U.S. Department of Transportation
Federal Aviation Administration

TAPS II Combustor Final Report

Continuous Lower Energy, Emissions and Noise (CLEEN) Program

Submitted by General Electric

DOT/FAA/AEE/2014-03

The Continuous Lower Energy, Emissions and Noise (CLEEN) Program is a Federal Aviation Administration NextGen effort to accelerate development of environmentally promising aircraft technologies and sustainable alternative fuels. The CLEEN Program is managed by the FAA's Office of Environment and Energy.

The report presented herein is the final report deliverable submitted by General Electric for a project conducted under the CLEEN Program to mature the TAPS II (Twin Annular Premixing Swirler) lean burn combustion system. This project was conducted under FAA other transaction agreement (OTA) DTFAWA-10-C-00046. This is report is report number DOT/FAA/AEE/2014-03 by the FAA's Office of Environment and Energy.

CLEARED FOR PUBLIC RELEASE. UNLIMITED DISTRIBUTION.

DTFAWA-10-C-00046

FAA
Continuous Lower Energy, Emissions and Noise (CLEEN) Technologies Development

TAPS II Technology
Final Report – Technology Assessment
Open Report

June, 2013

Rick Stickles, TAPS II Combustor Technology Program Manager
Jack Barrett, Program Manager

Prepared for

FAA

Rhett Jefferies
CLEEN Program Manager
Federal Aviation Administration
800 Independence Ave., S.W.
Washington, DC 20591

GE Aviation
One Neumann Way
Cincinnati, Oh 45215

Table of Contents

List of Tables

List of Figures

1.0 Executive Summary

TAPS (Twin Annular Premixing Swirler) is the GE lean burn combustion system that has entered service on the GEnx engine for the 747-8 and 787 wide-body applications. The CLEEN TAPS II development program was a cost share between GE Aviation and the FAA to scale the TAPS technology to narrow-body applications, make additional design improvements to meet the CLEEN NOx emission goal, and demonstrate the design in full annular and core engine testing. The TAPS II development program successfully achieved the FAA CLEEN NOx emissions goal of 60% margin to the CAEP/6 limit.

The FAA CLEEN TAPS II development program was divided into 3 phases:

1. Technology Maturation
2. System Engineering/Integration
3. Technology Demonstration

During the technology maturation phase of the program, single cup flame tube tests were conducted to screen designs for NOx, efficiency and combustion dynamics. More than 25 configurations were tested. Out of that phase main mixer and fuel injector designs were selected for further evaluation.

System engineering and integration included detailed design of the combustion system along with 5 cup sector and full annular component testing. Sector testing focused on altitude relight, efficiency, and emissions. Full annular testing evaluated all combustor characteristics - emissions, light off, lean blow out, efficiency, thermal data, exit temperature profile and combustion dynamics mapping. The full annular emissions data was used to assess engine emissions certification levels.

The technology demonstration phase is where the TAPS II combustor was run on the LEAP core engine. Testing on the core focused on combustion operability, ignition, lean blow out and dynamics. Combustion efficiency at cruise and thermal data on the combustion chamber were also evaluated. Emission Results are shown in Section 4.

Section 5 of this report summarizes the current technology readiness level of the TAPS II, additional development needs, and implementation into the field. The TAPS II is a part of the LEAP engine for the COMAC C919, the Airbus A320 Neo and the Boeing 737 Max.

2.0 Program Overview

The FAA CLEEN program has the objective of assisting the aviation industry in the development of technologies to reduce emissions, noise and fuel burn. These technologies are targeted to be near term product ready with entry into service within the next ~5 years. The specific CLEEN goals are summarized in Table 1 below.

Table 1 CLEEN Program Goals

	N+1 (2015) CONVENTIONAL CONFIGURATION RELATIVE TO 1998	N+2 (2020-25) UNCONVENTIONAL CONFIGURATION RELATIVE TO 1998	N+3 (2030-35) ADVANCED CONCEPTS RELATIVE TO 2005
NOISE	-32 dB cum below Stage 4	-42 dB cum below Stage 4	-71 dB cum below Stage 4
LTO NOX EMISSIONS (BELOW CAEP 6)	-60%	-75%	better than -75%
AIRCRAFT FUEL BURN	-33%	-50%	better than -70%

The CLEEN TAPS II technology development program was a cost share between GE and the FAA to further develop the low NOx TAPS (Twin Annular Premixing Swirler) combustion system. TAPS is currently in service on the GEnx wide-body application. The TAPS II is being developed for the next generation of narrow-body aircraft with entry into service expected ~2016. The TAPS II combustion system is designed to meet the CLEEN NOx reduction goal and will also contribute to the ability to meet the fuel burn goal since its improved NOx margin enables higher engine pressure ratios for better overall engine efficiency.

Consistent with and in addition to the CLEEN high level goals, the TAPS II combustor development program established the following targets.

1. **Reduce LTO NOx emissions to 60% below CAEP/6 requirement.** While CLEEN specified a 60% reduction at 30 OPR, GE believes that future commercial engines will operate at higher OPR for improved fuel efficiency. Therefore, it is not sufficient to just meet the goal at 30 OPR. GE is targeting NOx emissions 60% below CAEP/6 at a pressure ratio of 38.

2. **Reduce cruise NOx emissions to less than 9 g/Kg fuel at all cruise conditions.** Cruise NOx can affect climate, and may also affect air quality far from the flight path. Therefore, GE will concentrate on reducing cruise NOx levels in conjunction with reducing LTO values.

3. **Reduce solid carbon particulate matter (PM) to 90% below potential CAEP limit.** Currently, secondary PM is thought to account for most of aviation's health impact. However, with improved control of NOx emissions through improved combustor design and SOx emissions with reduced fuel sulfur content, the health impact of solid particulate is likely to become even more important. In theory, formation of soot should be reduced by orders of magnitude with lean-burn combustion. This benefit has not been well documented because lean-burn combustion systems have not been widely available for aircraft, but there is anecdotal evidence that solid carbon PM will be on the order of ambient concentrations during engine operation in the lean-burn mode.

4. **Scale the TAPS combustion system down to smaller core flow engines to support narrow-body and regional jet designs.** The GEnx TAPS meets the emission reduction requirements of the next generation of long range wide-body aircraft, but this does not solve the emissions problem. The shorter-range single aisle aircraft fleet emits almost as much NOx as the wide-bodies, so it is important to transition TAPS technology across the spectrum of commercial engines.

