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Hybrid Thermally Efficient Core (HyTEC) Phase 1 3-Stage Compressor Rig

Final Report - Unlimited Rights

G. Scott McNulty, Brandon Teitelbaum, Mike Paine, Arnesha Threatt, Kyle Fishleigh, Dave Goshorn, Krista Mitchell, and Mitchell Albrecht
GE Aerospace, Evendale, Ohio

August 2026

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List of Acronyms

Acronym	Definition
5HP	5-Hole Probe
ADP	Aero Design Point
Aero	Aerodynamics
ALF	Aft Looking Forward
BPF	Blade Pass Frequency
CAFMIX	GE 2D Streamline Curvature Code
CDI	Circumferential Distortion Index
CDP	Compressor Discharge Plane
CDR	Critical Design Review (NASA)
CFD	Computation Fluid Dynamics
CT	Casing Treatment
D-Factor	Diffusion Factor
EFFa	Adiabatic Efficiency
EGV	Exit Guide Vane
EL	Endurance Limits
ERA	Environmentally Responsible Aviation
FBH	Front Bearing Housing
FF	Fixed-Free
FLA	Forward Looking Aft
FR	Fixed-Restrained
FRAP	Fast Response Aero Probe
FWD	Forward
GEA	GE Aerospace
GRC	Glenn Research Center
H/W	Hardware
HF	Hot-Film
HP	Horsepower
HPC	High Pressure Compressor
HW	Hot-Wire
HyTEC	Hybrid Thermal Efficient Core
IGV	Inlet Guide Vane
KPP	Key Performance Parameter
LBM/S	Pounds Mass Per Second (Flow Rate)
LE	Leading Edge
LP	Low-Pass (Filter)
MRB	Material Review Board (Hardware Non-Conformance)
OB	Open-Beta (VSVs Open)
Op-Line	Operating Line
PCal	Power-Cal (Performance Testing)

PDR	Preliminary Design Review
Ph2	Phase 2
PL25	Plane 25 (Upstream of IGV)
PL30	Plane 30 (Compressor Exit)
PL31	Plane 31 (Diffuser Exit)
PR	Pressure Ratio
PS	Static Pressure
PSD	Power Spectral Density
PT	Total Pressure
R1	Rotor 1
R2	Rotor 2
R3	Rotor 3
RBH	Rear Bearing Housing
RDG	Reading
RPM	Revolutions Per Minute (Shaft Speed)
S1	Stator 1
S2	Stator 2
S3	Stator 3
SA	Stack-Axis
SG	Strain Gauge
SM	Stall Margin
TC	Test Completion
TF	Test Fire
TI	Turbulence Intensity
TM	Throttle Margin
TPM	Technical Performance Measure
TRR	Test Readiness Review
TT	Total Temperature
URANS	Unsteady Reynold's Averaged Navier-Stokes
VSV	Variable Stator Vane
W25R	Inlet (Plane 25) Corrected Flow

Executive Summary

The HyTEC Phase 1 3-Stage Compressor Rig project was conducted to mature and validate front-stage aerodynamic technologies in support of HyTEC Phase 2 and GEA's Compact Core compressor. Building on the prior ERA Phase 2 Baseline Rig, GEA and NASA collaborated on the design and testing of the HyTEC rig, incorporating advanced technologies such as increased radius ratio, higher aerodynamic loading, and advanced casing treatment. The HyTEC test campaign leveraged similar design and instrumentation philosophy, test execution approach, and the same facility (NASA W-7) to enable clear comparison with the legacy ERA rig results. The HyTEC rig was designed to deliver benefits in efficiency, tip loading, operability, and aeromechanics, with success measured against defined TPMs that were anchored to the ERA baseline rig data.

Serving as the comparison for HyTEC rig performance, the ERA Phase 2 baseline rig is first summarized, including a high-level overview of its design. Background on the NASA GRC W-7 facility and the ERA hardware and instrumentation is reviewed, along with ERA test objectives, test plan, schedule, and key ERA results. Subsequently, relevant background on the HyTEC design, instrumentation, and test plan is presented, emphasizing commonality with the ERA baseline rig to support direct, quantitative comparisons.

The remainder and majority of this report is focused on documenting and summarizing the key learnings from the HyTEC rig test. The initial test results are presented and discussed primarily in the context of the project TPMs. Focusing first on the aero technologies, the HyTEC rig demonstrated excellent high-speed performance. The measured design point adiabatic efficiency exceeded the TPM-3 full success criterion of 0.7 points improvement on a corrected basis compared to the baseline ERA rig. Rotor 1 tip loading increased by 7.3 percent relative to ERA, nearly achieving the full success TPM-1 goal for Rotor 1 tip d-factor. Operability also was improved across the map: HyTEC throttle stall margin exceeded TPM-2 minimum success criteria at all speeds and achieved the full success target at a majority of mapped conditions.

HyTEC testing also provided valuable aeromechanics data, with significant learnings around two responses of interest. One of these responses was seen at part-speed with the initial aero-optimized VSV schedule. The second response was observed, but was confined to high-speed, near-stall operating lines that are not expected to be directly relevant to the Compact Core front stages. Focused on the part-speed regime, extensive VSV derivative testing was performed with the objective of mitigating elevated aeromechanical responses. This effort produced an "aeromechanics-optimized" VSV schedule that significantly reduced airfoil vibratory amplitudes to within certifiable limits. The effective mitigation of airfoil vibration response with VSV optimization led to distinct "aero-optimized" and "aeromechanics-optimized" VSV schedules, both of which were fully characterized and assessed against the TPMs. The unique and extensive dataset also provides important opportunities for validating and improving aeromechanics analysis tools.

While aerodynamic performance at high speed exceeded expectations, part-speed efficiency was significantly lower than the ERA baseline rig. Although considerable efficiency could be recovered through VSV optimization focused on performance, the aeromechanics-optimized schedule exacerbated the part-speed efficiency deficit, creating significant tradeoffs between performance and aeromechanical stability in the part-speed regime. Even though part-speed efficiency was not explicitly captured in the project TPMs, the shortfall relative to ERA motivated a quantitative assessment of product-representative, mission-weighted efficiency. This assessment showed that the efficiency reduction at part speed with the aeromechanics-optimized schedule more than offset all performance gains at high speed. Conversely, the aero-optimized schedule significantly improved part-speed efficiency such that an equivalent of minimum success in efficiency was achieved on a mission-weighted basis.

Overall, the HyTEC Phase 1 3-Stage Rig test met all TPMs, subject to the VSV schedule caveats described above. As a result, the project is judged to have successfully achieved TRL-4 for the front-block aero technologies and to have provided important risk reduction for the HyTEC Phase 2 Compact Core compressor. The demonstrated gains in design-point efficiency, front-stage aero loading, and operability directly support key Phase 2 KPPs. Two principal technology maturation risks were identified: high aeromechanics response levels for multiple responses and lower-than-expected part-speed efficiency. These

areas now form the focus of a multi-pronged risk-mitigation plan that includes additional configuration testing, Compact Core design trades, and continued development and validation of analysis tools.

1. Introduction

The NASA Aeronautics Research Mission Directorate is currently operating a subsonic transport technology maturation program, called the Advanced Air Vehicles Program. A part of this program is the Hybrid Thermally Efficient Core (HyTEC) project, which focuses on accelerating technology development for compact core engine technologies, with the objective of meeting the Key Performance Parameters (KPPs) shown in Table 1. Under Phase 1 of the HyTEC program, GE Aerospace (GEA) is contracted to design, build, and test an advanced 3-Stage Compressor Rig to mature high-pressure compressor (HPC) front-stage aerodynamic technologies for the compact core engine that enables the next generation narrowbody transport. The relevant HyTEC Key Performance Parameters for the 3-Stage Compressor Rig are KPP-1, KPP-3, and KPP-4.

Table 1: HyTEC Project KPPs

KPP #	Key Performance Parameter (KPP)	Full Success Single Aisle ~2035 Entry Into Service	Minimum Success Single Aisle ~2035 Entry Into Service
KPP-1	Fuel burn reduction attributed to the high-power density core of the original equipment manufacturer's vision turbofan engine	10%	5%
KPP-2	Engine bypass ratio	>15	>12
KPP-3	Engine overall pressure ratio (defined at top of climb)	>50	>45
KPP-4	Durability, measured in operating hours between major refurbishments	Exceed state-of-the-art by 5%	Meet state-of-the-art of baseline
KPP-5	Degree of hybridization measured by level of power extraction from the turbofan engine at altitude	20%	10%
KPP-6	High pressure compressor exit corrected flow	<3lbm/s	<3.5lbm/s

The objective of the HyTEC Phase 1 3-Stage Compressor Rig project is to develop and mature advanced front-stage technologies, such as an increased radius ratio, high aerodynamic loadings, and an advanced casing treatment for GEA's Compact Core high pressure compressor. GEA and NASA collaborated on the design and testing of the advanced compressor rig. GEA aerodynamics, mechanical, and aeromechanics teams executed the conceptual, preliminary, and detailed design of the HyTEC rig, and NASA performed pre-test predictions using their advanced Computational Fluid Dynamics (CFD) codes. GEA was responsible for the manufacture and assembly of the HyTEC rig, while NASA was responsible for the installation and testing of the rig in their W-7 facility at the Glenn Research Center (GRC). GEA and NASA closely collaborated to plan and execute the test and to review the data.

The NASA Environmentally Responsible Aviation (ERA) Phase 2 3-Stage Compressor (designed by GEA in 2014) is the baseline rig for establishing the Technical Performance Metrics (TPMs) goals for the HyTEC rig. However, limited high-speed data was obtained during prior ERA rig testing in 2015 due to a throttle valve instability in the NASA GRC W-7 facility. For this reason, an early objective of this HyTEC project was to re-test the ERA Phase 2 Rig to acquire the baseline test data needed to assess the HyTEC rig's performance, operability, and aeromechanics TPMs. Re-testing the ERA rig allowed the throttle valve fixes to be implemented, as well as experience to be gained with a new inlet heater system prior to HyTEC rig testing.

The TPMs established for the HyTEC 3-Stage Compressor Rig are shown in Table 2. GEA and NASA subject matter experts agreed to these four TPMs: (1) Rotor 1 tip aerodynamic loading parameter (diffusion factor), (2) stall margin, (3) design-point efficiency, and (4) aeromechanical stability. The minimum and full success TPM goals are relative to the baseline ERA Phase 2 3-Stage Rig. Achievement

of these TPMs would be a significant advancement in front-stage aerodynamic technology over the baseline ERA rig which represents the current state-of-the-art in high pressure ratio compressors for commercial aircraft engines.

Table 2: HyTEC 3-Stage Compressor Rig TPMs

TPM #	Technical Performance Measure (TPM)	Full Success	Minimum Success
TPM-1	Higher Rotor 1 tip loading, measured through diffusion factor for an equivalent increase in operating line	+7.6% Rotor 1 tip diffusion factor, equivalent of 5% higher operating line	+5% higher Rotor 1 tip diffusion factor, equivalent of 3.3% higher operating line
TPM-2	Stall margin retention across the operating range	+3% stall margin vs. baseline	Stall margin equivalent to baseline
TPM-3	Efficiency improvement at the design point	+0.7pts adiabatic efficiency vs. baseline with radius ratio adjustment	+0.3pts adiabatic efficiency vs. baseline with radius ratio adjustment
TPM-4	Aeromechanical stability	Design is aeromechanically stable with final optimized variable stator vane schedule. Representative inlet temperatures, up to stall or within 5-13% operating line margin (consistent with legacy rig), whichever is lower, from 60% speed to 100% speed	Blade responses are below certifiable limits with final optimized variable stator vane schedule. Representative inlet temperatures, up to stall or within 5-13% operating line margin (consistent with legacy rig), whichever is lower, from 60% speed to 100% speed

2. ERA Phase 2 Baseline Rig

As previously mentioned, the ERA Phase 2 3-Stage compressor serves as the baseline rig for assessing the HyTEC TPMs. An early objective of this contract was to re-test the ERA Phase 2 rig to obtain a complete set of baseline data since this was not achieved during 2015 testing due to throttle valve issues. This section briefly describes the ERA Phase 2 compressor rig.

2.1 ERA Baseline Rig Design Overview

The ERA Phase 2 Baseline Rig cross-section is shown in Figure 1. This compressor rig was designed circa 2014 to mature front-stage aero technologies for a modern commercial HPC. All three stages are bladed disks which enabled the swap out of the rotor blades between Builds 1 and 2. Build 1 was the baseline blading while Build 2 was designed for higher pressure ratio and more tip strong radial profiles. The more advanced Build 2 blading was used for Build 3 of the ERA rig which is considered the baseline for the HyTEC rig TPMs.

All the stator vanes have variable setting angles, including the inlet guide vane (IGV). The variable stator vane (VSV) setting angles are controlled on test as a function of inlet corrected speed using a "milking machine". The milking machine actuates each vane row independently, but the schedules for each vane are developed to mimic the kinematics of a mechanically linked system on a real engine.

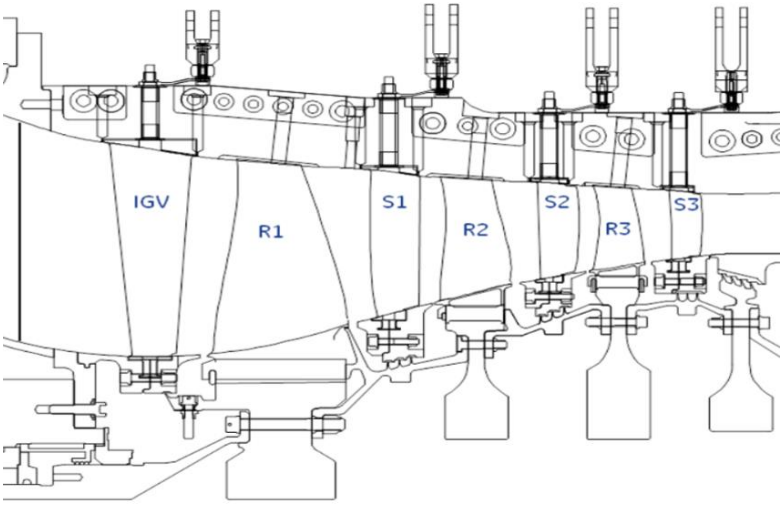

Figure 1: ERA Phase 2 3-Stage Baseline Compressor Rig

2.2 ERA Build 1/2 Test Summary (2015)

While HyTEC TPMs are grounded in ERA Build 3, this section provides a brief summary of the earlier 2015 ERA Phase 2 rig test results from Builds 1 & 2. Build 1 had high rotor vibrations caused by deflections of the stage 3 retainer ring (under centrifugal load) that could not be effectively mitigated with in-situ balancing. This limited operation of Build 1 to below 85% corrected speed. The rotor dynamics issue was fixed for Build 2 which allowed operation over the full speed range. However, the exit throttle valve position was unstable at higher speeds which prevented completion of speedline mapping to stall. The inlet corrected flow for Build 2 as a function of corrected speed along the nominal operating-line (op-line) was successfully measured over the entire speed range. Figure 2 shows that the compressor flow pumping met pre-test expectations for most of the speed range but was 3.4% below the design target at the aero design point (ADP) corrected speed of 98%. Several hypotheses were considered to explain the low flow that was measured, but the root cause was not definitively identified. Based on this prior result, several improvements were implemented for Build 3 to address the potential contributors to the flow shortfall: the facility inlet duct sealing was improved, Stage 1 and 2 rotor dovetails were sealed with room-temperature vulcanizing silicone, and the VSV angles were calibrated and rigged using digital protractors.

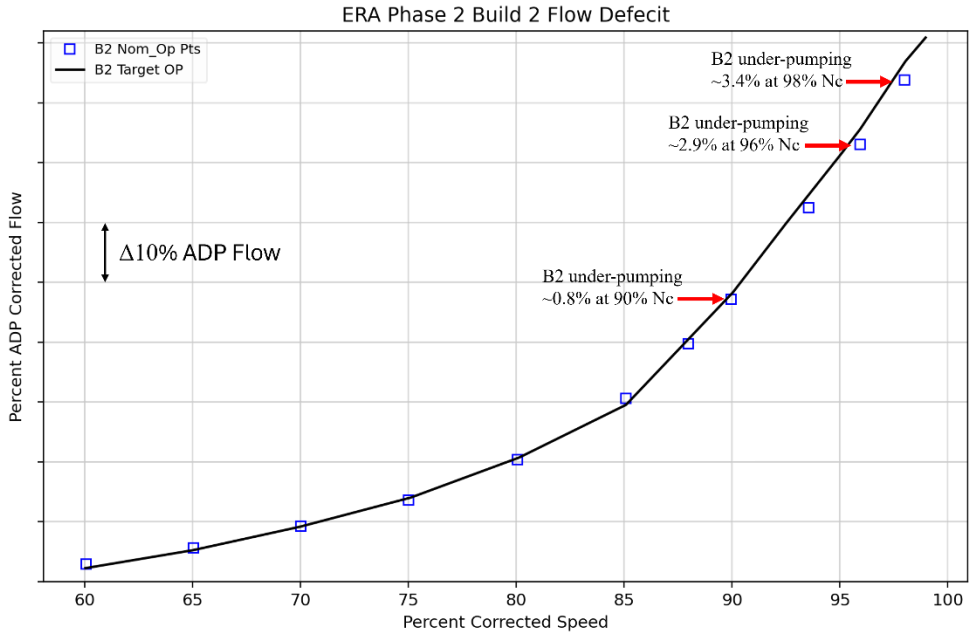

Figure 2: ERA Phase 2 Rig Build 2 Flow vs. Speed

2.3 ERA Phase 2 Build 3 Baseline Rig Test Results (2023)

The final section of this chapter focuses on the ERA Phase 2 Build 3 rig testing that serves as the baseline for HyTEC performance comparisons. First, this section outlines the test objectives for ERA Build 3 testing, primarily to acquire baseline data for HyTEC TPMs and to validate facility upgrades. Both the NASA W-7 facility and ERA rig hardware and instrumentation are then summarized. Next, the test plan and schedule for ERA Build 3 testing are briefly discussed. Finally, a brief summary of key results is presented, though detailed discussion of results is deferred to Chapter 4 in the context of comparison with HyTEC TPM results.

2.3.1 Test Objectives

The ERA Phase 2 Baseline Rig test Build 3 campaign was conducted to acquire baseline data for the HyTEC TPMs, including Rotor 1 tip loading, high-speed efficiency, throttle and open-beta stall margin, and aeromechanical responses. Secondary objectives were to validate the NASA W-7 facility upgrades and to fully map the compressor with the ERA Build 3 configuration updates, such as the new perforated-plate "intrinsic" inlet distortion screen, sealed dovetails on Rotors 1 and 2, and improved inlet duct sealing. In addition, the test plan included supplemental activities to generate useful derivatives and engineering data, including radial traverses at the inlet (to characterize turbulence) and rotor exits, as well as compressor mapping with a flat inlet profile achieved by removing the intrinsic (hub strong) distortion screen.

2.3.2 NASA W-7 Test Facility

The ERA Phase 2 Baseline Rig was tested at the NASA GRC facility in the W-7 test cell. A schematic of the compressor test facility is shown in Figure 3. Some key features of this facility are: atmospheric inlet, 15,000 HP electric drive motor with 5.21:1 gearbox, V-cone flow meter, and close-coupled exit throttle valve. Not shown in Figure 3 is an inlet heating system that enabled targeting of different product-representative cycle conditions and enabled completion of testing with below-freezing ambient temperatures for the ERA and HyTEC rig test campaigns. The inlet heater is a steam-fed coil system that can heat up to 100 lbm/s of flow up to 200°F. Additionally, a more modern, high response COBRA data acquisition system was installed in W-7 since the previous ERA rig test.

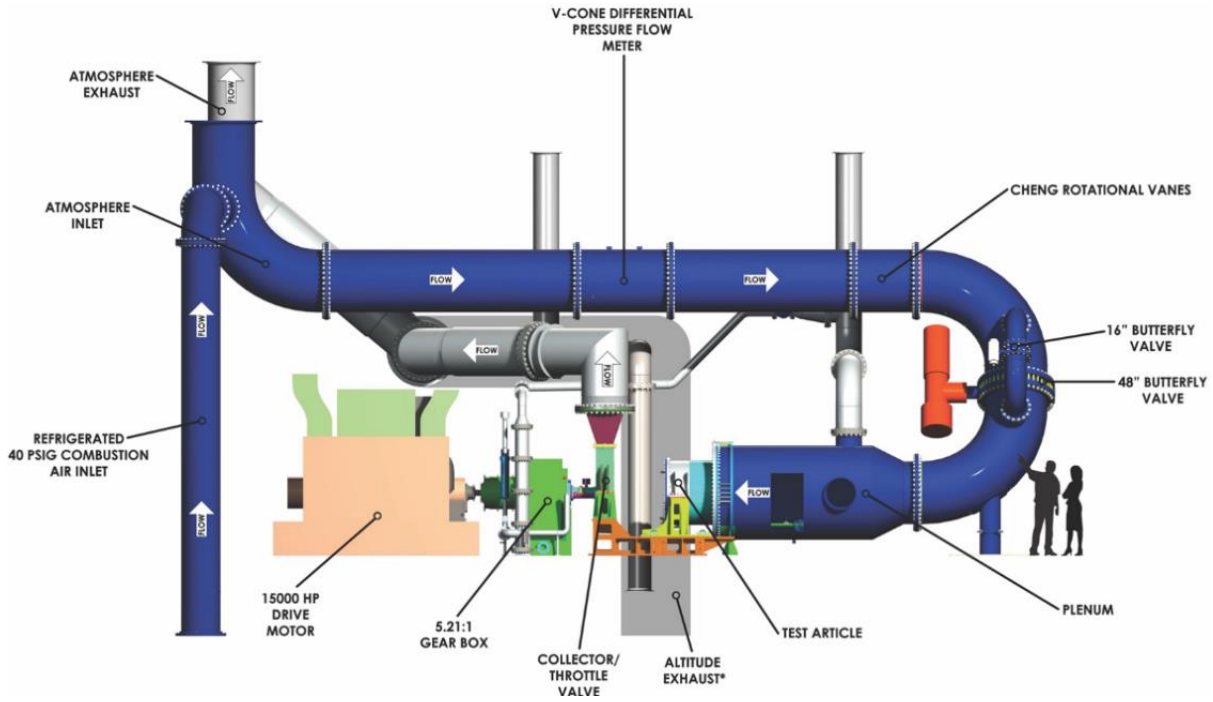

Figure 3: NASA GRC W-7 Compressor Test Cell Layout

2.3.3 Instrumentation and Hardware

Most of the instrumentation used for Build 3 of the ERA Phase 2 rig was the same as used for Build 1 and Build 2 in 2015. Figure 4 shows that this is a highly instrumented compressor with performance rakes at the inlet (Plane 25) and exit (Plane 30/31), inter-stage PT/TTs at the leading edge (LE) of Stators 1 through 3, casing static pressures and Kulites, light probes and clearanceometers over the rotors, strain gauges on the VSVs, and radial traverses at the compressor inlet and the exit of Rotors 1 through 3. The rig was designed for a hub strong total pressure inlet profile. For Build 1 and 2 a wire-mesh type distortion screen was designed and installed in the inlet duct to create the design intent inlet radial profile into the compressor. Unfortunately, the wire-mesh screen used for the prior ERA testing in 2015 was not found, so a new laser-cut perforated plate type screen was designed and manufactured for Build 3.

