

NASA Project Develops Next-Generation Low-Emissions Combustor Technologies

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NASA's Environmentally Responsible Aviation (ERA) Project is working with industry to develop the fuel flexible combustor technologies for a new generation of low-emissions engine targeted for the 2020 timeframe. These new combustors will reduce nitrogen oxide (NOx) emissions to half of current state-of-the-art (SOA) combustors, while simultaneously reducing noise and fuel burn. The purpose of the low NOx fuel-flexible combustor research is to advance the Technology Readiness Level (TRL) and Integration Readiness Level (IRL) of a low NOx, fuel flexible combustor to the point where it can be integrated in the next generation of aircraft. To reduce project risk and optimize research benefit NASA chose to fund two Phase 1 contracts. The first Phase 1 contracts went to engine manufacturers and were awarded to: General Electric Company, and Pratt & Whitney Company. The second Phase 1 contracts went to fuel injector manufacturers Goodrich Corporation, Parker Hannifin Corporation, and Woodward Fuel System Technology. In 2012, two sector combustors were tested at NASA's ASCR. The results indicated 75% NOx emission reduction below the 2004 CAEP/6 regulation level.

I. Introduction

NASA's ERA Project is working with the industry to develop the combustor technologies for a new generation of low-emissions engines targeted for the 2020 timeframe. These new combustors will reduce nitrogen oxide (NOx) emissions to half of current state-of-the-art (SOA) combustors, while simultaneously reducing particulate emissions.

NASA has been driving the NOx reduction effort in the aviation industry over the last three decades, resulting in approximately 50% reduction every generation of about 15 years. The initial concerns were health issues such as ground-level NOx and its contribution to photochemical smog. As a result, a series of increasingly stringent NOx emission standards by the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) has, over the years, regulated aviation emissions below 3,000-foot altitude. These standards cover the take-off, climb, descent, and taxiing/ground idle phases of the engine operation, the so-called landing and take-off (LTO) cycle, in a prorated fashion. With forward-thinking research, the aviation propulsion industry has turned these past NASA-sponsored combustor concepts into flight hardware.

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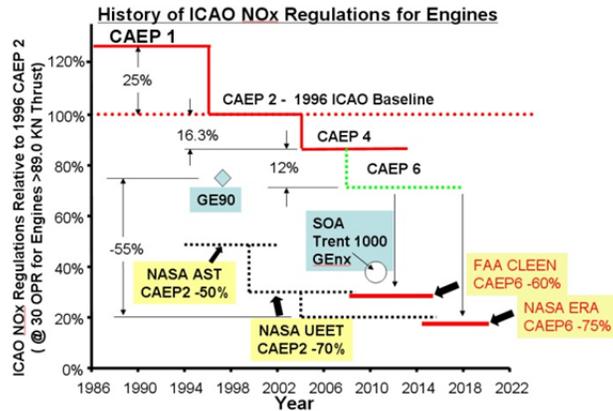


Figure 1 History of ICAO NOx regulation for engines and NASA program goals

This continuing NOx-reduction effort is even harder under ERA than it was under previous programs. After three decades, the existing NOx level is already pretty low and there's not much room from which to squeeze further improvements (Figure 1). At the same time, ERA's system-level goal also includes a 40% reduction in fuel consumption for the airframe platform. While much of these savings may be taken up by airframe drag reduction, the contribution required from engine efficiency improvement means increasing the engine Overall Pressure Ratio (OPR) to about 55 from the SOA 45. This increased combustor pressure and temperature also increases the NOx formation rate. Thus, ERA's NOx-reduction effort fights on two fronts. On top of these, these concepts also are required to operate on 50/50 blend of alternative hydrocarbon fuels.

Fuel-air mixture preparation before burning starts affects what a combustor emits. The fuel from the fuel injectors sprays in as liquid, and it needs to vaporize and mix with the air before burning can occur. A very non-uniform mixture (with some pockets being too fuel-rich and some too fuel-lean) can lead to unacceptable levels of carbon monoxide (CO), unburned hydrocarbons, and soot due to quenching or inadequate residence times to achieve complete burnout. In contrast, some near stoichiometric pockets of fuel-air mixtures will burn very hot and produce NOx very quickly. Since NOx emission level is the time integral of the nitrogen-oxide's formation rate, the latter being an exponential function of the air temperature, NOx emission level correlates well to the fuel injector's ability to prepare the fuel-air mixture. Mixing the fuel as quickly and uniformly as possible before burning starts is a key technology for clean burning. The difficulty is in doing it during the available time, which must decrease with increasing temperature and pressure due to risk of autoignition.

Fuel-air can mix faster if the fuel can be introduced through smaller holes in fuel injectors to speed up breakup and vaporization. However, fuel heats up going through the fuel passage. Eventually, some components in the fuel reacts with the dissolved oxygen and breakdown into a gummy substance which in time turns into carbon buildup (coking) that blocks the fuel passage. Increasing the OPR increases the air temperature and speeds up coking. The availability of alternative hydrocarbon fuels that don't coke easily enables the use of smaller injection passages to speed up fuel-air preparation.

Every fuel injector also has its own combustion dynamics characteristic in which fluid dynamics interact with the combustion process. When the time scale and phase match, they can interact with the combustor acoustics to set up instabilities or limit-cycle behavior that can result in severe pressure oscillations, or disrupt the normal flame stabilization process. Thus, designing a fuel injector that mixes quickly, resists coke formation, burns stably, and still operates over a wide range of power conditions is key in bringing a new generation of cleaner-burning combustors on line.

Higher OPR combustion will need combustor liners able to withstand higher temperatures. Ceramic matrix composite (CMC) liner materials and environmental barrier coatings (EBC) are complementary enabling technologies to the new injectors. A CMC liner can withstand higher temperatures than a traditional metal liner, while needing less cooling air. This capability allows the extra air to be used in the fuel injector to increase fuel-air mixing, which in turn provides a more uniform mixture with fewer hot spots such that the liner need less air for

cooling. EBCs protect the CMC surface from oxidation as well as allowing the CMC liner to operate cooler and extend the liner's life.

II. Ultra Low-Emissions Combustor Concept Developments

Currently, NASA's ERA project is working on fuel-flexible combustor technologies for the next generation commercial aircraft engines in the 2020 timeframe. This effort is proceeding on two parallel activities; the **first activity** engages industry partners General Electric (GE) and Pratt & Whitney (P&W) to develop combustor concepts that can achieve the 75% LTO NO_x reduction below CAEP/6 standard. These two contracts are cost-shared and leverage concepts from past NASA-sponsored works and industry partners' internally-developed technology. They cover the full set of combustor challenges with full-sized injectors, liners, as well as the challenge to manage combustor system-level dynamics. This activity starts from flame tube ((Technology Readiness Level (TRL) 3)), through sector combustor form (TRL4) and full-annular combustor (TRL 5), and potentially can go to an engine core demonstration (TRL 6). Both programs also need to demonstrate that their designs can burn a 50%/50% alternative fuel to jet fuel blend. As of the writing of this manuscript, Phase I of these efforts focused on proof of concept, and resulted in two different design concepts that both met the emission goal in multi-cup sector combustors.