The TAPS II development program plan is summarized in Figure 1.

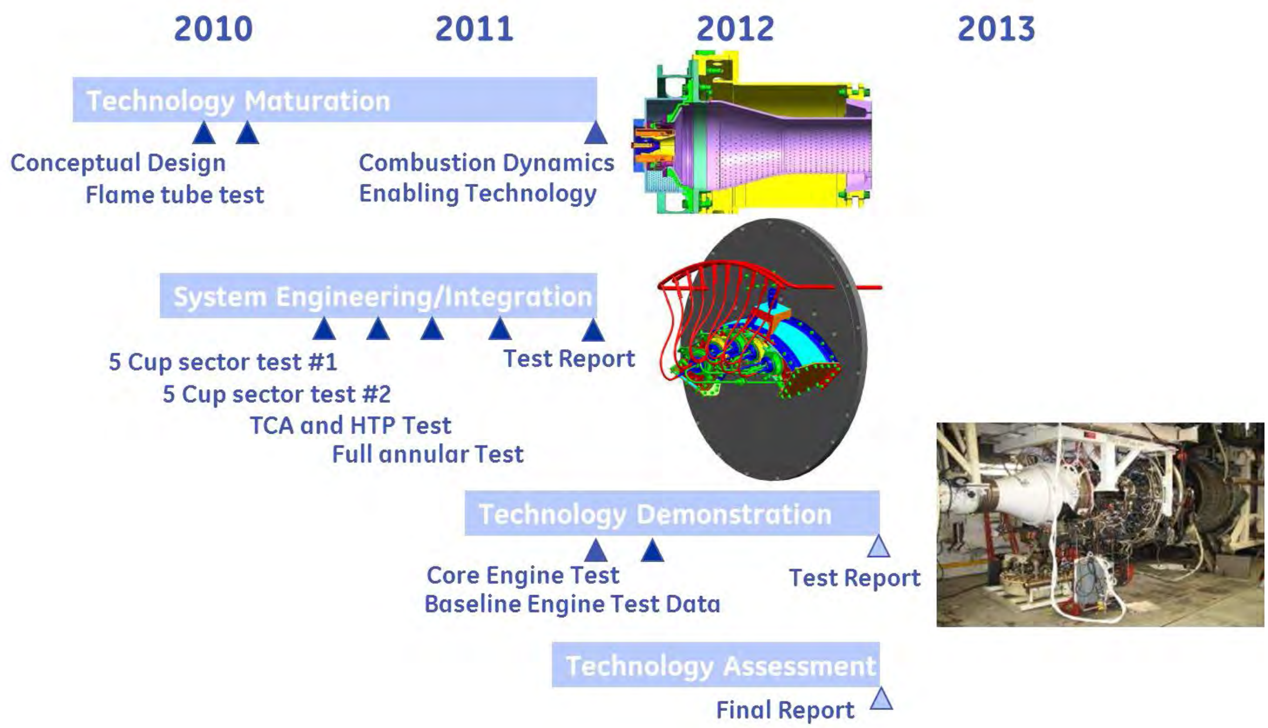

Figure 1 FAA CLEEN TAPS II Program Plan

.

3.0 Aircraft Emissions Background

3.1 Local Air Quality

For the past 30 years, most of the emissions focus for aircraft engines has been on reduction of NOx emissions at low altitude, in the vicinity of the airport. [1] The effects of low altitude aircraft engine emissions on US air quality have been described in detail by Ratliff et al. [2] The problem results in significant yearly health cost. [3]

A recent global atmospheric modeling study [4] indicates that the health impact of NOx emitted at high altitude climb and cruise conditions may be several times greater than the impact of low altitude emissions. This is not totally unexpected because approximately 90% or aircraft NOx emissions are at altitudes above 3000 feet. The study indicates that much of the NOx emitted at high altitude is transported to ground level via subsiding air masses, where it adds to formation of ozone and secondary particulate matter (PM).

Primary non-volatile PM, consisting primarily of soot particles, has a health impact similar to secondary PM from NOx, but the magnitude of damage cost due to primary PM is about 25% of the NOx damage [3]. However, reduction of primary PM is still needed and would provide a health benefit.

3.2 Climate

The most significant greenhouse gas is CO_2. However, according to the Intergovernmental Panel on Climate Change, [5] NOx emitted by aircraft during climb and cruise affect climate by increasing ozone, which leads to warming, and reducing methane, which leads to cooling. Since these impacts are offsetting, the combined impact is still undetermined.

The importance of soot to climate change has been stressed by Jacobson, [6] who maintains that in general, soot may account for 16% of gross global warming - an effect that would make it second only to CO_2 in importance to climate change. Aircraft may have a particularly significant impact on polar warming and ice melt because polar flights are the main source of soot PM in this region. Soot may also impact two other major aircraft contributors to climate change - contrails and cirrus clouds – because soot particles may be a source of condensation nuclei.

By substantially reducing NOx and soot formation at ground level and at cruise, the TAPS lean-burn combustor can provide a significant reduction in aviation's health impacts and climate change. [1]

3.3 Emissions Policies and Trends

Reducing aircraft engine NOx emissions over the ICAO LTO cycle has long been a priority for the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP). CAEP first established standards for emissions of NOx, HC, CO, and smoke in 1986.[7] Since that time, the standard for allowable NOx emissions has been reduced four times. At the most recent CAEP meeting in February 2010, the nominal NOx emission standard was reduced to less than 50% of the original standard. For the first time, reduction of climb and cruise NOx was given as a strong consideration in setting the stringency of the standard. The US Environmental Protection Agency (EPA) intends to adopt the new standard (CAEP/8) starting in 2014, and will also initiate mandatory emissions reporting for all engines sold to US airlines. [1]

In Europe, there has been a trend for airports to implement landing charges based on the amount of LTO NOx that an aircraft emits. The European Civil Aviation Conference (ECAC) has developed a standard methodology for NOx charging, ECAC Recommendation 27/4. Additionally, as part of the European Emissions Trading Scheme that focuses mainly on CO_2 emissions and climate change, there has been a proposal to require aircraft to buy additional credits to account for the impact of NOx, PM and other non CO_2 emissions. For now, this action is on hold, awaiting development of better scientific understanding of NOx impacts on climate. [1]

In light of the importance of high altitude NOx emissions on climate and health, CAEP is revisiting means to reduce NOx emissions at climb and cruise conditions. CAEP has also sponsored reviews of progress in NOx reduction technology, and has set a nominal goal of 45% reduction relative to CAEP6 NOx standards by 2016. [1]

CAEP is also working with the SAE E-31 Aircraft Exhaust Emissions Measurement Committee to develop a certification procedure for a future non-volatile PM emissions standard. Both mass of PM emissions and particle size will be measured. [1]

The potential for future increased requirement stringency and local landing fees in addition to local air quality and climate concerns are driving the development of the TAPS II combustion system.