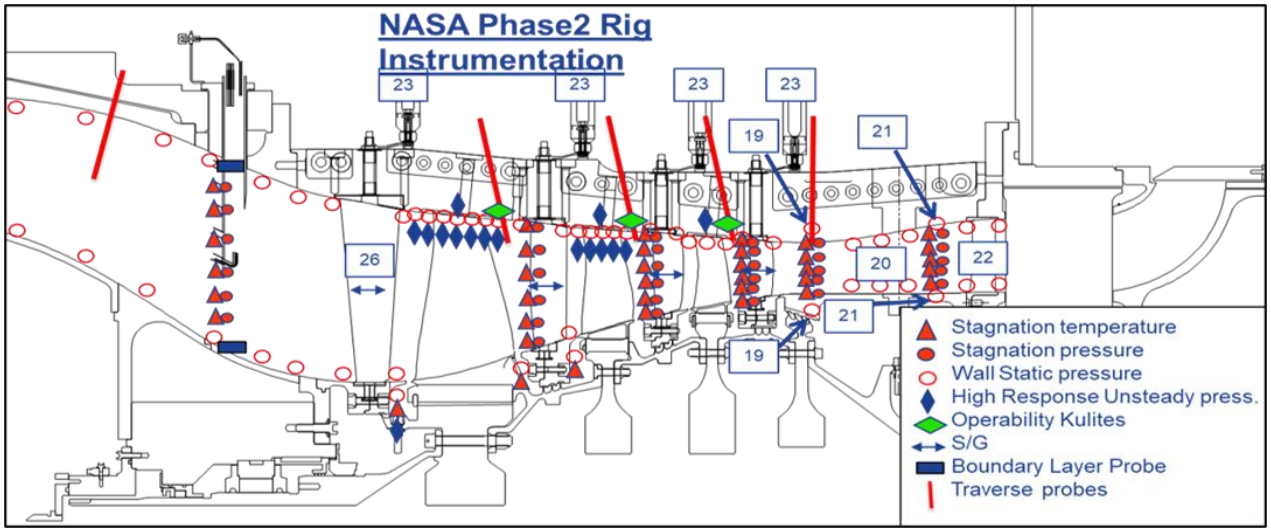

Figure 4: ERA Phase 2 Baseline Rig Instrumentation

2.3.4 Test Plan and Schedule

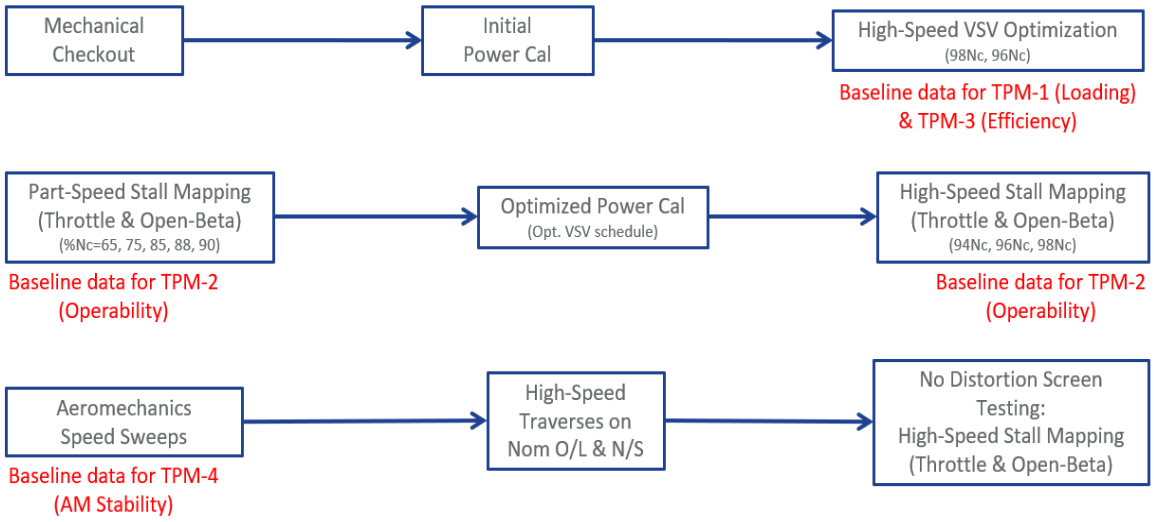

Figure 5: ERA Phase 2 Build 3 Test Plan

Figure 5 is a block diagram illustrating the overall test plan and sequence of testing for the ERA Build 3 Baseline Rig. Detailed test cards were developed for each of the blocks of testing to specify the key rig parameters for each test point and to estimate the amount of time required for each of the 9 test cards. Figure 6 is a summary of the final ERA rig test schedule with green squares being successful test days and black squares represent days where testing was not completed due to weather, maintenance, or other issues. Testing of the baseline ERA rig started on December 12th, 2022, and ended on March 14, 2023. Testing lasted approximately 3 months with 20 total test periods and approximately 6 weeks of down time due to maintenance, repairs (2.5 weeks to repair exit duct failure), troubleshooting throttle valve instability, holidays (2.5 weeks at end of year), and weather. The average run-time per test period was 5.3 hours. The rig was stalled 40 times, and 1,980 steady-state readings were obtained.

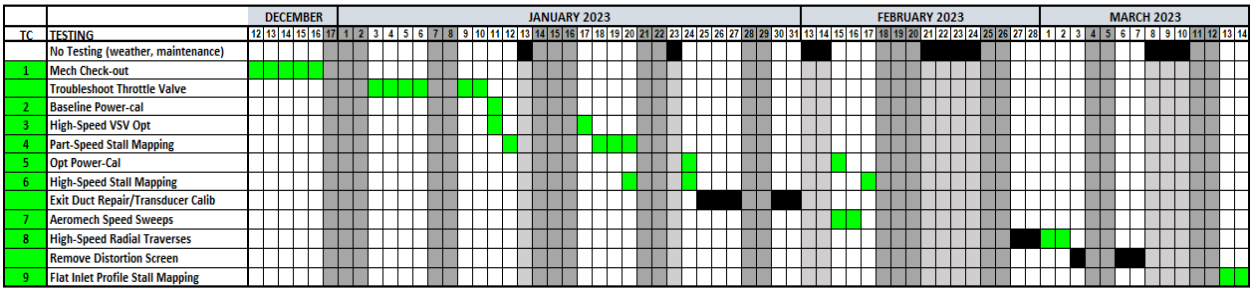

Figure 6: ERA Phase 2 Build 3 Test Schedule

2.3.5 Key Results

This section summarizes the key results from the ERA Phase 2 Build 3 testing which is the baseline data for this project. Limited data is shared here, as most of it will be shown later as the baseline data in the HyTEC TPM results section.

The total pressure profile measured at the inlet to the compressor (Plane 25) is shown in Figure 7. The inlet profile created by the new Build 3 screen reasonably matches that of Build 2's wire-mesh screen. There is a region between 20 to 50 percent immersion (50 to 80 percent span) where the laser-cut screen has slightly lower loss (higher PT). The Build 3 screen also has a slightly lower inlet PT near the hub.

As previously mentioned, one of the key findings from the prior testing of Build 2 of this rig in 2015 was that the inlet flow was approximately 3% lower than the design intent. Figure 8 shows that the inlet corrected flow for Build 3 was 2.3% higher than Build 2 at the design speed of 98% for the same VSV schedule. This improvement is likely to be due to steps taken to improve the inlet duct sealing, sealing the

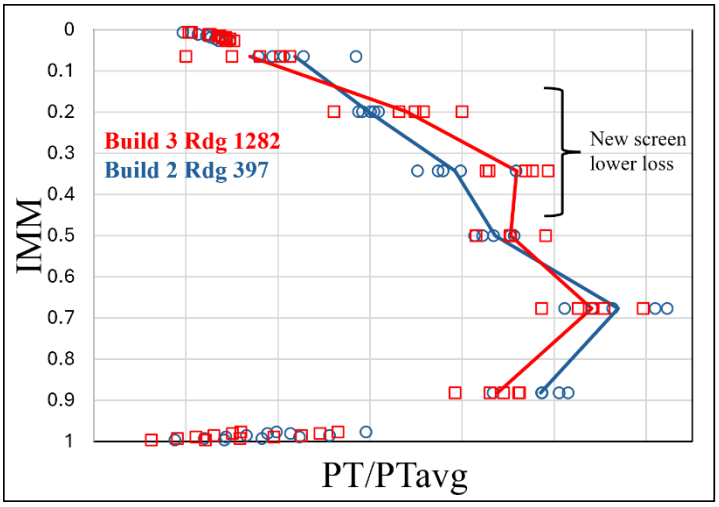

Figure 7: ERA Phase 2 Baseline Rig Inlet PT Profile: Build 3 vs. Build 2

Rotor 1 and 2 dovetails, and using a digital protractor to calibrate and rig the VSV system. Although the flow was significantly closer to the target, it was still 0.5 to 1.0% low. The VSV schedule was opened 0.5 deg. (variable vanes together as a "gang", following their individual schedules) at high speed to hit the compressor's ADP flow and pressure ratio target. This was done to give a more precise set of baseline TPM data.

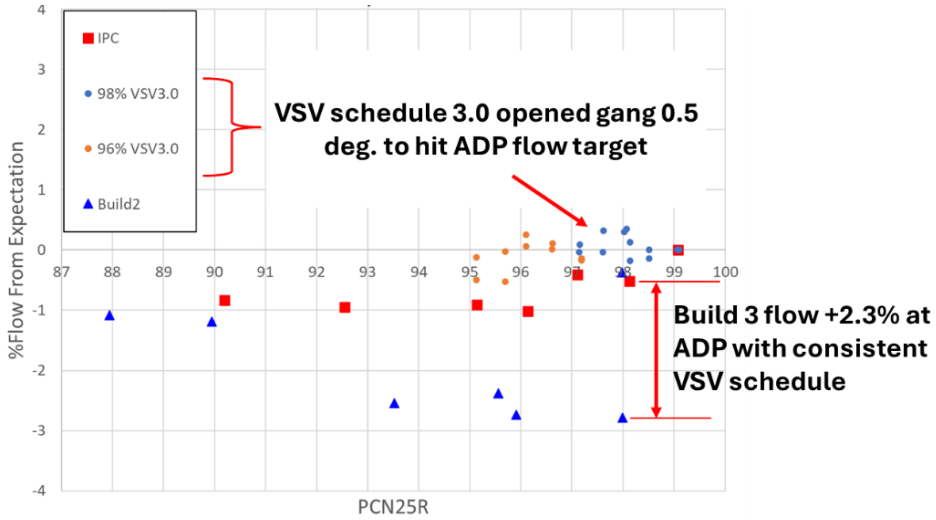

Figure 8: ERA Phase 2 Baseline Rig Inlet Corrected Flow: Build 3 vs. Build 2

The majority of the ERA rig test plan focused on acquiring the baseline aero data for the HyTEC TPMs related to efficiency (TPM-3), stall-margin (TPM-2), and Rotor 1 aero loading (TPM-1). Most of the early testing involved investigating individual VSV offsets at high and low speeds. This data was used to develop an optimized VSV schedule that maximizes both high-speed efficiency and part-speed operability. The optimized VSV schedule was then used for the remainder of the test. A power-calibration was performed to measure the ERA rig's performance over the entire corrected speed range - from ground idle to high power - it is expected to operate in an engine. The compressor was then fully mapped over the entire speed range as shown in Figure 9. Constant speed "speedlines" were obtained from 65% to 98% corrected speed by incrementally adjusting the exit throttle value from a fully open position (high flow, low PR) to a closed position (low flow, high PR) until the compressor eventually stalls. The ERA rig was mapped to stall with both the nominal VSV schedule and the VSVs opened up to 8 deg. to measure the so called "open-beta" stall-line. Open-beta stalls are used to evaluate stall margin for conditions that might occur due to transient operation or deterioration in the compressor. For all results presented herein, both stall margin and

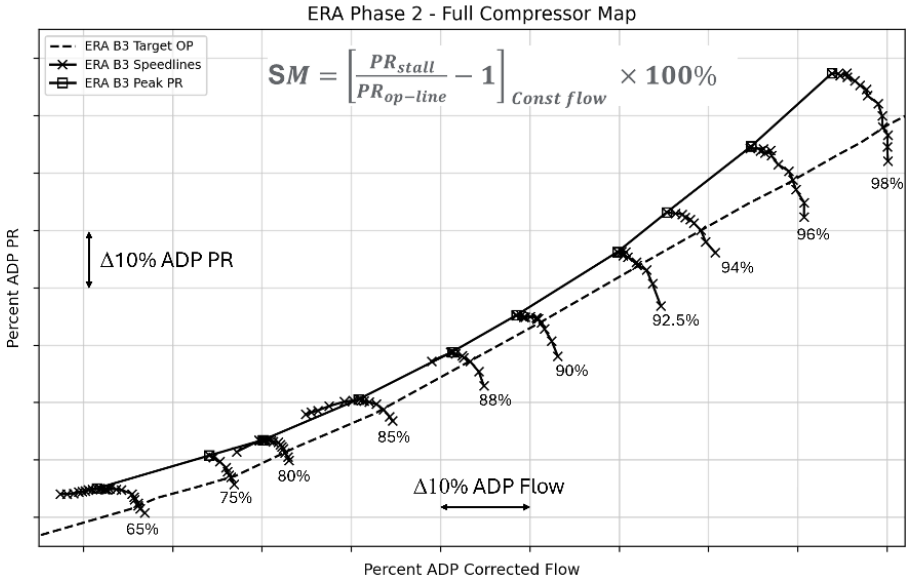

Figure 9: ERA Phase 2 Baseline Compressor Map

percent op-line are calculated at constant flow. The equation used for stall margin calculation is shown in Figure 9, where the stall condition is selected to be the point of peak pressure ratio along a speedline.

The next phase of testing involved characterizing the aeromechanical behavior of the compressor using the inlet heating system to target various cycle conditions. Speed transients were performed at various throttle settings (low to high operating-lines) and VSV settings to identify any significant responses of interest. This testing was performed with the heater set at various inlet temperatures up to 180 deg. F., though no significant aeromechanical responses were observed.

The remainder of the test plan involved obtaining useful engineering data not directly related to the TPMs. Radial traverse measurements were acquired at the compressor inlet and at the exit of each rotor. Hot-film and hot-wire traverses were done at the inlet to measure the turbulence created by the distortion screen upstream of the compressor. A 5-hole probe (5HP) was used to obtain radial traverse data at Rotor 1, 2, and 3 exits at multiple corrected speeds (96% and 92.5%) and operating-lines (nominal and near-stall).

Lastly, the compressor was mapped to stall with the inlet distortion screen removed to assess its sensitivity to a flat (opposed to hub strong) inlet total pressure profile. The resulting flat inlet throttle stall and open-beta stall-lines were obtained from 90% to 98% corrected speed. VSV derivatives also were performed to identify the stalling stages.

2.3.6 Summary

The ERA Phase 2 Baseline Rig test Build 3 campaign was completed in the first quarter of 2023. All planned test cards were successfully executed, and the NASA W-7 facility updates were validated, including resolution of the throttle valve control issues and validation of heated inlet capability up to 180°F. The team obtained the baseline TPM data for HyTEC performance, operability, and aeromechanics (with no significant responses of interest observed at any cycle conditions). High-value engineering data was collected, including radial traverses at the inlet and behind each rotor, as well as compressor maps with and without the inlet distortion screen installed. The ERA test campaign provided an excellent training and collaboration opportunity for the GEA and NASA engineering teams, drove the development of test procedures and best practices, and identified improvement opportunities, delivering a significant risk burn-down for subsequent HyTEC rig testing. Data analysis showed that the ERA rig's flow pumping was much closer to expectation and that the empiricism deduced from the test data aligned closely with that used in the HyTEC rig design, increasing confidence in the design approach. Following completion of testing, the ERA rig was removed from NASA W-7 and shipped to Steven Douglas Corp. for disassembly.

3. HyTEC 3-Stage Rig Design Summary

This chapter focuses on summarizing the design of the HyTEC 3-Stage Compressor Rig. The following sections only provide a high-level overview of the HyTEC 3-Stage compressor rig design, as the detailed aero and mechanical design content has previously been presented and reviewed in the various NASA design reviews. The first section of this chapter focuses on the overall rig design philosophy and comparison to the ERA baseline rig. Subsequent sections focus on mechanical and aero design details, respectively. Finally, the predicted performance improvements for the HyTEC rig are presented.

3.1 Rig Design Overview

The rig was designed in accordance with GEA standard processes and best practices and followed the formal GEA internal review framework throughout its design evolution. Table 3 summarizes the NASA design reviews conducted for the HyTEC rig.

Table 3: HyTEC 3-Stage Rig NASA Design Reviews

NASA Reviews	Date
Project Kick-Off	Oct. 31, 2021
TPM Review	Nov. 28, 2021
Aero PDR	Apr. 24, 2022
Mechanical PDR	Sep. 22, 2022
Aero CDR	Sep. 27, 2022
Mechanical CDR	May 3-4, 2023

The overall objective of this rig is to develop and mature advanced front-stage technologies for GEA's Compact Core high-pressure compressor, with particular emphasis on a highly loaded Rotor 1 featuring advanced casing treatment, vector diagram changes, and an increased radius ratio. The HyTEC rig was designed at a higher radius ratio than the ERA rig to address shaft packaging and rotor dynamics challenges associated with the small physical size of the Compact Core compressor. Although this higher radius ratio helps mitigate mechanical integration constraints, it also introduces additional aerodynamic challenges, including lower efficiency potential and reduced blade tip-speed that increases tip loading (diffusion factor). The multi-stage configuration is valuable because it enables assessment of how the advanced casing treatment over Stage 1 interacts with downstream stages. In addition, the rig's heated inlet capability enables evaluation of how aeromechanical responses are affected by elevated inlet temperatures, further enhancing the relevance of the test environment to engine-realistic operating conditions.

Table 4 compares the key design parameters for the HyTEC rig against the ERA baseline rig. The higher radius ratio is one of the key differences between ERA and HyTEC, with HyTEC having a radius ratio ~15.8% higher than that of ERA. Despite the higher radius ratio, HyTEC was designed to have a similar specific flow rate to ERA. Additionally, the overall pressure ratio is increased by ~1.5%, while the Rotor 1 tip-speed is reduced by about 3%, contributing to the higher tip diffusion factor (d-factor).

Table 4: HyTEC Rig Aero Design Parameters (vs. ERA)

Parameter	ERA Ph2 ADP (98% Nc)	HyTEC ADP (98% Nc)
R1 Radius Ratio	-	+15.8%
Specific Flow (W/A)	-	-0.5%
Pressure Ratio	-	+1.5%
R1 Tip Speed (ft/s)	-	-3%

3.2 Mechanical Design Summary

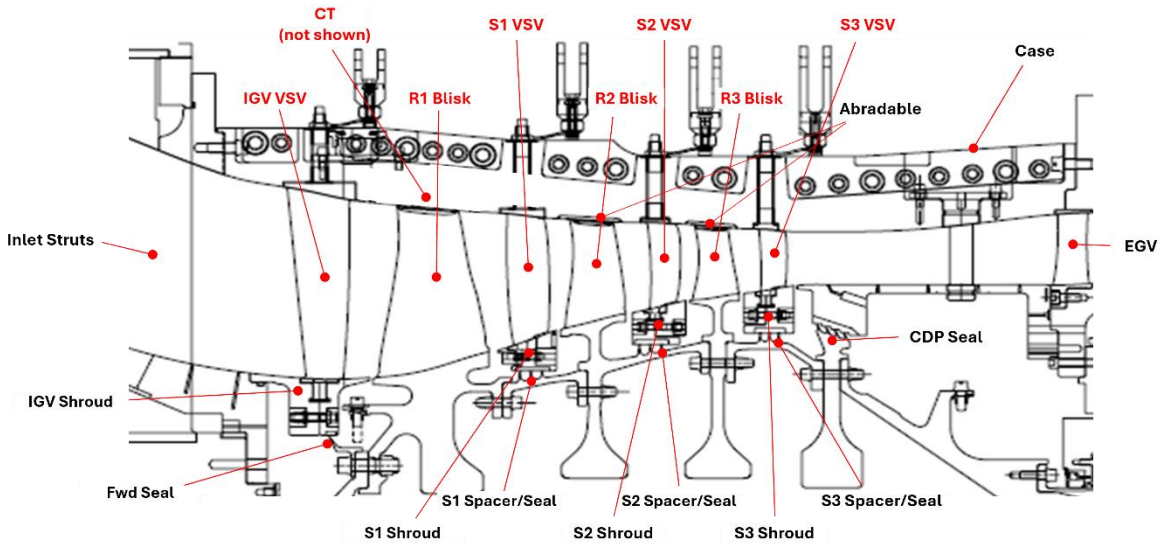

Figure 10: HyTEC 3-Stage Rig Cross-Section

Figure 10 shows a cross-section of the HyTEC rig, with the turbomachinery airfoils highlighted in red. All three rotor stages are blisks. The rig has VSVs for each stage, in addition to IGVs. The VSV setting angles are adjusted using a milking machine actuation device and are individually scheduled as a function of corrected speed. Each stage has a labyrinth seal consisting of three teeth that rub into the abradable material sprayed into the stator shroud. Near the exit of the rig is a row of exit guide vanes (EGVs) that turns the swirling flow toward the axial direction before it passes through the throttle valve and into the exit plenum.