A. GE N+2 Advanced Low-NO_x Combustor Technology (ERA Phase I)

GE's concept design started with the legacy Twin Annular Premixing Swirler (TAPS) design that was developed via multiple technology and commercial programs, including GENx and LEAP (Figure 2), and advance the capabilities of this technology to meet the aggressive N+2 NO_x and performance goals. The engine architecture, scale, and cycle were set by an engine-aircraft system analysis, pointing to a conceptual Hybrid Wing Body (HWB) aircraft and engine that could meet the key N+2 objectives for NO_x, fuel burn, and noise reduction. The basic concept behind GE's N+2 combustor design is to increase the fraction of air used for premixing in the front end of the combustor beyond the 70% used in previous TAPS designs [1], while simultaneously adding features that further enhance the fuel-air mixedness. Increased premixing air can present a significant challenge to both operability (efficiency and combustion dynamics) as well as durability (less cooling air for the combustor dome and liner). To meet durability challenges, high temperature ceramic matrix composite (CMC) materials with advanced cooling are utilized for the combustion liners. The new combustor design concepts were benchmarked against data from previous successful development programs. A series of combustion tests ultimately provided the opportunity to down select and further optimize the designs, leading up to the testing of one final configuration in a new 5-cup sector at NASA.

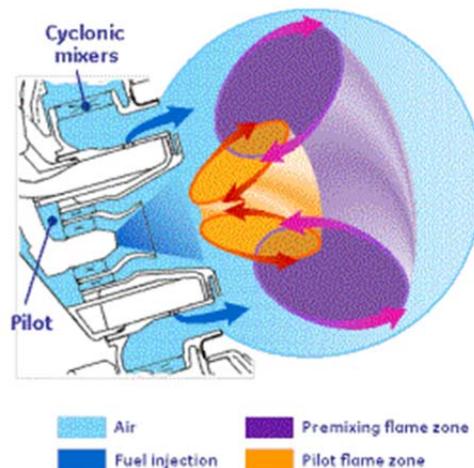


Figure 2. TAPS Mixer Concept [1]

The combustor development program began with an extensive CFD effort to identify and optimize a suite of main mixer/swirler and main fuel injector concepts that could increase fuel-air mixedness while maintaining the required operability across the range of engine cycle conditions. Main stage swirler concepts included multiple designs intended to increase turbulence for fuel-air mixing, while simultaneously avoiding generation of such excessive turbulence that the swirl number was detrimentally decreased (impacting flame stability) or transporting coherent

turbulence downstream into the flame front (impacting combustion dynamics). Concepts included both co-rotating and counter-rotating vanes. Seven different swirler concepts were down selected and manufactured for the initial flame tube testing, denoted here as M1-M7. (Figure 3)

The CFD effort also explored options for the number and sizing of the main stage fuel injection orifices. Main stage fuel injection concepts included varying both the radial and axial location of fuel injection (relative to the mixer exit), as well as varying the number of fuel injection points. Other concepts explored means for increasing jet penetration into the main stage air flow either mechanically or aerodynamically. Seven different main injection concepts were down selected and manufactured for the initial flame tube testing, denoted F0-F6 (Figure 3). In all of the concept fuel nozzles, a GENx-style pilot was scaled and utilized for the N+2 combustor due to its proven operational capability.

Flame tube testing

In the first combustion screening tests, 13 fuel/air mixer concepts were evaluated in a single-cup flame tube (FT) rig at GE Aviation. The test facility was able to achieve pressure and temperature conditions up to 250 psia and 1000 °F. While this is significantly lower than the take-off and climb cycle points important to the LTO NOx evaluation, the conditions were high enough to enable fully-staged operation (fuel splits similar to the takeoff design point) and perform a relative assessment of the NOx performance of the different designs. NOx emissions and dynamic pressures were measured over a range of temperature & pressure conditions, fuel/air ratios, and pilot/main fuel splits. Comparative data at the 100% ICAO fuel/air ratio (FAR) is shown in Figure 3.

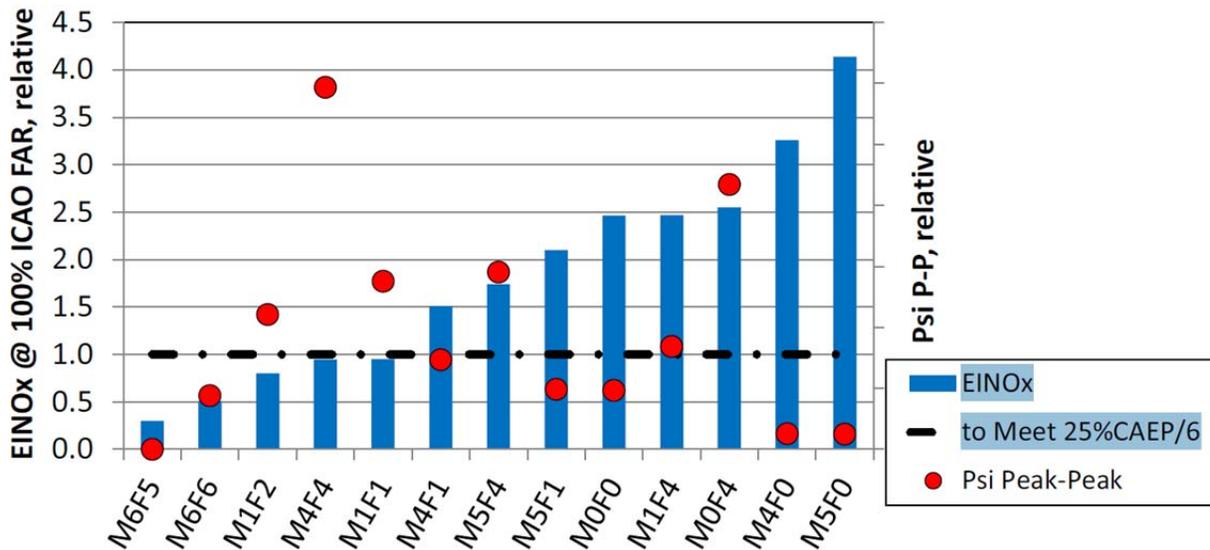


Figure 3: Flametube EINOx emissions and combustion dynamics (100% ICAO fuel/air ratio) at max rig conditions (1000 F/250 psia). The dynamic pressure data represent the maximum peak-to-peak amplitude recorded during steady-state operation at these specific conditions, and serves as a relative indicator of potential dynamics concerns for each concept. A normalized EINOx = 1 indicates the target EINOx value required at these conditions and fuel/air ratio to meet 25% CAEP/6 LTO NOx in the full combustor.

The expected performance of each concept relative to the LTO NOx goal is a critical assessment, and provides a quantitative target for acceptability of any given design. Rig data at this stage of the program was limited to low T₃/P₃ conditions (1000 °F/250 psia) in the flame tube geometry. LTO NOx was therefore estimated from the flame tube data – corrected for T₃, P₃, and flametube-to-engine combustor correlation factors based on legacy programs. Those calculations provide a target EINOx level for the 100% ICAO fuel-to-air ratio, as measured at maximum flame tube conditions, which would be required to meet the 25% CAEP/6 objective in the eventual sector test.

The flame tube testing provided a fairly clear comparison of the performance of the various concepts. The configurations were ranked based on NOx emissions, the most important factor in the down select. Efficiency calculations, based on CO and unburned hydrocarbon measurements, were also evaluated and used to compare concepts. Quantitative efficiency measurements are considered less reliable in the flame tube vs. an actual

combustor due to the differences in flame geometry and recirculation zones; however, these measurements highlight a potential challenge that must be met as combustor designs continue to get leaner and more premixed. At the lower cruise fuel/air ratios, the lowest-NO_x designs also tend to have efficiencies that fall off faster as fuel/air ratio decreases. Finally, dynamic pressure data identified two concepts with elevated concerns for combustion dynamic sensitivities, specifically the M0/M1 mixer family and F4 fuel nozzle design.

