing two major work plans as part of the HyTEC Phase 2 contract. The first is Contract Line Item Number (CLIN) 001 and its objective is to mature High Pressure Turbine (HPT) aerodynamics technology to TRL 5 through multiple rigs so that it may be incorporated into a complete TRL 6 evaluation and unlock learnings for the engine core demonstration as applicable. CLIN 002, the second work plan, is to design, procure and test a cost shared portion of technologies on the TRL6 Compact Core test vehicle.

The compact core demonstrated through HyTEC Phase 2 along with the HPT rig TRL advancement directly matures the technologies being developed as part of the CFM RISE demonstrator program which is targeting a 20% fuel burn reduction at the engine level versus today's state of the art. The RISE program's objective is to advance both the novel Open Fan architecture, compact core technologies and advanced systems such as hybrid electric needed to achieve the desired fuel burn reduction to TRL6 ahead of a new product introduction in the single-aisle class aircraft in the 2030s timeframe.

2.0 Overview of Technical Plan

2.1 KPPs

The GE Aerospace Open Fan product vision is currently projected to meet or exceed the Key Performance Parameters (KPP) as summarized in **Table 1**.

Table 1:HyTEC KPPs with GE Aerospace product vision status, bold denoting required KPPs versus desired

KPP #	Key Performance Parameter (KPP) (NASA required KPPs in bold)	Single Aisle Success Full / Minimum
KPP-1	**Fuel burn reduction attributed to the high-power density core of the OEMs vision turbofan engine**	**10% / 5%**
KPP-2	**Engine Bypass Ratio**	**> 15 / > 12**
KPP-3	**Engine Overall Pressure Ratio (OPR) (Defined at top of climb)**	**> 50 / > 45**
KPP-4	Durability, measured in operating hours between major refurbishment	Exceed SOA by 5% / Meet SOA baseline
KPP-6	**HPC Exit Corrected Flow**	**< 3 lbm/s / < 3.5 lbm/s**
KPP-7	**Combustor operability using Sustainable Aviation Fuel (SAF) is comparable to its performance using Jet-A/A1 fuel, as measured by lean blowout and ignition performance.**	**Combustor operability demonstrated with 100% SAF / > 80% SAF**
KPP-8	Degree of hybridization measured by level of power extraction/insertion from the core	10% / 5%

2.1.1 Assessment Methodology

The technical performance metric progress will be monitored throughout the execution of the core demonstrator program with integrated core system assessments proposed in the content for the PDR, CDR, pre-test data assessment, and VDR. To assist in NASA's parallel, independent, progress assessments, GE Aerospace will periodically provide an Assessment Data deliverable in conjunction with life-cycle reviews, the first of which is planned in conjunction with the Preliminary Design Review. Assessment reviews and associated data deliverables will:

- Provide appropriate quantification of effects of the technology on engine performance, operability, durability, and physical characteristics.
- Identify gaps or risks for maturing and integrating technologies in a small core ground demonstration.
- Quantify the benefits of quoted and measured technical performance measurements relative to the HyTEC goals and contribution to the KPPs.
- Quantify the integrated benefits of the HyTEC funded advanced technologies that are implemented into the core demonstration as well as the synergistic combined benefit of all advanced technologies relative to the KPPs for the Product Vision when compared to a 2020 baseline.
- Provide an evaluation of the TRL level achieved using the NASA's TRL definitions.
- Identify lessons learned and technology gaps needed to mature the technology for product insertion.

In addition to formal Assessment Data deliverables the GE Aerospace team has worked over the past year and will continue to support informal collaboration with the NASA Systems Analysis and Integration (SA&I) team to assist in improving overall understanding of HyTEC funded technology potential. A summary of these activities to date can be found below in Section **4.1.2**.

To facilitate clear traceability to KPPs, the GE Aerospace team has worked with NASA to select a 2020 industry average single aisle baseline. Progress of GE Aerospace's Open Fan Product Vision toward the KPPs, relative to this baseline, will be monitored through the progression against the TPMs of the core demonstrator.

Through the SA&I activities and planned deliverables GE Aerospace will continue to strive to provide definition of the 2020 SoA baseline and Product Visions to allow for quantification of the integrated effects and benefits of the HyTEC technology. As appropriate, TPM baselines for improvement calculations will be aligned with the average baseline.

3.0 CLIN 001 HPT Rigs

3.1 TRT Phase 3 Rig

3.1.1 Rig description and overview

The Transonic Research Turbine (TRT) rig is a low pressure / temperature single stage uncooled HPT aero test rig located at the University of Notre Dame. The rig can test isolated technologies and flow/clearance derivatives. The TRT rig allows for the test of multiple configurations while optimizing cost efficiency. It also has a low measurement uncertainty due to magnetic bearings. TRT Phase 3 will utilize clearance, speed and purge derivatives to test various designs.