3.3 Aero Design Summary

This section provides a high-level summary of the HyTEC rig aerodynamic design. The HyTEC compressor rig incorporates a highly loaded Rotor 1 with an advanced casing treatment and vector diagram changes. TPM-1 was defined with the objective of increasing the Stage 1 tip d-factor by at least 5%. Figure 11 compares the design tip d-factor for each rotor of the HyTEC rig (red) with that of the ERA baseline rig (blue). The Rotor 1 tip d-factor was designed to exceed the full success criteria for TPM-1, representing a significant technological advancement. This increase is driven by a combination of higher Stage 1 loading,

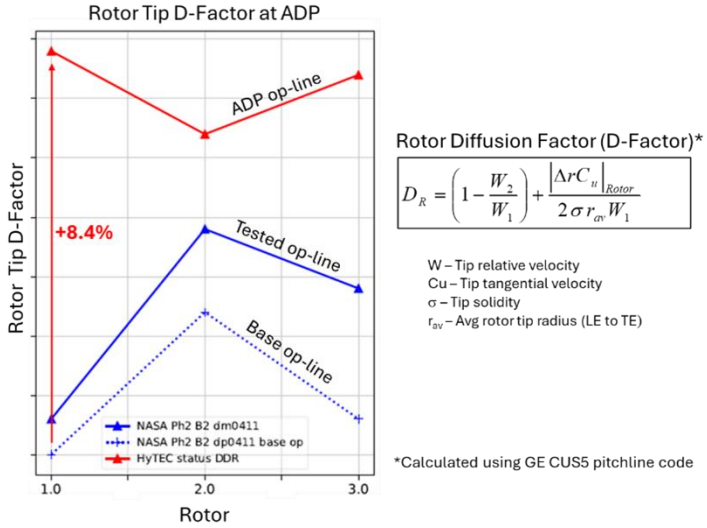

Figure 11: HyTEC Rotor Design Intent Tip Loading (D-Factor)

a lower blade tip speed associated with the higher radius ratio, and the vector diagram changes. The advanced casing treatment enables the higher Rotor 1 tip loading to be achieved while maintaining adequate stall margin. The higher radius ratio and vector changes also contribute to elevated tip d-factors for Rotors 2 and 3, primarily due to the lower blade tip speeds.

The maximum thickness-to-chord ratio is similar to the ERA blade across the span. The chordwise thickness distribution is also generally similar, although the HyTEC blade includes some additional thickness on the outer 35% span on the front half of the chord to ruggedize the design for ice ingestion in a future product configuration. This added thickness introduces a small efficiency penalty for HyTEC, which will be bookkept in the performance stack since it is not directly related to the aero technologies being developed.

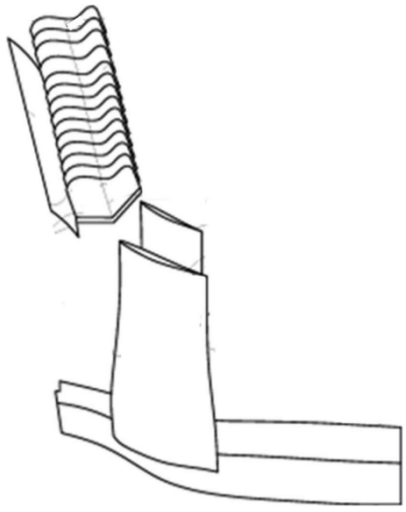

Figure 12: Advanced Casing Treatment Schematic

Figure 12 shows a schematic of advanced casing treatment, which is one of the enabling technologies of the HyTEC rig. The advanced casing treatment functions by recirculating flow: fluid enters the rear portion of the slots within the blade passage and exits on the front half of the slots near the rotor leading-edge. This recirculation is driven by the chordwise pressure gradient within the blade passage, which includes a bow shock for this transonic blade. The recirculation of flow within the casing treatment is passively regulated, increasing in magnitude as the pressure gradient rises as the rotor is throttled toward stall, which is when additional stability is needed. Figure 13 shows an axial plane downstream of the rotor trailing edge comparing meridional velocity contours for both a smooth-wall and casing treatment configuration. These results show that the casing treatment recirculation reduces the flow blockage (low-momentum fluid, blue) near the blade tip, thereby improving the stall margin capability of the rotor.

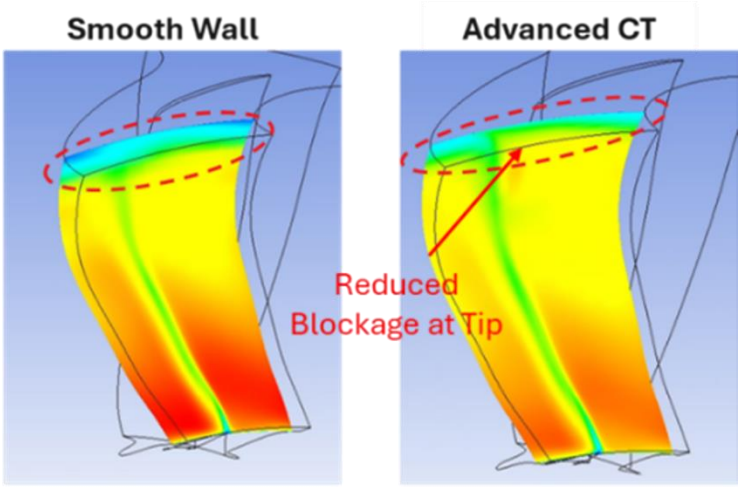

Figure 13: URANS CFD Analysis of Advanced Casing Treatment

3.4 Predicted Performance Improvement

GEA developed a CAFMIX through-flow model of the HyTEC rig and ran CFD analyses on all the final airfoil designs. These analyses were used to estimate the performance improvement expected for the aero technologies as summarized in Table 5. CAFMIX predicts an efficiency improvement of 0.54 points due to the aero technologies, such as the HyTEC vector diagram changes compared to the baseline ERA rig. The CAFMIX analysis also included 0.13 points in penalties from mechanical features such as more ruggedized rotor blades and open VSV end-gap clearances compared to the ERA rig, which are not attributable to the aero technologies. The "Most Likely" column reports the change in adiabatic efficiency (in percentage points) predicted by the analysis. To account for uncertainties in the analytical models, corresponding best-case and worst-case efficiency impacts are also included, to provide a range of potential outcomes. CFD analyses of the HyTEC airfoils predicted a smaller efficiency improvement than the CAFMIX model - these results were used to reduce the performance prediction of the HyTEC rig. A Monte Carlo analysis was applied to statistically combine the individual effects and their uncertainties, yielding the overall most likely adiabatic efficiency improvement of 0.48 points due to the HyTEC aero technologies at the aero design point.

Table 5: Predicted Efficiency Improvement due to HyTEC Aero Technologies

Analysis	Worst	Most Likely	Best
CAFMIX Analysis	0.40	0.54	0.64
Mechanical Penalties in Analysis	0.10	0.13	0.15
CFD Adjustments	-0.40	-0.19	-0.14
Aero Technology Improvement (pts)	0.11	0.48	0.66

4. HyTEC 3-Stage Rig Test Results and Analysis

This chapter presents the details of the HyTEC Phase 1 rig testing and associated outcomes. While the Test Results and Analysis in Section 4.4 form the core of this chapter, that discussion is preceded by essential background material. Section 4.1 summarizes the HyTEC instrumentation suite and assesses the hardware, with particular emphasis on MRB dispositions and ensuring safe rig operation. Section 4.2 outlines the pre-test plan and the as-executed test sequence, including key deviations from the original plan and their rationale. Section 4.3 then provides background on the evolution of the VSV schedules used throughout testing, a thorough understanding of which is critical to interpreting the results. With this context established, Section 4.4 presents and analyzes the test results, with subsections addressing rotor dynamics, clearances, aerodynamics, radial traversing, and aeromechanics, respectively.

4.1 Instrumentation and Hardware

This section summarizes the HyTEC Phase 1 hardware and instrumentation configuration, along with hardware assessments that were critical for safe completion of testing and accurate assessments of rig performance.

The HyTEC rig is a highly instrumented test article, equipped with an instrumentation suite broadly similar to that used on the ERA rig, and summarized previously in Figure 4. The full HyTEC instrumentation package includes five combination total pressure/total temperature performance rakes at Plane 25 (compressor inlet), Plane 30 (compressor exit), and Plane 31 (diffuser exit), as well as stator LE PT/TT measurements with six immersions at two circumferential locations per stage. In addition, the rig is outfitted with four strain gauges per variable stator vane row, six clearanceometers per stage, and at least ten light probes per stage, along with wall static taps, interstage cavity pressure and temperature measurements, and casing-mounted Kulites. Radial traversing capability is provided at the rig inlet, Plane 25, and downstream of each rotor stage. Additional rig and facility instrumentation is not described here. Overall, the installed instrumentation was sufficient to ensure safe rig operation and to deliver high-quality data suitable for meeting HyTEC Phase 1 test objectives.

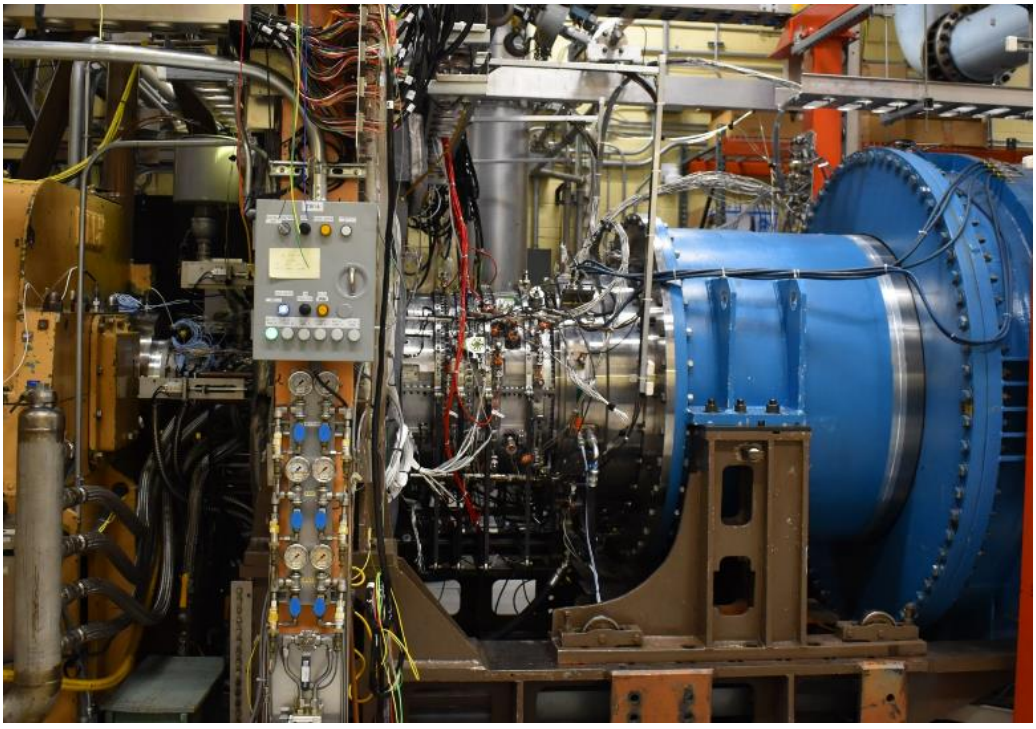

Figure 14: HyTEC Rig Installed in W-7 Facility

Rig instrumentation was reviewed at the assembly stage, prior to rig delivery, as part of a dedicated instrumentation perfection review. Overall, instrumentation quality was carefully assessed and deemed comparable to that of the ERA rig, providing confidence in the integrity and consistency of the HyTEC data set. Overall hardware quality was also good and generally consistent with ERA. All hardware was carefully inspected, and all non-conformances (i.e. MRBs) were reviewed, with the vast majority disposed with no performance impact. Two MRB items did require additional rework but are estimated to have small performance penalties of 0.01 points each. All other hardware was accepted as-is without additional rework or performance corrections. The assembled rig, installed in the NASA W-7 facility, is shown in Figure 14.

In conclusion, the HyTEC rig entered testing with a robust, ERA-consistent instrumentation suite and high-quality hardware, supported by instrumentation perfection and MRB review processes. The hardware non-conformances identified at assembly were corrected and assessed to have only minor performance impacts. Taken together, these measures provide confidence that the HyTEC Phase 1 dataset is both reliable and well understood from a hardware and instrumentation standpoint, forming a solid foundation for the test results discussions later in this section.

4.2 Test Plan & Execution

This section reviews the HyTEC Phase 1 test plan and its execution. The original test plan is first described, with emphasis on how it leveraged ERA experience and was structured to prioritize acquisition of key TPM data. Subsequent discussions include the primary challenges encountered during the campaign, their impact on actual test execution, and the resulting deviations from the original sequence, highlighting how these changes were made to minimize risk and maximize productivity while adapting to on-test realities. The as-executed test sequence is then examined in detail, contrasting the planned and actual paths through the test blocks. Finally, the effectiveness of the overall execution is quantified by documenting continuous improvement in test productivity relative to ERA and by summarizing the breadth and volume of data captured during HyTEC Phase 1 testing.

The HyTEC test plan was developed using the ERA campaign as its foundation, with similar test sections and overall sequencing. A block diagram of the planned HyTEC test sequence is shown in Figure 15, with test blocks that are new additions relative to ERA highlighted in red. The plan begins with Mechanical Checkout, whose primary objective is to break in the rig by systematically stepping up to maximum rig speed. Testing then commences in earnest with an Initial Power-Calibration to benchmark compressor performance across the speed range, followed by High-Speed VSV Optimization focused on improving design point efficiency. Subsequent Part-Speed Stall Mapping is performed to generate data for TPM-2, after which an Optimized Power-Calibration is conducted to obtain final performance data for TPM-1 and TPM-3. High-Speed Stall Mapping, which carries an increased risk of rig deterioration, is

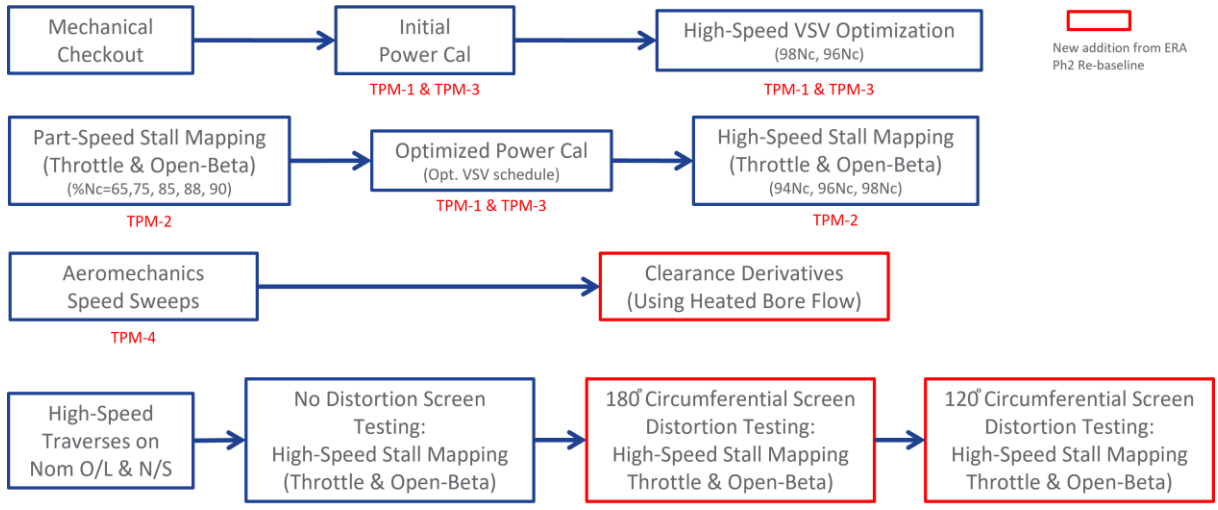

Figure 15: Test Plan at TRR

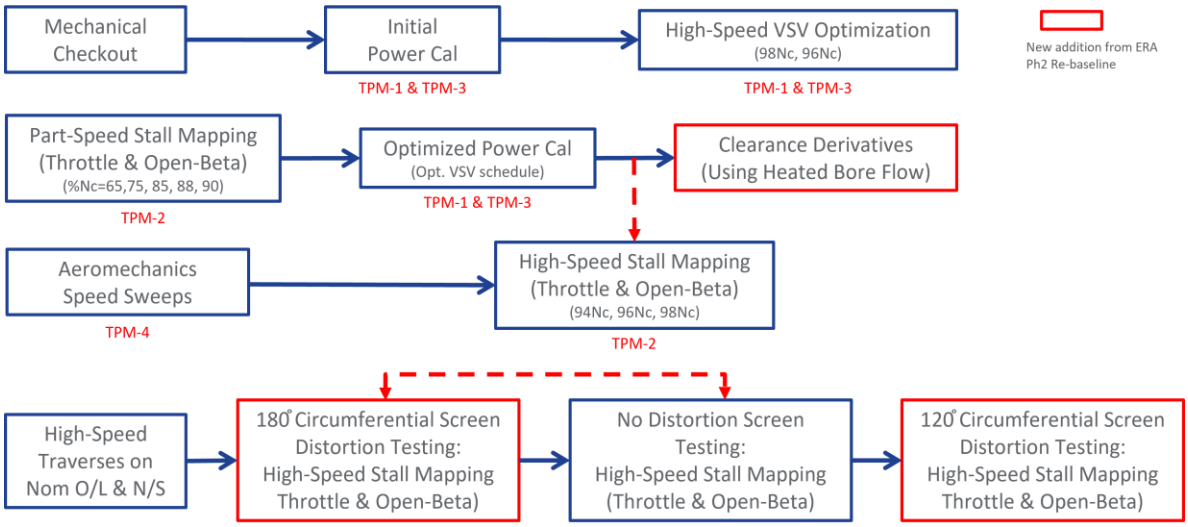

Figure 16: Test Plan As Executed

performed after the collection of all critical performance data. Aeromechanics Speed Sweeps are then done to gather data for TPM-4. The plan then continues with additional testing aimed at obtaining useful engineering data, beginning with a new HyTEC-specific block to acquire rotor tip clearance derivatives using the new heated bore flow system, followed by High-Speed Radial Traversing to collect unique, high-quality interstage measurements. The test program concludes with three distortion test blocks: flat inlet profile testing without the intrinsic inlet distortion screen, and 180-degree and 120-degree circumferential distortion testing, the latter two represent new additions for HyTEC relative to the ERA rig test.

While the HyTEC test campaign largely adhered to the planned sequencing, the practical realities of on-test execution necessitated several adaptations. Two high-level departures from the original test sequence are highlighted in Figure 16. The first major change was implemented even before testing began. As mentioned previously, High-Speed Stall Mapping carries an increased risk of rig deterioration, and re-evaluation of this risk led to a deliberate decision to move High-Speed Stall Mapping to after the Aeromechanics Speed Sweeps so that all other TPM data could be secured prior to any potential deterioration. Second, during the campaign the team agreed to swap the order of No Distortion Screen Testing and 180-degree Circumferential Distortion Testing to improve test logistics, providing additional time to install the backer grid on the 120-degree distortion screen and thereby avoiding unnecessary downtime. Finally, it is noted that Clearance Derivative testing was attempted on two occasions but produced smaller-than-anticipated clearance closures, making it difficult to extract meaningful conclusions; as a result, most of that test card was not executed, and the limited data obtained are not presented herein.

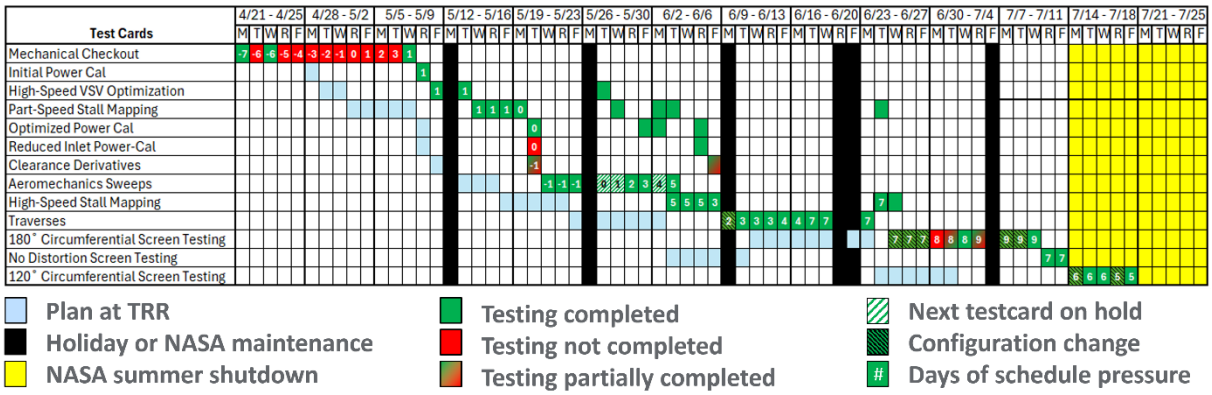

Figure 17: Detailed Test Timeline

A more detailed comparison of the test schedule execution relative to the pre-test plan is shown in Figure 17. In this figure, the light blue path represents the test sequence as planned and documented at TRR, while the green and red paths depict the test schedule as actually executed. Several additional deviations and adaptations to the plan are evident and worth noting. First, an extended investigation during Mechanical Checkout resulted in a delay of approximately 8 test days. Most of the remaining adjustments were driven by the observation of various notable responses during the Aeromechanics Speed Sweeps, which prompted an expansion of the Aeromechanics Speed Sweeps. Furthermore, additional aerodynamic testing was conducted to better understand the trade-offs among the various responses, performance, and operability. The additional aeromechanics testing, combined with the associated aero testing, added roughly 6 days of test time. Radial Traversing was similarly expanded to enable further study of the tradeoff between aeromechanics, performance, and operability, but contributing an additional ~4 days of test time. Following completion of Radial Traversing, the team agreed to spend ~1.5 days filling out maps with two VSV schedules (VSV 2.2 and VSV 2.4 – to be discussed later) to enable a full and accurate comparison. Finally, during the 180-degree circumferential distortion testing, borescope inspection revealed Rotor 3 leading-edge damage to two airfoils, leading to an additional ~1.5-day delay to assess the condition and attempt repairs. Despite the challenges and significantly expanded test scope, testing progressed efficiently and the objective of completing all testing prior to NASA's summer shutdown was effectively met.

Effective collaboration between the GEA and NASA teams enabled a high level of test execution and efficiency on HyTEC despite the technical challenges and schedule pressures discussed above. This collaboration contributed directly to the desired continuous improvement in test productivity relative to ERA, as summarized in Table 6. HyTEC testing achieved approximately 2x and 2.5x increases in total test periods and total test time, compared to ERA, over a similar 3-month test window. The objective of increasing average run time per test period by 1 hour was met. Collectively, these improvements increased the total number of readings from 1,980 on ERA to 6,542 on HyTEC and supported the successful completion of 133 speedlines (including full mapping of two different VSV schedules), 10 power-calibrations, 75 aeromechanics speed sweeps, and 81 radial traverses. This extensive dataset provides substantial value to the HyTEC program and delivers critical insights to inform the HyTEC Phase 2 HPC design effort.

In summary, the HyTEC test campaign closely followed the pre-test plan in structure and intent, while adapting in a disciplined way when needed. Targeted resequencing of test blocks and the expansion of both aeromechanics and aero testing added scope and complexity, yet effective GE–NASA collaboration enabled the team to complete all planned work before the NASA summer shutdown and to substantially surpass ERA in overall test productivity. The resulting dataset—spanning multiple VSV schedules, extensive aeromechanics sweeps, and a wide range of operability and distortion conditions—provides a robust experimental foundation for interpreting Phase 1 results and de-risking key design choices for HyTEC Phase 2.