Based on flame tube data, 3 concepts were chosen for further design and testing. The M6F6 concept was chosen due to its ultra-low NO_x performance and a slightly better efficiency than the M6F5. The M1F2 concept provided the next-best NO_x performance, with better relative efficiency than M6F6 but somewhat higher dynamic pressure signatures. Finally, the M4F1 concept was chosen for its fairly good NO_x performance, but especially its improved dynamics and slightly better efficiency than the M1F2 concept. These 3 designs provided a range of mixer and fuel injection strategies going into the next round of screening tests.

Tunable combustor acoustics testing

The 3 concepts down selected from flame tube testing were further evaluated in a similar flame tube rig with tunable acoustic boundary conditions. This rig allows a more detailed mapping of the relative acoustic sensitivities of the designs. The dynamics data provide relative comparisons of the operability limits of the three tested configurations, and delineate the differences and features of these designs. At 1000 °F, the M4F1 and M6F6 configurations show acceptable acoustics throughout the desired FAR36 and main/pilot split range of the nozzles. The M1F2 design, with its more aggressive mixer, encounters the dynamic pressure boundary limit at lower FAR36 and Main fuel flow split, making it the less attractive design from an acoustics point of view.

High Temperature/Pressure flame tube testing

In the next round of testing, new engine-style fuel nozzles were manufactured to advance the concepts into the form that would eventually be tested in the 5-cup sector. These final single-cup flame tube tests were designed to validate the concepts at high T₃, P₃ conditions near the 100% ICAO cycle point, including high power emissions measurements and evaluation of durability risk due to autoignition. Three concept nozzles were manufactured, F1, F2, and F6. The F1 and F2 nozzle concepts were slightly modified to improve durability as well as achieve an expected further reduction in NO_x emissions. Both nozzles were tested with the M4 mixer due to its lower acoustics sensitivity compared to M1.

Area-averaged NO_x data for all three tested configurations at 85% and near-100% ICAO generated the final ranking of the concepts for with respect to LTO NO_x. The less aggressive mixing of the M4F2 resulted in predictably worse NO_x than the M4F1. Similar to the initial flame tube measurements, the M6F6 configuration exhibits the best NO_x performance but worse CO (and therefore efficiency) compared to the M4 designs.

Autoignition margin data

The high temperature/pressure flame tube rig also was utilized to collect autoignition data for all 3 configurations. Autoignition boundaries were mapped at various combustor inlet conditions up to the maximum facility capabilities. Autoignition data were reduced using GE design tools, and a relative risk is calculated for the different designs at 100% ICAO N+2 conditions on Jet-A fuel. Of the three designs, only the M4F1 meets the criteria for acceptable operational margins. The risk level can be reassessed for the specific alternative fuels of interest for use in future NASA testing at the Advanced Subsonic Combustion Rig (ASCR).

Conclusions for flame tube testing

Data from the 3 flame tube test campaigns is summarized in Table 1, and leads to the down select of one design for the 5-cup sector. An LTO NO_x reassessment, based on the high temperature & pressure flame tube data, indicated that all 3 designs could likely meet the 25% CAEP/6 NO_x target. This assessment uses a correction for flame tube vs. sector emissions data. Among the 3 designs tested in all 3 rigs, the M4F1 design resulted in the best balance between NO_x emissions performance, combustion efficiency, autoignition margin, and combustion dynamics; and was selected for the sector test.

Table 1: Summary of flametube results at 100% ICAO FAR for the top concepts

TCA/HTP Configs	FT Normalized EINO _x	FT P4' p-p Ranking 1=Best	FT Cruise Eff. Randing 1=Best	TCA P4' p-p Relative to max limit	HTP Normalized EINO _x	HTP A/I margin Relative to limit
M6F6	0.512	1	3	-	0.343	-
M1F2	0.8	3	2	>		
M4F2					1.07	-
M4F1	1.509	2	1	<	0.72	+

Sector testing

A major part of the combustor development program was the design and manufacturing of a new 5-cup sector rig for operation at the NASA ASCR facility (Figure 4). The combustor design utilizes high temperature CMC liner materials in order to reduce cooling air requirements and enable the high mixer air flow split. Mechanical and thermal analyses were performed, and the cooling design and mechanical construction were optimized to ensure viability of the hardware up to the takeoff conditions of the engine cycle.



Figure 4: GE N+2 5-cup CMC combustor sector rig.

The combustor rig has 4 emissions rakes, each with 4 sample elements. Rakes are located within Cups 2, 3, and 4 and are spaced in different locations relative to the cup centerline in order to capture a comprehensive averaged sample when all 16 sample points are ganged together (Figure 5). Generally, data is taken at a fixed rig T₃, P₃, and dP/P₃ while the overall fuel-to-air ratio is swept over the range of interest.

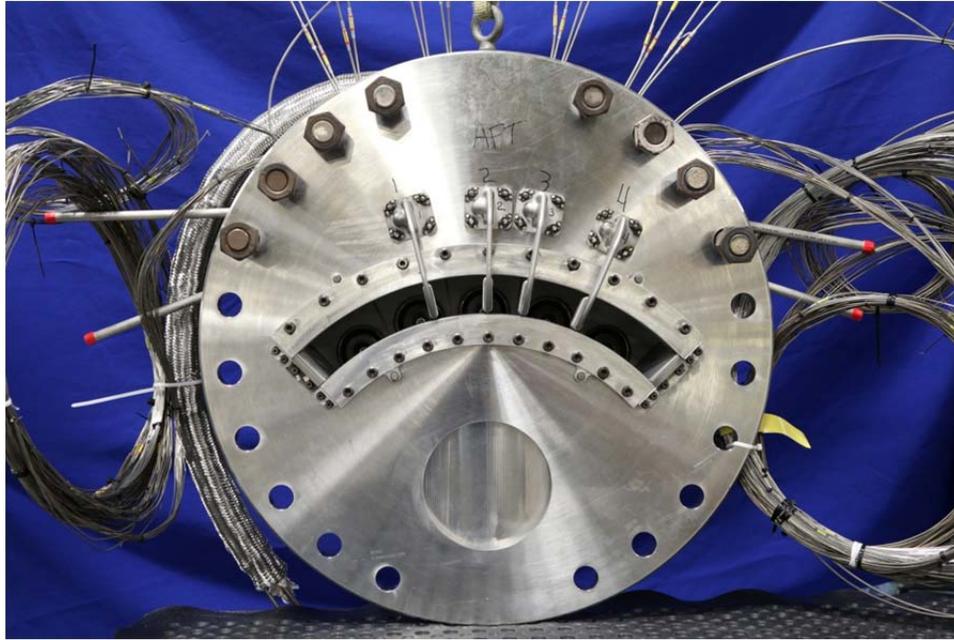


Figure 5: GE N+2 sector rig - emissions rake layout.

Combustor emissions data is presented in Figure 6 through 8. Data for 7% ICAO is shown in Figure 6. Additional single points taken on 2 other test days are shown to confirm fairly good repeatability of the data. Data for 30% ICAO is shown in Figure 7. High pressure data at the maximum main fuel split, used to determine NO_x at the 85 and 100% ICAO points, is shown in Figure 8.