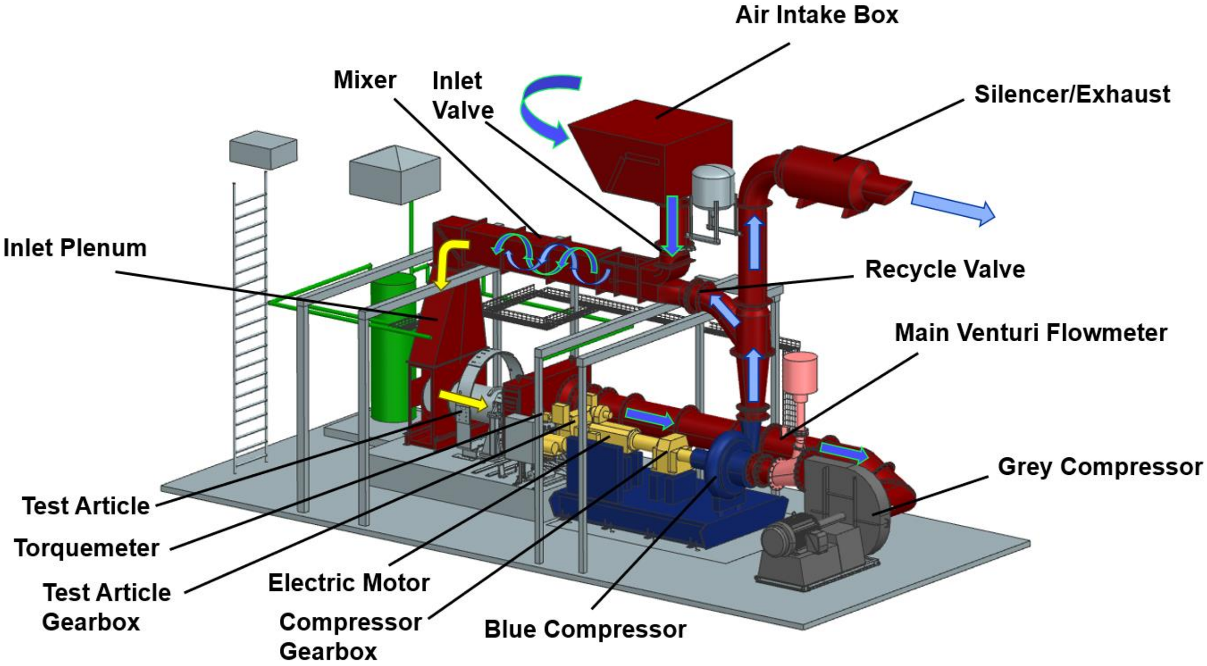


Figure 1: Rig Overview (Photo Credit: University of Notre Dame Test Lab)

3.1.2 Annual Accomplishments

In February 2024, GEA launched Problem Solving Report (PSR) as a result of Phase 1 clearance data quality issues and overall rig improvement. In June 2024, the Phase 2 PSR closure review with all actions, either closed or on track to closure, was completed. Those actions included improvements to test operations, clearances and leakages. The PSR actions were largely successful for Phase 2 testing. Phase 3 will incorporate several design improvements to further improve clearance control and ensure compliance with CTQ requirements.

TRT Phase 3 officially commenced in November 2024 with a Tollgate 0 review, during which the entire team agreed to initiate the project. In December 2024, the Aero team conducted an Aero Design Consensus Review (DCR) to gain concurrence on the test purpose and objectives, the design plan, and to obtain approval to proceed to the Aero CDR. In January 2025, the clearances team conducted a clearances DCR to secure agreement on the approach for Phase 3 clearances to meet CTQ requirements. Later in January, the mechanical/rig DCR was completed to gain concurrence on the design plan and received approval to move forward to the CDR. Finally, in February 2025, Tollgate 1 was completed, demonstrating the purpose of Phase 3 and how it will be executed, and obtaining concurrence to proceed with the design phase.

3.2 MISTICC (Cold Flow)

3.2.1 Rig description and overview

The objective of the cold flow rig, also known as MISTICC is to explore opportunities to improve coupled combustor/turbine system performance. This rig **Figure 2** will run in a low-temperature environment to enable detailed measurements of the flow field upstream of the turbine stage 1 nozzle (S1N) and the impact of the compact core S1N design on system performance. This rig will first assess the S1N performance in axial flow for commissioning and comparing to turbine-only rigs. Following the axial configuration, product representative combustor swirlers will be installed to create a more engine-like flow field upstream of the S1N. The impact of this increased turbulence flow field on the S1N performance will be assessed.

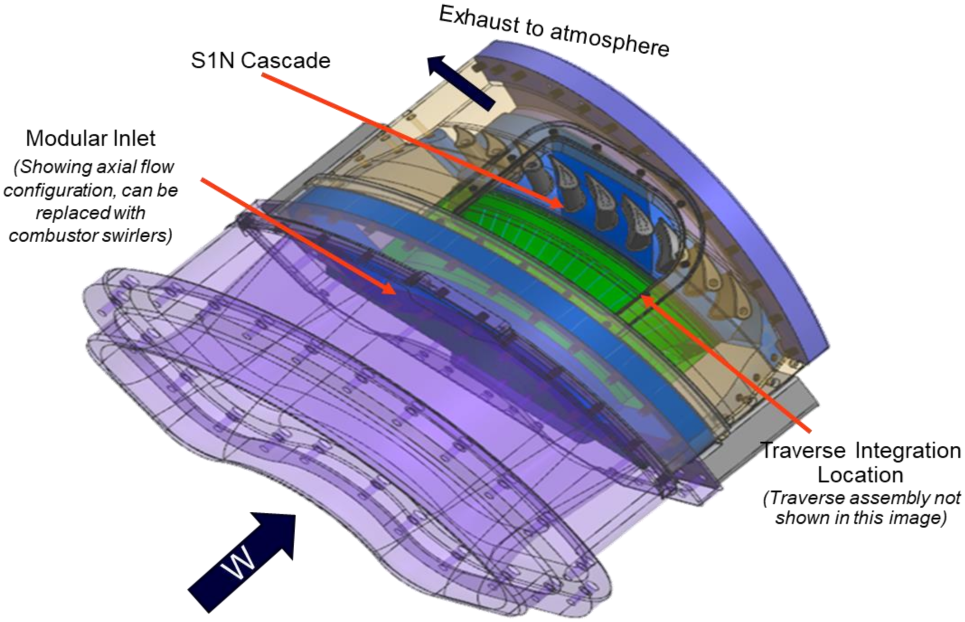


Figure 2: Cold Flow Rig (MISTICC) Overview

3.2.2 Annual Accomplishments

The focus this year has been on developing the details of the MISTICC rig design, instrumentation plan, and test matrix required to meet program objectives. The preliminary design is shown in **Figure 3**. The rig is designed to be modular to allow for quick transition between a variety of test geometries to include multiple flow fields, various S1Ns, an adjustable gap, and various S1N band designs.

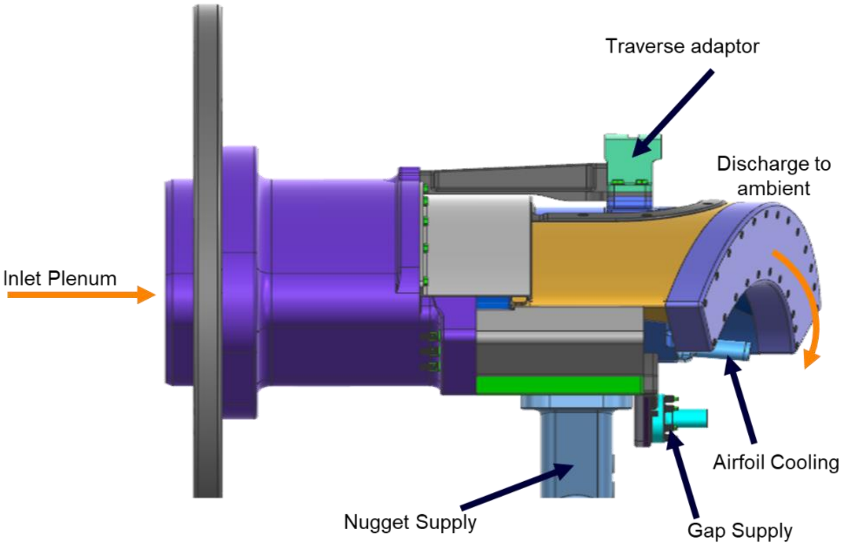


Figure 3: MISTICC Rig Configuration Preliminary Design

As part of the design effort, multiple reviews took place beginning with the Rig DCR (design consensus review) in June 2024. This review was completed to gain concurrence between Engine Systems, Design Engineering, and the Chief Engineer Office on the design, review, and technical maturation plans, as well as to address program and execution risks and their abatements.