Table 6: HyTEC Test Execution

	ERA Build 3	HyTEC Build 1
Test Periods	20	41
Run Time	107 hrs	255.75 hrs
Average Run Time	5.3 hrs/day	6.25 hrs/day
Total Readings	1980	6542

4.3 Variable Vane Schedule Background & Evolution

The HyTEC Phase 1 rig was tested with multiple VSV schedules. This section provides background on the motivation and implementation of these schedules prior to a more detailed discussion of test results. The schedules resulted from efforts to optimize and balance competing objectives, namely efficiency, operability, and aeromechanics. While a total of four different schedules are discussed, particular emphasis is placed on two schedules that are the primary focus of the majority of test results: the aero-optimized VSV 2.2 and the aeromechanics-optimized VSV 2.4.

The initial VSV schedule used for HyTEC rig testing was VSV 1.0, which is identical to the final optimized VSV schedule 3.0 from ERA Build 3 testing. VSV 1.0 was first assessed in an initial power-calibration and was observed to produce part-speed flow and efficiency levels significantly below those achieved in ERA, as documented in Figure 18. Due to this significant discrepancy, an updated VSV schedule, VSV 2.0, was developed prior to any further testing, with the objective of improving the alignment of flow and efficiency with ERA performance by opening the VSV angles as a gang below 98% speed. Although no power-calibration was performed with VSV 2.0, testing proceeded to part-speed stall mapping with VSV 2.0 as the primary schedule. Initial part-speed stall mapping demonstrated excess throttle margin over most of the part-speed region, with the exception of 65% speed where VSV 2.0 exhibited diminished operability compared to ERA, as shown in Figure 19. While challenged at 65% speed, the excess throttle margin across the remainder of the part-speed regime motivated the development of VSV 2.1, which further opened the VSV schedule at part-speed, intentionally trading the excess throttle margin to recover additional efficiency. VSV 2.1 also sought to recover throttle margin at 65% speed, where the gang opening of VSV 2.0 had been detrimental; this was achieved by reducing the gang opening of VSV 2.0 below approximately 71% speed. The resulting VSV schedule evolution of VSV 2.0 and VSV 2.1 is summarized in Figure 20 by the changes in Stator 1 angle which is the control vane used for scheduling the VSVs as a gang.

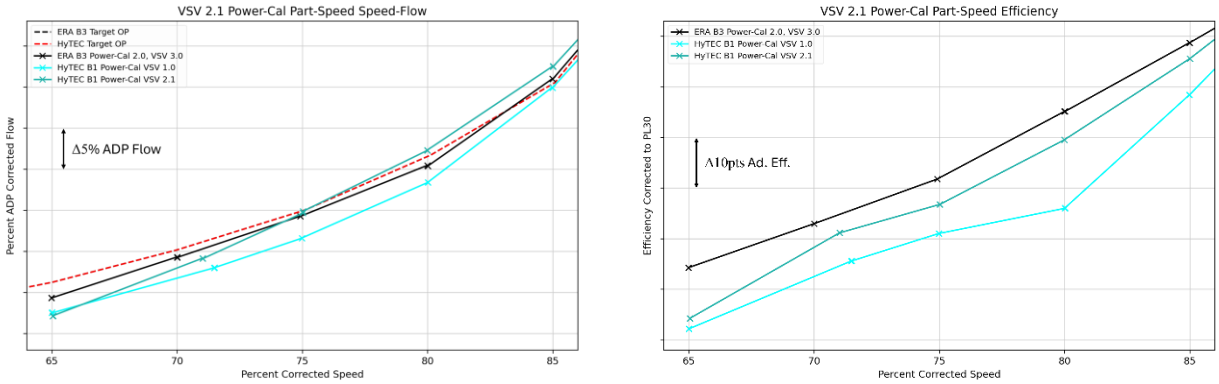

Figure 18: VSV Optimization for Part-Speed Flow and Efficiency

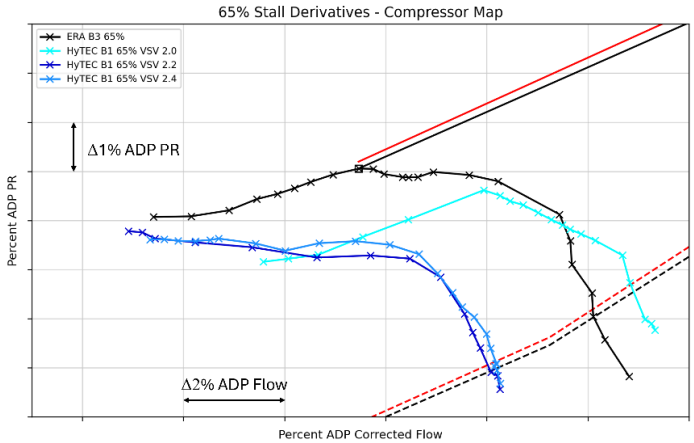

Figure 19: 65% Throttle Stall Derivatives

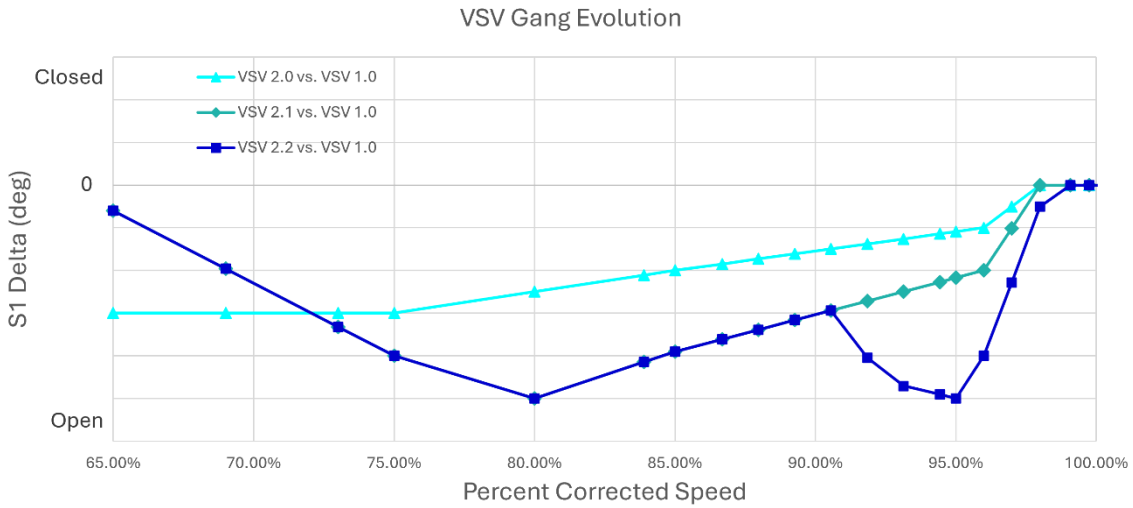

Figure 20: VSV Schedule Gang Evolution

Subsequent development of the VSV schedule focused on aerodynamic optimization for high-speed efficiency. This optimization was conducted after observation of aeromechanical responses in the part-speed regime, which constrained any VSV schedule changes to speeds above 90%. High-speed optimization was initially performed at 98% and 96% speeds, examining both individual vane derivatives and vane combinations. At 98% speed, the vane derivatives showed no consistent efficiency benefit, indicating that the HyTEC rig design was well executed and that the stages were well matched at high speed. However the measured flow at the aero design point was slightly below the design target, which led to a minor 0.25 degree opening of the VSV schedule at 98% to more precisely hit the design intent flow. Additional high-speed VSV schedule optimization from 92.5% to 96% speed demonstrated a benefit of further opening the gang within this speed range. The resulting aero-optimized VSV 2.2 schedule is shown in Figure 20. Since no changes were implemented in VSV 2.2 at part speed, references to VSV 2.1 and VSV 2.2 at speeds below 90% may be used interchangeably.

VSV schedule 2.4 was developed to address high aeromechanical response levels that were observed during the aeromechanics sweeps. The motivation for these VSV schedule updates will be discussed in Section 4.4.4, but VSV derivatives done during aeromechanics speed sweeps showed to be very effective at reducing airfoil vibratory amplitudes. Unlike prior schedules, VSV 2.4 is the first schedule

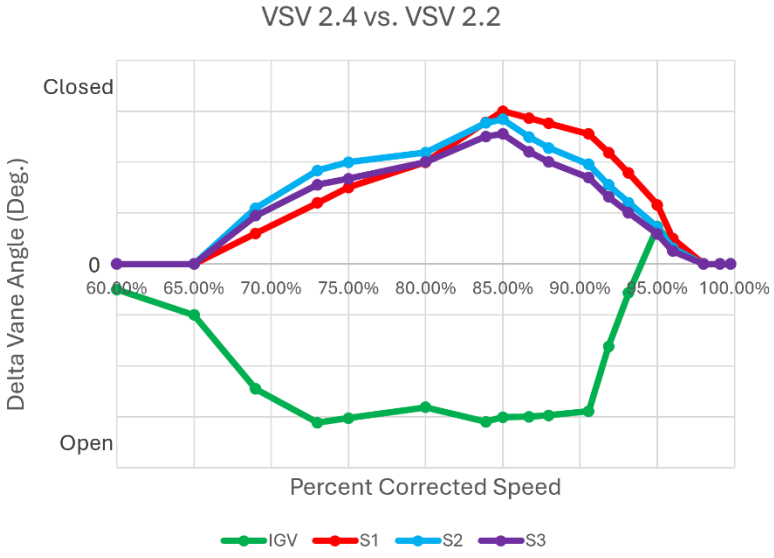

Figure 21: VSV Angle Comparison - VSV 2.2 vs. VSV 2.4

change not implemented as a pure VSV gang adjustment: while Stators 1–3 are closed together, the IGV is opened within the part-speed range. Unfortunately, VSV 2.4 largely reverses the previous opening of the schedule over much of the part-speed regime, which results in reduced efficiency. Changes outside the speed range of interest are minimized to preserve the efficiency benefits of VSV 2.2. As VSV 2.4 is not implemented as a pure gang change, a comparison of all four variable stator angles between VSV 2.2 and VSV 2.4 is provided in Figure 21; these two schedules constitute the primary focus of the results section.

In summary, VSV schedule development for HyTEC Phase 1 proceeded from an ERA-based baseline (VSV 1.0) through aero performance and operability refinement, resulting in an aero-optimized schedule VSV 2.2 that achieved efficiency gains across the speed range, and finally to an aeromechanics-optimized schedule VSV 2.4 that deliberately trades efficiency for improved aeromechanics behavior in the part-speed range. The competing objectives in the part-speed range led to significantly different vane schedules and motivates discussion of VSV 2.2 and VSV 2.4 as distinct, parallel design paths. The following Test Results Section 4.4 quantifies the performance, operability, and aeromechanics impacts of these VSV schedules, with particular emphasis on comparing VSV 2.2 and VSV 2.4 and assessing their suitability for future implementation.

4.4 Test Results

This section presents the key results and analysis of the HyTEC Phase 1 test campaign. Comparisons to ERA test results are made to provide context and quantify success relative to the defined TPMs. First, brief subsections on Rotor Dynamics and Clearances are presented to document overall rig performance. The bulk of the test results are Aerodynamics and Aeromechanics results which are presented in 4.4.3 and 4.4.4, respectively. Finally, the Radial Traverse results are presented to provide further learnings and context to the results.

4.4.1 Rotor Dynamics

The forward and aft bearing vibrations were monitored using two proximity probes installed adjacent to the respective bearings. Coupler vibration levels were monitored by separate proximity probes installed at the forward and aft ends of the coupler. Vibration acceptance criteria were defined with red/yellow alert thresholds of 4 mils and 3.6 mils double amplitude, respectively. Prior to testing, the driveline, including NASA facility rotating hardware such as the gearbox and coupler, was verified for adequate balance through high-speed pre-test checkouts, and piece-part balancing with assembly stack projection was performed on the test article.

The resulting vibration signature indicates a well-balanced configuration. Bearing vibration levels remained well within the established limits, and coupler vibration levels did not exceed those limits, as shown in Figure 22. A vibration peak was observed near ~5500 rpm, driven by a 0.5/rev gearbox response that is consistent with behavior previously observed on ERA Build 3.

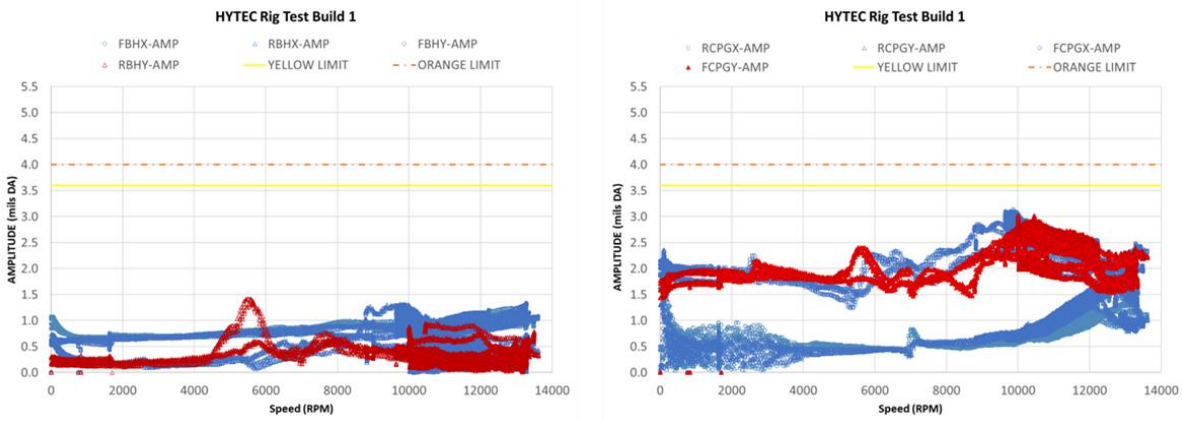

Figure 22: Bearing and Coupler Vibration Signatures vs. Rotor Speed

4.4.2 Clearances

Assembly drawings were developed to document critical axial and radial clearances. Despite inspection equipment constraints, all rotor and stator axial drops met print specifications, and axial and radial seal gaps were successfully confirmed at assembly using shim measurements.

Clearance probes were installed across all three stages with six probes per stage (18 total). Thermocouples were added on the case to supplement the clearance probe data. Several probes were non-functional at test initiation, particularly over Rotor 2 and Rotor 3. Additional probes developed noise/intermittent signals during testing. Root cause of this was thought to be lead-wire damage from overworking and/or excessive bending. Replacement attempts were unsuccessful due to limited access and risk of damaging functioning instrumentation during repair attempt.

A blade tip clearance prediction algorithm was created using steady-state hardware models. Pre-test predictions closely matched the actual clearances measured during testing as seen for Rotor 1 in Figure 23. Additional comparisons for Rotor 2 and Rotor 3 are shown in Figure 24 and Figure 25, respectively. In each of these figures, the blue series represents averages of stabilized points from the Initial Power-Cal, Part-Speed Stall Mapping, and daily health checks.

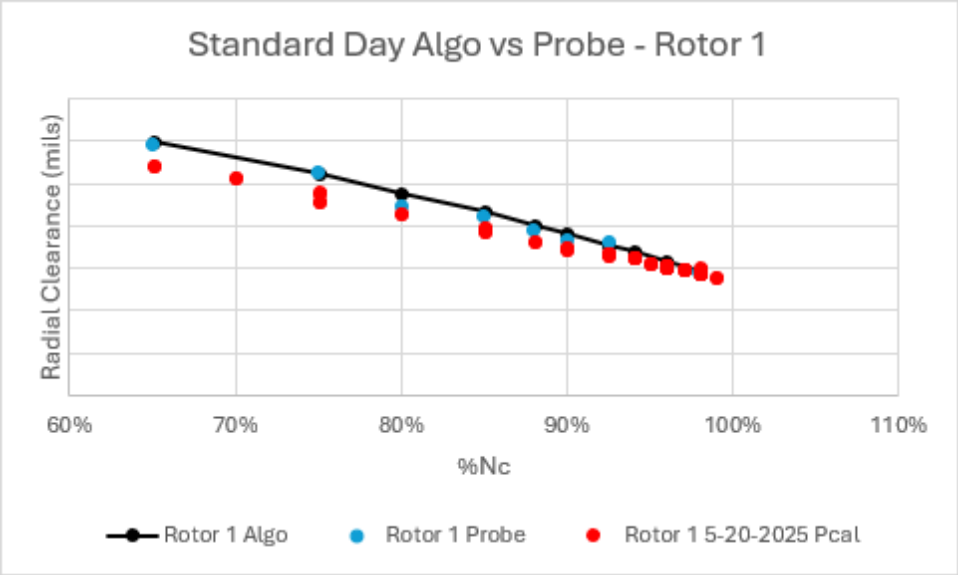

Figure 23: HyTEC Actual Clearances vs. Pre-Test Predictions (Rotor 1)

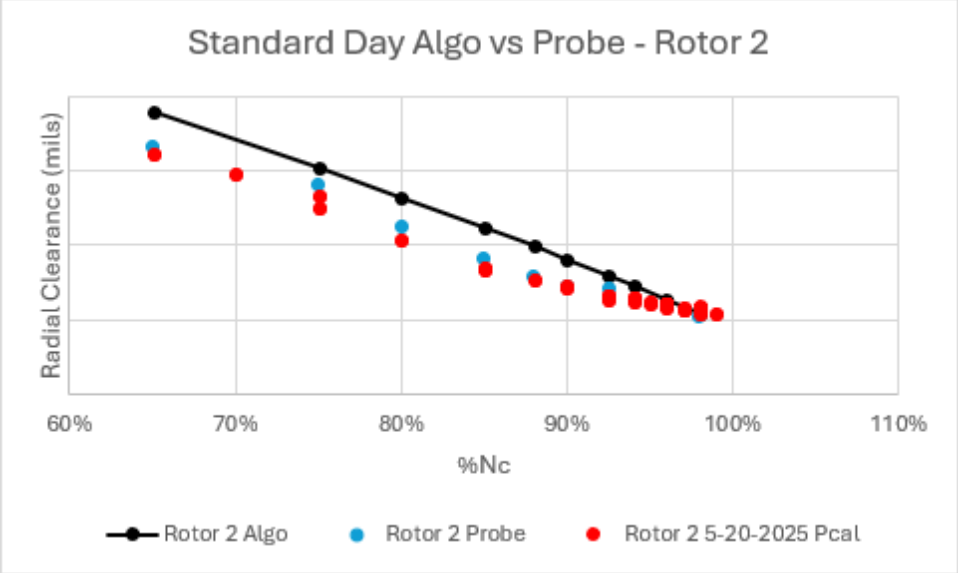

Figure 24: HyTEC Actual Clearances vs. Pre-Test Predictions (Rotor 2)

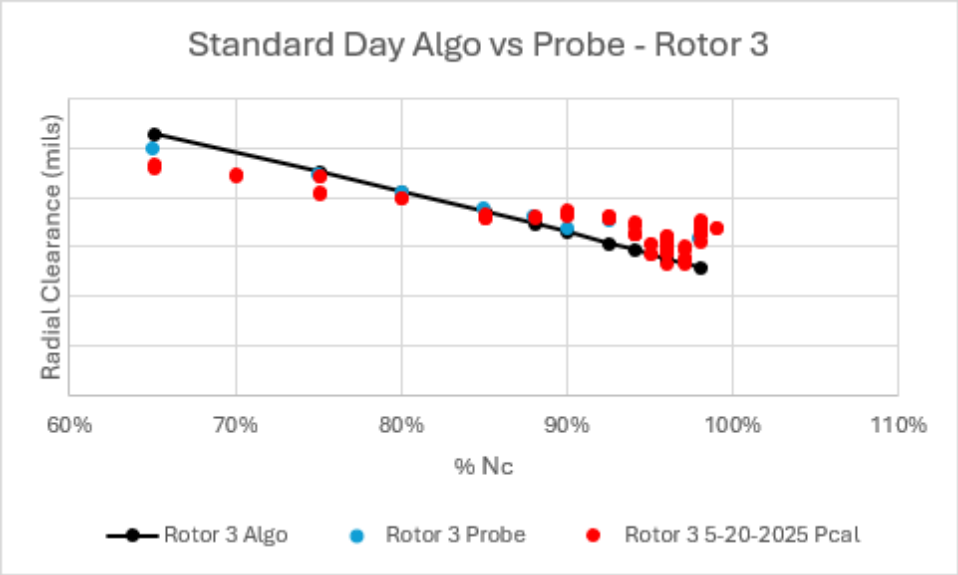

Figure 25: HyTEC Actual Clearances vs. Pre-Test Predictions (Rotor 3)

Cold motoring readings were taken daily. After initial rotation to facility idle (~1640 RPM), the start was tripped and spooled back down. The cold motor reading was recorded at the last point where the clearance probes were still reading. Cold motoring readings were consistent throughout testing and did not indicate any blade tip loss. The corrected clearances fell within 3 mils of the target specification, as shown in Table 7. These clearance corrections result in a -0.01 points adjustment to ADP efficiency.

Interstage seal rub depths exceeded predictions, though potential causes are still under investigation. Increased leakages are believed to have resulted in performance deterioration as will be discussed in Section 4.4.3.1

Table 7: HyTEC ADP Rotor Clearances

ADP Stack Axis Tip Clearance	R1	R2	R3
HyTEC Target (Scaled ERA Ph2B3)	-	-	-
HyTEC Pre-Test Projection	+1.0 mil	-1.7 mil	-3.3 mil
HyTEC Nominal (RDG 3239)	+6.8 mil	+1.1 mil	+1.1 mil
HyTEC Average Correction	-7.6 mil	-3.8 mil	+0.7 mil
HyTEC Corrected Clearances	-0.8 mil	-2.7 mil	+1.8 mil

4.4.3 Aerodynamics

This section presents the aerodynamic test results from the HyTEC 3-Stage Rig campaign, primarily focusing on the impact of the aero-optimized VSV 2.2 and aeromechanics-optimized VSV 2.4 schedules on the aerodynamics-related TPMs. The first subsection addresses high-speed performance and its relation to TPM-1 (R1 tip loading) and TPM-3 (design-point efficiency). The second subsection focuses on operability, TPM-2, across the speed range for both VSV schedules, and is followed by a deeper investigation of part-speed efficiency. Finally, results from the radial (flat inlet) and circumferential distortion testing are presented.

4.4.3.1 High-Speed Performance

This High-Speed Performance section evaluates the aerodynamic behavior of the HyTEC rig near design speed, with particular emphasis on achievement of the key high-speed TPMs. The discussion begins with the high-speed VSV optimization campaign. The various HyTEC power-calibrations are compared to ERA across the high-speed regime to evaluate overall performance. Next, an objective methodology is applied to select an ADP reference point, from which design-point efficiency is quoted and assessed against TPM-3 success criteria using a detailed performance stack. Finally, the section examines Rotor 1 tip loading at design point, as captured by TPM-1, to assess whether HyTEC meets or exceeds the targeted increases in Rotor 1 tip d-factor relative to ERA.