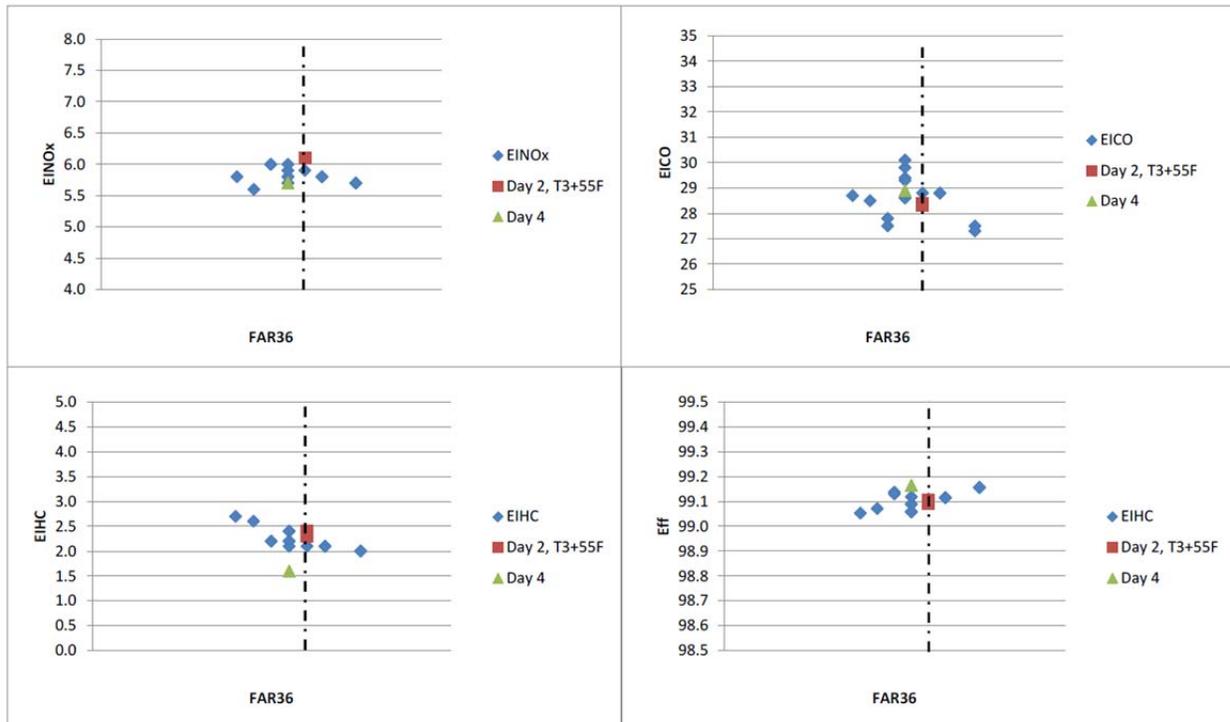


Figure 6: Sector rig emissions data (EINO_x, EICO, EIHC, and combustion efficiency) at the 7% ICAO point, plotted vs. the fuel/air ratio based on sampled emissions. Repeated points taken on 2 additional test days are shown for repeatability. The vertical line indicates the target 7% ICAO cycle fuel/air ratio.

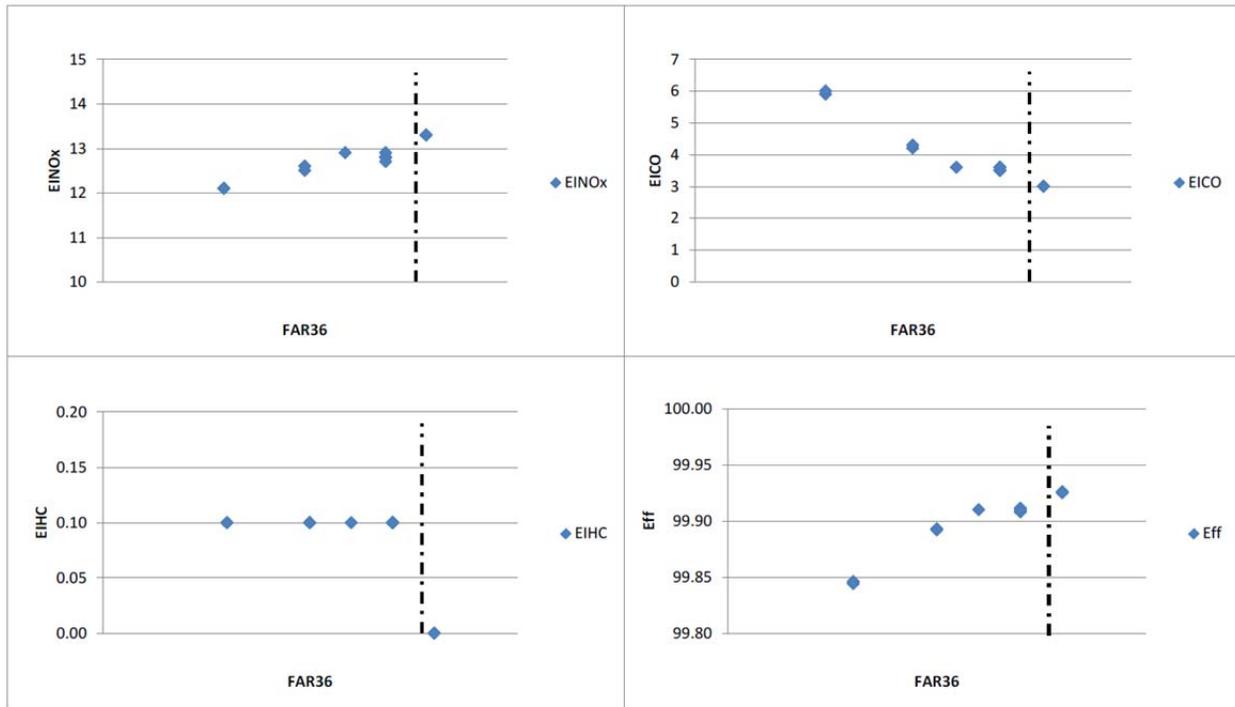


Figure 7: Sector rig emissions data (EINOx, EICO, EIHC, and combustion efficiency) at the 30% ICAO point. The vertical line represents the target fuel/air ratio.

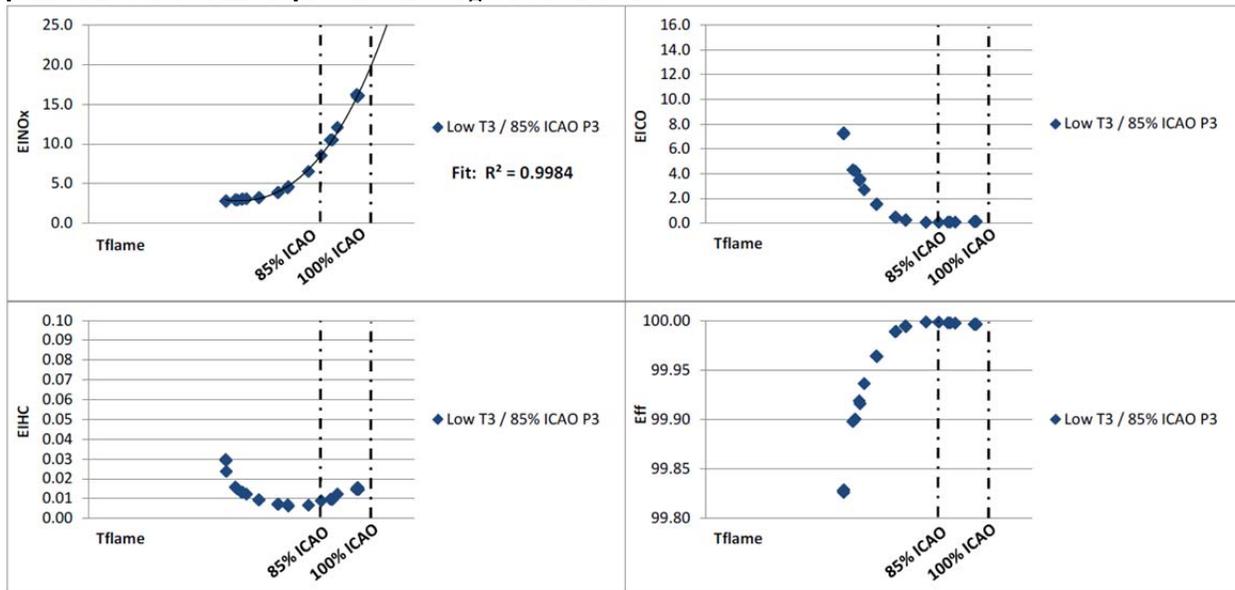


Figure 8: High pressure, fully staged emissions data at the 85% ICAO P₃ and maximum facility T₃ for this air flow rate, for determination of the 85 and 100% ICAO NO_x values. Vertical dashed lines represent the target cycle flame temperature for 85% and 100% ICAO.