3.4 Baseline Design

The baseline combustor used for comparison to the CLEEN TAPS II is the CFM56-5B3/3. The CFM56 engine family is the most popular engine in the field today with over 22,000 engines produced. More than 520 airlines, charter operators, militaries and leasing companies use the CFM engine. [8] It is on both Boeing and Airbus Narrow-body aircraft (737 and A320 families). The -5B3 is the highest thrust rating of the CFM family with application on the Airbus A321. The /3 designation is for the latest technology insertion model which has a lower emissions rich burn combustor (LEC) and improved turbomachinery aerodynamics for reduced fuel burn. The combustor cross section is shown in Figure 2.

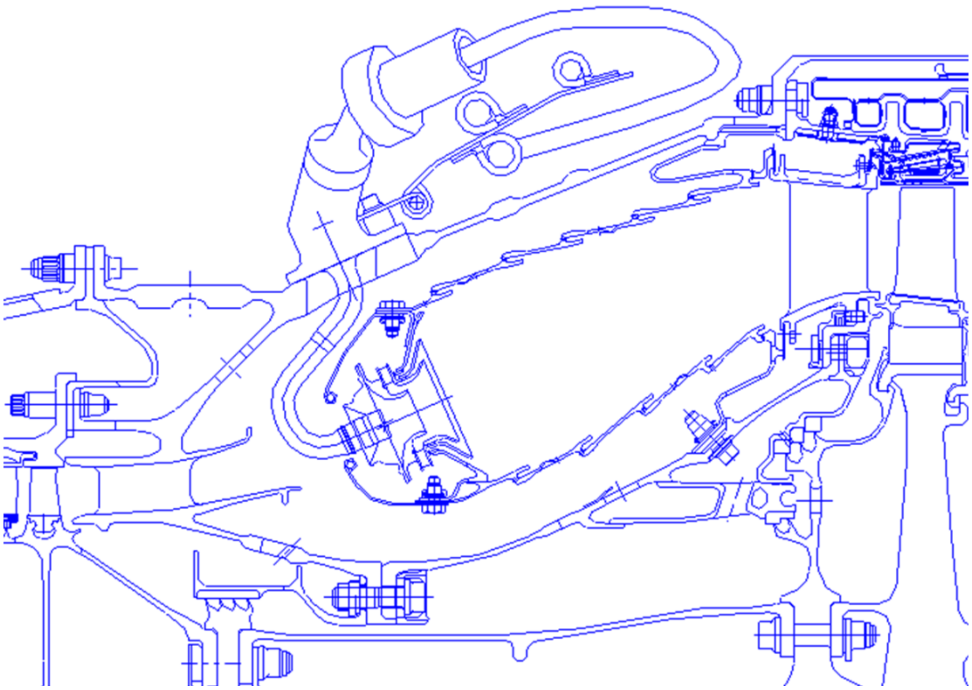

Figure 2 CFM56-5B3/3 Combustor Cross-Section

The certification LTO emission levels are shown in Table 2. Average measured emissions are the average values from the actual test data set. The characteristic value is what is reported against the certification requirements and accounts for engine to engine variation with an uncertainty factor that is a function of the number of engines tested. The emphasis of the FAA CLEEN program is to impact fleet average emissions, therefore average measured values will be used to assess the TAPS II technology and compare with the baseline.

Table 2 CFM56-5B/3 Emissions Certification Test Results

LTO Emissions Results	CFM56-5B3/3 31990 lb thrust (32.6 OPR)			
	NOx	CO	HC	Smoke
Avg Measured emission (g/Kn thrust)	48.3	33.47	1.43	16.0
% of CAEP/6 Limit	75.2%	28.4%	7.3%	74.5%
3 Engine Characteristic (g/Kn thrust)	51.2	36.2	1.67	17.6
% of CAEP/6 Limit	79.8%	30.7%	8.5%	81.9%

3.5 GE Low Emissions Combustor Evolution

Figure 3 shows the evolution of low emissions combustors at GE. Most current fielded products use the GE rich-burn LEC concept. This is an adaption of the RQL (rich quench lean) concept where there is a rich combustor primary zone to provide low CO and HC emissions and good ignition capability. NOx formation rates are low in the primary zone because the flame temperature of the rich primary mixture is relatively low, and there is little free oxygen available to form NOx. Flow exiting the primary zone is rapidly diluted, or "quenched", to a uniform lean mixture. With this concept, fast and uniform mixing during the quenching process is critical in order to minimize the time available for NOx formation as the mixture goes through stoichiometric fuel air ratio, where maximum flame temperatures lead to maximum NOx formation rates. Over the past 35 years, the LEC combustor has been developed to reduce NOx by 25-50% relative to first generation combustors. The rich burn combustion process is shown in Figure 4.

