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Environmentally Responsible Aviation: Propulsion Research to Enable Fuel Burn, Noise and Emissions Reduction

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Abstract

The NASA Environmentally Responsible Aviation (ERA) program is maturing technologies to enable simultaneous reduction of fuel burn, noise and emissions from an aircraft/engine system. Three engine related Integrated Technology Demonstrations (ITDs) have been completed at Glenn Research Center in collaboration with Pratt & Whitney, General Electric and the Federal Aviation Administration.

The engine technologies being matured are a low NOx, fuel flexible combustor in partnership with Pratt & Whitney, an ultra-high bypass, ducted propulsor system in partnership with Pratt & Whitney/FAA and high pressure ratio, front-stage core compressor technology in partnership with General Electric. The technical rationale, test configurations and overall results from the test series in each ITD are described.

ERA is using system analysis to project the benefits of the ITD technologies on potential aircraft systems in the 2025 timeframe. Data from the ITD experiments were used to guide the system analysis assumptions. Results from the current assessments for fuel burn, noise and oxides of nitrogen emissions are presented.

Nomenclature

AAC Advanced Aero Combustor Rig
AFRL Air Force Research Laboratory
ASC Axial Stage Combustor
ASCR Advanced Subsonic Combustion Rig
B1,B2 Compressor Build 1 and 2
CAA Computational Aeroacoustics
CAEP Committee on Aircraft Environmental Protection
CLEEN Continuous Lower Emissions and Noise
CMC Ceramic Matrix Composite
EIS Entry Into Service
FAA Federal Aviation Administration
FEGV Fan Exit Guide Vane
FPR Fan Pressure Ratio
GTF™ Geared Turbofan
ITD Integrated Technology Demonstration
LDI Lean Direct Injection
LE Leading Edge
LTA Large Twin Aisle
OPR Overall Pressure Ratio
NOx oxides of nitrogen
OTR Over the Rotor
P3 Combustor entrance pressure
RTO Rolling Takeoff
SV Soft Vane
T3 Combustor entrance temperature
TC Technical Challenge
TFA Technical Focus Area
TOC Top of Climb
TRL Technology Readiness Level
UTRC United Technologies Research Center

Introduction

ERA is a finite length, technology maturation program with the objective to meet the “N+2” goals, shown in Figure 1, simultaneously for an aircraft/engine system. The evaluation of progress towards the goals was done through ‘demonstration by analysis’ using a notional baseline system and a NASA

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines
** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015
‡ CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used

Figure 1: NASA subsonic transport system level metrics.

defined, advanced technology aircraft/engine system. The advanced system assumes technologies used are Technology Readiness Level (TRL) 6 by 2020 for an entry into service (EIS) of 2025.

ERA was constructed as a two phase program with a Key Decision Point at the transition from Phase 1 to Phase 2. For ERA propulsion phase 1, higher maturity concepts were selected from the NASA fundamental research programs for further maturation. The most promising technologies from Phase I were downselected (i.e. the Key Decision Point)in Phase 2 to demonstrate a TRL of 4-6 in an integrated system demonstration. Phase 1 engine technologies included Lean Direct Injection (LDI) combustor concepts, lean-lean combustor designs, combustor control strategies, low FPR fans, open rotors, boundary layer ingesting propulsors, high OPR core compressors, ceramic matrix composite (CMC) turbine vanes, combustor liners and mixer nozzles. For Phase 2, phase 1 technologies were selected for further maturation which culminated in Integrated Technology Demonstrations or ITDs . For example, of the 3 propulsor technologies (UHB ducted, UHB unducted, and UHB embedded fans) the ducted UHB propulsor was selected for phase 2. This downselection process occurred in all major disciplines. The eight Phase 2 ITDs are listed in Table 1 The propulsion focused ITDs are denoted as 30A, 35A and 40A.

Individual ITDs are meant to mature selected technologies to TRL 5/6 by September 2015 and also validate the performance of those technologies in a more complex system environment. ERA also defined Technical Focus Areas (TFAs) and associated Technical Challenges (TCs). The TFA/TCs are listed in Table 2 ITD 30A and 35A contribute directly to TFA3. ITD 40A contributes to TFA4. Details of progress towards the TFA/TC goals are discussed in a later section.

The baseline system is a Boeing 777 aircraft with GE90-110 engines. NASA has constructed notional 2025 timeframe aircraft/engine systems that include the technologies of the engine ITDs. The contribution of the engine technologies to the overall goals can be assessed using these notional systems. Details of the aircraft/engine system are in a later section. First the technical content and objectives of the propulsion ITDs are described.

Table 1: Phase 2 ITD names and primary industrial partners.	
ITD Title	Partner
12A+: Active Flow Control Enhanced Vertical Tail (Lead) & Adv. Wing Flight Experiment (Support)	Boeing
21A: Damage Arresting Composite Demonstration	Boeing
21C: Adaptive Compliant Trailing Edge Flight Experiment	Flexsys/AFRL
35A: Second Gen UHB Propulsor Integration	Pratt and Whitney, FAA
30A: Highly Loaded Front Block Compressor	General Electic (GE)
40A: Low NOx Fuel Flexible Combustor Integration	Pratt and Whitney (P&W)
50A: Flap Edge and Landing Gear Noise Reduction Flight Experiment	Gulfstream
51A: UHB Integration for Hybrid Wing Body	Boeing

Propulsion Integrated Technology Demonstrations

The three propulsion ITDs focused on increased thermal efficiency (30A), increase propulsive efficiency and reduced noise (35A) and low NOx combustor designs for high OPR engines (40A). The technical content, goals and objectives of the propulsion ITDs are described next.