High-speed VSV optimization was performed at 98%, 96%, 95%, and 92.5% speeds – the resulting evolution of the VSV schedule was previously shared in Section 4.3. No measurable efficiency benefit was achieved from either individual vane derivatives or VSV combinations, demonstrating that the stages were well matched at the aero design point. At the lower high-speed conditions (96%, 95%, and 92.5%), optimization indicated modest benefits from separately opening the IGV, Stator 1, and Stator 2; these findings were ultimately incorporated into VSV 2.2 as an incremental gang opening below 98% speed.

`HyTEC rig power calibration data for VSV schedules 1.0, 2.1, 2.2, and 2.4 are compared to the ERA baseline rig in Figure 26. The results indicate that the HyTEC rig achieves higher efficiency at the aero design point at 98% speed but exhibits a more rapid efficiency roll-off with decreasing speed. HyTEC efficiency peaks at 98% speed, whereas ERA peaks at 97% speed. The additional high-speed gang opening implemented in VSV 2.2 effectively mitigates this faster roll-off and maintains an efficiency advantage over ERA through most of the high-speed regime. However, this benefit is lost and the roll-off is further exacerbated with the aeromechanics-optimized VSV 2.4 schedule. Peak efficiency lies near the nominal operating line at both 98% and 96% speeds, further supporting the conclusion that the HyTEC stages are well matched at the design point. Design-point efficiency is significantly higher than both ERA and pre-test predictions for all HyTEC power-calibrations, but VSV 2.4 shows lower efficiency at the design point despite VSV 2.2 and VSV 2.4 schedules being identical at 98% speed. VSV 2.4 power-calibration was performed after the rig experienced some deterioration in performance due to high-speed stall testing with VSV 2.2. Deterioration in HyTEC performance is shown in Figure 27 and will be discussed further in the next paragraph.

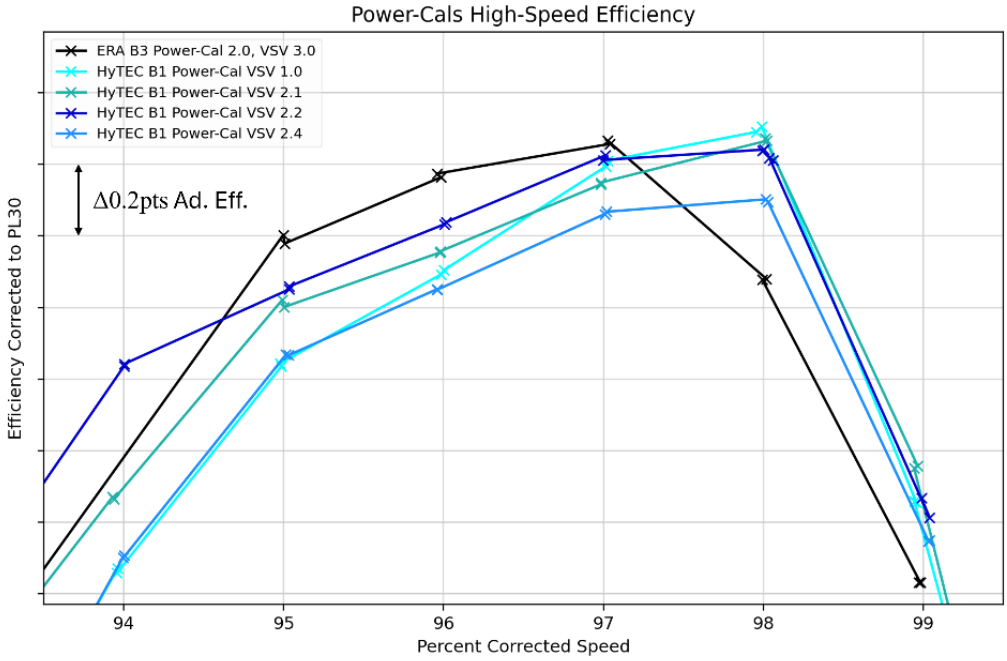

Figure 26: High-Speed Efficiency

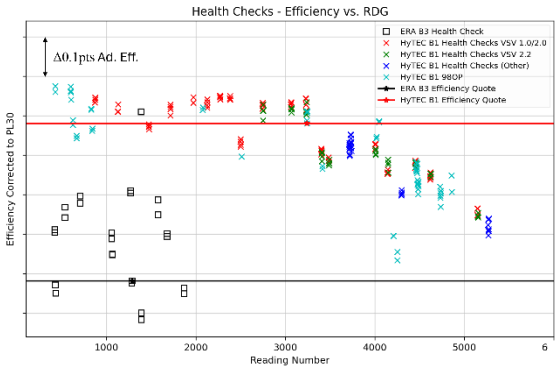

Figure 27: 98% Health Checks

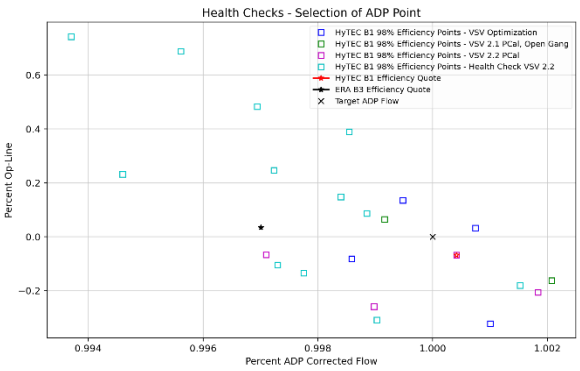

Figure 28: Selection of ADP Point

Prior to quoting efficiency at the aero design point to assess performance against TPM 3, an official ADP reference point must be selected from the available data. To support this selection, all readings taken near the 98% nominal op-line, including daily health-checks, power-calibration points, and any other relevant data, are plotted in Figure 27. This figure shows that HyTEC efficiencies are relatively stable and tightly clustered up to readings around 3200, with clear evidence of rig deterioration after high-speed stall testing started. Accordingly, the first criterion for ADP selection is that the reading must be prior to the onset of deterioration. The second criterion is that the reading must include the 0.25 deg gang opening implemented to hit the ADP design intent flow, meaning it must employ VSV 2.2, VSV 2.4, or an earlier manual implementation of this setting. All readings satisfying these two criteria are plotted in Figure 28 as percent ADP corrected flow versus percent operating line – the ADP point was chosen as the reading closest to both the target flow and nominal operating line. Based on these criteria, Reading 3239, obtained during the VSV 2.2 power-calibration, was selected as the ADP point for quoting HyTEC rig performance. The corresponding reading (RDG 1282) selected for the ERA baseline rig (Build 3) is also shown in Figure 27.

Based on the selection of RDG 3239 as the HyTEC ADP, the performance is now formally quoted and compared to the pre-test prediction and to the minimum and full success levels defined in TPM-3. The performance stack in Table 8 shows both “As Measured” and “Corrected” adiabatic efficiency deltas. The applied correction of ~0.38 points includes adjustments for radius ratio and other hardware differences between the two rigs such that a corrected efficiency delta of zero would demonstrate equivalent performance between HyTEC and ERA. Any positive delta on a corrected basis can then be directly interpreted as the aero technology improvement demonstrated by the HyTEC rig. The minimum and full success criteria are defined as +0.3 and +0.7 points versus ERA on a corrected basis, while the pre-test prediction of +0.48 points is equivalent to the predicted aero technology improvement shown in Table 5. The raw measured efficiency delta between HyTEC RDG 3239 and ERA RDG 1282 is +0.40 points, equivalent to +0.78 points on a corrected basis. A small rotor tip clearance correction that introduces a 0.01-point penalty is applied, yielding an official quoted adiabatic efficiency delta of +0.77 points for the

Table 8: HyTEC ADP Performance Stack

Performance Stack (Adiabatic Efficiency Delta)	Corrected	As Measured
Updated ERA Adiabatic Efficiency Quote	**-**	**-0.38**
Pre-Test Prediction (Aero Technology Improvement, Most Likely)	+0.48	+0.09
Minimum Success Criteria	+0.3	-0.08
Full Success Criteria	+0.7	+0.32
HyTEC Measured Efficiency Delta	+0.78	+0.40
Rotor Tip Clearance Adjustment	-0.01	-0.01
HyTEC Quoted Adiabatic Efficiency Delta	**+0.77**	**+0.39**

HyTEC 3-Stage rig on a corrected basis. This official HyTEC ADP adiabatic efficiency delta exceeds the full success target and directly represents the demonstration of 0.77 points of aero technology improvement. This is close to the statistical best-case pre-test prediction based on a Monte Carlo analysis that estimated uncertainties of each line item in the performance stack. Exceeding full success criteria with respect to design-point efficiency (TPM-3) demonstrates the value of the front-stage aero technologies and indicates a well-executed aerodynamic design.

In addition to design point efficiency, another important HyTEC aero technology goal is the Rotor 1 tip loading at design point, represented by TPM-1. The Rotor 1 tip d-factor is shown in Figure 29, with the ERA value used to define the minimum and full success thresholds for HyTEC. TPM-1 was defined with the goal of increasing the Rotor 1 tip d-factor, by at least 5% (min success, red line), while the HyTEC Rotor 1 was designed to achieve the full success criteria of 7.6% (green line). As indicated in Figure 29, all HyTEC 98% operating-line points exceed the minimum success criterion, and most are generally distributed near the full success line. Using RDG 3239 as the ADP reference, the HyTEC Rotor 1 tip d-factor at design point is quoted as +7.29% compared to ERA, near the full success criterion of +7.6%. Accordingly, relative to TPM-1 the HyTEC rig is formally quoted as meeting minimum success, although the achieved Rotor 1 tip loading at ADP essentially demonstrated the full success target.

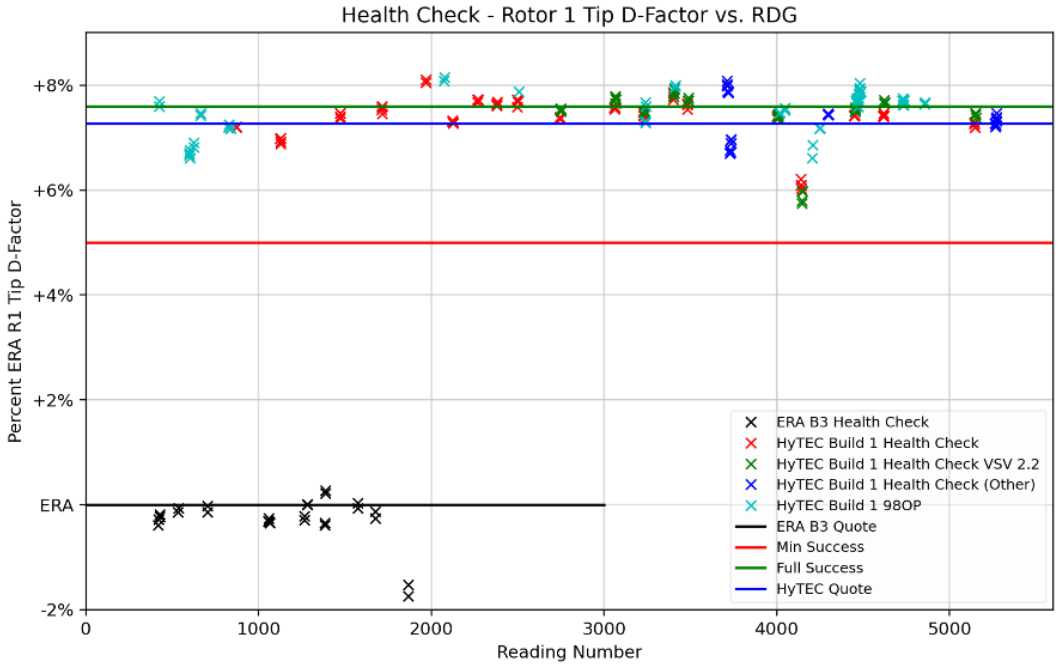

Figure 29: ADP Rotor 1 Tip D-Factor

In summary, the high-speed performance test results demonstrate that the HyTEC rig achieves well-matched stages at design point, resulting in successful demonstration of TPM-1 and TPM-3. VSV optimization at high-speed, implemented in VSV 2.2, allows for efficiency gains compared to ERA over most of the high-speed regime. An ADP reference point is objectively selected and used to measure performance against relevant TPMs. HyTEC surpasses the TPM-3 full success criterion, achieving a design-point efficiency representing the demonstration of +0.77pts of efficiency benefit over ERA on a corrected basis. Evaluation of Rotor 1 tip loading results in an official ADP quote which meets TPM-1 minimum success criteria and falls just short of full success. Collectively, these results confirm that the HyTEC design was well executed and meets or exceeds its primary high-speed aerodynamic performance objectives.

4.4.3.2 Operability

This operability section evaluates HyTEC throttle stall and open-beta stall capability across the full speed range and compares performance for the aero-optimized VSV 2.2 and aeromechanics-optimized VSV 2.4 schedules against the ERA baseline in the context of TPM-2. The discussion begins with global throttle stall and open-beta maps and associated percent operating-line scorecards to establish how each schedule performs relative to TPM-2 minimum and full success criteria. It then examines low-, mid-, and high-speed regimes in more detail, highlighting where the two HyTEC schedules diverge from one another and from ERA. Finally, this section considers the role of advanced casing treatment and Stage 1 behavior in enabling the observed operability improvements.

Throttle stall maps comparing VSV 2.2 and VSV 2.4 to ERA are shown in Figure 30, together with the ERA and HyTEC nominal operating lines and approximate target line corresponding to the TPM-2 minimum success level. While the individual speedlines are discussed in more detail below, the HyTEC speedlines with both VSV schedules appear generally healthier than ERA across the full map, and the impact of increased gang opening on flow is evident both in the HyTEC–ERA comparison and between the two HyTEC schedules themselves. It is also noted that HyTEC throttle stall mapping was completed at two additional speeds, 71% and 97%, for which ERA did not conduct equivalent testing. Figure 30 also includes a scorecard summarizing the percent operating line reached for each case at each speed, where percent operating line is defined by the steady-state point with the highest pressure-ratio rather than the final stable point, and the TPM-2 minimum (red line) and full success (green line) levels are shown for reference. From this scorecard, it is evident that HyTEC exceeds the minimum success criterion for stall margin (equivalent to ERA) at all speeds for both VSV schedules, and that each schedule meets or exceeds the full success criterion (3% more than ERA) at more than half of the mapped speeds. Finally, while similar over much of the speed range, it is clear that the aeromechanics-optimized VSV 2.4 also provides a benefit to part-speed stall margin, particularly from 70-80% speed.

Similarly, HyTEC open-beta stalls with both VSV 2.2 and VSV 2.4 are compared to ERA in Figure 31. For front-stage rigs such as ERA and HyTEC, open-beta stalls are conducted by opening the VSVs as

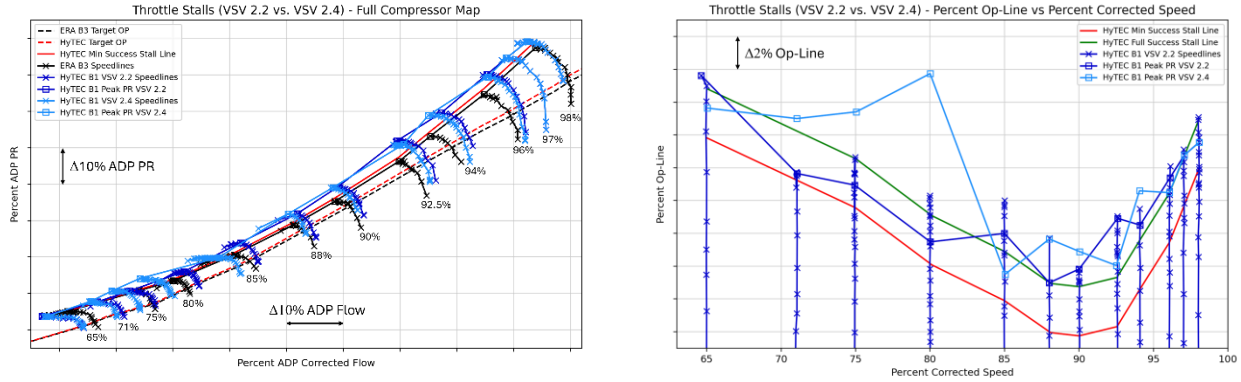

Figure 30: Nominal Throttle Stall Mapping

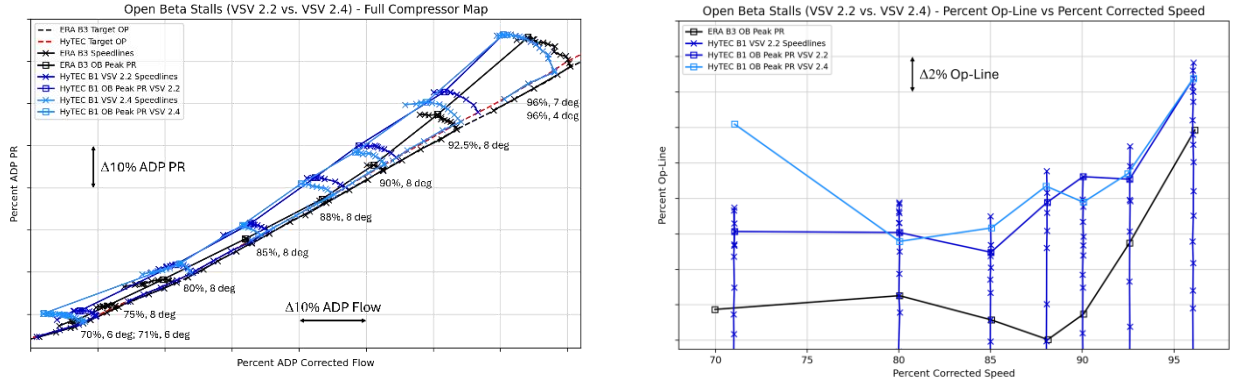

Figure 31: Nominal Open-Beta Stall Mapping

a gang (each vane following the particular VSV schedule) a predetermined amount (typically between 4 and 8 degrees) on the nominal op-line and then throttling to stall. Although TPM-2 does not formally specify success criteria for open-beta stall margin, an equivalent minimum success level can reasonably be taken as parity with ERA, with a clear objective to significantly improve upon ERA's open-beta stall capability. As shown in Figure 31, this objective is met: HyTEC open-beta speedlines are substantially healthier than ERA for both VSV schedules, and the percent operating line reached exceeds ERA at all speeds, generally by a wide margin. The largest benefit is observed in the 85–90% speed range, which is the region of low open-beta margin for the ERA rig.

To examine operability in greater detail, throttle and open-beta stall results are considered together across low-, mid-, and high-speed regimes. Beginning with low speed, Figure 32 & Figure 33 present the throttle and open-beta stall maps, respectively. The HyTEC 65% speedlines for VSV 2.2 and VSV 2.4 are nearly identical (VSV schedule is very similar at this speed) and exhibit substantial flow roll-back with relatively limited pressure rise; stall was generally not attained at this speed, as the speedlines were terminated due to significant flow recirculation at the compressor inlet at very low flows, which made it difficult to hold corrected conditions. At 71% speed, the speedline shapes for the two schedules remain similar, though the higher flow and reduced stall margin for VSV 2.2 are evident. By 75% and 80% speed, the differences in both flow level and speedline shape between the HyTEC schedules become more pronounced, with VSV 2.4 exhibiting healthier speedlines than VSV 2.2, while VSV 2.2 remains broadly similar to, but still improved relative to, ERA. For open-beta stalls, there are minor differences in the lowest mapped speeds—ERA was mapped at 70% while HyTEC was constrained to 71% due to a facility keep-out zone—and ERA completed a 75% open-beta speedline that was not obtained for HyTEC. Nevertheless, the HyTEC open-beta speedlines appear significantly healthier than ERA at low speed. The comparison between VSV 2.2 and VSV 2.4 open-beta speedlines at 71% is particularly noteworthy, with VSV 2.4 showing a noticeably healthier speedline despite relatively small schedule differences at this speed, though this is consistent with other evidence of high sensitivity to Stator 1 and Stator 2 closure in this regime. By 80% speed, the HyTEC speedlines for the two schedules converge and appear much more similar, even though the gang opening delta between VSV 2.2 and VSV 2.4 at 80% is approximately twice that at 71%.