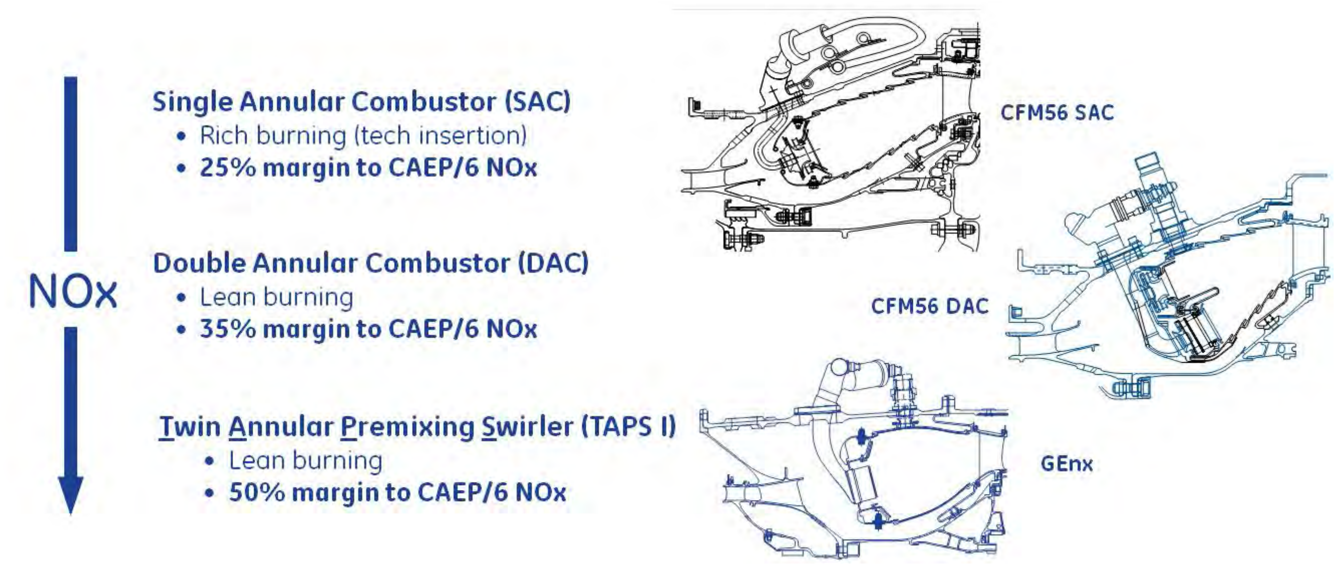

Figure 3 GE Low Emissions Combustor Evolution

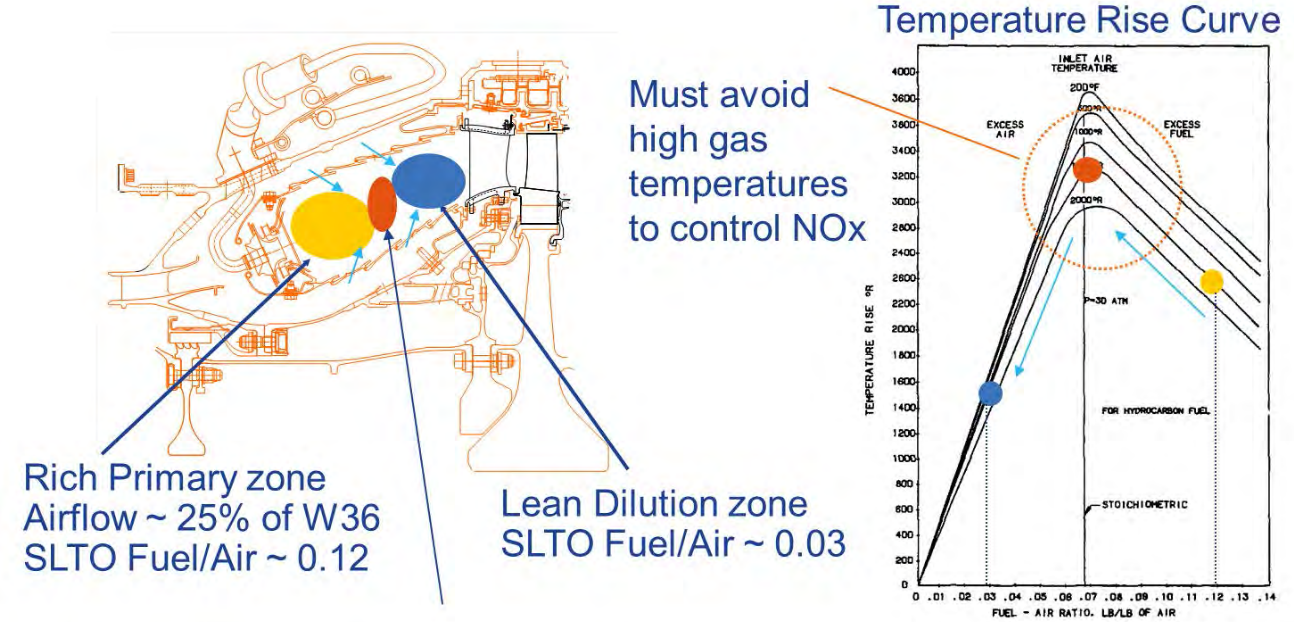

Figure 4 Rich burn Combustion Process

Programs to develop new low emission combustor concepts for aircraft engines have been underway since the mid-1970s. One of the first large aircraft engine emissions reduction programs was the NASA Experimental Clean combustor program, which sponsored early development of the Dual Annular Combustor (DAC) at GE. [9] After many years of intermittent development, the DAC entered service in the CFM56-5B and –7B engines in the mid-1990s. The DAC was designed with two stages: a pilot stage in the outer annulus of the burner, and a main stage in the inner annulus.[10] Only the outer (pilot) stage was fueled during light-off and at low power. The pilot was designed with low airflow and low through-flow velocity to achieve good ignition and low CO and HC emissions. The main stage was designed with high airflow and high velocity to provide a lean flame with minimal time for NOx formation. Although the DAC flame was lean, the fuel and air were inserted through a conventional fuel nozzle and swirl cup, so it was not a premixed flame. An issue with the DAC was the combustor exit temperature profile could be non-uniform during the different staging conditions.

3.6 Twin Annular Premixing Swirler (TAPS) Combustor

The TAPS combustor evolved based on lessons learned with fuel staging of the DAC, and also benefitted from extensive experience with Dry Low Emissions lean-premixing combustors in aero-derivative industrial gas turbines. [11] The TAPS combustor concept is a lean burn system where each fuel injector contains a center pilot and concentric outer main as shown in Figure 5. The central pilot tip is a rich burn configuration similar to traditional combustors. At starting and low power operation fuel is 100% in the pilot. At higher power fuel is split between the pilot and main. The main injection is a set of radial jets that enter a larger main air swirler. The main is a large effective area swirler to burn fuel lean. At high power most of the fuel is injected through the main. This makes both the pilot and main mixers fuel lean with approximately 70% of combustor total air flow through those 2 mixers. Figure 6 shows the lean burn combustion process.

TAPS combustor development started in 1995 as a GE/NASA emissions reduction technology program. The TAPS system is used in the GEnx engine which entered service in 2010. Figure 7 shows the TAPS development program.