30A: Highly Loaded Front Block Compressor

ITD30A addresses the compressor technologies to enable high efficiency and high Overall Pressure Ratio core engines. OPR and component efficiencies are known to be key drivers to reduce gas turbine engine fuel consumption. Specifically the goal of ITD30A is to increase efficiency and to increase pressure rise by

Table 2: Technical Focus Areas (TFAs) and Technical Challenges (TCs).	
TFA 1	**Innovative Flow Control Concepts for Drag reduction**
	TC 1- *Demonstrate drag reduction of 8 percent, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, without significant penalties in weight, noise, or operational complexity*
TFA 2	**Advanced Composites for Weight reduction**
	TC 2- *Demonstrate weight reduction of 10 percent compared to SOA composites, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, while enabling lower drag airframes and maintaining safety margins at the aircraft system level*
TFA 3	**Advanced UHB Engine Designs for Specific Fuel Consumption and Noise reduction**
	TC 3- *Demonstrate UHB efficiency improvements to achieve 15% TSFC reduction, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, while reducing engine system noise and minimizing weight, drag, NOx and integration penalties at AC system level*
TFA 4	**Advanced Combustor Designs for Oxides of Nitrogen Reduction**
	TC 4- *Demonstrate reductions of LTO NOx by 75 percent from CAEP6 and cruise NOx by 70 percent while minimizing the impact on fuel burn at the aircraft system level, without penalties in stability and durability of the engine system*
TFA 5	**Airframe and Engine Integration Concepts for Community Noise and Fuel Burn Reduction**
	TC 5- *Demonstrate reduced component noise signatures leading to 42 EPNdB to Stage 4 noise margin for the aircraft system while minimizing weight and integration penalties to enable 50 percent fuel burn reduction at the aircraft system level*

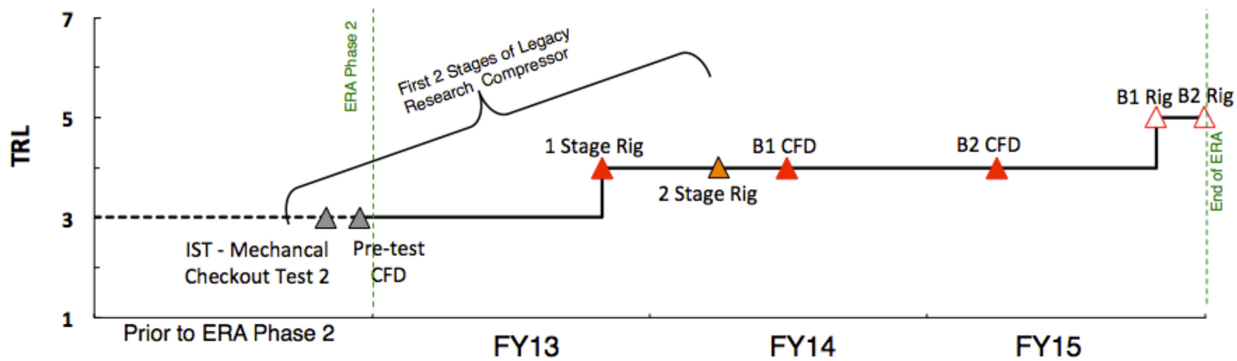


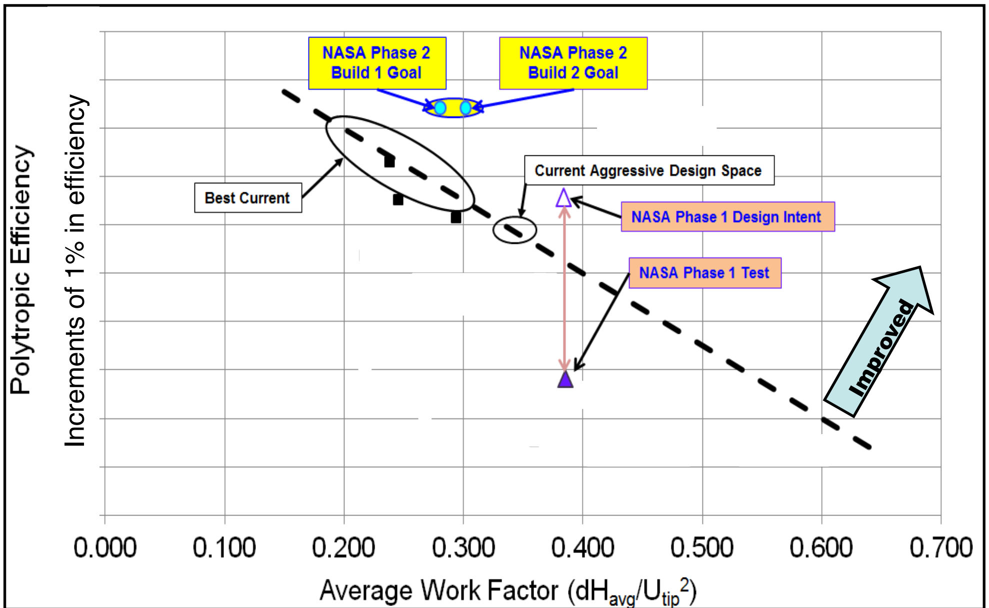
Figure 2: ITD30A TRL maturation timeline.