Following the DCR, Tollgates 0 and 1 were successfully completed. The purpose of Tollgate 1 (TG1) was to discuss the overall schedule and milestones for the rig, test program deliverables, key test objectives, an overview of the rig, and the current plan to conduct testing at GEA. The outcomes included alignment of all stakeholders and identification of any potential risks or issues early in the program. This review included the overall objectives and high-level testing plans. Since this rig has cross-module and interdisciplinary objectives, there are many stakeholders. Approval of TG1 was an important milestone.

Upon completion of TG1, progress was made on the detailed design of the rig, and the mechanical design of the rig was completed. The design effort included creating detailed models of all components and assemblies to ensure proper fit and function, incorporating details to allow for necessary instrumentation, checking for unintended steps or part interferences, and designing part interfaces. The design was evaluated to ensure novel rig hardware and combustor assembly is producible and ready for test. The rig instrumentation plan was outlined, which includes a layout for static pressure taps and the design of the S1N inlet traverse.

The test matrix details were developed to include a step-by-step approach to commissioning the rig, comparing to legacy data, and deriving baseline performance data. Upon the completion of the instrumentation plan and detailed rig design layout, a Detailed Test Design Review (DTDR) was held as the final technical review before hardware procurement. The objective of this review was to evaluate the final test plan including design, test matrix, facility readiness, schedule, risks, and assembly plan with the extended review team and all technical stakeholders. The review team approved the rig DTDR.

3.3 Hot Flow Rig

3.3.1 Rig description

The Hot Flow Rig is a key development to validate HPT in an engine representative environment for TRL 5 maturation. A baseline version of the test is intended to validate the rig and data match to existing engine data.

3.3.2 Annual Accomplishments

The rig has made significant progress in the design development in the Detailed Design Review phase (DDR) for the test article and test enabling hardware. To date, the rig has completed over 24 design reviews, and systems Tollgate 1 and 3 reviews. Most recently, the combustor component completed a manufacturing release review, the test enabling hardware system has completed a heat transfer DDR, HPT aero completed an aero DDR, and the controls system completed a DCR. The design review included additional sensitivities to reconcile impacts of as manufactured hardware. Additional reviews completed in 2024 included the Pressure Vessel DDR, instrumentation hardware DDR, and test enabling hardware system PDR's (thermal and mechanical). The rig design overall has made substantial progress in finalizing the design, and is on track to meet key technical requirements.

3.4 HPT Aero Rig

3.4.1 Rig description and overview

The objective of the HyTEC Phase 2 HPT Aero Rig is to advance various High-Pressure Turbine (HPT) technologies to Technology Readiness Level (TRL) 5, including low Solidity, bow wave mitigation, advanced trailing edges, endwall contouring, advance tips, and advanced 3D aero. Achieving TRL 5 for these technologies will be accomplished by integrating them into an HPT aero rig with product-representative interfaces in an engine relevant environment. GEA will execute the design of the HyTEC rig. GEA will also be responsible for the manufacture, assembly, installation and testing of the rig in Evendale, OH.

The figure below shows a turbine rig installed in the Evendale test cell with the test enabling hardware. Air flows from right to left with the HPT rig hardware installed just to the right of the exhaust duct.

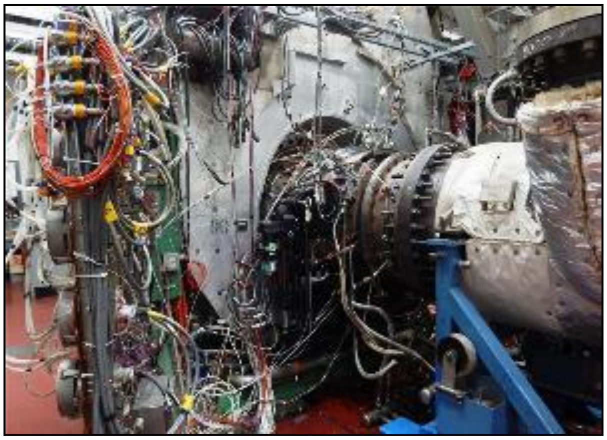


Figure 4: HPT Aero Rig Overview

3.4.2 Annual Accomplishments

In 2024, the GEA team initiated the HPT aero rig project. The HPT aero rig design project includes several significant program-level reviews and accomplishments. The goal is to advance the HPT aero design technology to TRL 5 and fulfill the contractual commitments for NASA's HyTEC Phase 2.

Program-Level Reviews

The first accomplishment was issuing the initial revision of the Technical Requirements Document (TRD), which established the overall technical requirements and communicated them to the engineering design teams. The second was the system-level Design Consensus Review (DCR). This review outlined the next steps in the design process, with agreement on the proposed approach key stakeholders allowing each design discipline to move forward to subsequent reviews. The third accomplishment was completing the Tollgate 1 review. This review encompassed the overall schedule, milestones, test program deliverables, primary test objectives, rig overview, and test facility plans. Approval of this review was significant as it validated the project's progress and readiness to advance to the next phase.

Discipline-Level Reviews

After completing all program-level reviews, the team proceeded with multiple discipline-specific DCRs for Test Enabling Hardware (TEH) HPT rotating parts, TEH structural parts, TEH mechanical parts, dynamics design, clearance design, and thermal system design. The objective of these reviews was to agree on the requirements, analysis approach, method, and level of detail for the CDR. This involved clearly defining the overall strategy and next steps, detailing the methodologies and tools to be used. The significance of these reviews was to ensure that all aspects of the design were thoroughly vetted and agreed upon by the relevant disciplines.

Aero Design Review

Two significant Aero design reviews were conducted. The Aero Design Consensus Review (DCR) outlined the technical requirements, necessary design reviews, analysis plan, design approach, documentation requirements, and target technology readiness level (TRL). This review ensured that aero technical and procedural details were planned and aligned with the program goals.