In general, NO_x emissions results in the sector tests were in line with expectations based on correlations (low power, pilot-only points) and the high temperature/pressure flame tube data (high power, fully staged operation). Table 2 summarizes the LTO NO_x data for the ICAO points. The facility was unable to deliver T₃ temperatures high enough to run the 85% and 100% ICAO points at the exact T₃/P₃/flow/FAR (fuel-to-air-ratio) conditions. The 85% ICAO point is taken directly from the data in Figure 8 at the appropriate mixer flame temperature. For the 100% ICAO point, the data in Figure 8 was curve fit and extrapolated to the appropriate flame temperature. The standard

humidity correction, based on the measured dew point in the combustor inlet air, was applied to the data in Figure 6 through 8 to arrive at the final EINOx values in Table 2.

Table 2: LTO NOx results for the GE N+2 5-cup sector

M4F1 in the Sector				
% ICAO	Time [min]	EINOx	dp/Foo	% CAEP/6
100	0.7	17.6	20.6	18.9
85	2.2	7.9		
30	4	13.2		
7	26	5.8		

Cruise NOx emissions and efficiency were also measured. The data resulted in a 60-70% reduction in EINOx over the previous state-of-the-art, with better than 99.9% efficiency.

GE Phase I Conclusions

The GE combustor delivered 19% CAEP/6 NOx, surpassing the N+2 goal of 25% CAEP/6, with good combustion efficiencies and acceptable dynamic pressures for this stage of development. Further development of this technology will focus on thermal and mechanical durability, manufacturability, and optimization of the design to balance combustion efficiency and dynamics vs. LTO NOx capability.

B. P&W N+2 Advanced Low-NOx Combustor Technology (ERA Phase I)

The approach taken by P&W and the United Technologies Research Center (UTRC) to meet the challenge of the NASA ERA program revisited the concept families that had been explored previously and determine their potential for emissions and operability. These concepts include lean-staged multi-point designs, radially staged swirlers, axially staged combustors, and rich-quench-lean (RQL) combustors. P&W has achieved significant improvements in TALON X Rich-Quench-Lean Technology and is continuing to develop additional emissions capability.

For the NASA ERA program, P&W/UTRC reviewed the various staged and lean combustor concepts. Roadblocks that prevented their adoption in the past were identified and possible approaches to address those roadblocks were developed. Computational Fluid Dynamics (CFD) and single nozzle rig tests were performed to explore and understand key features in order to meet both emissions and operability requirements. Exploration of the designs continued into the rig design phase. A multi-sector rig of the preferred design was designed and fabricated, then tested at UTRC and at NASA.

In conjunction with the NASA ERA program, Pratt continues to develop the TALON X combustor technology. The basic technology was developed with support from NASA under the UEET program, and is the combustor for the P&W Geared TurboFan engine on upcoming Airbus, Bombardier and Mitsubishi aircraft, meeting all program metrics. Work performed on the TALON X as part of the program includes further reductions in smoke, LTO NOx, and cruise NOx.

Staged/Lean Combustor Concepts

Over the past 40 years, PW/UTRC has explored and developed various combustor concepts to reduce NOx. For example, an axially staged combustion systems was developed for the V2500 in the 1990's. More directly related to the current NASA program, PW explored and developed several concepts for the NASA sponsored High Speed Civil Transport (HSCT) Program, the Advanced Subsonic Technology (AST program and the Ultra Efficient Engine Technology (UEET) program. In addition to the RQL technology embodied as the TALON X, these technologies can be classified as multi-point, fuel-nozzle radially staged, multi-dome and various axially staged concepts. Each of these concepts was identified as having particular challenges which was then addressed through the process described above.

Multi-point injection

The multi-point injection concept is challenged by the large number of injection points. Modern manufacturing techniques such as additive manufacture have reduced the cost of fabrication of a multi-point combustor. The many fuel passages are still susceptible to coking. It was seen as advantageous to reduce the number of injection points with the challenge to maintain excellent mixing.

Improvement in mixing was obtained by applying lessons learned through the development of PW TALON X combustors. Swirl cups with swirl distributions in the range of PW legacy high shear swirler design experience were conceptualized, analyzed using PW experience based tools, modified, then improved using CFD. Swirlers with desired fuel-to-air distributions were produced using rapid prototyping techniques and tested in the UTRC spray facility, which has the capability to measure velocities of gas and liquid phases, droplet size, and spray uniformity. Tests were then performed of the concepts in the Advanced Aeroengine Combustor (AAC) single nozzle test facility at UTRC. This facility has moderate pressure capability (up to 150 psi) and the test section has optical access as well as extraction probes that can traverse axially and radially. Emissions results from these single nozzle rig tests of the multipoint design showed acceptable levels of NO_x, with estimated NO_x at cruise conditions to be significantly less than 5 EI, an indication that the concept could meet the program goals.

Radially Staged Swirlers

The challenge identified for the radially staged swirler was to aerodynamically separate the pilot from the main in such a fashion to ensure good low-power efficiency, yet permit sufficient mixing for stability over the range of operation. In addition, the radially-staged swirler concept is challenged to obtain uniform mixing in a large swirler. The mechanical packaging of this concept is also difficult due to the combined size of the multiple swirlers. Coking is an issue here, as in all lean staged systems, due to the many fuel injection points and the need to distribute these points in such a fashion to allow for uniform mixing with air.

Once again, improvements to this concept were derived from P&W legacy swirler design experience. Swirler mixing and pilot stability were improved over previous UEET concepts with the application of lessons learned during TALON X development. Various swirler combinations and swirl distributions were conceptualized and analyzed, modified, then improved using insight gained from CFD analyses. Spray tests were made of key designs, and results used to further modify the designs. Tests of the final concept were then performed in the UTRC AAC rig and then, as part of another NASA contract examining potential Low-NO_x concepts for supersonic engines, the P&W radially staged swirler concept was tested at the NASA CE-5 single nozzle test facility. NO_x results were significantly less than 5 EI, once again experimentally demonstrating the capability to meet program emissions goals. Importantly, low power efficiency was also very good, showing that the necessary separation and stabilization of the pilot flame had been achieved.

Axial Controlled Stoichiometry

The challenge identified for the axially staged combustor was to implement it in a simpler fashion than the version developed for the V2500. Axially staged combustors characteristically have good separation of the pilot with accompanying positive stability and efficiency. Packaging and mixing of the main stage is traditionally the concern in such systems. Coking again is an issue.