30% relative to the ERA baseline engine (described later) to achieve a 2.5% reduction in engine specific fuel consumption.

ITD30A included two test and analysis campaigns that explored the design space to improve the compressor OPR (blade loading) and efficiency without negatively impacting weight, length, diameter, and operability. The timeline and major milestones for this activity are identified in Figure 2. The two major campaigns will be referred as ERA Phase 1 and ERA Phase 2 in this paper. ERA phase I investigated the front 2 stages of a legacy high OPR 6 stage core compressor and its major milestones are those up to and including the 2 stage rig element in Figure 2. Whereas, ERA Phase 2 focused on 2 major builds of a new compressor design and its elements are represented by the build 1 and build 2 CFD analyses (B1 CFD and B2 CFD) and rig tests (B1 Rig and B2 Rig) shown in Figure 2. A pictorial view of the design space evaluated by ITD30A is found in Figure 3. More details and results to date for each Phase of ITD30A are described below.

ERA PHASE 1

In ERA phase 1, a high OPR compressor design that failed to meet the efficiency and operability design goals was investigated. This design pushed the SOA design space to higher blade loading levels (pressure rise per stage) with increased efficiency relative to the best current designs. Unfortunately the efficiency and operability goals were not obtained at this high blade loading. The high losses and operability issues were attributed to the front 2 stages of this highly loaded 6-stage compressor design. The front 2 stages are transonic across the span and therefore, their performance is very sensitive to variations in the effective flow area which can affect the location and strength of the passage shocks and further impact flow separations and/or low momentum and loss regions due to the shock and/or blade row interactions. Figure 4 shows the results of an unsteady CFD analysis of the front 2 stages of the compressor and it highlights the entropy (loss) regions for the transonic compressor flow field. Therefore, the goals in phase 1 were to isolate, analyze and test the first two stages of a transonic state-of-the-art high pressure compressor in order to 1) understand the flow physics that resulted in high losses, 2) characterize the blade row interactions and their impact on loss, and 3) validate the design methodology and capability of the prediction tools by comparisons with the experimental results.



Compressor loading diagram showing low measured efficiency of legacy highly loaded compressors relative to design intent, and aggressve Phase 2 goals

Figure 3: ITD30A Compressor Design Space for phase 1 and phase 2 relative to state-of-the-art best current practices as indicated by the dashed line.

NASA tested the first two stages of an advanced GE Core Compressor using state-of-the-art research instrumentation to investigate the loss mechanisms and interaction effects of embedded transonic highly loaded compressor stages. The high-speed multistage compressor test facility, W7 in the Engine Research Building (ERB) at NASA Glenn Research Center was used to run this test. The inlet to the core compressor modeled the inlet conditions to an HPC of an engine inclusive of fan frame struts and a transition duct from the LPC to the HPC compressor. GE provided the advanced two-stage compressor rig and test support. The test plan focused on making steady and unsteady measurements for the single stage and then again after adding the 2nd stage to enable evaluation of the performance and losses in each stage. This approach enabled the ability to sort out the loss contributions from each stage and provided detailed data to define the inlet boundary conditions to the compressor.

For both stage 1 and 2-stage configurations, detailed data was taken at 97% design speed, acquiring data from LE instrumentation, wall statics, over the rotor Kulites, and traversing probes. The results indicated that stage 2 was choking at a mass flow rate that prevented stage 1 from reaching its peak efficiency point, leading to a stage mismatch issue. The mismatch is thought to be due to a loss in the first stage that was unpredicted by design tools. Assessment of stator 1 leading edge measurements in both test configurations revealed that the level of performance at this location is unaffected by the presence of the second stage. Therefore, the major source of unexplained loss resulted from the first stage of the compressor. For additional details and discussion of the CFD analysis and experimental test results refer to Celestina, et al., 2012 and Prahst, et al., 2015.

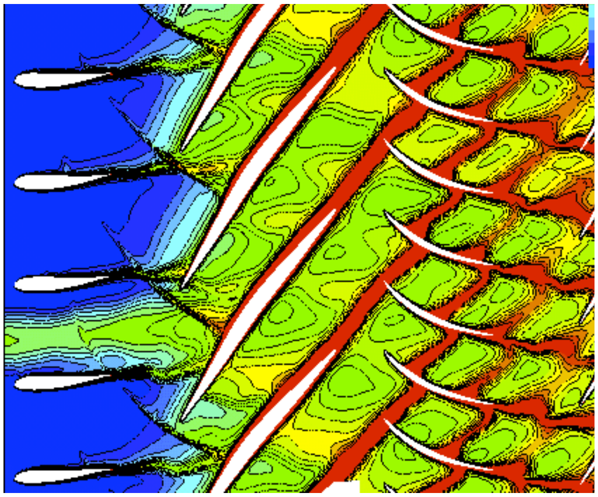


Figure 4: Unsteady Interactions Predicted by CFD: Entropy Plot

ERA PHASE 2

ERA Phase 2 utilized a completely new core compressor design strategy and leveraged lessons learned from the phase 1 compressor design. The Phase 2 compressor was designed for increased efficiency and blade loading. Note the efficiency levels are higher than phase 1 and the blade loading levels were increased relative to best current design but not to the higher levels of blade loading that were attempted in the Phase 1 design which was discussed in the previous paragraphs. Refer to Figure 3 which highlights the design space of the phase 1 and phase 2 compressors, relative to each other and to the SOA designs.