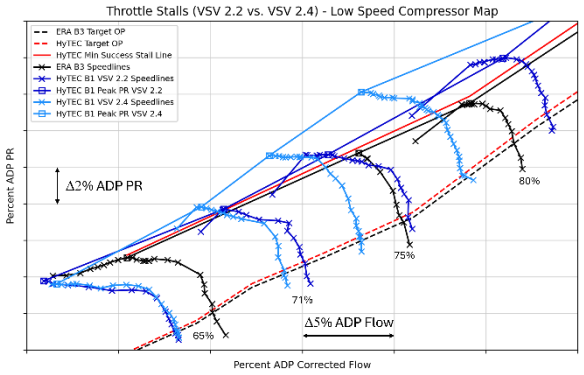

Figure 32: Low-Speed Throttle Stalls

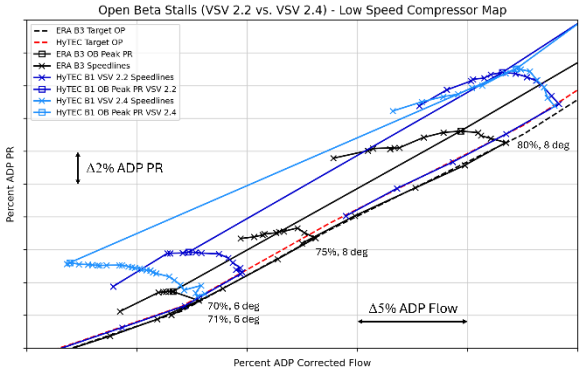

Figure 33: Low-Speed Open-Beta Stalls

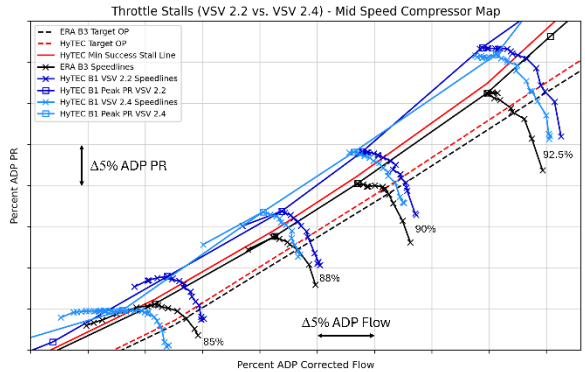

Figure 34: Mid-Speed Throttle Stalls

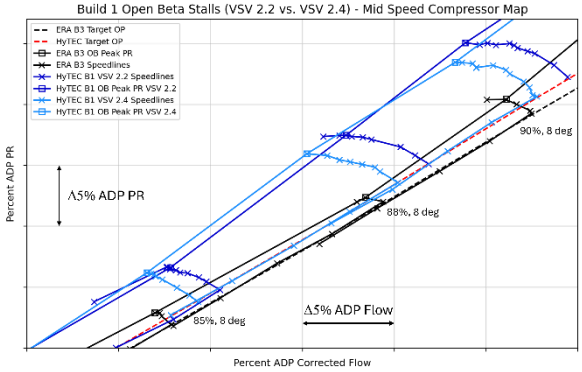

Figure 35: Mid-Speed Open-Beta Stalls

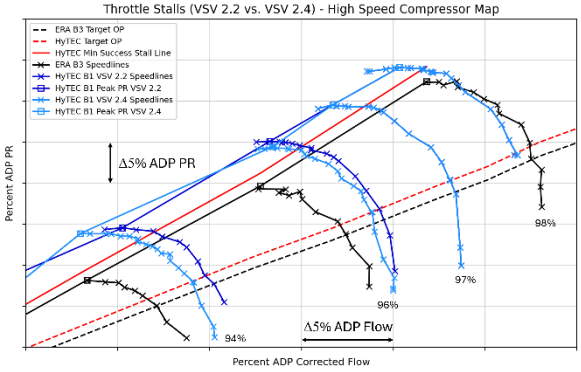

Figure 36: High-Speed Throttle Stalls

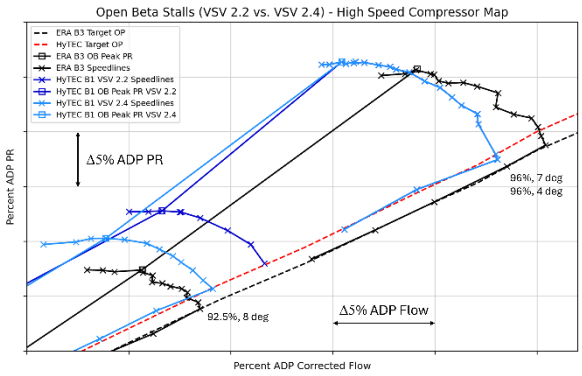

Figure 37: High-Speed Open-Beta Stalls

Mid-speed throttle stalls are shown in Figure 34. At 85% speed, notable differences between the HyTEC schedules are observed, with VSV 2.4 exhibiting an extended flow roll-back that was repeatable across other conditions (not shown) but not present in nominal VSV 2.2 mapping. The remaining mid-speed throttle stalls display more similar behavior between the HyTEC schedules, although the generally healthier speedlines and extended throttle capability relative to ERA remain evident. Open-beta stalls for the mid-speed regime, presented in Figure 35, likewise show relatively small differences between VSV 2.2 and VSV 2.4. However, Figure 35 clearly highlights the substantial extension of open-beta throttle capability compared to ERA, with HyTEC throttling to 4-8% higher operating lines than those achieved for ERA. As mentioned previously, the largest improvements in open-beta throttling occur in this speed range where ERA was most challenged.

High-speed throttle and open-beta stalls are shown in Figure 36 & Figure 37, respectively. Several nuances of the high-speed regime should be noted before interpreting these results. A 97% throttle stall was completed for HyTEC but not for ERA, and the 98% throttle stall shown for HyTEC was performed with a VSV offset to mitigate an aeromechanical response that will be discussed further in the next paragraph and in the aeromechanics section. Similarly, the 96% open-beta mapping for HyTEC was conducted with a 4-degree open gang, rather than the nominal 7 degrees, to mitigate an aeroelastic instability. Within this high-speed range, differences between the two HyTEC schedules are relatively small, and the highest-speed conditions were not re-mapped separately, as the schedules are identical at these speeds. In contrast, comparisons to ERA continue to show a significant improvement in this regime, with HyTEC exhibiting generally healthier speedline characteristics and extended throttle capability at high speed.

As mentioned in the previous paragraph, the highest-speed throttle stall and open-beta stall were both limited by an aeroelastic instability. To ensure sufficient high-speed operability despite this constraint, additional high-speed derivative tests were conducted, some of which are shown in Figure 38. This figure illustrates that the two highest-flow conditions, the nominal 98% throttle stall and the 96% 7-degree open-beta stall, were both limited by the aeroelastic instability, indicated by red boxes at the end of their

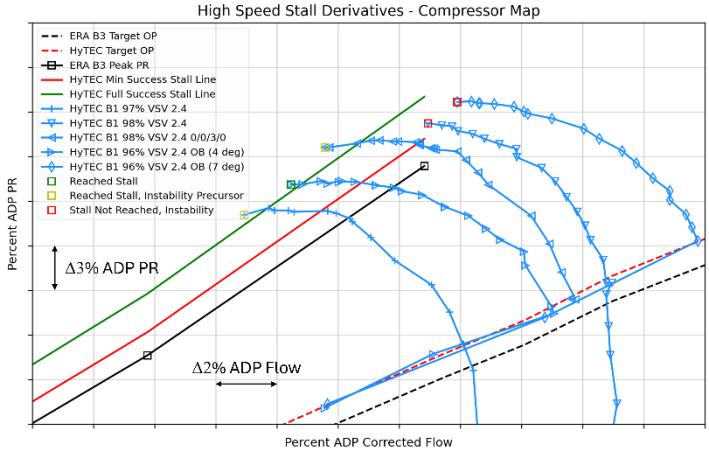

Figure 38: High-Speed Stall Derivatives

speedlines. Although these two speedlines were called off before reaching stall, both terminations occurred at higher operating lines than the equivalent ERA stall point. Additional cases, namely the 97% throttle stall and the 98% throttle stall with a VSV offset, exhibited signatures considered precursors to instability, but stall was achieved prior to the onset of complete aeroelastic instability, as denoted by yellow boxes. Finally, reducing the 96% open-beta gang opening to 4 degrees enabled completion of that stall without any indications of aeroelastic instability, represented by a green box at the end of the speedline. Importantly, all high-speed cases reached a peak pressure-ratio point beyond the TPM-2 minimum success criterion, irrespective of whether they attained stall or were called off, and therefore the observed aeroelastic instability did not prevent demonstration of high-speed operability or TPM-2 minimum success claims.

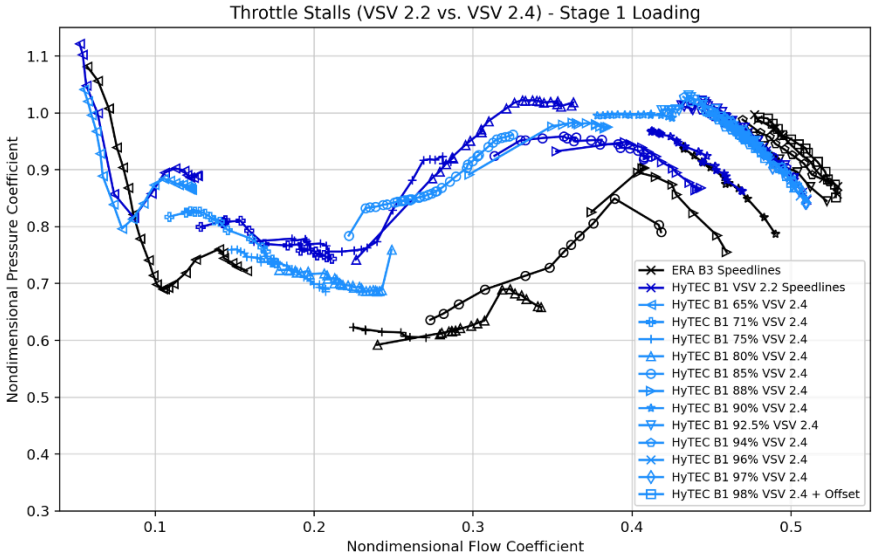

Figure 39: Stage 1 Characteristic

The impact of the advanced casing treatment on Rotor 1 is evident throughout the operability results, with HyTEC exhibiting improved throttle margin across the full speed range, even when operating with the more open gang setting of VSV 2.2. To examine this impact more directly, Figure 39 presents the effective stage map for Stage 1. Comparing both HyTEC VSV schedules to ERA, the benefit of the casing treatment is apparent across the speed range, with healthier speedlines and higher peak loadings at high speed, a significantly delayed and shallower roll-off in the mid-speed region, and higher pressure rise at low speeds after the stage has already rolled over. Figure 39 also illustrates the influence of the HyTEC schedule changes on Stage 1 behavior. The higher Rotor 1 loading associated with VSV 2.4 causes that schedule to roll over at 90% speed, compared to 88% for VSV 2.2. However, VSV 2.4 exhibits a somewhat shallower positive characteristic in the mid-speed range, which may contribute to the additional operability demonstrated by VSV 2.4 in this regime. Overall, the effectiveness of the advanced casing treatment across the speed range is clearly demonstrated and is a key contributor to HyTEC's improved operability relative to ERA despite significantly higher tip loading.

In summary, the operability results demonstrate that HyTEC delivers a substantial improvement over ERA in both throttle and open-beta stall capability, with HyTEC exceeding TPM-2 minimum success criteria at all mapped speeds and achieving full success at more than half of them for both VSV 2.2 and VSV 2.4. Detailed low- and mid-speed comparisons show that VSV 2.4 provides additional stall margin in the 70–80% range, while both schedules offer significantly enhanced open-beta capability, particularly in the 85–90% band where ERA was most limited. At high speed, despite test limitations due to aeroelastic instability, all key cases reached peak pressure ratios beyond the TPM-2 minimum success threshold, confirming good high-speed operability. The Stage 1 maps further indicate that the advanced casing treatment is a primary enabler of these gains, yielding healthier speedlines and delayed roll-off across the speed range. Collectively, these findings confirm that HyTEC meets or exceeds its operability objectives, with the advanced casing treatment providing significant benefit and flexibility for VSV schedule implementation.

4.4.3.3 Part-Speed Performance

As discussed previously, the initial power-calibration showed that both flow and efficiency at part-speed were significantly below ERA levels. This motivated the subsequent VSV optimization implemented in VSV 2.0 and VSV 2.1 which generally recovered the part-speed flow deficit relative to ERA and partially recovered efficiency as well. However, part-speed efficiency remained noticeably lower than ERA with all VSV schedules. While TPM-3 is focused on design-point efficiency, where HyTEC exceeded expectations, the lower-than-anticipated part-speed efficiency motivates a more detailed assessment of rig efficiency behavior across the entire speed range.

Before examining part-speed efficiency, it is necessary to first describe the methodology used to calculate efficiency and its limitations at lower speeds. The ADP efficiency calculation, which is consistent with ERA is based on quantities measured at Plane 31 and then corrected back to Plane 30 under the assumption of a constant diffuser loss. This approach works well at high speed because diffuser and stator losses are generally small. However, Figure 40 shows that diffuser and Stator 3 losses are much larger and have significant variation at part-speed as the VSV schedule is closed. Since the exit diffuser and Stator 3 losses are not directly representative of a full HPC design, their magnitude and sensitivity obscure the assessment of the part-speed efficiency of the 3-Stage rig using the standard performance rakes at the diffuser exit. For this reason, an alternate efficiency calculation is proposed and employed for part-speed conditions, using total pressure at the Stator 3 leading edge and total temperature from Plane 31. This alternate efficiency definition is applied for speeds below 92%, where diffuser and Stator 3 losses increase dramatically and the standard method becomes less appropriate.

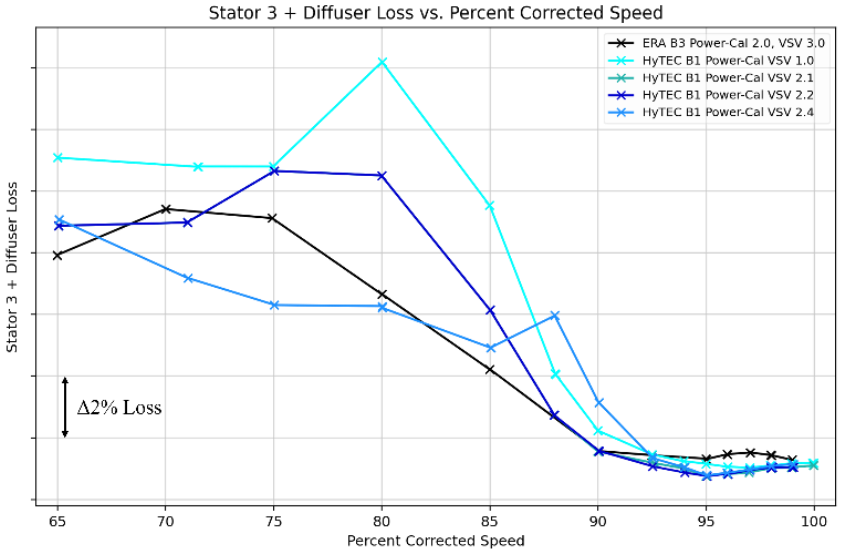

Figure 40: Stator 3 & Diffuser Loss

Using this alternate efficiency definition, the part-speed efficiency for each of the HyTEC power-calibrations is shown in Figure 41 and compared directly to ERA, which was calculated using the same method. This figure again demonstrates that the initial power-calibration with VSV 1.0 exhibited efficiency well below ERA across the entire part-speed regime. Subsequent VSV optimization with VSV 2.1 recovered a substantial portion of this deficit over most of the part-speed range, with the notable exception of 65% speed, where operability constraints limited further gang opening. Figure 41 also illustrates that the aeromechanics-optimized VSV 2.4 schedule had the opposite effect of the earlier optimizations, not only eliminating the performance gains achieved with VSV 2.2, but in fact producing part-speed efficiency levels even worse than those of VSV 1.0 over the full part-speed regime. Although part-speed operation represents a relatively small percentage of the overall mission profile, the observation that HyTEC efficiency is more than 10 points below ERA at some part-speed conditions highlights the importance of understanding how the high-speed benefits demonstrated by HyTEC are impacted by this significant sensitivity of performance to VSV schedule at part-speed.

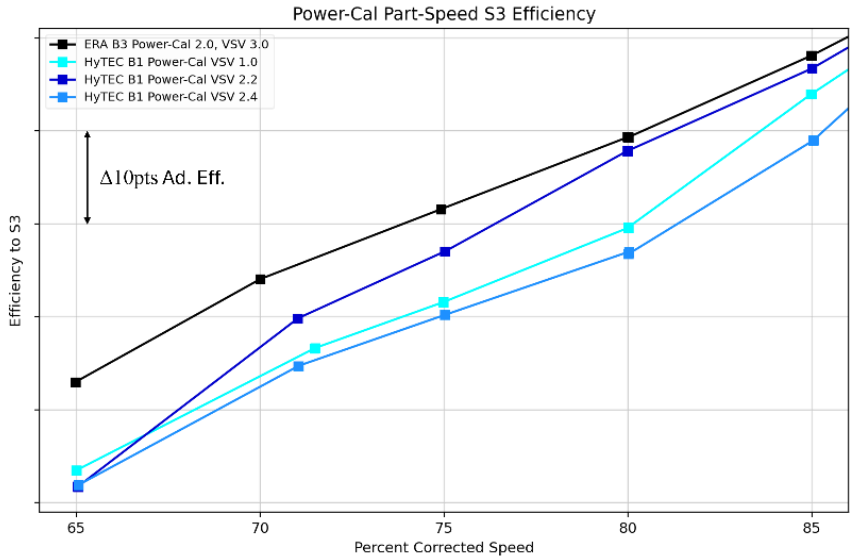

Figure 41: Part-Speed Efficiency (S3)

Thus, for completeness, the various HyTEC VSV schedules have been assessed on a mission-weighted basis for a notional mission profile representative of a future product. The power-calibration point at the speed closest to each cycle point is used. For all cycle points above 92% speed, the standard Plane 30 corrected efficiency is employed, whereas for speeds below 92% the alternate Stator 3-based efficiency definition is used. To translate the TPM-3 benchmarks from high speed to this mission-weighted efficiency, the +0.37-point correction is assumed to be applicable at all speeds. Finally, as noted in the high-speed performance discussion, the VSV 2.4 power-calibration data exhibited reduced high-speed efficiency due to rig deterioration (post high-speed stalls); because VSV 2.4 is identical to VSV 2.2 at high speed, the 0.09-point difference between the two schedules at 99%, the highest-speed cycle point, is taken as a deterioration correction and applied to VSV 2.4 efficiencies at all speeds. While this methodology requires several key assumptions, it results in an objective assessment of the HyTEC rig's performance over the entire mission, as discussed below.

Based on the process outlined above, the HyTEC efficiency deltas are calculated at each cycle condition and summarized in Table 9 as contributions from the part-speed and high-speed portions of the mission. This summary shows that both VSV 2.2 and VSV 2.4 provide solid efficiency benefits over ERA at the high-speed cycle conditions, which account for the majority of the mission weighting, while, as expected, both HyTEC schedules exhibit lower efficiency than ERA at part-speed. However, the magnitude of the part-speed penalty differs substantially. This contrast underscores the importance of a mission-weighted assessment. When the impacts of all cycle conditions are integrated, VSV 2.2 yields a mission-weighted net benefit of 0.34 points over ERA. Applying the TPM-3 criteria defined for high-speed efficiency, this corresponds to an outcome equivalent to minimum success on a mission-weighted basis, albeit still below a mission-weighted equivalent of the pre-test prediction, despite better-than-expected high-speed performance. In contrast, VSV 2.4 produces a mission-weighted efficiency change of -0.12 points, representing a net deficit relative to ERA and demonstrating that VSV 2.4 is not an acceptable path forward, as its severe impact on part-speed performance more than offset the technology benefits demonstrated at high-speed.

Table 9: Mission-Weighted Adiabatic Efficiency

Compact Core Mission Weighting	Weighted Part-Speed Mission	Weighted High-Speed Mission	Total Mission (Raw)	Total Mission (Corr.)
Mission Weighting	7.6%	92.4%	-	-
HyTEC VSV 2.1/2.2 – ERA EFFa Delta	-2.42 pts	+0.16 pts	-0.03 pts	+0.34 pts
HyTEC VSV 2.4 – ERA EFFa Delta	-8.23 pts	+0.15 pts	-0.49 pts	-0.12 pts

Taken together, the part-speed analysis shows that HyTEC's VSV optimization strategy for performance successfully recovered much of the initial efficiency deficit relative to ERA but could not fully eliminate the shortfall in part-speed efficiency, especially for the aeromechanics-optimized VSV schedule. The adoption of an alternate, Stator 3-based efficiency definition was essential to isolating true compressor performance from diffuser and Stator 3 loss effects and revealed that VSV 2.1/2.2 provides meaningful, though incomplete, improvements over the original VSV 1.0 schedule, while VSV 2.4 incurs a substantial additional performance penalty across the part-speed regime. The contrast between high-speed and part-speed performance trends motivates a more wholistic view of HyTEC compressor performance across the entire speed range. When evaluated on a mission-weighted basis, the aero-optimized VSV 2.2 schedule recovers enough part-speed performance to still deliver a moderate net efficiency benefit over ERA and grades out at an equivalent of minimum success under TPM-3. Conversely, the VSV 2.4 schedule, which was optimized to reduce aeromechanics responses, yields a slight mission-weighted deficit, confirming that its large negative impact on part-speed efficiency outweigh the high-speed gains. Overall, these results demonstrate that VSV 2.4 is not a viable path forward for mitigating the observed aeromechanics responses. Further analysis is necessary to understand the cause of the lower part-speed performance in order to realize the full technology benefit of the HyTEC 3-stage rig design.

4.4.3.4 Radial & Circumferential Distortion

This section presents the results of distortion testing performed with the HyTEC rig, with the goal of assessing compressor sensitivity to both radial and circumferential inlet non-uniformities. While the assessment in the previous section on part-speed efficiency concluded that VSV 2.4 was not the preferred schedule for performance, it was used for distortion testing since it maintains aeromechanics responses at acceptable levels. All distortion testing was completed with VSV 2.4 and compared to the nominal (intrinsic) inlet profile operability results for VSV 2.4. Since distortion sensitivity is not strongly influenced by the VSV schedule no additional distortion testing was done with VSV 2.2. First, flat inlet profile test results are shown and compared to equivalent testing previously completed on ERA, enabling a consistent assessment of any changes in radial distortion sensitivity between the two rigs. Second, circumferential distortion testing is examined using both 120-degree and 180-degree distortion screens. The 180-degree screen is a standard 1/rev circumferential distortion pattern, while the 120-degree screen provides an additional derivative for varying extent of circumferential distortion. Although circumferential distortion testing is new for the HyTEC test, the responses to the two screens are compared to one another to evaluate the robustness of the HyTEC rig design to the measured circumferential inlet distortion levels.

The intrinsic distortion screen used for all nominal testing provided the rig with a circumferentially uniform but hub-strong radial profile. Flat inlet profile testing was performed by removing this intrinsic distortion screen. With this configuration, the compressor was remapped at speeds of 90% and above, where differences between the nominal and flat inlet profiles are strongest. The resulting throttle stall maps are presented in Figure 42 and compared to ERA nominal and flat inlet results. Whereas ERA consistently exhibited diminished throttle margin with a flat inlet at all speeds, HyTEC demonstrated improved throttling at 90% and 92.5% speeds and reduced throttling at higher speeds. This behavior suggests a change in the dominant stall mechanism for HyTEC in this speed range and indicates that the healthier tip profile

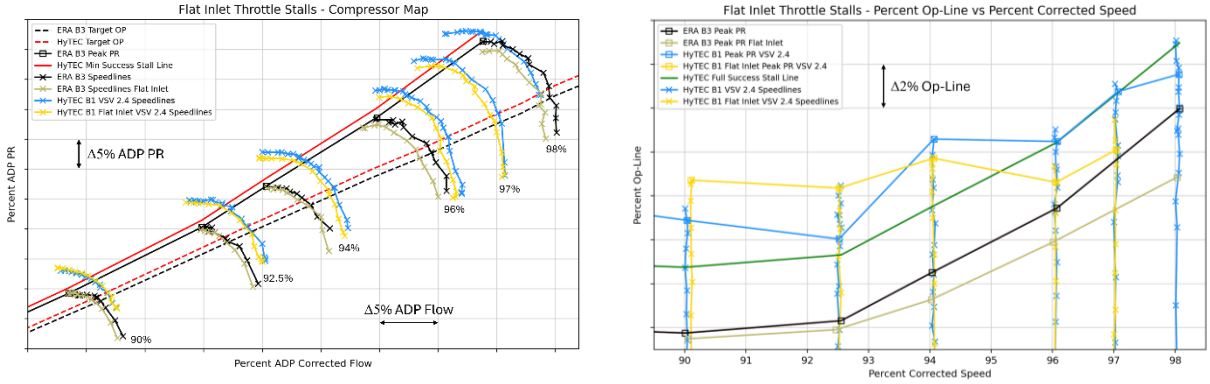

Figure 42: Flat Inlet Throttle Stall Mapping

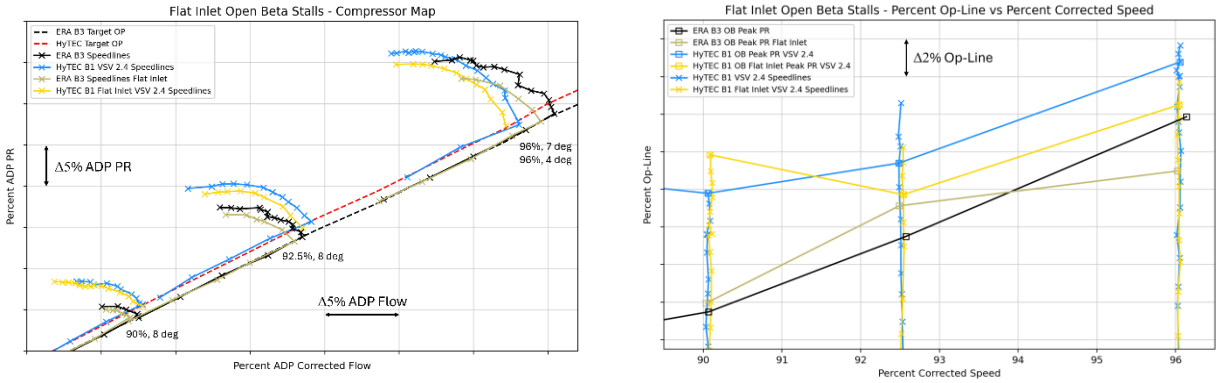

Figure 43: Flat Inlet Open Beta Stall Mapping

associated with the flat inlet is likely beneficial to Rotor 1 stability at the mid-speed conditions. Although HyTEC throttling is reduced with the flat inlet at higher speed conditions, it still exceeds ERA throttle margin for both nominal and flat inlet configurations. Open-beta mapping, shown in Figure 43, exhibits a similar trend, with HyTEC throttling slightly improved at 90% speed but diminished at higher speed, higher flow conditions. While HyTEC was unable to complete throttle stall mapping at 98% speed with the flat inlet due to gearbox temperature limits, the impacts are compared at 96% speed and show that the flat inlet results in approximately 0.7% lower flow and 1.65% lower throttle margin for HyTEC, compared with approximately 1.1% lower flow and 1.55% lower throttle margin for ERA.