In addition, the aero rig CDR focused on addressing program requirements, overall test objectives, engine-to-rig scaling, and the selection process for rig aero design points. This review included discussions on the preliminary instrumentation plan, test support equipment selection (main venturi, torquemeter, bearing cartridge, water brake), risk assessment, and planning the next steps towards the aero Preliminary Design Review (PDR). The importance of this review is to show a technical path for the HPT rig design that meets TRL5 goals, identify potential risks, and establish a clear path forward.

The overall HPT rig has several key features to create a more engine like testing environment. There is an inlet temperature profile generator to generate a temperature profile to simulate a combustor temperature profile. A passive turbulence grid will generate a turbulence profile upstream of the HPT stage 1 nozzle. The active clearance control (ACC) system has been designed to be more engine like. The exit duct will not include any downstream components to match the compact core test environment.

The HPT rig is sized to match engine aero design point aerodynamics quantities. The HPT rig scale is a 1:1 physical scale with the engine. The inlet conditions are set to match engine condition delH/T , corrected speed, and engine Reynolds number. The cooling flow to main air flow temperature ratio in the rig are also set to match the engine conditions ratios while staying within facility limits. With these items set, the rig operates at aerodynamic similarity to the engine.

The rig speed and pressure ratio across the HPT can be varied to understand efficiency change as a function of corrected speed and delH/T. The facility and the test enabling hardware will limit the range over which the HPT can operate in both speed and HPT pressure ratio. These limitations include torquemeter capability, water brake keep out zones, and exhaust pressure and temperature conditions of the Evendale facility.

The variation in HPT conditions is sufficient to cover aero design point (ADP), max climb, take off, and a ground idle range, the key efficiency specification points required by the engine cycle.

By thoroughly addressing these areas in both the DCR and CDR, we ensured that all necessary elements were in place to advance with the aero design next phase.

Progress Achieved – Trade Studies

The team discussed several rig architecture and Test Enabling Hardware (TEH) equipment trade studies focused on the HPT Stator/ ACC architecture "product like vs traditional HPT aero rig", Turbine Vane Frame (TVF) on or off the rig, and TEH hardware selection.

The HPT stator and ACC architecture initial design process involved completing trade studies to compare different stator architectures, specifically product-like versus legacy rigs. The team evaluated multiple criteria, including stator secondary flow circuits, ACC system, case/shroud roundness and distortion, and understanding of blade tip clearance. The results of these comparisons and recommendations were reviewed with the key stakeholders and the decision was made to move forward with a product representative HPT stator/ACC architecture. This decision marks a significant step in ensuring that the chosen architecture meets the requirements of the HPT aero rig.

The TVF inclusion down-select process involved conducting trade studies to compare the implications of having the TVF on the rig versus off the rig. The team assessed various factors, including schedule risk, manufacturing risk, cost, resources, TVF component performance, and interfacing complexity with HPT. After reviewing the results with the key stakeholders, it was concluded to not include the TVF in the HPT aero rig as this best represents the core testing environment.

The TEH mechanical systems team conducted additional trade studies to select the appropriate TEH facility equipment. They concluded that a four-disk water brake configuration meets the test matrix requirements for the HPT aero rig, based on test points provided by the aero design team and comparisons with available water brakes.

Additionally, a 1.5kN-m HBM torquemeter was chosen for the HPT Aero rig test plan, as it meets the required speed capability of 14,000 RPM, torque capability of 1,475 ft-lbf, and limit torque of 2,950 ft-lbf. An existing bearing cartridge with good previous experience was selected for its compatibility with the planned speed capability. Re-used hardware is scheduled to be rebuilt, refurbished, and calibrated. The TEH equipment is appropriately sized to allow for testing key specification points to generate the HPT map.

3.5 HPT CFD Collaboration Plan

3.5.1 Collaboration Plan Overview

The HPT CFD collaboration will include CFD analyses and/or comparisons to data to support the understanding of combustor turbine interactions and the impact of compact core S1N designs on system performance. This effort is focused on influencing the development and understanding the results of the combustor-turbine interaction rigs. NASA's CFD collaborative analysis tasks may include, but are not limited to, performing pre-test and post-test analysis to support understanding of combustor/turbine integrations, developing cooling designs for additional MISTICC rig builds, completing probe interaction analysis to support rig design, and providing input on rig instrumentation. The culmination of this effort will be collaborative builds installed in the MISTICC rig that consist of GE state-of-the-art S1N airfoils with NASA-developed cooling designs.

3.5.2 Annual Accomplishments

To support this program, GE and NASA maintain weekly working meetings to sustain a true collaboration mindset and minimize the time between connections so that questions can be answered, data can be supplied, and challenges can be discussed in a timely manner. During these meetings GE and NASA have worked together to define the analysis strategy and scope for the program.

Together, the team has identified an airfoil geometry and count to use as the bases for this collaboration. To support NASA's design efforts, GE handed off an initial airfoil model that included two parts: 1) simplified aero model including airfoil and flowpath curves and 2) component airfoil model including internal cavities. In addition, GE supplied steady-state, non-reacting flow inlet boundary conditions corresponding to the simplified aero model.

Following delivery of the model and boundary conditions, NASA completed initial CFD runs. The chosen analysis approach is to start with simple models and gradually add complexity. The first models were completed with axial flow, without swirl. These initial runs did not include cooling flows and were used to complete a grid dependency study. In Q1 2025, NASA began to complete cooling studies with the addition of swirl. The first airfoil cooling models included only showerhead cooling before moving on to showerhead plus pressure side and suction side cooling. These models are currently in progress.

3.6 Advanced Instrumentation Collaboration Plan

3.6.1 Collaboration Plan Overview

This task is a collaboration between GE, the University of Notre Dame (UND), and NASA to develop advanced instrumentation for detailed unsteady measurements in turbine testing facilities. The objective is to improve the ruggedness, reliability, and accuracy of sensor technologies that are traditionally restricted in low TRL environments; specially targeting TRL5 rig environments for end-use. The measurements of interest include time-averaged and unsteady velocity, total pressure, total temperature, and turbulence parameters. The culmination of this effort is intended to be the integration of the newly developed instrumentation into the HPT Performance rig (Aero Rig 1).

The focus of the development will be on probe-based instrumentation rather than optical methods, concentrating on sensor type, probe size, calibration, frequency response, independence from contaminating variables, and sensor stability/life. The goal is to create new technologies that optimize the various trade-offs for specific measurement needs. During the instrumentation development, UND will utilize their calibration jets, wind tunnels, turbine rigs, and existing testing programs to provide opportunities for low-cost assessment of the new instrumentation techniques prior to integrating into the HPT Performance rig.