NASA plans to test the first 3 stages of a high efficiency, high OPR core compressor design in the same NASA facility as the phase I testing. The phase II compressor test program will consisted of a build 1 test and a build 2 test where the primary difference is that build 2 is designed to achieve higher compressor blade loading (pressure rise per stage) at the same efficiency levels of build 2 - as shown in Figure 3. The higher blade loading of build 2 would provide an overall system benefit because the compressor bleed locations could be moved further upstream; thereby reducing the compressor work required to provide the bleed flow. Extensive CFD simulations have been conducted by both NASA and GE and the CFD results are not only in agreement with each other but are also in agreement with the design intent. Testing of the phase 2 build 1 and build 2 tests is expected to occur in the 3rd and 4th quarters of 2015. No results are available to report at this time.

35A: Second Gen UHB Propulsor Integration

ITD35A matured several low FPR propulsor technologies through a series of model scale wind tunnel tests as shown on the timeline in Figure 5. Test results validated both aerodynamic and acoustic performance of the technologies. Performance goals for ITD35A for TC3 were a 9% reduction in TSFC and a 15 EPNdB cumulative noise reduction relative to the baseline engine due to the propulsor section technologies. The test hardware configuration, objectives and overall results are described next for each major test entry.

GTF Gen-2 Test (Rig 1):

Prior to the current ERA effort the Gen-1 GTF test series demonstrated the efficiency gains that were possible with low FPR, geared fan propulsor systems. The fan architecture tested eventually evolved into the PW1500G engine shown in Figure 6. The success of the Gen-1 propulsor motivated the desire to 'grow' the technology to larger thrust class engines and to further mature the technologies necessary to enable these larger engines. The addition of a gear to the fan drive system allows the low tip speed, low FPR fan to be coupled to a smaller, more efficient, high speed core. This shifts the minimum fuel burn FPR to a lower value as shown in Figure 7. However, note that the fan diameter is also increasing to produce an

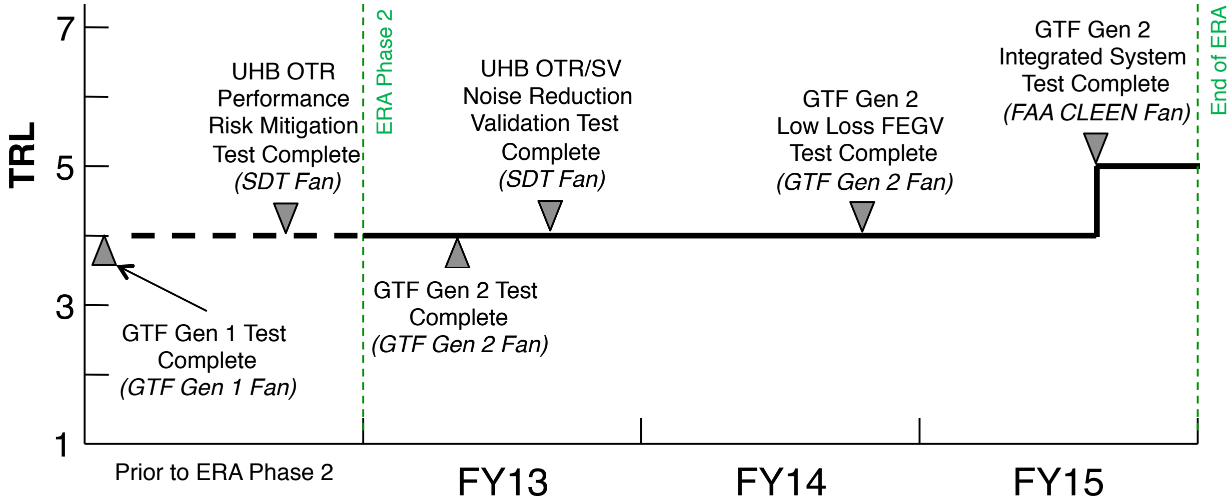


Figure 5: ITD35A TRL maturation timeline.

equivalent amount of thrust. For higher thrust class engines, the nacelle will become prohibitively large with high drag unless reduced length nacelles are also implemented (Peters, et al., 2014). These configuration changes are beneficial for fuel burn but potentially detrimental for acoustics thus additional noise reduction technologies were explored as well.

Figure 6: PW1500G engine on test stand (from P&W, 2015).

NASA Noise Reduction Technologies:

For engines with large diameter fans and reduced length nacelles the internal surface area for acoustics liners is reduced and the effectiveness of the liners is also lowered due to the less optimal L/D of the bypass duct. To increase the acoustic treatment area in the propulsor the NASA ERA program developed two advanced liner concepts; over the rotor (OTR) and soft vanes (SV).

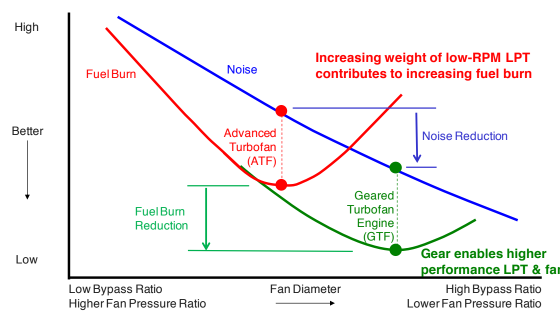


Figure 7: Fuel burn and noise characteristics of advanced turbofans and geared engines (from P&W, 2015).