Circumferential distortion testing was conducted to better understand the impact of circumferentially non-uniform inlet profiles, which may be more representative of future product applications. Two distortion screens were evaluated: a 180-degree screen and a 120-degree screen. Prior to interpreting the operability results, it is important to note that both screens produced high levels of circumferential distortion, with the 120-degree screen producing approximately 17% distortion and the 180-degree screen producing approximately 24% distortion, as shown in Figure 44. Mapping was completed down to 85% speed as distortion levels are still significant even at these lower speeds. These high distortion levels led to significant reductions in throttle capability and yielded valuable engineering insight into the HyTEC compressor's sensitivity to circumferential distortion and its implications for future design margins.

The resulting throttle and open-beta maps for the 180-degree distortion screen, shown in Figure 45, clearly illustrate the strong impact of the high distortion levels. At high speed, the speedlines roll over and become flat – the rig is unable to reach the nominal operating line, and the corrected flow is dramatically reduced. At 90% speed and below, the impact is diminished, although still significant, and the rig is able to throttle more reasonably; however, both the flow deficit and the distortion-induced changes in speedline shape remain substantial. Open-beta mapping demonstrates a similarly strong effect, with the rig struggling to reach the nominal operating line even at the lowest speeds. The higher-speed open-beta stalls with the 180-degree screen were not completed.

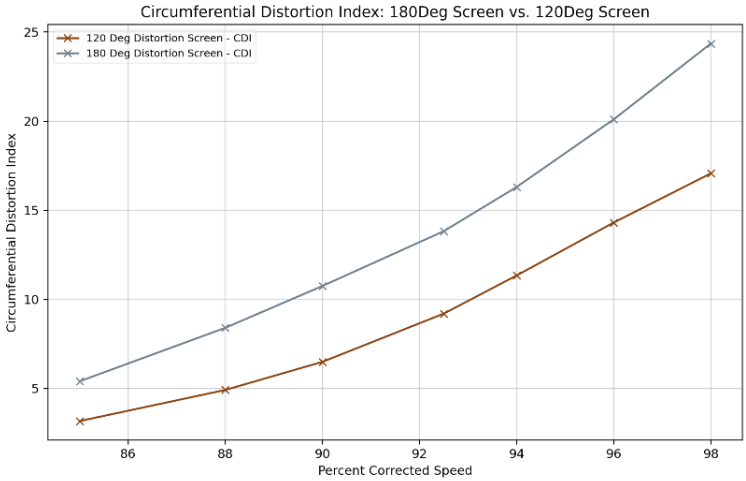

Figure 44: Circumferential Distortion Index

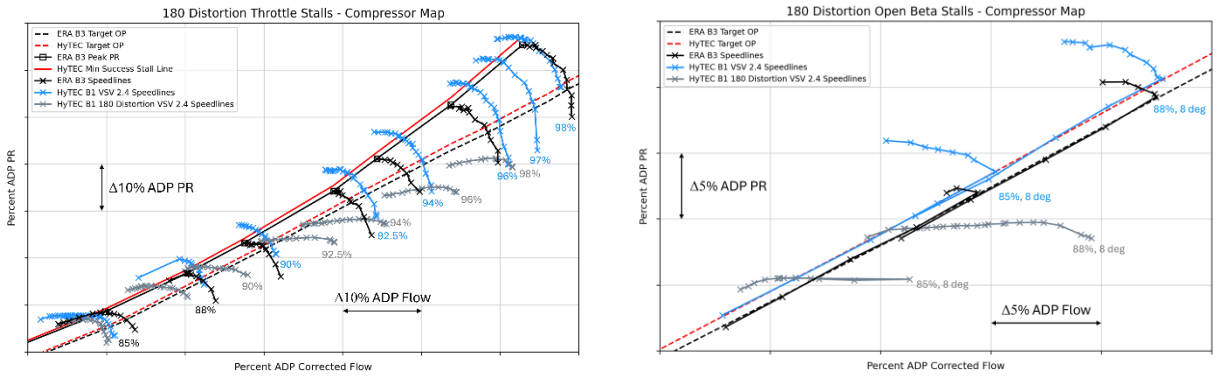

Figure 45: 180 Degree Distortion Stall Mapping

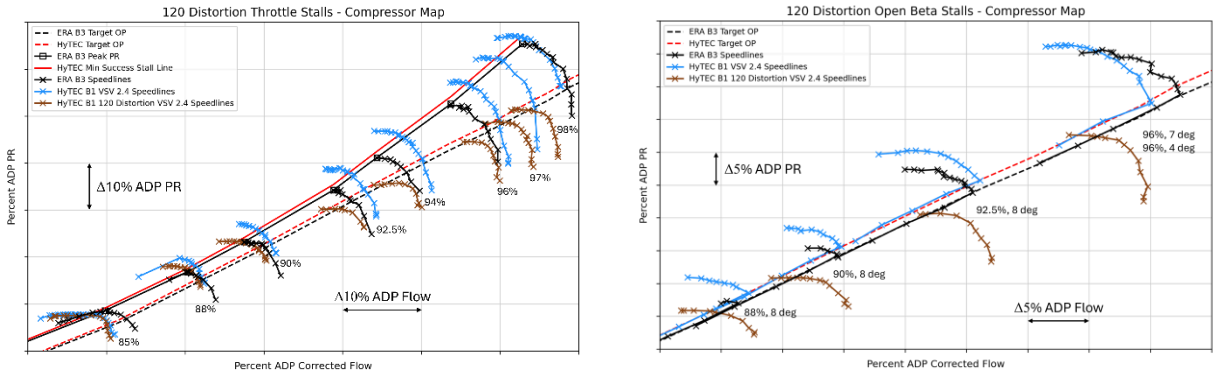

Figure 46: 120 Degree Distortion Stall Mapping

Throttle and open-beta maps for the 120-degree screen, presented in Figure 46, show qualitatively similar but less extreme behavior, consistent with the lower distortion strength of this configuration. The speedline shapes are noticeably less impacted than in the 180-degree case, although at high speed the rig still struggles to reach the nominal operating line. A distinct shift in behavior is observed above 90% speed, where the impact of the 120-degree distortion becomes more pronounced; a similar trend was present with the 180-degree screen but is more clearly discernible here. Open-beta stalls were completed at all speeds at and above 85% with the 120-degree screen and show significantly diminished capability relative to nominal, though still more reasonable than the limited 180-degree open-beta cases.

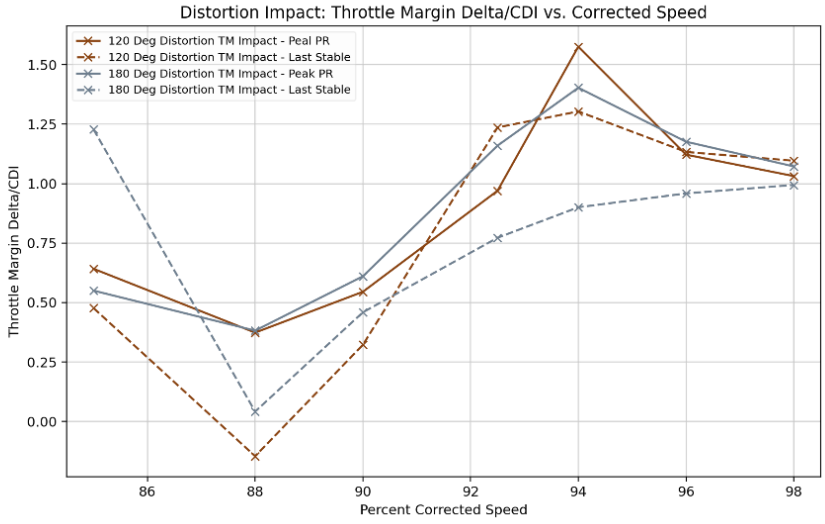

Figure 47: Circumferential Distortion Sensitivity

Finally, the impact of the two circumferential distortion screens is compared against one another. Whereas ERA and HyTEC throttle margin have generally been measured to the peak pressure-ratio point, the significantly altered speedline shapes observed under distortion motivated evaluating throttle margin both to peak pressure ratio and to the last stable point on each speedline. Using these criteria, Figure 47 presents the distortion sensitivity of both screens measured across the speed range, quantified as the effective loss in throttle margin per percent circumferential distortion at each speed. The overall trends for the 180-degree and 120-degree screens are remarkably consistent, despite their substantial difference in distortion strength and circumferential pattern. However, the results also make clear that the distortion impact is not independent of speed.

Overall, the distortion testing demonstrates that the HyTEC rig design is robust to inlet profile variations while revealing important sensitivities that must be considered for future designs. Flat inlet testing showed that, unlike ERA, HyTEC demonstrated improved throttling at certain mid-speed conditions with a stronger tip profile, and even where throttle margin is reduced at higher speeds, it remains superior to ERA for both nominal and flat inlets. Circumferential distortion testing with the 120-degree and 180-degree screens confirmed that HyTEC experiences substantial degradation in throttle capability under the strong distortion levels, with the 180-degree screen producing the most extreme impacts. Nevertheless, the two screens exhibited consistent trends. The observed dependence of distortion sensitivity to speed, combined with the limited leverage from VSV schedule changes, underscores the need to carefully account for such behavior in setting future design requirements.

4.4.4 Aeromechanics

This section documents the aeromechanical response observations from HyTEC Phase 1 rig testing and summarizes how those observations were evaluated against TPM-4 requirements. The intent is to provide awareness of the two observed responses that challenged TPM-4 compliance and to summarize the effectiveness of mitigation actions implemented during the test campaign, including VSV schedule changes.

While testing with VSV 2.1/2.2, the team observed a part-speed aeromechanical response that exceeded certifiable limits and therefore did not meet TPM-4. Certifiable limits can be defined as the threshold in terms of aeromechanical response in which a product can be certified for introduction into the field with conservatism included to account for known sources of variation and other experience-based factors. As part of the expanded testing scope, repeated speed sweeps through the speed range of interest were conducted, utilizing low acceleration rates to allow for complete characterization of the aeromechanical responses. The expanded test plan included additional VSV schedule derivatives and throttle setting derivatives, among other things, to determine their impact on the aeromechanical response. The VSV schedule derivatives tested were selected to adjust the operating line of the stage where the aeromechanics response was observed. A sufficient range of stage loadings were tested to allow for a comprehensive understanding of the impacts on aeromechanics. Overall, VSV 2.4 proved to be most effective at reducing this aeromechanics response amplitude and was thus selected as the aeromechanics-optimized vane schedule. With VSV 2.4 implemented, the response amplitude decreased to well within certifiable limits, restoring margin and operational capability. Thus, VSV 2.4 enabled the ability to meet minimum success on TPM-4. Additionally, during high-speed, near-stall operation, an aeroelastic instability was observed on the last-stage rotor. Although this instability occurred on operating lines above the 13% margin (which satisfies the TPM-4 requirement), it is noted here because an additional VSV schedule modification was required to enable mapping to stall at this speed. This instability is likely associated with unrepresentative aerodynamics of the last-stage rotor in a partial-stage compressor rig and is not expected to occur when operating in a full-stage compressor.

In summary, testing with the VSV 2.4 schedule enabled the HyTEC rig to achieve the TPM-4 minimum success criteria. In addition, all other observed rotor and stator aeromechanical responses remained within certifiable limits during testing using the performance-optimized VSV 2.1/2.2 schedule.

4.4.5 Radial Traversing

This section presents the results of radial traverse testing performed during the HyTEC 3-Stage rig test campaign. The goals of this testing were to characterize the inlet duct velocity profiles and turbulence statistics, as well as measure the steady-state and/or phase-locked flow characteristics at the exit of the rotors for each stage of the compressor. All traverse results herein were completed with the VSV 2.4 schedule. Measurements were conducted at five axial locations, specifically the compressor inlet, Plane 25, and behind Rotors 1, 2, and 3, respectively. The various traverse probes utilized, and the capabilities thereof, are summarized in Table 10. For the purposes of this report, selected results will be presented to highlight key findings and capabilities, rather than a comprehensive analysis. Due to limited time and scope, no standard day corrections have been applied to any of the radial traversing results.

Table 10: Traverse Probes

Probe Type	Parameters Measured	Frequency Response	Purpose for HyTEC
Fast Response Aero Probe (FRAP)	Phase Locked Pt, Ps, 3D Vel Comp	50 kHz	Phase Locked Aero Quantities
5-Hole Probe w/ Total Air Temperature (5HP)	Pt, Ps, 3D Vel Comp, Tt	Steady State	SS Aero Performance
Hotwire (HW) / Hotfilm (HF)	1D: Absolute Velocity	Wire: 100 kHz Film: 30 kHz	Turbulence statistics
	2D: Velocity Comp (Axial/Tang)	Wire: 100 kHz Film: 30 kHz	Turbulence statistics Phase Locked Aero Quantities

4.4.5.1 Inlet Radial Traversing

Radial traversing in the HyTEC inlet gooseneck duct was conducted at two axial locations, namely near the duct inlet (upstream of the struts) and Plane 25. The mid-span inlet plane turbulence power spectral density at 98% speed is shown for three different wire types in Figure 48. A band-stop filter was applied to remove content from the first five blade-pass frequency harmonics, and a digital low-pass filter was applied to remove contamination from high-frequency content. These results show that the hot-film (HF) probe does not sufficiently measure the spectral content to high enough frequency compared to the two hot-wire (HW) probes under the same conditions. Starting at around 1kHz, the HF probe shows a roll-off that continues through the universal range, is well below that of the HWs, and does not align with the typical -5/3 slope. While this is expected, the overall successful testing using the HW probes demonstrates that the more fragile HWs are sufficiently robust to handle the conditions of the W-7 inlet. For both of these considerations, the "bare wire" style HW probes should be considered most suitable for current and future testing in the W-7 facility at similar conditions.

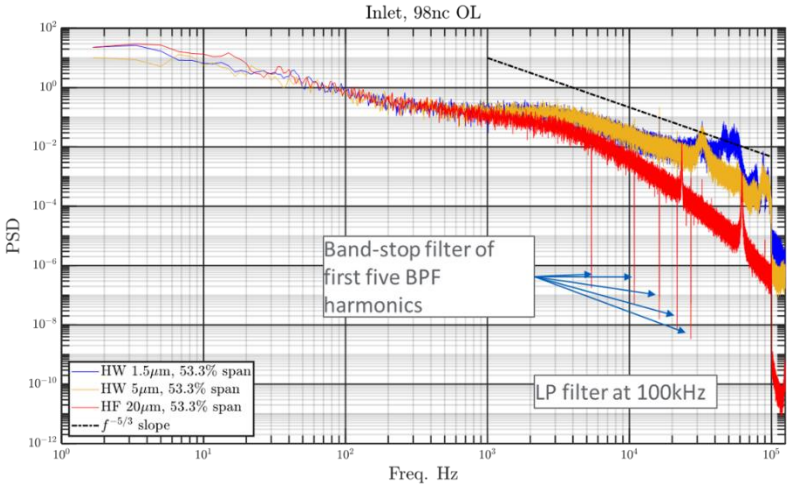

Figure 48: Inlet Plane Turbulence Power-Spectral Density at Mid-Span

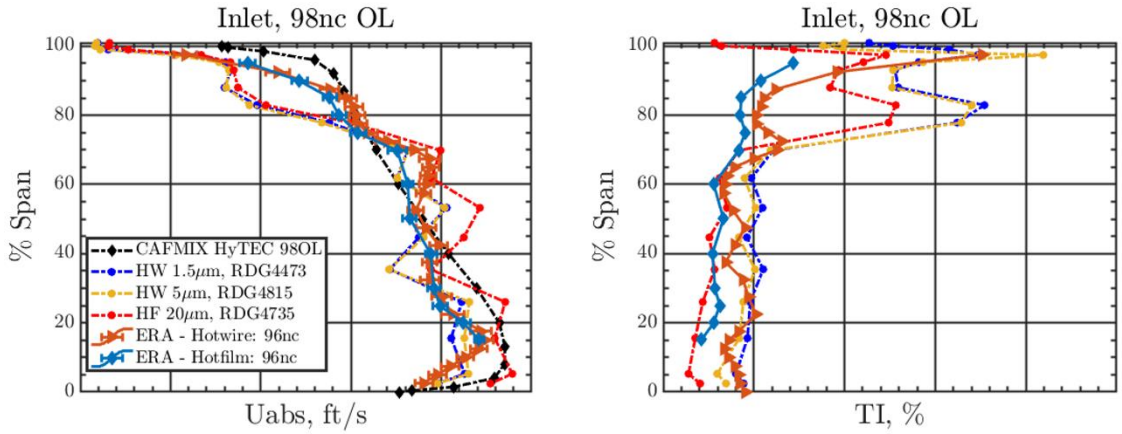

Figure 49: Inlet Plane Absolute Velocity and Turbulence Intensity Profiles

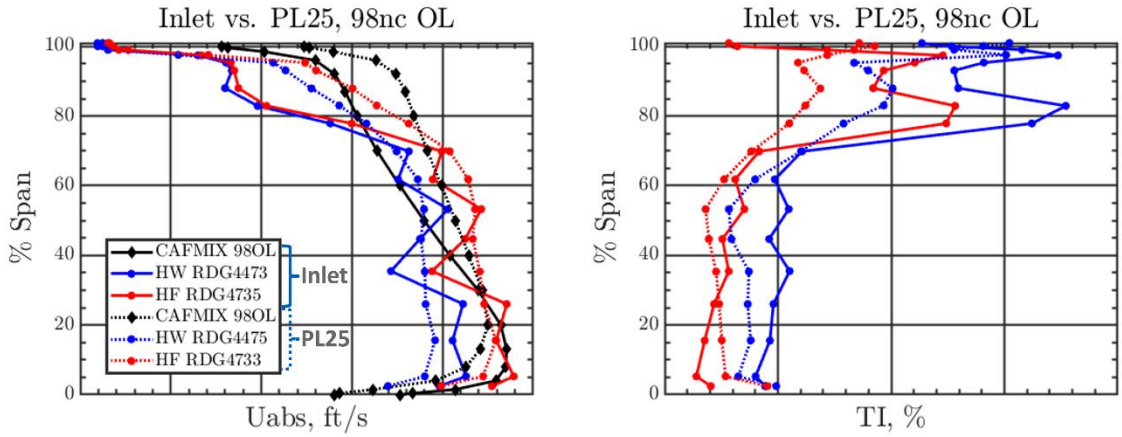

Figure 50: Inlet Plane and Plane 25 Absolute Velocity and Turbulence Intensity Profiles

Figure 49 continues the comparison between the HF and HW probes, both for the HyTEC and ERA rigs, showing the absolute velocity and turbulence intensity (TI) profiles at the inlet plane at 98% speed. Whereas both the HF and HW probes measure similar absolute velocity profiles back-to-back in the same test, the HW consistently measures higher TI compared to the HF. The reason for this is evident from the results discussed above related to Figure 48, where the HF signal is attenuated too early in the frequency domain. An interesting observation from the HyTEC test is the region roughly between 75%-95% span where the velocity is lower, and the TI is significantly higher, compared to ERA results and the HyTEC CAFMIX prediction. The root cause of this discrepancy is not fully understood at this time.

Similar results are shown in Figure 50, which compares the inlet (solid lines) and Plane 25 (dotted lines) absolute velocity and TI profiles. The additional inlet duct measurements at Plane 25, newly implemented for HyTEC testing, enables turbulence measurements closer to the IGV leading edge, as well as characterization of turbulence decay within the inlet duct, both of which support ongoing CFD studies where accurate turbulence characterization is critical. Relative to the rig inlet, Plane 25 shows the lower velocity and higher TI region between 75%-95% span is appreciably less pronounced, but still evident.

4.4.5.2 Interstage Radial Profiles

Interstage measurements were taken with both 5HP and FRAP (subject to temperature limitations) for all three stages on the HyTEC rig at several conditions of interest. This interstage radial traversing provides validation for stator leading edge PT/TT measurements, while also enabling finer resolution, phase-locked unsteady measurements, and measurement of additional aerodynamic parameters that are not otherwise possible. While PT and TT profiles are the focus of this discussion, the full set of quantities enabled by radial traversing also includes flow angles (alpha, lambda), static pressure, and Mach number.

Radial traverse results for all three stages are compared to stator LE Kiel data at 98% op-line (ADP), as shown in Figure 51. At this condition, the traverse data shows good general agreement with the stator LE Kiel data. Notably, the radial traverse and stator LE data both suggest the PT profile is slightly less tip strong than the CAFMIX design intent across all three stages. The 5HP TT traverse measurements show good agreement with the Kiels on Stage 1 and Stage 2, with some deviation near the hub, while Stage 3 shows more discrepancy between the traverse data and stator Kiels across the span.