For the system envisioned for this effort, the pilot stage was kept simple, using experience gained in developing TALON combustors. Various concepts for the mains were conceptualized, analyzed, and explored with CFD. The level of mixedness required to achieve low levels of NO_x was a key question that was explored through a series of idealized UTRC AAC rig tests. Mixer designs were then created that achieved the desired level of mixedness. The resulting mixers were then evaluated in the UTRC AAC rig to determine if they achieved the desired level of emissions. NO_x results were the lowest observed of the PW configurations tested, providing significant developmental margin.

Testing the ACS Combustor in the NASA ASCR Facility

The performance, strengths and challenges of each of the concepts were reviewed. Each of the concepts had demonstrated the potential to meet the program goals for NO_x. Each of the concepts has challenges with complexity, packaging, and coking. Approaches were conceptualized for each of the concepts to overcome these challenges.

The P&W team chose the Axially Controlled Stoichiometry (ACS) concept for testing at NASA. The arrangement of the separation of the pilot and the main provides for efficiency and stability at low power, and stability at all operating conditions. Mixing of the pilot and main is controllable according to PW experience. P&W has experience in the design and manufacture of axially staged combustion systems due to the V2500 design. The ACS distributes the heat release axially, reducing susceptibility to acoustics. Finally, the NO_x emissions were the lowest tested, providing the most margin for development of any of the concepts.

The ACS concept was then implemented in a 3-sector arc rig that was tested first at UTRC, then at NASA in the ASCR facility (Figure 9). Results between the two series of tests were consistent. Acoustic issues were only experienced at off-design conditions. Efficiency was above 99.9% at all fully staged high power points. Due to the conventional pilot zone, high efficiency was also achieved at idle and approach conditions. Cruise NO_x levels were 2 EI and below (Figure 10). Emissions were measured idle, take-off, climb, and approach, and a NO_x EPAP of 88% below CAEP/6 was calculated using an N+2 cycles based on an advanced Geared Turbo Fan. Performance with respect to all CAEP regulated emissions are shown in Figure 11.

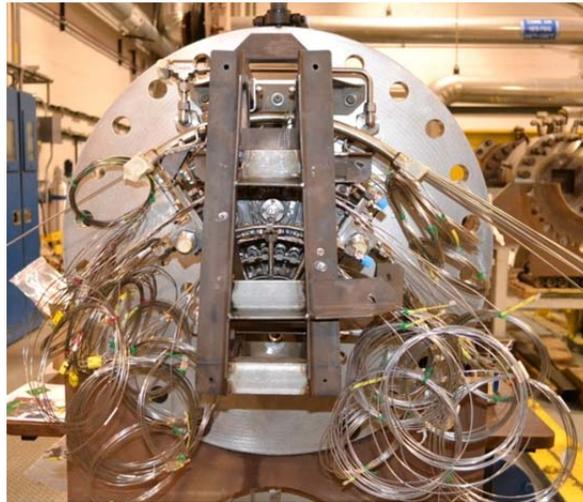


Figure 9. Axially Controlled Stoichiometry Combustor Rig Installed at NASA ASCR Facility.

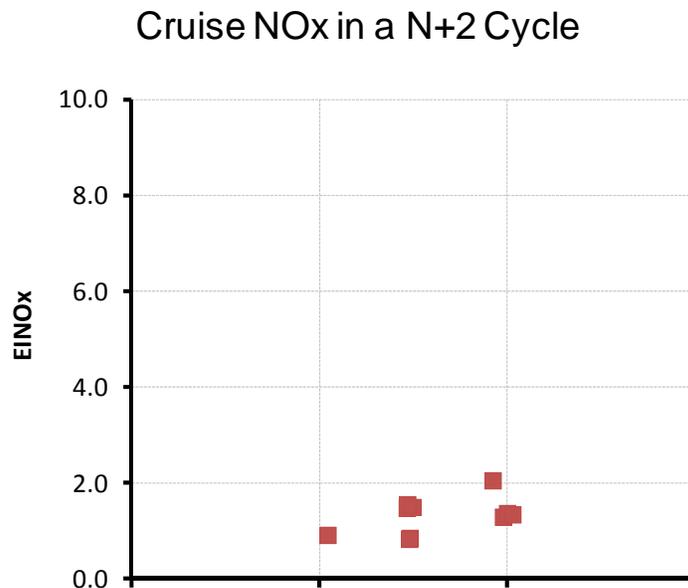


Figure 10. PW ACS configuration achieved less than 2 EI NO_x at typical cruise conditions of an advanced N+2 GTF Cycle.

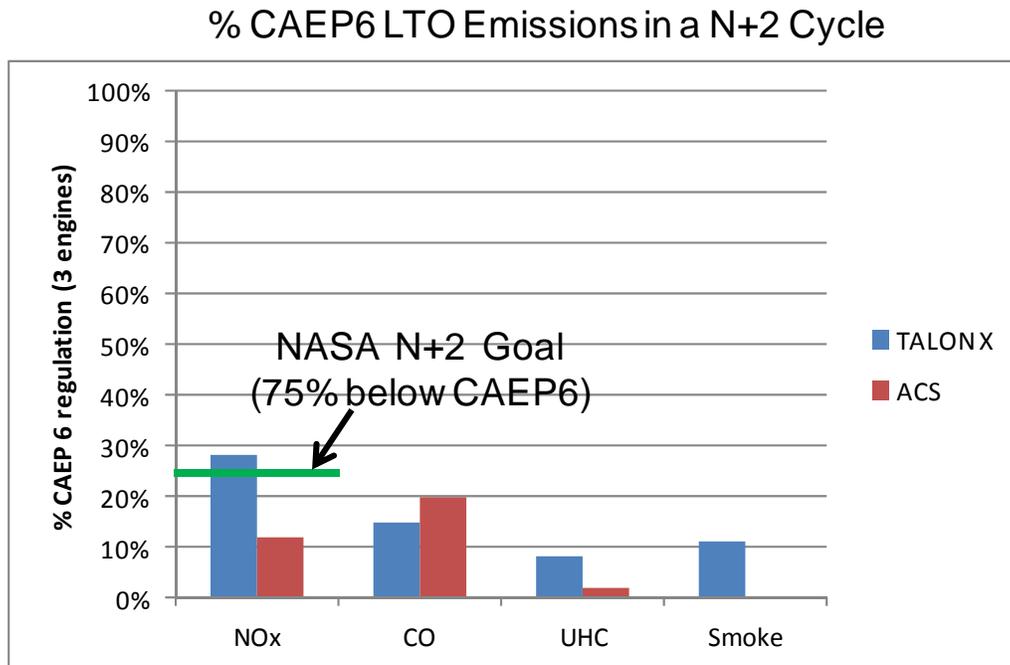


Figure 11. The PW ACS configuration achieved 88% margin to CAEP/6 LTO NO_x regulations as measured in rig tests at NASA and UTRC for an advanced N+2 GTF cycle. TALON X is projected to achieve 72% margin to CAEP/6 NO_x for the same cycle

P&W ERA Phase I Conclusion

The next stages in the development of the concept include exploring approaches to make the concept more product-ready and simplify the packaging. The concept must fit into the envelope available in the current and planned Geared Turbo Fan engines. Further, the concept must be verified and matured in a full annular design. The evaluation and testing of the Phase I effort provided an excellent basis for the continued development of this concept.

Continued Development of the TALON X combustor

In conjunction with the NASA ERA program, P&W continues to develop the TALON X combustor. In particular, swirler and front end modifications were explored that continue to reduce the low smoke and NO_x levels demonstrated in the TALON X combustors which were developed and tested in the Gear Turbo Fan family of engines.