The OTR concept is an acoustically designed casing treatment which is located over the rotor tip region. The details are not releasable as a patent is in process. The design intent is to absorb pressure fluctuations at the source before the sound can propagate to the far field. The SV concept uses cylindrical, folded passages in the fan exit guide vanes to absorb pressure fluctuations at their source. Both concepts are used to increase the acoustically treated area within the propulsor.

The OTR/SV concepts were tested in a legacy 1.5 FPR fan, both in a rotor only configuration to analyze any performance impact (Bozak, 2014) and in a flight nacelle configuration to measure the acoustic character. The nacelle configuration is shown schematically in Figure 8. The rotor alone measurements showed a minimal and acceptable loss in efficiency due to the OTR treatment. The acoustic results from the flight nacelle showed a noise reduction for the SV concept of 1.5 dB but no noise reduction for the OTR concept. Manufacturing difficulties for the OTR concept and acoustic design limitations for the rotor tip flowfield conditions are the likely causes of the inconclusive acoustic results for the concept.

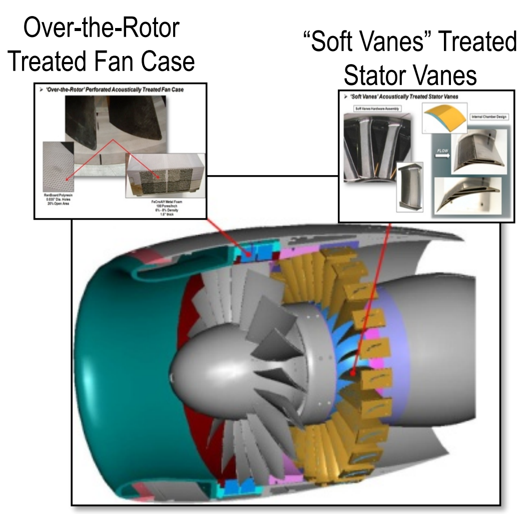


Figure 8: Over the rotor (OTR) and Soft Vane (SV) acoustic concepts in the legacy 1.5 FPR fan model.

Gen-2 Low Loss FEGV Test (Rig 1a):

For low FPR engine cycles the pressure losses in the bypass duct have an increased influence on engine SFC relative to legacy engines. P&W/NASA tested concepts for low loss fan exit guide vanes (LLFEGVs) and 3D endwall contouring with the wind tunnel model configuration known as Rig1a. As implied by the name, the Rig 1a test used the same low FPR fan as Rig 1, but replaced the FEGVs with two more advanced configurations that incorporated lean, sweep and/or endwall contouring in combination with axial spacing changes to limit total nacelle length. Legacy values for duct/FEGV pressure loss are on the order of 1.2%. The Rig1a test was successful at validating lower duct/FEGV pressure losses for the advanced configurations. The acoustic character of the configurations was measured and used to inform the system analysis for the 2025 Vision System discussed later.

UHB Gen-2 Integrated System Test (Rig 2):

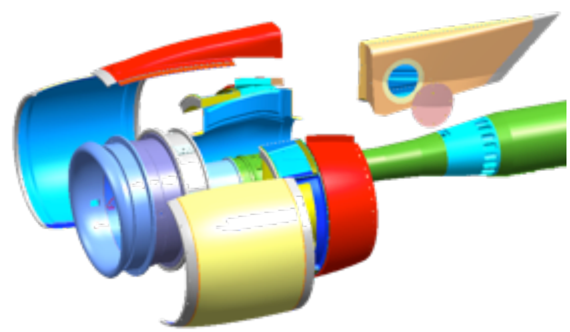


Figure 9: The UHB Integrated system (Rig 2) test wind tunnel model geometry (from P&W, 2015).

The final test of the series, known as Rig 2, used a model scale version of the FAA CLEEN engine. The wind tunnel model contained many of the features of an engine such as a drooped inlet, pylon/bifurcation in the bypass duct, classed exit guide vanes and a non-axisymmetric bypass duct. An exploded view of the model is shown in Figure 9. A primary objective of the experiment is to compare model scale acoustic results to those from the engine during a static test. The wind tunnel test finished in June 2015; not in time to include results in this paper. The static engine test is scheduled for early 2016 as part of the FAA CLEEN program. Results and comparisons of