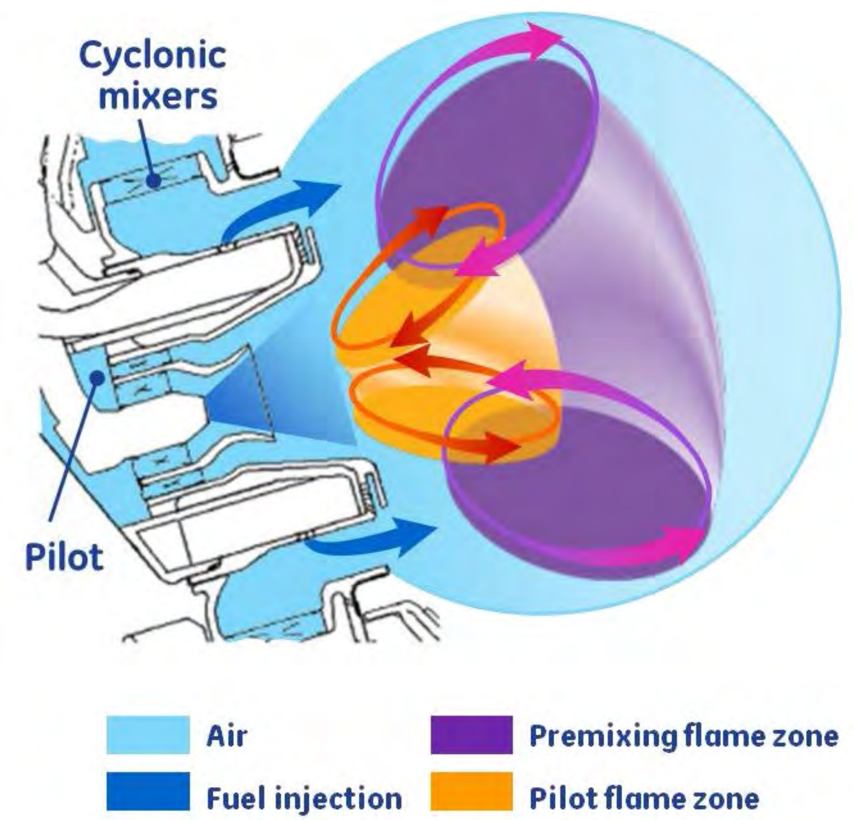

Figure 5 TAPS Fuel Injection Concept

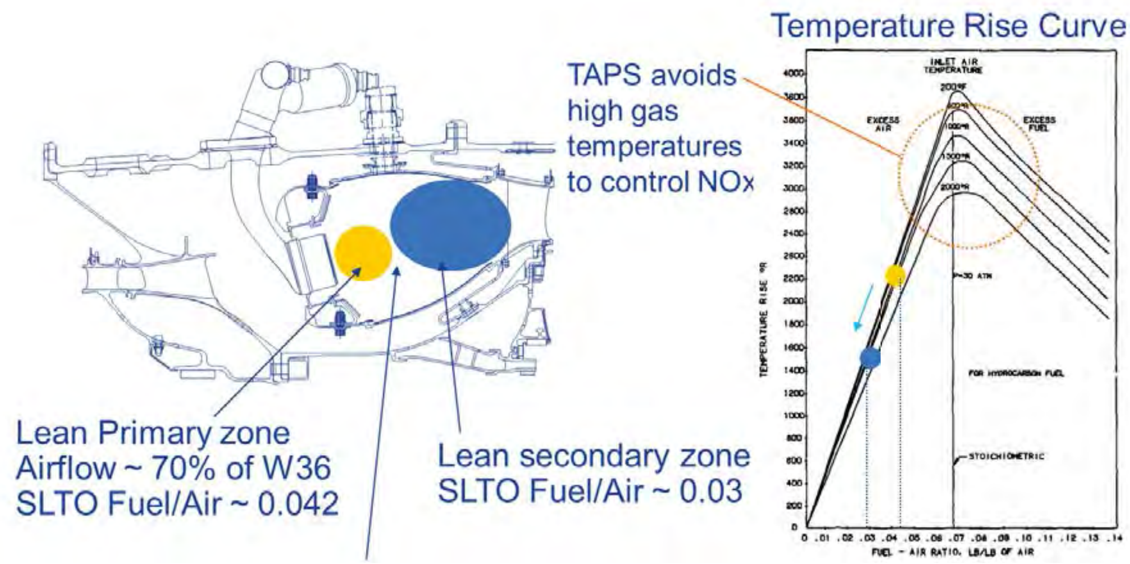

Figure 6 Lean Burn Combustion Process

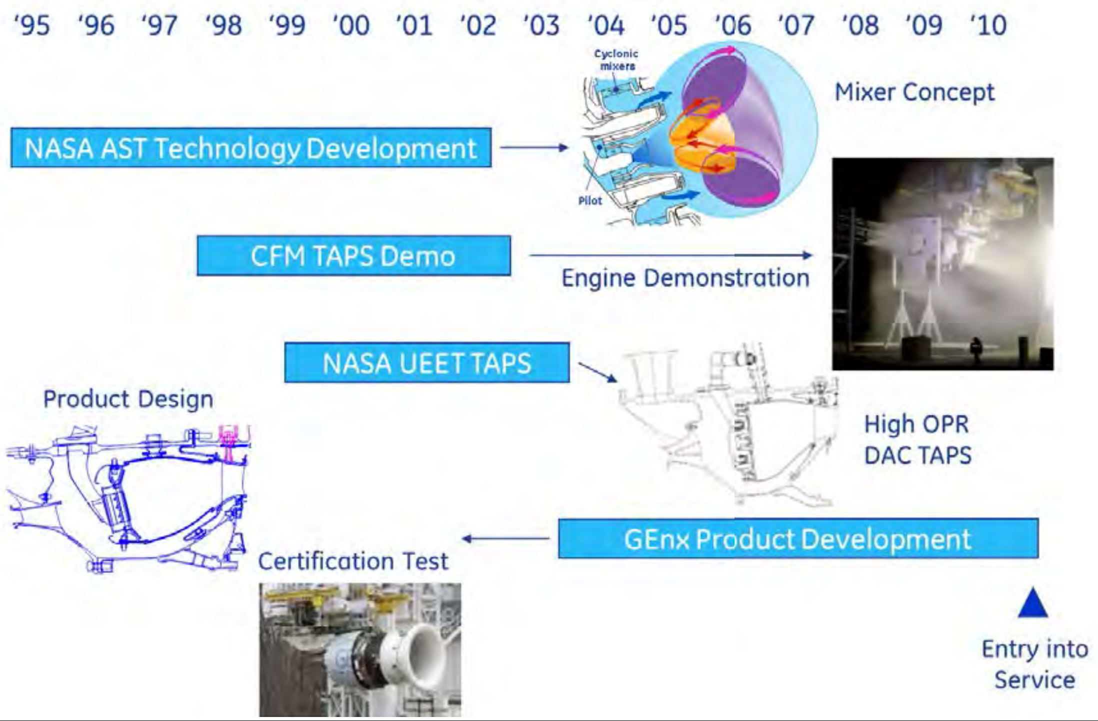

Figure 7 TAPS Development History

4.0 TAPS II Design Development

The FAA CLEEN TAPS II development program was divided into 3 phases:

1. Technology Maturation
2. System Engineering/Integration
3. Technology Demonstration

During the technology maturation phase of the program, single cup flame tube tests were conducted to screen designs for NOx, efficiency and combustion dynamics. More than 25 configurations were evaluated. Out of that phase main mixer and fuel injector designs were selected for further evaluation.