A design of experiments approach was followed to further improve the swirlers. They were analyzed, evaluated using CFD, and tested in the spray facility at UTRC in order to determine critical uniformity parameters. A five sector rig was designed and fabricated that was shown to duplicate the results of the full annular tests and the engine emissions. Tests were performed of the chosen concepts.

Results indicated smoke levels below those for the swirlers currently used in the engines. NO_x levels were also improved. When results are projected, using P&W experienced based methods, to the same advanced GTF cycle used for the staged results, a NO_x EPAP of 72% margin to CAEP/6 is calculated, closely approximating the N+2 program goal of 75% reduction to CAEP/6. Thus, the TALON X remains a viable option for the current generation of aero engines.

III. Ultra Low-Emissions High-Pressure Lean-Direct-Injection Injector Concept Developments

The second type of activity engaged three fuel-injector companies to develop fuel injector concepts that can accommodate faster-burning fuel blends at the more aggressive higher-pressure engine cycle conditions envisioned for the future. Goodrich, Woodward FST, and Parker Hannifin are on contract to design and develop these more aggressive ideas, but their scopes are limited to the injector and its dynamic behavior to keep the cost low. These concepts have to demonstrate being able to burn the more aggressive 80%/20% alternative fuel to jet fuel blends. Some of these concepts will incorporate fuel-flow control features to provide fueling precision while others instability control. While these industry partners will be able to verify their performances at low power, they also will verify their higher-power performance at NASA's test facility. All three of these efforts utilized CFD to provide design screening.

The LDI concept is a natural fit for ultra-high-pressure operation. While a majority of ERA's fuel reduction goal can be reached through airframe drag reduction or increasing propulsive efficiency, improving the thermodynamic cycle efficiency by raising the compression ratio also is considered. Both of the previously mentioned engine cycle concepts considered in the combustor development activity raised the maximum combustor pressure from the current 45 bar to over 50. This means that the combustor inlet air temperature will be hotter, and the liquid fuel sprayed into the combustor will heat up quicker and ignite sooner than current designs. Since good emission characteristics heavily depend upon mixing the fuel and air well before the burning starts, certain amount of premixing is used in current designs. However, at the elevated air temperatures, such a feature may not be available as auto-ignition or flash-back of the flame into the fuel-air mixing nozzles can pose a serious hardware damage hazard. LDI averts this issue by directly injecting the fuel into the flaming zone, mixing quickly to keep the residence time of the non-uniform mixture to a minimum.

LDI typically manifest itself in arrays of smaller nozzles. Quick fuel-air mixing can be done by increasing air flow turbulence where the fuel is injected, but this is done sacrificing air pressure across the fuel nozzle which no longer will be available for expansion in the turbine for work extraction. The alternative is to use an array of small nozzles to reduce the physical distance that the fuel needs to travel to achieve uniform mixing. All three of the design concepts in this current program fall into this form. For comparison, fuel-air mixing nozzles in current engines are from 2 to 4 inches in diameter. In the current program a typical size is about 1 inch.

All three LDI fuel injector designs to accommodate using alternative hydrocarbon fuels. All alternative fuels are saturated hydrocarbons that do not have sulfur. They are not as easy to coke as currently used petroleum distillate fuels. As a result, the designers can use smaller fuel orifices to make the liquid fuel jets smaller to speed up break up and vaporization. This will help greatly as these new fuels also generally have faster kinetics and will start to burn earlier than the current distillate fuel, resulting in flames that can be much closer to the fuel injector. While the combustor programs mentioned in the earlier portion of this paper are designed to accommodate using 50%/50% blend of alternative with distillate fuels, these injectors are designed to take advantage of up to 80%/20% mixture of alternative fuel so that the amount of soot-producing aromatics and coking precursors are greatly reduced.

A. Goodrich Multi-Point Combustion System

Goodrich (currently UTC Aerospace Systems) designed their modular LDI array around discrete-jet-based airblast fuel nozzles. (Figure 12) Intense mixing turbulence level is created very close to where the fuel is injected through strong shear layers. The resulting rapid breakup and vaporization promotes a more homogeneous and burnable mixture quickly, especially at low power conditions.

The multi-stage array (Figure 13) is distributed with the row of slightly recessed pilot nozzles that will be fueled independently to provide ignition stability. While it may burner a little hotter and generate more NO_x than the main burners, it only flows 10% of the air flow. The separately fueled stages will be scheduled to generate the minimum emissions and broadest operating range. A more through discussion can be found on ref. [2]. This design concept has gone through low-power testing with Jet-A and an alt-fuel, and is awaiting for mid-to-high pressure testing at a NASA.

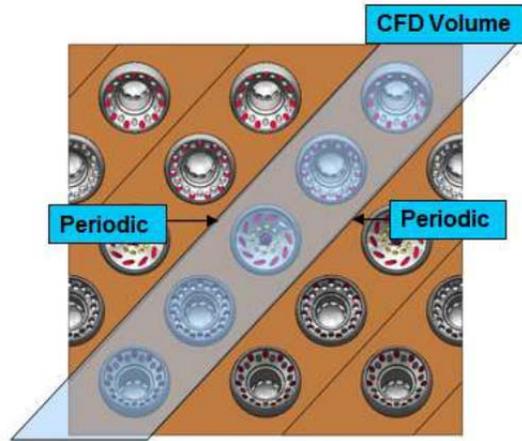
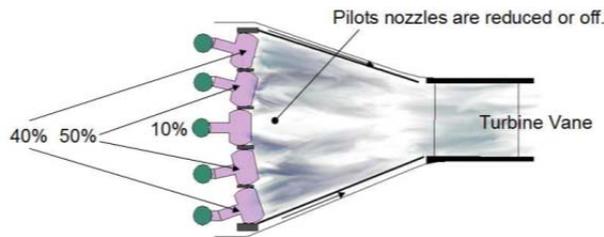


Figure 12 CFD assessment strategy. From ref. [2]



At high power, adjacent nozzles become dominant.
 Combustor runs lean. Core effects are diminished

Figure 13 Goodrich multi-zone multi-stage LDI concept. From ref. [2]

B. Woodward Multi-Point LDI

Woodward FST based their designed concept on mixed types of fuel nozzles aided by simple swirl-generated shearing action. Their LDI array module consists of multi-staged series of smaller and leaner-fueled nozzles surrounding a central larger pilot that provides the low-power operations. The modules may be stacked as a multi-cup sector. (Figure 14) The recessed pilot provides a zoned effect and shields the pilot from its neighbors. At low powers, evenly-distributed fuel-air mixture may be too lean to burn. As a result, multiple fueling stages are used to distribute the fuel so that burnable mixtures at very low overall equivalence ratios are achievable. Of particular concern is the staging process to provide stable light off and ultra-low- power operation. Figure 15 shows a 5-cup arc sector undergoing lean-blowout testing. A more precise fuel-staging system that can reduce fuel flow drift are under development for demonstration on this modular injector concept.