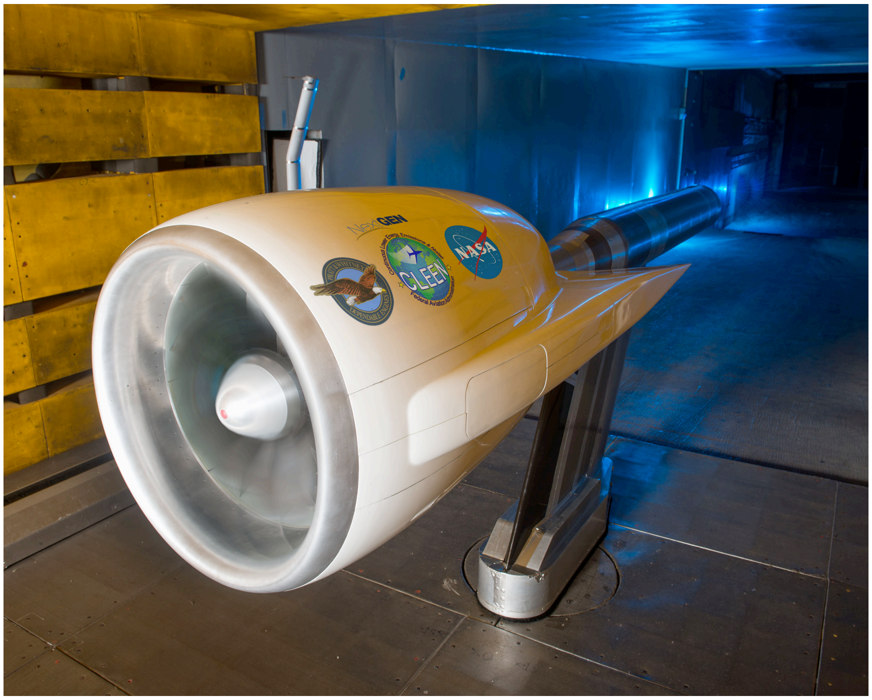


Figure 10: The UHB Integrated system (Rig 2) test wind tunnel model in the acoustic configuration in the 9x15 LSWT.

the data will come after the engine test is complete.

40A: Low NOx Fuel Flexible Combustor Integration

ITD40A matured a new fuel-flexible combustor concept from P&W that maintains low NOx emissions at the higher P3/T3 cycle conditions of future engines. The performance goal for ITD40A for TC4 was a 75% reduction in LTO NOx relative to the CAEP6 standard. The lean-lean concept, called the Axial Stage Combustor (ASC), is shown schematically in Figure 11. The ASC concept uses a pilot injector at the front of the combustor for low power conditions. Additional main injectors are used in addition to the pilot injector for high power conditions. The fuel-air mixture is kept lean through the entire axial length of the combustor. The lean burn configuration is necessary to maintain low NOx production at the N+2 cycle conditions.

A series of flame tube, sector and full annular rig tests both at P&W and NASA validated the performance of the concept. The technology maturation timeline is shown in Figure 12. The objectives and results of the various tests are described next.

ERA Phase 1 technologies:

The 75% LTO NOx reduction goal was considered a significant challenge for partial pre-mix combustor configurations at the start of ERA Phase 1. ERA pursued partial pre-mix concepts from both P&W and GE. As risk mitigation, ERA studied lean direct injection (LDI) concepts from three injector manufacturers in case the partial pre-mix systems showed unresolvable autoignition issues at the higher P3/T3 conditions. Active control strategies were also studied to mitigate any stability issues that may arise for the lean burn concepts. Finally, alternative fuel blends up to 100% were studied as a possible replacement for Jet-A to improve NOx performance. Details of the ERA Phase 1 testing are described in Suder, et al., 2013.

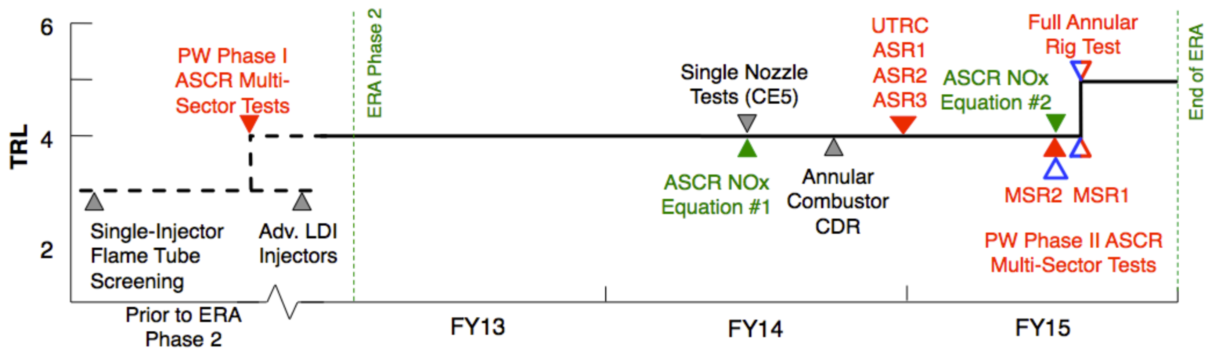


Figure 12: ITD40A technology maturation timeline.

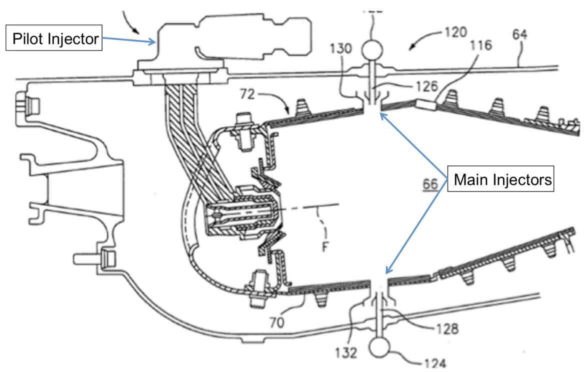


Figure 11: Axial Stage Combustor cross-section from U.S. Patent 9,068,748.

At the conclusion of Phase 1 testing the partial pre-mix concepts from both P&W and GE had shown the potential to meet the LTO NOx goal, without LDI, active combustion control or alternative fuels. The P&W concept was chosen for continued technology maturation in ERA Phase 2.