System engineering and integration included detailed design of the combustion system along with 5 cup sector and full annular testing. Sector testing focused on altitude relight, efficiency and emissions. Full annular testing evaluated all combustor characteristics, emissions, light off, lean blow out, efficiency, thermal data, exit temperature profile and combustion dynamics. The full annular emissions data were used to predict engine emissions certification levels.

The technology demonstration phase is where the TAPS II combustor was run on the LEAP core engine. Testing on the core focused on combustor operability, ignition, lean blow out and dynamics. Combustion efficiency at cruise and thermal data on the combustion chamber were also evaluated

4.1 Emission Results

NOx, CO, UHC and smoke emissions were sampled over a wide range of inlet temperature, pressure and fuel air ratios in the full annular combustor component test. Data taken at the 4 ICAO landing and take-off (LTO) cycle points (7%,30%,85% and 100% nameplate thrust) for a LEAP engine were used to calculate LTO emission levels and margin to the CAEP/6 regulatory limit. Figure 8 shows the ICAO LTO cycle definition.

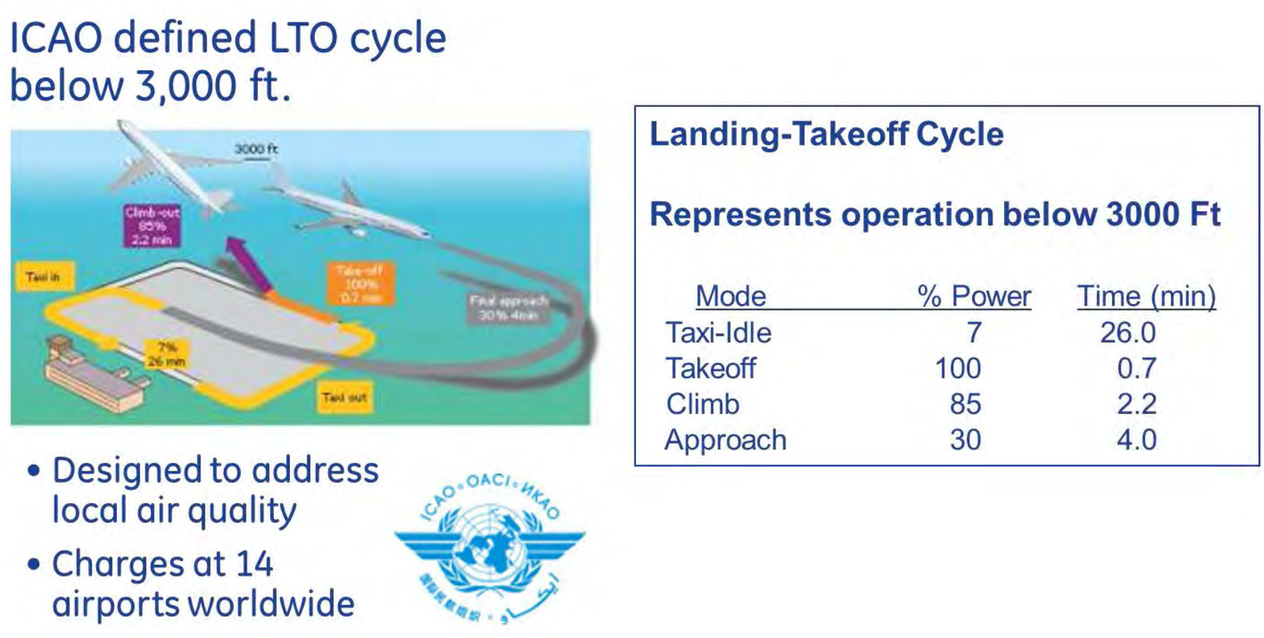

Figure 8 ICAO Landing and Takeoff Cycle (LTO)

The TAPS II combustor operates on pilot only at 7% and 30% thrust and operates with pilot and main fueling at 85% and 100% thrust. Full annular rig data established pressure and fuel air ratio exponents to correct measured emissions to the exact LTO condition

The average measured full annular rig data demonstrated 47.3% of the CAEP/6 NOx limit (52.7% margin). However, the main mixer flow on the full annular combustor was below the design target. This increases main stage flame temperature and NOx emissions. Using fuel/air ratio derivative test data to correct to the design intent main mixer flow results in average measured NOx data at 39.3% of CAEP/6. Table 3 summarizes the average measured ICAO Landing and Take-off (LTO) cycle emissions.

Table 3 TAPS II average measured Emissions

TAPS II	LTO Emissions				
	NOx		CO	HC	Smoke
	As Measured	Design Intent			
Avg Measured emission (g/Kn thrust)	35.5	29.7	25	0.82	4.2
% of CAEP/6 Limit	47.3%	39.3%	21.2%	4.2%	19.5%

The “design intent” emissions results are consistent with the earlier sector test data. The sector test had the correct main mixer flow and the average measured NOx data met the CLEEN goal. The higher NOx on the full annular rig is due to the low flowing main mixer. The reduced flow to the main mixer is due to a geometry issue in the cowl/mixer flow path. An improve design has been developed through CFD analysis and future testing will include the improvement. The sector was run in a plenum rather than the engine flow path so it had the design intent air flow splits.

Smoke data was also taken on the full annular rig. On TAPS combustion systems, the peak smoke number occurs at the maximum pilot only (rich burn) condition, which is the 30% LTO point. When the mains are fueled (lean operation) there is no measurable smoke. Peak smoke number measured on the TAPS II was 4.2 at 30% power.