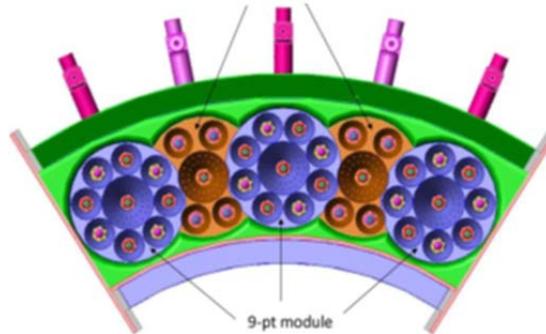


Figure 14 Woodward LDI array in 5-cup sector from ref. [3]

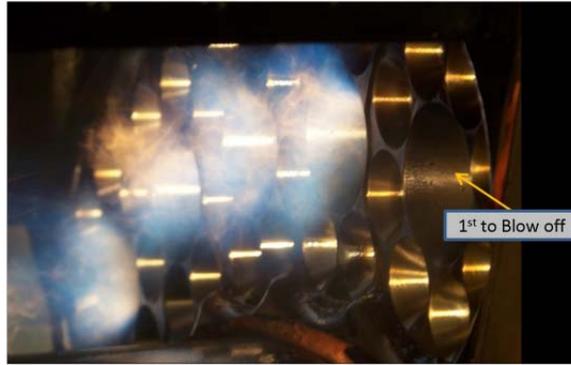


Figure 15 Woodward LDI array undergoing lean-blowoff testing from ref. [3]

C. Parker 3-Zone Lean Direct Injection

Lastly, Parker introduced a variation of their multi-staged 3-zone injector module from their work under NASA's UEET Program. The concept originated from the idea of retrofitting current combustor injectors with better performing new hardware (Figure 16). The module is composed of miniature mixing cups each fueled by a pressure-swirl nozzle. The cups are formed using Parker's platelet technology and introduce intense turbulence where the fuel injection takes place. The three zones are formed by canting the side nozzles away from the middle layer to provide some relief from inter-injector interaction. Multiple fuel stages are used to shift fuel spatially to provide the leanest and acceptably-stable burnable fuel-air mixture (Figure 17). Figure 18 shows the flame distribution during lean-blowoff. This array has gone through low-power testing and is being adopted for mid-to-high pressure testing at NASA.

Part of this particular task also includes a high frequency fuel actuator development that is capable of being integrated into the 3-zone fuel module to provide spatial and temporal fuel redistribution (Not shown.)

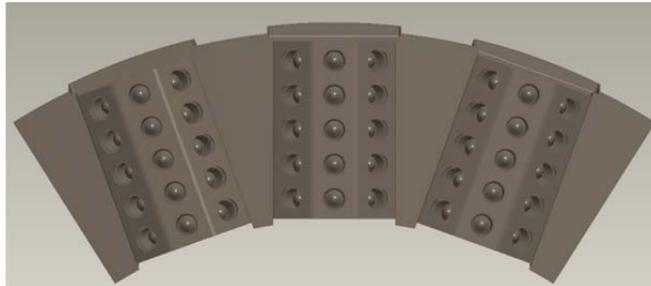


Figure 16 Conceptual 3-zone module implementation;

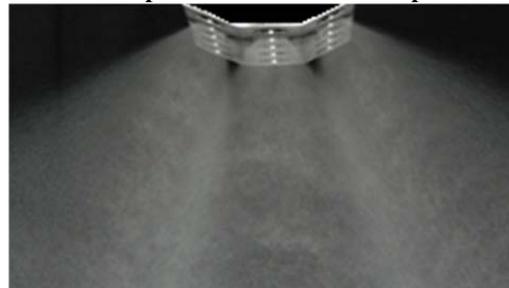


Figure 17 Parker 3-zone module spray testing.

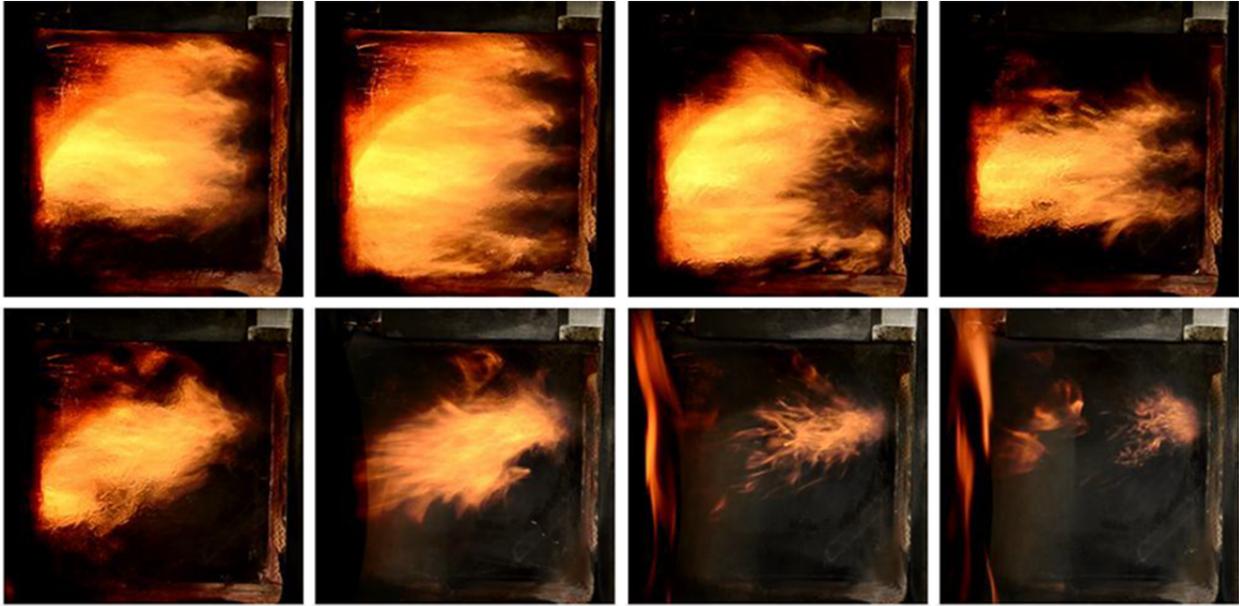


Figure 18 Parker 3-Zone injector module during lean-blowoff testing.

All three of these injector designs under this second activity have achieved scaled NO_x reduction levels for the two lower-power ICAO test points and have achieved their desired lowered lean-blowoff levels.

IV. Summary and Next step - ERA Phase 2

We have accomplished all the phase I objectives:

- 1) Demonstrated emissions and fuel burn reductions through multi-sector combustor testing at realistic engine operating conditions with General Electric and Pratt & Whitney sector hardware.
- 2) Identify enabling technologies for the follow up full annular combustor demonstration.
- 3) Demonstrated low NO_x injector performance, emissions reduction at low power conditions.
- 4) Demonstrated ERA emissions reduction goals: 75% LTO of CAEP/6 and 70% cruise NO_x reduction (relative to 2005 state-of-the art) at TRL 4 level.

We have two winning combustor concepts from GE and P&W, both surpassing the N+2 goal of 25% CAEP/6, with good combustion efficiencies and dynamic pressures at TRL 4 level. Both companies also met the 70% cruise NO_x reduction (referenced to 2005 state-of-the-art combustor technology). A progressive competition strategy will be used with down-selection of sources from the initial phase to determine the second phase contractors. The competition for the second phase will build on the results of the initial phase, and the award criteria for the second phase includes successful completion of the initial phase requirements.

Goodrich, Woodward, and Parker have obtained excellent results at the lower pressure flametube testing: demonstrated ignition, flame propagation, lean blowout capabilities and NO_x reduction. NASA plans to continue with testing their hardware at NASA's intermediate pressure rig to assess their NO_x reduction potential to decide on the next step.

NASA's ERA Project will end in 2015. The Phase II combustor concept development effort will end with the demonstration of a full-annular combustor hardware that is capable of 75% NO_x reduction capability. Currently ICAO is discussing whether to regulate cruise NO_x in the future. The combustor technologies developed under ERA will be helpful in meeting such future requirements.

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