3.6.2 Annual Accomplishments

Progress on this task to date has been focused on agreeing upon a scope of work, schedule, and plan for collaboration with UND. GE and UND have outlined and refined the options for approaching the advanced instrumentation development and gained consensus on the top-level objectives and strategy.

Upon agreement on the scope of the program, UND, GE, and NASA met to kick-off the collaboration effort. Following this meeting, UND provided GE with a statement of work, and a corresponding Purchase Order (PO) was sent to UND for review.

UND has been preparing to fully launch this program once the purchase order is executed. First, UND has identified and hired a dedicated PhD student that will focus their research on this program. As part of their preparations, UND has been developing plans to establish a calibration facility specifically for this project. Additionally, they have initiated preliminary discussions with faculty members in various UND manufacturing laboratories to discuss the feasibility of several instrumentation concepts. These technologies and others will be further explored upon full execution of the PO which will include a literature search and technology downselection which will inform the plan for the remainder of the collaboration effort. The goal is to establish an initial TRL plan within 180 days of probe technology downselection.

4.0 CLIN 002 Compact core

4.1 Systems

Systems engineering encompasses a comprehensive approach to the development and integration of complex modules. It begins with the definition of requirements, ensuring that all necessary specifications and constraints are identified and addressed. This process includes the overall integration of various modules, to they work together to achieve the desired functionality. Additionally, systems engineering involves the management of trade studies, balancing different design options and their impacts on the system. Systems also maintains the official demonstrator cross section.

Disciplines such as dynamics, controls, and performance along with specific thermal system design activities such as rotor thrust analysis are also considered at the system level due to their cross-module and cross-system implications.

4.1.1 Annual Accomplishments

Systems Design Consensus and Program Launch: The guiding principles for the Compact Core demonstration program were summarized and communicated to the broader organization as part of the Systems design consensus review (DCR) held in March 2024. This review served as a springboard for each of the module design teams to launch their individual discipline DCRs and leverage the content from the Systems DCR related to:

- Core design execution and target to fire (TTF) milestones with specific focus on CDR execution
- Core technology demonstration scope and TRL goals
- A designer data package (DDP) with key cycle points and plans for post-DCR updates
- Design life requirements for low cycle fatigue (LCF) and Hot Time. Exceptions were noted for test enabling hardware and instrumented components
- Clearance assumptions in the DCR cycle to meet performance objectives
- Combustor emissions and smoke requirements
- Guidance on engine dynamics requirements
- Weight targets and allocation to each module
- Quality and safety requirements for the core and test enabling hardware components
- High level descriptions of each module including test enabling hardware with summary of requirements and key trade studies that need to be executed as part of CDR
- Preliminary cross-section release and management process
- Summary of risks as identified at the DCR timeframe and abatements planned before CDR

Engine Dynamics and Thermal Model Cross Section Release: Subsequent to the Systems DCR review, a series of high-level trade studies were completed in April, May and June of 2024 with the primary intent being to release an updated engine cross section for CDR dynamics load assessment and thermal system (TSD) model developments. Inputs from the engine dynamics, secondary flow and heat transfer models are needed to support CDR execution for each of the individual modules and are typically coordinated by the Systems leadership team. A series of Systems trade study and engine cross-section reviews were held, and the overall effort culminated in a systems tech review in July 2024. The tech review (TR) documented the key architecture decisions and requirements updates since March of 2024 in a single forum and served as a formal communication update to all module teams.

Rear Frame and Aft Sump Integration*:* An updated Rear Frame Flow path cross-section was released after the appropriate Chief Engineer and Systems trade-study reviews. Each of the adjacent module (HPT, Sump, Test Enabling Hardware – Mounts, VEN, Aft Slip Ring) hardware owners also made the appropriate cross-section updates to match the rear frame flow path. Completing this study was key to the rear frame meeting requirements.

Dynamics Conceptual Design Reviews: Engine dynamics CDR was completed in early September after which an initial set of dynamics data were released to the module teams for incorporation into their respective CDRs.

Performance Conceptual Design Review: The performance conceptual design review was held over two sessions starting in late December and concluding in January. The performance review's main focus was to review the status of cycle with feedback from the modules on overall performance.

TRD Updates: A key deliverable from the Systems Team has been the completion of updates needed for the TRD (Technical Requirements Document) in the ERM tool. Leveraging the best practices and lessons learned from prior core and new product introduction (NPI) TRDs, the team has assembled a list of individual requirements for the overall core, test facility, test enabling hardware, controls, SPOCT (Systems, Performance, Operability, Controls and Transient Analysis) and individual modules where appropriate. Several workshops have been held to coordinate the overall layout and organization of the document with the intent to carry it forward into the product-vision demonstration phase.

Cross Section Updates: Throughout the design process systems has maintained an official core demonstrator cross section. Weekly cross section reviews were established post systems DCR in which all modules discuss changes made throughout the past week, results of trade studies and physical interfaces between modules are reviewed. Through this process the cross section is maintained and frequently updated reflecting the latest status of the demonstrator.

4.1.2 Systems Analysis & Integration Update

Starting in May 2024, the systems analysis and integration (SA&I) collaboration effort commenced, and a monthly operating rhythm was established between the GE Aerospace and NASA working teams to ensure consistent progress and alignment across various project activities.

One of the key milestones achieved in this period of performance was the convergence on the engine baseline approach for Key Performance Parameter (KPP) and Technical Program Metric (TPM) evaluations. A baseline engine was selected for the 2020 engine technology baseline.

An NPSS model of the baseline engine has been created by the NASA team. GE Aerospace has completed comparisons of the NASA engine model to internal higher fidelity NPSS models, produced at company expense, and provided high-level feedback to confirm the applicability of the NASA model for independent KPP and TPM evaluations.

Additionally, the SA&I team has reviewed the vision for open fan architecture, providing valuable information to assist in NASA's independent evaluation in advance of formal SA&I deliverables. This includes details on technologies, benefits, modeling approaches, fundamental component sizing, and performance class information, as well as feedback from GE Aerospace on NASA's funded technology list.

Deep dives into advanced systems with ties to the compact core have been conducted. These sessions covered use cases and benefits related to KPPs, architecture, and technology maturation plans. Furthermore, feedback has been provided on NASA's vision engine and open fan-powered advanced low wing (gulled) aircraft study, including performance and weight estimates of an open rotor propulsion system concept for next-generation aircraft (Chapman, Bennett, & Tong, 2025) and the conceptual design of a gulled-wing commercial transport (Taylor, 2025).