Similar stage comparisons are shown for 98% near-stall in Figure 52. This generally shows good agreement between 5HP, FRAP, and stator LE Kiel data. However, notable discrepancy is again seen near the hub, especially on Stages 2 and 3. This demonstrates the unique value of radial traverse testing, as the traverse data provides a second witness to the LE Kiel data and more detailed assessment of the rig conditions. Comparisons between 85% op-line and 85% near-stall are shown in Figure 53 and Figure 54,

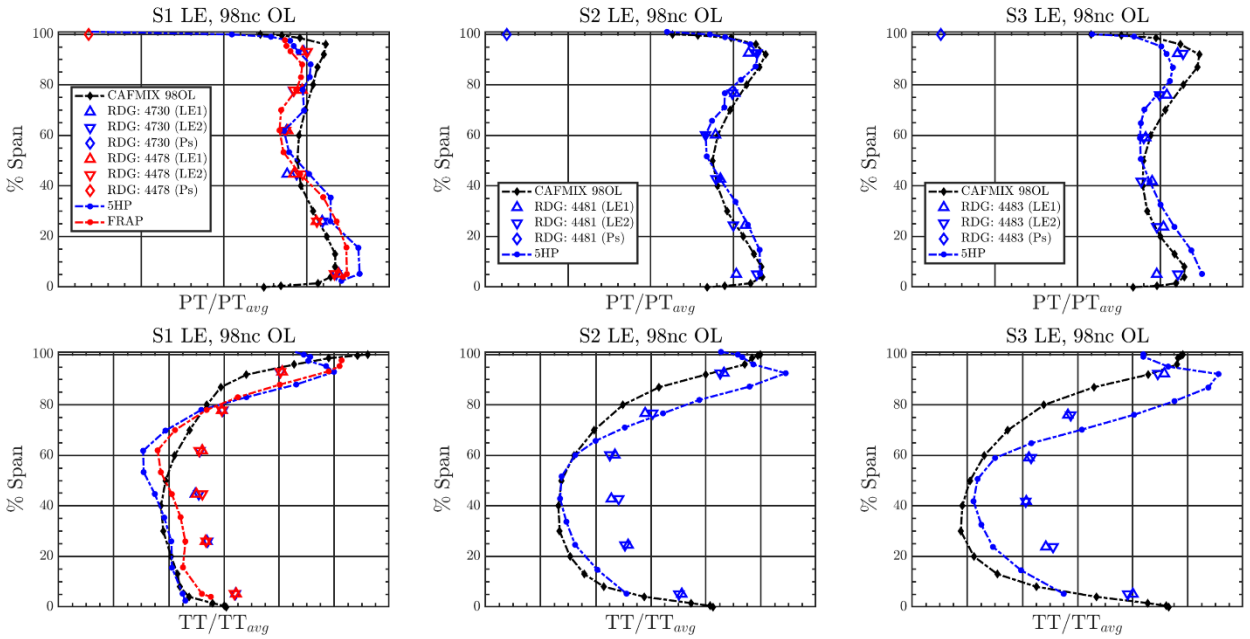

Figure 51: Interstage Radial Profiles at 98% Op-Line

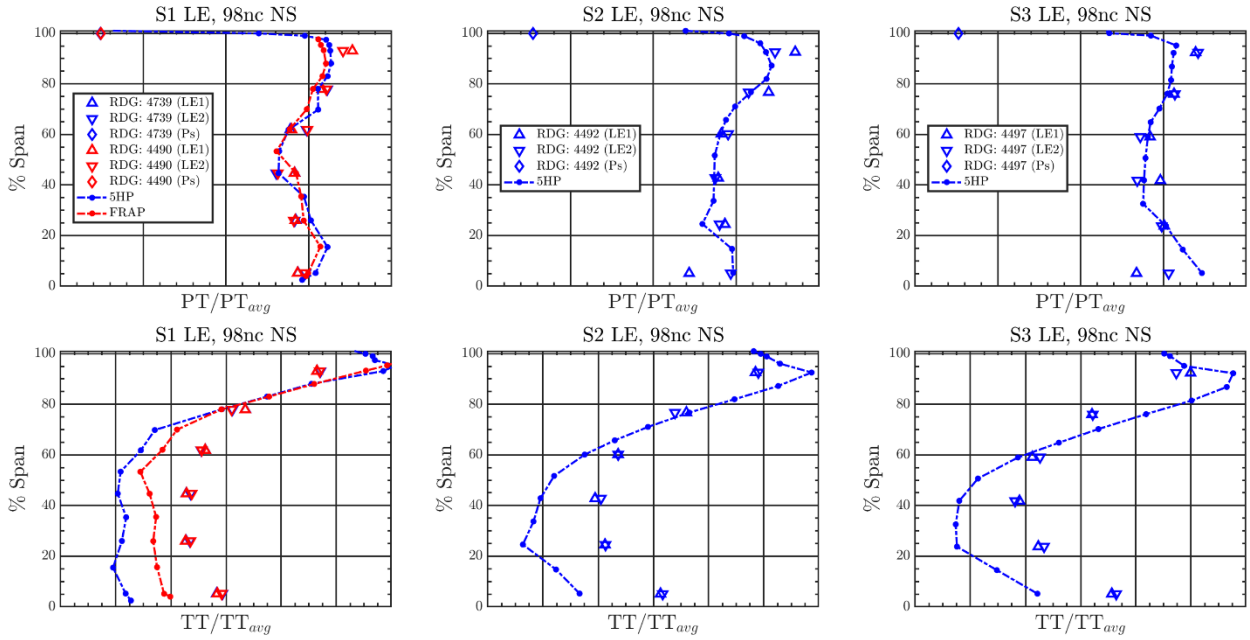

Figure 52: Interstage Radial Profiles at 98% Near-Stall

respectively. At 85% op-line the profile shapes are very similar to the stator LE data. The 85% near-stall condition again shows significant hub discrepancies, though the radial traverse data now also points towards the rotor hubs getting weak, just to a significantly lesser degree than the stator LE data.

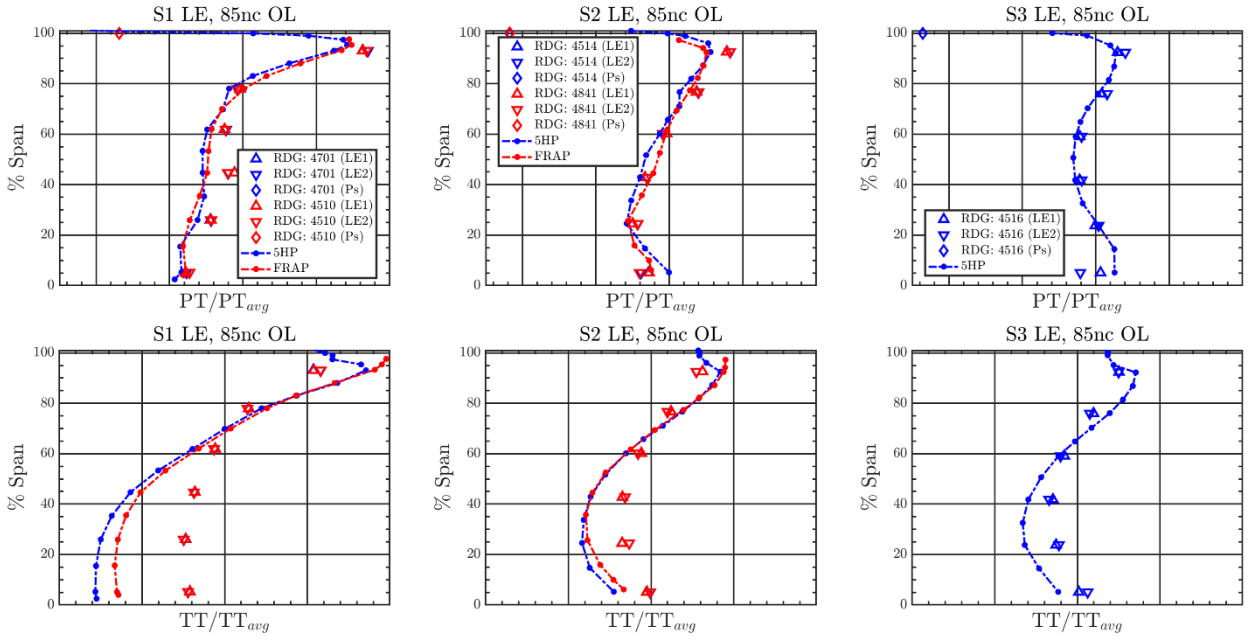

Figure 53: Interstage Radial Profiles at 85% Op-Line

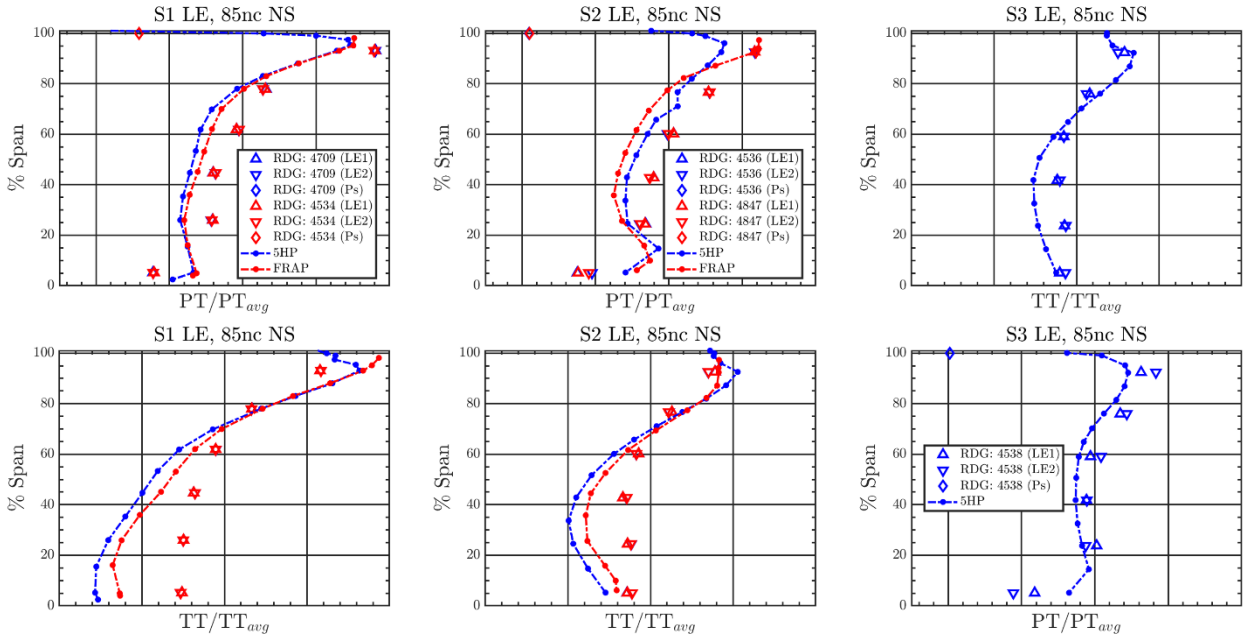

Figure 54: Interstage Radial Profiles at 85% Near-Stall

5. Technical Performance Measures and Key Performance Parameters Assessment

Technical Performance Measures for HyTEC Phase 1 and Key Performance Parameters for HyTEC Phase 2 were outlined previously in Chapter 1. Having shown the HyTEC Phase 1 test results, the corresponding assessments of these TPMs and KPPs are summarized in this chapter. As discussed in Chapter 4, competing aerodynamic and aeromechanic considerations led to the development and full characterization of two VSV schedules – aero-optimized VSV 2.2 and aeromechanics-optimized VSV 2.4 – and both schedules are evaluated here to provide a more complete and balanced view of technology readiness entering HyTEC Phase 2. In addition, the lower part-speed efficiencies documented in Section 4.4.3.3 motivate an expansion of the TPM-3 assessment beyond design-point efficiency to include mission-weighted efficiency, as described in that section, to better reflect representative engine operation in a future product application.

Table 11: TPM Assessment Summary

	TPM-1	TPM-2	TPM-3 (ADP)	TPM-3 (Cycle)	TPM-4
VSV 2.2 (Aero-optimized)	Min Success: Demonstrated +7.3% higher d-factor vs. ERA, exceeding Min Success of 5% and nearing Full Success target of 7.6%.	Min Success: Throttle margin exceeds ERA at all speeds. Exceeds Full Success (ERA +3%) target at 7/10 speeds.	Full Success: Quoted adiabatic efficiency delta of +0.77pts on a corrected basis exceeds Full Success target of +0.7pts.	Min Success: Estimated mission-weighted adiabatic efficiency exceeds ERA by 0.34pts on a corrected basis, compared to +0.3pts Min Success target.	Aeromechanical response levels exceeded certifiable limits at product-representative inlet temperatures.
VSV 2.4 (Aeromech-optimized)	Same as VSV 2.2. No VSV differences at ADP.	Min Success: Throttle margin exceeds ERA at all speeds. Exceeds Full Success (ERA +3%) target at 7/10 speeds.	Same as VSV 2.2. No VSV differences at ADP.	Estimated mission-weighted adiabatic efficiency is -0.12pts below ERA on a corrected basis.	Responses are below certifiable limits. Aeroelastic instability occurs outside op-line range of TPM and expected loadings for Compact Core.

The performance of both VSV schedules relative to the HyTEC Phase 1 TPMs is summarized in Table 11. As discussed in Section 4.4.3.1, HyTEC demonstrated a 7.3% increase in Rotor 1 tip loading relative to ERA, which is very close to the full success target of 7.6%; because VSV 2.2 and VSV 2.4 are identical at design point, both schedules have the same outcome for TPM-1. Operability results in Section 4.4.3.2 showed that HyTEC throttle margin exceeds ERA at all speeds for both schedules, thereby meeting the TPM-2 minimum success criterion, and that both schedules also achieve the full success criterion by exceeding ERA throttle margin by at least 3% at 7 of 10 mapped speeds. While broadly similar at a high level, VSV 2.4 provides improved part-speed stall margin compared to VSV 2.2. Additionally, while TPM-2 does not define open-beta stall margin targets, both schedules exceed ERA for all open-beta conditions tested. Design-point efficiency results in Section 4.4.3.1 further demonstrated excellent performance relative to TPM-3 and pre-test expectations: the quoted HyTEC adiabatic efficiency delta of +0.39 points exceeds the full success target of +0.32 points (+0.7 points on a corrected basis) and corresponds to a demonstrated 0.77-point technology improvement over ERA, again identical for both schedules due to their convergence at high speed. When TPM-3 is applied on a mission-weighted basis in Section 4.4.3.3, the lower-than-anticipated part-speed efficiency of VSV 2.2 partially offsets the high-speed gains, but VSV 2.2 still achieves an outcome equivalent to minimum success, whereas the large reduction in part-speed efficiency with VSV 2.4 more than negates the high-speed benefits and yield a mission-weighted efficiency deficit of 0.11 points relative to ERA, failing to meet minimum success. Finally, aeromechanical response levels with VSV 2.2 exceeded certifiable limits at product-representative inlet temperatures and therefore do not satisfy the TPM-4 minimum success definition, while the mitigations with VSV 2.4 reduced

responses to within certifiable limits. Furthermore, the observed aeroelastic instability occurred only at high, near-stall operating lines outside the TPM-4 range and above expected loading levels for the Compact Core compressor. Accordingly, VSV 2.4 is assessed as meeting minimum success for TPM-4.

The TPM performance discussed above directly relates to, and feeds into, the Key Performance Parameters defined for HyTEC Phase 2 and shown in Table 1. For KPP-1 (fuel burn), the design point efficiency measured under TPM-3 demonstrated a 0.77-point adiabatic efficiency improvement on the three-stage HyTEC rig, providing an SFC benefit for the full HPC. Although part-speed efficiency must be improved to sustain this fuel burn advantage across the full mission, VSV 2.2 still delivers a benefit to the full HPC on a mission-weighted basis. For KPP-3 (overall pressure ratio), the improved operability demonstrated under TPM-2, together with the higher pressure-ratio front stages implied by TPM-1, are important enablers to achieve the 20:1 class HPC pressure ratio in Phase 2. Any level of success for KPP-4 requires at least minimum success for TPM-4, as any airfoil response that exceeds certifiable limits could result in fatigue failure before the major refurbishment interval. The demonstrated aeromechanical stability of the HPC airfoils with VSV 2.2 is therefore a critical component of KPP-4. Finally, while the larger flow size of the HyTEC rig relative to Compact Core limits direct applicability for KPP-6 (HPC exit corrected flow), exceeding TPMs 1–3 for Rotor 1 loading, operability, and design-point efficiency provides strong confidence that the front stages can meet the performance and operability requirements for HyTEC Phase 2 at the smaller core sizes.

6. Technology Readiness Level & Technology Maturation

This chapter summarizes how the HyTEC Phase 1 rig test supports technology maturation for the HyTEC Phase 2 Compact Core compressor. Based on the assessment of HyTEC rig test results in the proceeding chapter, all TPMs were met or exceeded, subject to the VSV schedule caveats previously discussed. Consequently, the HyTEC 3-Stage rig test is judged to be a successful TRL-4 validation of front-block aerodynamic technologies for the HyTEC Phase 2 Compact Core compressor. In particular, HyTEC demonstrated excellent design-point efficiency with a higher loaded Rotor 1 incorporating advanced casing treatment, in combination with vector diagram changes. In addition, HyTEC showed improved operability across the entire compressor map, even with the increased Stage 1 tip loading. Finally, although HyTEC was not specifically intended to advance aeromechanics TRL, the campaign generated important aeromechanics insights and data that will be used to reduce aeromechanics risk for future designs.

While HyTEC Phase 1 was a highly successful technology demonstration, two risks to technology maturation were identified that will require additional mitigation in HyTEC Phase 2. First, HyTEC showed high aeromechanical response levels in the part-speed regime. Although some response levels could be reduced substantially through VSV optimization, they could not be fully eliminated, and the associated schedule changes were detrimental to part-speed efficiency. Second, part-speed performance was below expectations regardless of VSV schedule: VSV optimization with VSV 2.2 recovered a substantial portion of the deficit, but part-speed efficiency, particularly at the lowest near-idle speeds, remained an issue. Aeromechanics mitigations implemented in the VSV 2.4 schedule further degraded part-speed performance and mission-weighted efficiency, more than offsetting the excellent high-speed gains and proving an unviable path forward. While the improved part-speed efficiency of the aero-optimized VSV 2.2 schedule was sufficient to demonstrate a net mission-weighted benefit, further part-speed improvements will be important to fully realize the technology advantages demonstrated at high speed.

Based on the technology maturation risks identified above, the team is pursuing a multi-pronged strategy to mitigate these risks for HyTEC Phase 2. First, additional 3-Stage rig testing, outside of the HyTEC contract, in alternate configurations is critical to further characterize the various responses observed during this test campaign. In parallel, the Compact Core Rotor 1 design for HyTEC Phase 2 is being compared directly to HyTEC and assessed for relative aeromechanical risk. At the same time, HyTEC Phase 1 data are being used to validate and improve aeromechanics analysis tools. While part-speed efficiency is expected to benefit from alternative aeromechanics mitigation approaches, additional avenues are also being pursued. Collectively, these efforts, together with continued mining and analysis of the extensive HyTEC dataset, are intended to reduce both aeromechanics and part-speed performance risks to acceptable levels for HyTEC Phase 2.

7. Conclusion

The HyTEC Phase 1 3-Stage Compressor Rig project successfully matured and validated front-stage aerodynamic technologies in support of HyTEC Phase 2 and GEA's Compact Core compressor. Building on the successful legacy ERA Phase 2 Baseline Compressor Rig, GEA and NASA collaborated on the design and testing of the HyTEC rig, incorporating advanced technologies to deliver significant benefits in efficiency, tip loading, operability, and aeromechanics, as measured against defined TPMs. Use of a common facility (NASA GRC W-7) and similar instrumentation and test execution approaches enabled an accurate quantitative comparison to the baseline technology ERA rig test data. The HyTEC Phase 1 rig met all defined TPMs, subject to VSV schedule caveats, and successfully matured the front-stage aero technologies to TRL-4.

At high speed, the rig demonstrated excellent aerodynamic performance. The aero design point adiabatic efficiency exceeded the TPM-3 full success criterion of 0.7 points improvement on a corrected basis relative to ERA, and Rotor 1 tip loading increased by 7.3%, nearly achieving the full success TPM-1 goal for Rotor 1 tip d-factor. Operability was also improved across the map, due to the advanced casing treatment over Rotor 1, with throttle stall margin meeting TPM-2 minimum success criteria at all speeds and achieving full success at most mapped conditions.

HyTEC testing also provided valuable aeromechanics data, with significant learnings around several responses of interest HyTEC exhibited elevated response levels at product-representative inlet temperatures with the initial aero-optimized VSV schedule. High response levels also were observed at part speed and aeroelastic instability was detected at high speed near stall operating lines. Focused VSV derivative testing in the part-speed regime produced distinct aero-optimized and aeromechanics-optimized schedules. The aeromechanics-optimized schedule reduced response amplitudes to within certifiable limits but at the expense of part-speed efficiency, while the aero-optimized schedule achieved better efficiency but with unacceptably high response levels. Both VSV schedules were fully characterized against the TPMs, creating a rich dataset for validating and improving analysis tools.

The substantial tradeoff between part-speed efficiency and aeromechanical stability was a key finding from the HyTEC rig test campaign. Part-speed efficiency with the aeromechanics-optimized schedule showed a significant reduction relative to ERA. Although part-speed efficiency was not explicitly defined in the TPMs, this shortfall prompted a mission-weighted efficiency assessment based on a notional product engine mission profile. The analysis showed that the reduced efficiency at part speed with the aeromechanics-optimized schedule more than offset the performance gains demonstrated at high speed. Conversely, the aero-optimized schedule showed significantly improved part-speed efficiency such that an effective minimum success outcome in efficiency was achieved on a mission-weighted basis, although with un-certifiable response levels. These results clearly map the performance–aeromechanics trade space and highlights the need for integrated optimization in future design and test activities.

In conclusion, the HyTEC Phase 1 3-Stage Compressor Rig met the objectives in terms of the project TPMs, with the VSV schedule caveats described above. Retesting the legacy ERA rig provided the key baseline TPM data and validated critical NASA facility upgrades. The HyTEC rig demonstrated that the front stages can achieve the targeted gains in tip loading, efficiency, and operability required for the Compact Core compressor. Two principal technology maturation risks were identified: high aeromechanics responses at part-speed and lower-than-expected part-speed efficiency. These risks are now the focus of a multi-pronged mitigation strategy including additional configuration testing, Compact Core design trades, and continued development and validation of analysis tools. Collectively, these test results support achievement of TRL-4 for the front-stage aero technologies and provide significant risk reduction for the HyTEC Phase 2 Compact Core compressor TRL-6 demonstration and for future engine architectures that employ a compact core compressor.