The technology maturation plan involved parallel research activities at different TRL levels. For example, low TRL flame tube tests of swirler concepts were ongoing throughout much of Phase 2 as shown in Figure 13. The most promising swirler concepts at the time were downselected for demonstration in sector tests. Furthermore, it was necessary to freeze the swirler design for the full annular rig before all of the sector rig tests were complete. In this way the best technology available was demonstrated to the highest TRL possible as allowed by the design/test schedule.

The LTO NOx performance of ASC concepts was validated in the ASCR facility at NASA GRC. The ASCR test chamber can reach pressures of 900psia at inlet temperatures of 1300F for flow rates to 30 lb/s thus allowing concepts to be tested at N+2 P3/T3 conditions. Injector/swirler concepts for the sector test at ASCR were pre-screened in flametube tests at NASA and UTRC as well as a sector test at UTRC at lower pressure conditions. The combustor sector mounted for the test at UTRC is shown in Figure 14. The same sector hardware was subsequently tested at ASCR to full engine conditions including SLTO P3/T3.

The ASC sector was tested over the range of P3/T3 conditions estimated for the engine cycle. Pressure, temperature and fuel/air ratio excursions were investigated around each set point to characterize the emissions sensitivity and to better optimize the combustor design. The emission performance of the Phase 2 hardware was good; results from the UTRC sector tests are shown in Figure 15. Additionally, the sector was tested with a 50/50 blend of alternative fuel to evaluate any fuel flexibility issues. The combustor emissions performance and operability characteristics with the fuel blend were nominally unchanged from the results with Jet-A.

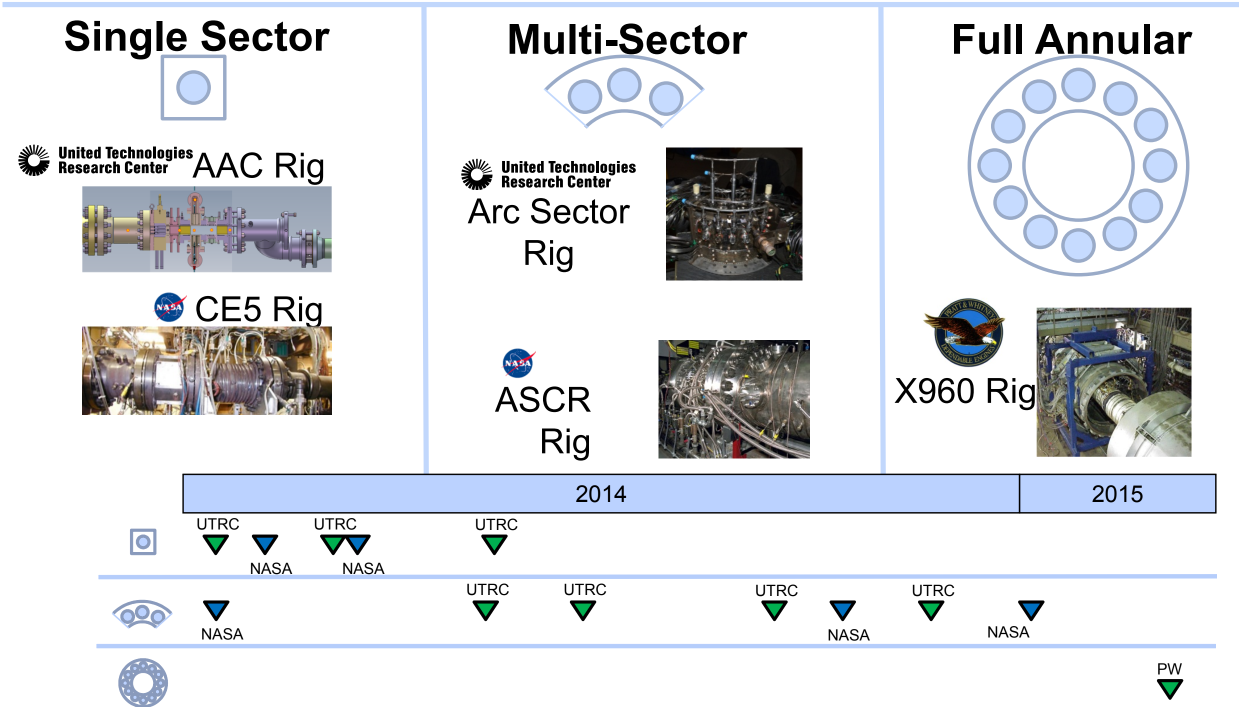


Figure 13: The ASC development strategy for concurrent low and mid TRL testing. (from Smith, 2015)

The full annular combustor test, which used the same injectors/swirlers as the ASCR sector, was completed in June 2015. Preliminary analysis of results confirmed the LTO NOx data from ASCR. The full annular test included thermal paint measurements to assess combustor durability. Complete results from the test will be included in a future publication.

System level contributions of propulsion technologies

ERA used a 2025 Vision System and demonstration by analysis to evaluate the performance of the propulsion technologies, both aerodynamically and acoustically, on the future system and fleet. The baseline system is a NASA derived representation of a Boeing 777-200LR aircraft with GE90-110 engines. The baseline mission is 7500nm with 301 passengers and 50,000lb of cargo. This is a Large Twin Aisle (LTA) class aircraft.

NASA modeled an LTA aircraft/engine system that incorporated the specific ITD technologies as well as other N+2 timeframe technologies. The technologies included must be TRL6 by 2020, so that inclusion in a 2025 product is feasible.