Mean line High-Pressure Turbine (HPT) inputs have been delivered, along with an initial review of High-Pressure Compressor (HPC) inputs. The performance status of compact core technologies has been established through Critical Design Review (CDR) activities to date, including methods review, model review, and performance review. The team is in the process of incorporating modeling updates to represent the CDR design status for the evaluation of KPPs at the systems conceptual design review.

4.2 SLIN 1 HPC

4.2.1 Annual Accomplishments

- Throughout the past year, the team has focused on the conceptual design of the HyTEC Phase 2 project high pressure compressor (HPC). Major achievements include defining and optimizing the design from historical experience and tests. The improvements identified in this phase are critical to meeting the program requirements.
- HPC Aero Conceptual Design Review (CDR) was completed in October 2024 marking a significant milestone. The team set the initial aero design and axial length specified to meet system requirements. This review involved a comprehensive evaluation of the design.
- Rotor design CDR was completed in December 2024. Studies were completed to define the rotor conceptual design to meet configuration and operational requirements. In this effort, the rotor architecture was selected, material selections were made, and initial sizing was completed.
- Structures design CDR was completed in December 2024. For this effort, the casing architecture for the HPC was defined. This includes the fwd case, the aft extension case, and the aft inner cases and support arms. The configuration was defined consistent with the released aero flowpath and designed to integrate key features such as liners and bleed slot/port requirements. Initial material selections were made to meet operational requirements.

- Stator airfoils mechanical and aeromechanical CDR's were completed in November 2024. This includes a review of the design of all variable and fixed vanes in the compressor. Leading up to this review, studies were completed to set counts and layouts, shroud configurations and material selections. Using preliminary airfoil definitions, initial mechanical and aeromechanical assessments were performed.
- Rotor airfoils mechanical and aeromechanical CDR's were completed in November 2024. This includes review of the design of all rotating airfoils including blisks and inserted blades as applicable. During this phase, configuration studies were completed, materials were selected, and initial mechanical and aeromechanical assessments were conducted.
- The Variable Geometry System CDR was completed in December 2024. In this effort, the initial VG system arrangement was developed including lever arms and unison rings and integrated with the case and vane designs.
- The Thermal Systems Design CDR was completed in November 2024. This design effort included layout of the secondary flow systems, boreflow circuits, and bleed circuits needed to meet system level requirements. A CDR-level thermal model was developed and analyzed to produce thermal results for the system for planned design intent operating conditions. This information was used by the design teams for material selections, trade studies and feedback to the systems and performance teams.
- The Clearances CDR was completed in December 2024. For this effort, the axial and radial clearances were set for the HPC and an assessment was completed to determine operating clearances versus intended targets.
- The Module CDR was completed in December 2024. The module review is a holistic review of the full compressor relative to the system level requirements. In this review, status of the HPC module design as a system relative to requirements was discussed. This review included cross section development/trade studies, TRL/MRL plans, hardware plans, ICD's and Risk/Mitigation discussions.
- After the completion of the CDR reviews, work continued on the HPC design to address actions items. Key actions from the review included efforts to further improve weight, performance and clearances. During 1Q 2025 (GFY Q2 2025), additional studies were conducted to reduce weight, further increase performance, and identify opportunities to improve clearances to meet system level requirements.

4.2.2 HPC Collaboration Update

Over the past year, GE Aerospace has engaged in several strategic activities to support our collaboration with NASA. A key milestone was the successful completion of an internal review of both aerodynamic and mechanical conceptual designs. This was followed by a debriefing session with NASA, where information was exchanged to align our designs with the Technical Performance Measures (TPMs). These reviews ensured that our efforts were in sync with NASA's expectations.

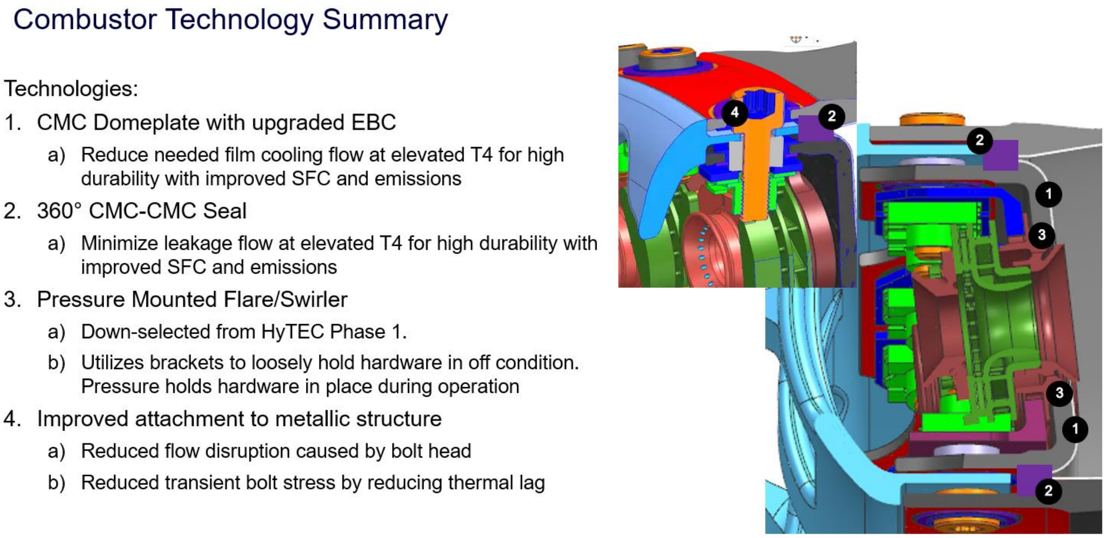
We have also established a robust framework for ongoing collaboration, including monthly meetings to discuss progress and address challenges. Additionally, we have been providing GE externally available, published nozzle geometries to NASA to allow for a comparison of GE Large Eddy Simulation (LES) with NASA's LES solver. The goal of this is to understand our differences for future comparison of HyTEC airfoil geometries.

These activities have set a solid foundation for success in the next year of the contract. The insights from reviews and debriefing sessions have informed our design progress, while ongoing meetings and collaborative simulations ensure opportunities to address questions. By maintaining this level of engagement, we are well-positioned to achieve our project milestones and deliver high-quality outcomes that meet both GE Aerospace and NASA expectations.