The initial proposal included PM measurement. However, at the time tests were conducted, the standard for PM measurement had not been selected by the E31 committee, so this effort was dropped from the program plan. The 0 smoke number at higher power suggest that the lean burn TAPS II system should have low PM levels.

The results of the TAPS II combustor with a LEAP engine cycle can also be compared to the baseline engine it will replace. The CFM56-5B3/3 average measured emissions certification data was shown in back in Table 2. Figures 9 and 10 compare the TAPS II results to the baseline engine. TAPS II has significant reduction for all 4 regulated pollutants and the TAPS II technology NOx emissions are at 39.3% of CAEP/6 (or 60.7% margin to CAEP/6), which meets the CLEEN NOx goal of 60% margin to CAEP/6.

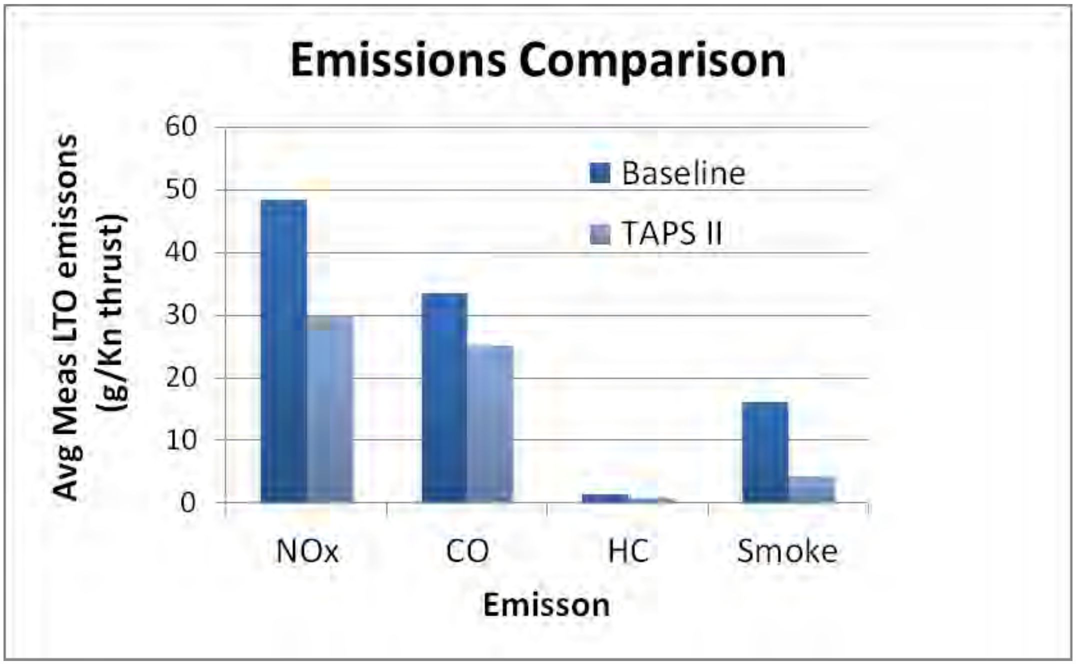

Figure 9 Average Measured Emissions Comparison

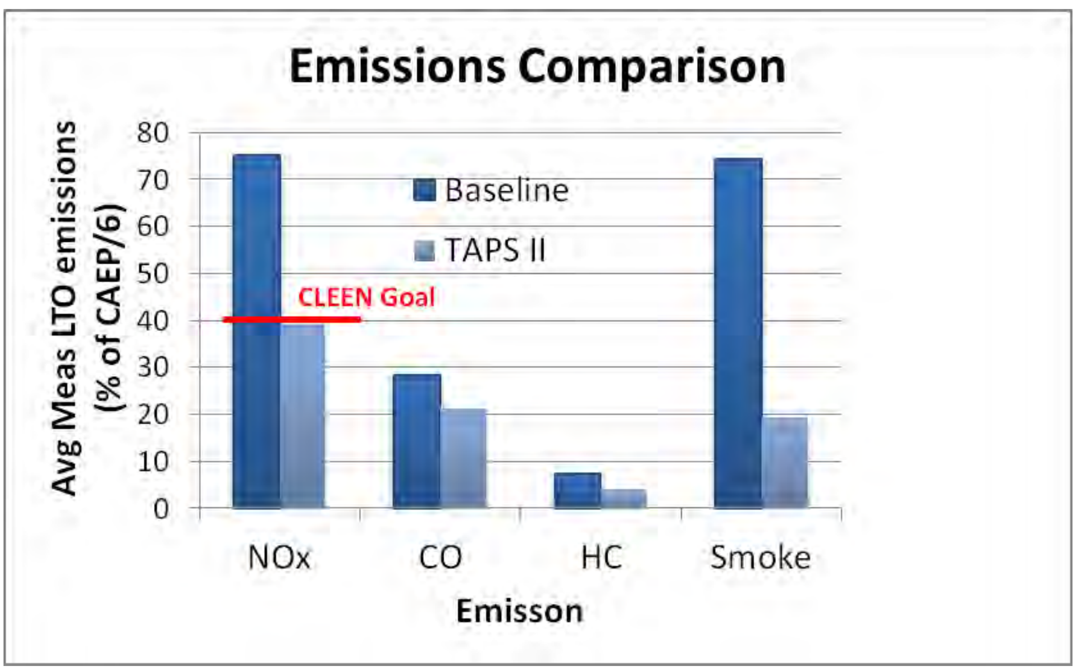

Figure 10 Average Measured % of CAEP/6

4.2 Cruise Efficiency and Mission NOx Assessment

When lean burn combustion systems are optimized for low NOx over the ICAO LTO cycle, they can become too lean for high combustion efficiency at cruise. The requirement of any commercial engine combustion design is to meet >99.9% efficiency at cruise to minimize fuel burn. One alternative is to stage the combustor to pilot only operation at cruise, but this leads to higher NOx emissions and a more peaked exit temperature profile.

As an example of the potential trades, Figure 11 compares total NOx emissions for a 500 nm mission for an A320 aircraft equipped with a LEAP engine. The first column represents the NOx emissions for a traditional rich burn combustor, the second the TAPS II combustor operating in pilot only mode for the cruise leg, and the third column is the TAPS II combustor operating fully staged (lean) for the cruise leg. The stacked bar chart has the NOx produced over the ICAO LTO cycle shown on the top and the bottom portion of each bar is the NOx produced for the mission above 3000 ft altitude (climb, cruise and descent).