CFD and CAA results were also used as interim input for the systems analysis for 30A and 35A while waiting for final experimental confirmation from the test programs. For example, P&W did extensive CAA predictions of the pylon/bifurcation acoustic effect that was then validated with the Rig 2 test.

For the propulsion system, both a direct drive and a geared fan drive engine system were modeled. The overall engine parameters are shown in Table 3 for two of the four conditions considered in the cycle design. The direct drive compression system cycle design was directly influenced by the technologies and results from the

ITD30A work. Similarly, the geared engine propulsor cycle details were informed by results from ITD35A.

The LTO NOx evaluation was done using engine state information from the advanced engine NPSS models and the NOx production correlation equations derived from the ASCR test data. The ITD40A technology influence comes through the measured combustor emissions performance and not through any direct change to engine cycle parameters.

Figure 14: Phase 2 sector rig being prepared for testing at UTRC. (from Smith, 2015)

The acoustic system analysis used the ANOPP code with a combination of existing acoustics models and wind tunnel test data. The acoustic data from ITD35A was used to estimate the propulsor noise contribution from the geared engine. The direct drive engine used the internal ANOPP fan noise model. All propulsor noise estimates were adjusted for engine configuration specific parameters such as rotor-stator spacing, FEGV sweep and lean and pylon/bifurcation effects. Details of the system noise estimates will be contained in a future publication.

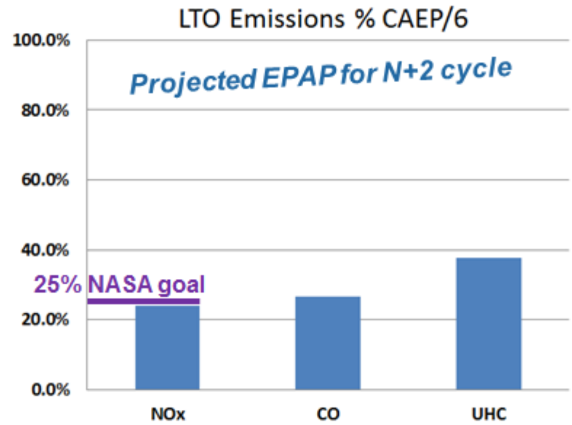


Figure 15: Emissions estimates for the ASC combustor based on sector tests at UTRC. (from Smith, 2015)

Table 3: Cycle parameters for advanced geared and direct drive engines for the LTA seat class aircraft.

Architecture	Geared		Direct Drive	
Flt Condition	TOC	RTO	TOC	RTO
Mach, Alt	0.8, 35 kft	0.25, 0	0.8, 35 kft	0.25, 0
Fnet, Lbf	16100	59090	15800	57265
OPR	60.0	46.3	60.0	46.9
BPR	20.6	23.6	14.6	16.7
FPR	1.35	1.25	1.50	1.36
HPC PR	14.8	13.6	27.0	24.4
% Turbine Cooling	17.2		16.1	

The advanced engine cycles were not only used to assess progress of the 2025 aircraft systems toward the overall ERA goals but also to evaluate the ERA technologies' progress toward the technical challenge level goals. ITD30A and 35A contribute to the TC3 goals of 15% TSFC reduction and 15 EPNdB cumulative noise reduction relative to the baseline system. The TC4 goal is 75% LTO NOx reduction relative to the CAEP6 regulation.

The propulsion ITD results to date are shown in Table 4 for TC3 and TC4. Note that the total TC3 TSFC goal cannot be achieved with only the ITD technologies. Additional core engine technologies, such as ceramic matrix composites, would be required to fully achieve the TSFC goal. The ITD technologies are sufficient to achieve the noise and NOx goals.

Table 4: TC level system analysis results for the propulsion ITDs.

	30A	35A	40A	Goal
TC3: TSFC	2.4%	10.4%	N/A	15%
TC3: noise	N/A	20.9	N/A	15 EPNdB cum.
TC4: LTO NOx	N/A	N/A	78.8	75% rel. CAEP6

Summary

ERA was the first NASA Aeronautics Research Mission Directorate Project that was established for a finite lifetime of 6 years and therefore, was very much schedule driven. ERA was focused on the N+2 Aeronautics Subsonic transport goals and strived for simultaneous reductions of Noise, NOx emissions, and fuel burn as evaluated at the integrated vehicle level. Systems analysis integrated the results from the technology demonstrations to assess the impact of the technologies toward meeting the Aeronautics goals. This paper focused on the combustion, propulsor, and core technologies that were developed and demonstrated in partnership with industry to enable an aircraft that reduces fuel burn by 50%, reduces Landing and Take-off Oxides of Nitrogen emissions by 75% relative to the CAEP 6 guidelines, and reduces cumulative noise by 42 Decibels relative to the Stage 4 guidelines. The reductions in fuel burn, emissions, and noise are based on a reference mission of 7500nm flight of a Boeing 777-200LR with GE90-110 engines. The benefits of the propulsion technologies developed in the ERA project have been assessed and the results to date indicate the advanced engines can reduce the fuel burn by 15% and the LTO NOx goal of 75% reduction below CAEP 6 is feasible. The noise reduction goal for the higher bypass propulsors is exceeding the goal of 15 EPNdB. The systems analysis to evaluate benefits of all the ERA technologies and 8 integrated technology demonstrations in the ERA project is still underway, but results are promising towards meeting the fuel burn and emissions goal. However, in order to meet the noise goal advanced vehicle architectures that help shield the engine noise are required. Results of the overall ERA system level assessments are expected in early CY2016.

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