4.3 SLIN 2 Combustor

4.3.1 Module Technology Overview

Within the Combustor, two technologies will be matured. The first of these technologies is the use of a single wall Ceramic Matrix Composite (CMC) dome. CMCs enable small core sizes via hotter cycles and/or reduction in required cooling air. GE Aerospace's latest evolution in the use of CMC technology is the Combustor Dome. The use of a single walled CMC dome requires the development of several items including upgraded EBC, a metallic swirler attachment mechanism, a CMC to CMC seal, and an improved attachment mechanism between the CMC dome and the cold structure supporting the combustor. These items can be seen in **Figure 5**.



Combustor Technology Summary

Technologies:

1. CMC Domeplate with upgraded EBC
    a) Reduce needed film cooling flow at elevated T4 for high durability with improved SFC and emissions
2. 360° CMC-CMC Seal
    a) Minimize leakage flow at elevated T4 for high durability with improved SFC and emissions
3. Pressure Mounted Flare/Swirler
    a) Down-selected from HyTEC Phase 1.
    b) Utilizes brackets to loosely hold hardware in off condition. Pressure holds hardware in place during operation
4. Improved attachment to metallic structure
    a) Reduced flow disruption caused by bolt head
    b) Reduced transient bolt stress by reducing thermal lag

Figure 5: Combustor Technology Overview

In addition to the use of the CMC dome, the combustor will also continue to develop its ability to utilize SAF (Sustainable Aviation Fuel). This testing spans from single-cup fundamentals testing to Core testing and will focus on examining its effect on Light-off and Lean Blow Out.

4.3.2 Annual Accomplishments

To date, multiple accomplishments have been achieved relative to design, manufacturing, and testing. From a design perspective, two major reviews were completed. First, a combustor technology readiness assessment (TRA) was completed and approved in early 2024. The TRA was reviewed with subject matter experts and completed through the Chief Engineer's Office for the aerodynamic and thermal/mechanical design of the All-CMC combustor. This maturation plan was then reviewed and approved with the System / Module level team to highlight the key deliverables and ensure clear communication of the risk reduction activities to the broader core team.

Once the planned technologies and maturation plans were approved, the second and third quarters focused on developing a combustor design that could be produced and would meet all program deliverables. Many trade studies were completed to assess the designs capability. This included multiple CFD assessments to determine which producible CMC dome shapes resulted in acceptable gas temperatures as well as multiple studies on cooling strategies that would reduce material temperatures to acceptable levels. These resulted were reviewed within the aerodynamic team to assess their relative impact on combustor performance. Mechanically, multiple trades studies were completed to evaluate concepts. One such trade study evaluated strategies for attaching the CMC dome to the cold structure. Evaluations included impacts on both low cycle fatigue capability, high cycle fatigue capability, as well as impacts on items like leakage flows and pressure recoveries. Other studies include strategies for mechanically holding the pressure load swirler in place while in engine off conditions. These studies focused on impacts on high cycle fatigue capability as well as the ability to assemble the combustor reliably.

After the completion of these studies, the combustor aerodynamic and thermal/mechanical Conceptual Design Reviews (CDR) were completed in late 2024. These CDRs were completed and approved through the Chief Engineer's Office. They included a full review of the conceptual design and analysis with inputs from the manufacturing lessons learned as well as results from completed testing. The aerodynamic CDR also included a downselect of the planned SAF to be used in the core as well as a review of risks and mitigations for the use of this SAF fuel. This review resulted in a test plan to retire risk prior to the core and ensure successful testing within the core.

Post CDR, the team has continued its trade studies with more focus on optimizing the conceptual design. These studies have focused on items such as CMC thickness, support structure shapes, and metallic support hardware to improve the overall design capability prior to start of the preliminary design phase. These studies will continue to occur through the first half of 2025 and include discussion with the CMC manufacturer as well as the metallic hardware manufacturer to ensure the improved design is producible prior to initiating PDR level analysis.

From a manufacturing perspective, multiple CMC Dome trials have been completed including at least four sector and two annular trials. These trials are key to dialing in a lay-up process and understanding where improvements are needed in areas such as dimensional stability and defect capability. Learnings from these trials resulted in adjustments to the conceptual design prior to the CDRs. With these learnings and successful completion of the CDRs, the Full Annular Rig (FAR) CMC dome and liner preform definitions were released to begin the manufacturing process. Prior to releasing, a review was completed to show the design and manufacturing plans were sufficiently developed to ensure successful manufacturing of these components.

Relative to testing, early low TRL rigs (TCA2, HTP1, LPS2) have been completed outside of the HyTEC Phase 2 contract to down select swirler/ferrule/fuel nozzle configurations. These configurations will continue to the next round of testing (TCA3, HTP2, LPS3). This next round of testing utilizes the aerodynamic learnings and incorporates all features/learnings that are specific to the use of a CMC dome and liners. Combining these learning allows for further risk reduction in lower level TRL rigs continue the maturation of the overall CMC dome design. The TCA3, HTP2, and LPS3 designs have been completed, approved through test article technical reviews, and manufacturing is underway for testing in 2025.

4.4 SLIN 3 HPT

4.4.1 Module Technology Overview

Low Solidity

Reducing airfoil counts while maintaining axial chord (resulting in lower solidity, defined as axial width / tangential pitch) increases the amount of lift each individual airfoil is required to do, typically increasing the profile and secondary flow losses. Machine learning optimization has been used to develop new aerodynamic profiles that minimize the aerodynamic penalties at reduced solidity. Removing airfoils reduces the cooling requirement (especially due to reducing the number of edges: life-limiting locations on turbine airfoils), as introduction of cooling typically comes with a degradation of aerodynamic performance.

Combustor – Turbine Interaction

Removing airfoils reduces the cooling requirement (especially due to reducing the number of edges: life-limiting locations on turbine airfoils), as introduction of cooling typically comes with a degradation of aerodynamic performance.

Endwall Contouring (EWC)

Aerodynamic optimization of turbine blade design also extends to the platform at the base of the airfoil. Contouring of the platform, as shown in **Figure 6** can modify the local pressure field to offset secondary flow development.

Figure 6: Endwall Contouring

Bow Wave Mitigation

Cooled High Pressure (HP) turbine airfoils have increased thickness to provide internal volume for cooling flow, and the blockage from those aerodynamic shapes creates a static pressure bow wave that projects forward of the leading edge. This effect is magnified in compact core turbines, where elevated firing temperatures require increased cooling flow, and mechanical features such as minimum wall thickness do not scale down, resulting in effectively thicker airfoils with stronger bow waves. To meet turbine durability, it is important to prevent ingestion of the combustion air into off-flowpath spaces where the material capability is not as high, and pressure variations in these gaps increase the purge flow required to prevent ingestion. Like EWC (which is focused on reducing secondary losses in passages between airfoils), nozzle bands can be contoured upstream of the airfoil to manipulate the static pressure field. Bow Wave Mitigation (BWM) technology will use aerodynamic optimization of the band contouring to reduce the strength of the local pressure gradient

Advanced Tips

Leakage through the tip gap between the blade and the stationary shroud results in aerodynamic loss via several mechanisms: throat bypass (no or limited work extraction from the leakage air) and induced effects on the lift of the blade (similar to unloading of an aircraft wing by the tip vortex). Shaping of the tip of the airfoil can change the interaction of the tip vortex with the suction side of the blade, reducing the interaction and induced drag and thus resulting in improved turbine efficiency.

Advanced 3D Aero

This technology utilizes a combination of radial vortexing and stacking parameters on each airfoil to optimize the turbine performance. The vortexing component changes the radial exit flow angle distribution along the span of the airfoils. It is manifested as a change in the radial throat and radial work distribution. The stacking component changes the manner in which the 2D sections are placed relative to each other, manipulating the 3D throat plane. Optimizing the combination of these parameters for improved turbine performance results in a noticeable bending or curving of the airfoil surfaces, especially near the trailing edge.

4.4.2 Annual Accomplishments

Preliminary 3D aero optimization was completed in September- the radial work distribution and airfoil stacking (axial & tangential relative positioning in spanwise direction) were perturbed in a DOE study to maximize HPT efficiency and minimize loss. The resulting airfoils from this study were released for initial mechanical feedback and to establish design requirements.

In October the HPT Aero Conceptual Design Review was completed. The team reviewed the results from the base 1D design which was designed to stay withing GE’s experience base (with the exception of the Low Solidity technology). Bow wave mitigation, end wall contouring, and advanced tip features will be part of the design, but development of these features will occur at later phases of the design. Early estimates of the performance presented at the Conceptual Design Review match closely to the estimates that were used by the Performance team to establish the initial cycle. As expected due to the nature of this program as a tech maturation demonstrator, the design carries more risk at this phase than our typical new product design process.

In December the basic airfoil shape for use in mechanical/thermal conceptual design review was agreed upon between the aero, mechanical, and thermal designers. A key decision point was the shape and thickness of the trailing edge feature. To meet the durability requirements and elevated cycle temperatures defined for the RISE Compact Core, a balance between the wedge angle and trail edge thickness was selected to result in the lowest overall impact to performance when considering the cooling flow required to meet the durability requirement, the aerodynamic efficiency effects of the shape, and trade factors provided by the SPOCT and Systems teams.

4.5 SLIN 4 Hybrid Electric

4.5.1 Module Technology Overview

The Hybrid Electric System (HES) is being integrated with the Core through a drivetrain to the High Speed Spool, enabling supplemental injection and extraction of power to improve performance of the Core.

The HES integrated with the core demonstrator is focused on enabling characterization of a hybridized core and expanding on previous turbomachinery integration and controls development. The HES used on the Core was designed for a previous GE program and has been tested extensively at the EPISCenter in Dayton, OH. The re-use strategy allows the team to focus on integration and turbomachinery characterization, with low risk around the HES itself. In addition to the degree of Hybridization specified in the KPPs/TPMs, through the HyTEC Phase 2 program, a more detailed understanding of the mechanical integration challenges and solutions are being developed around future use-cases.

The integration plan includes a test enabling gearbox to ensure robustness for testing higher torque loads than those within the mechanical capability of previous programs. The increase capability opens up opportunity to demonstrate the full range of power injection and extraction levels that are currently in the RISE product vision scope, as well as introduce transient behavior that further increases loading within the drivetrain. Prior to demonstration, torsional dynamics analysis will provide insight into the system interaction when accounting for the Motor/Generator inertia, and unique electrical forcing functions. The HES module will also include torque sensor to validate all steady state and transient torques throughout the test campaign.

4.5.2 Annual Accomplishments

The HES Module progressed from the Design Consensus Review (DCR) in Q2 2024 through the Conceptual Design Review (CDR) in Q4 2024. The major accomplishments focused on requirement definition, hardware procurement plans, hardware capability, and integration.

The DCR, reviewed by the technical community, covered program overview / schedule, program scope, component overviews in the broader system, proposed hybrid use cases, key program/module requirements, and required trade studies. The review outcome was positive, with support from the Chief Engineers Office to initiate the conceptual design phase of the program, where the team could focus on how to integrate the HES with the engine system (mechanical and controls) and the facility (mechanical, controls, electrical, thermal management) and show path to satisfying program requirements.

Adjacent to Hybrid Electric design, one critical decision coming out of the Mechanical Systems team was how to design the drivetrain to enable the Hybridization of the Core. The decision was around re-using an existing Accessory Gearbox focusing on hardware procurement or designing a new gearbox focusing on mechanical capability. A Chief Engineer review in middle of 2024 concluded with concurrence to proceed with the design of a new gearbox to accommodate integration with the Compact Core and to allow for higher power operating points and fault mode demonstration.

Another significant integration effort was with engine controls team. A baseline for hybrid integration and communication procedure was selected leveraging best practices from previous program learnings. Engine controls requirements including the new operating cases were communicated. The new operating cases will build upon component level controls developed during previous Hybrid Electric programs.

Later in Q3 2024, the torsional dynamics team completed both their DCR and CDR, which included the inertia of the Motor/Generator and unique electrical forcing functions. The reviews highlighted where to focus near term activities to address unique risk associated with integrating the HES with the core. The team will complete a CDR+ review (as proposed in the DCR) in the upcoming weeks to review an initial set of results capturing these system interactions. Modeling is complete and initial results have already been shared with the internal team, preparing for the official chief engineer review.

In Q4 2024, the Hybrid Electric team completed their CDR. The team evaluated the conceptual HES design and reviewed the analysis path moving towards the Preliminary Design Review (PDR) planned for late 2025.

5.0 References

Chapman, J. W., Bennett, M., & Tong, M. (2025). Performance and Weight Estimates of an Open Rotor Propulsion System Concept for Next Generation Aircraft. *AIAA 2025-0092*.

Taylor, R. B. (2025). Conceptual Design of a Gulled-Wing Commercial Transport. *AIAA 2025-0460*.