The plot shows that the TAPS II NOx advantage over rich burn is larger when you include the full mission rather than just the LTO cycle. It also shows that lean burn at cruise greatly reduces total NOx emissions. This would suggest that optimization of the combustor design to be fully staged at cruise will result in lower total mission NOx emissions even if LTO NOx were to increase.

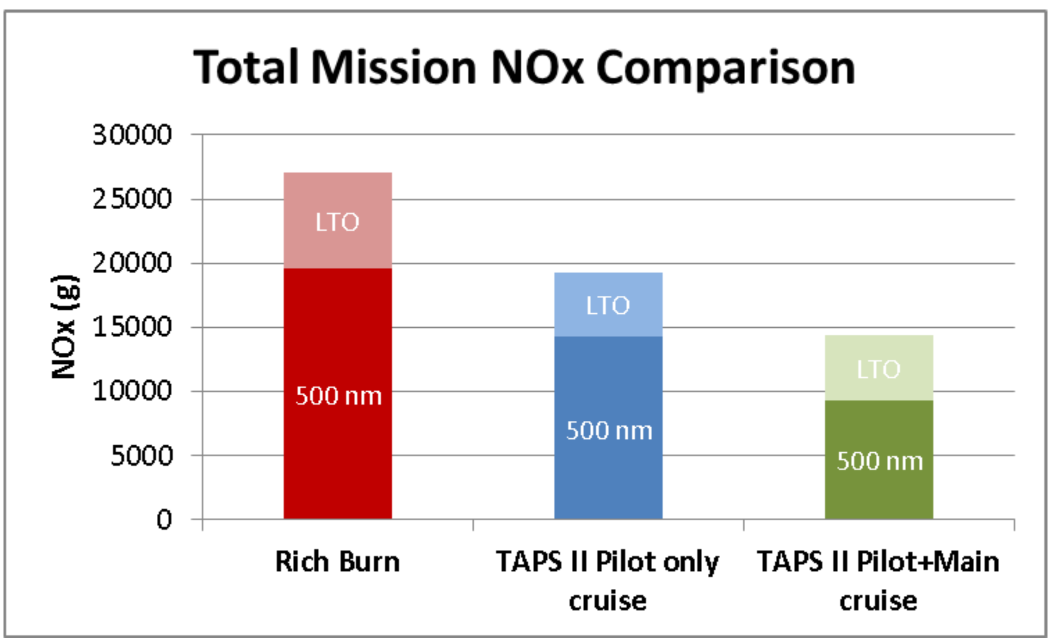

Figure 11 Mission NOx Comparison

5.0 Technology Assessment

The TAPS II combustion system successfully demonstrated capability to meet the FAA CLEEN NOx emissions goal of 60% margin to CAEP/6. The TAPS II meets this goal at a higher pressure ratio (38 OPR) than what was specified in the CLEEN goals (30 OPR). Therefore the TAPS II also contributes to the FAA CLEEN fuel burn goal by enabling higher engine efficiencies due to the higher pressure ratio. The program also met the internal GE targets of cruise NOx < 9 g/Kg fuel burn and the design has been scaled to a narrow body application. PM measurements were not completed because the PM measurement method and standard had not been established during the TAPS II program.

Specific technologies demonstrated during the TAPS II development included scaling the TAPS lean burn concept from a wide-body application (GEnx) to a narrow-body (LEAP), development and evaluation of an improved main mixer and pilot stage designs, improved durability combustion liners and better combustion dynamics test and modeling capability.

The TAPS II technology completed full annular combustor and core engine test demonstrations. In addition to meeting the CLEEN NOx goal, CO, HC and smoke emissions were improved relative to the baseline combustor design and were well below CAEP/6 limits.

Although PM measurements were not taken, the 0 smoke number measured for staged operation shows the potential for much lower PM emissions with a lean burn TAPS II system. A PM limit has not been established by ICAO, but the staged lean burn smoke number has > 90% margin to the smoke number limit which meets the program goal. Rich burn pilot only smoke had 80% margin to the ICAO limit.

The design demonstrated acceptable lean blowout and altitude relight. Exit temperature profile and pattern factor met requirements. High frequency combustion dynamics were present but the fuel and control system has the ability to avoid them. Combustor pressure loss and turbine backflow margin met requirements. Metal temperatures were at acceptable levels.

5.1 Technology Readiness Level

The goal of the CLEEN program was to develop the TAPS II combustor to a technology readiness level of 6. TRL6 requires a systems level demonstration. A successful system demonstration was accomplished by the LEAP core engine test. Therefore, the TAPS II combustor with a dual orifice pilot is at TRL6. The TAPS II TRL was 2 at the beginning of the CLEEN program.

5.2 Development Through Certification

The TAPS II demonstration was performed on a smaller LEAP core engine. The product design is a larger core so the combustion chamber will be scaled up and the number of fuel nozzles increased.

Because of these changes sector and full annular testing will be completed as part of the product development. Flame tube testing is not required because the mixer down select was completed in the technology program.

Combustor operability will continue to be developed as part of the certification effort. Improvements will be made in air start capability.

Durability of the combustor liners will be improved by cooling optimization. This will be worked through analysis and full annular rig testing. Fuel nozzle durability will also be worked through heat shielding and geometry optimization. Again analysis, full annular rig and coking tests will be the primary tools.

The main mixer flow may be reduced in the product design to better balance cruise efficiency and LTO NOx as described in section 4.2. Trade studies and additional full annular testing is planned to assess this in the product design.

After conceptual, preliminary and detailed design and analysis and the associated component testing, the product development program will move into engine testing – both for engineering data and certification.

5.3 Introduction to the Field

An objective of the CLEEN program was to work technology development with the potential for near term field introduction and impact commercial fleets. The TAPS II combustion system meets that requirement as it is planned for introduction in the LEAP engine family in 2016. The aircraft applications are shown in Figure 12. The TAPS design on the GEnx wide-body application has been in service for over 1 year. Introduction of TAPS II to narrow-body applications will greatly increase the fleet impact.

Lean burn TAPS combustion

- TAPS I in service on 747-8 and 787 wide body aircraft
- TAPS II (FAA CLEEN) scaled technology to narrow body aircraft

Application/Engine	1st Engine To Test	Entry into Service
COMAC C919/Airbus A320 NEO		
– LEAP-1A/-1C	Sept 2013	2016
Boeing 737 Max		
– LEAP-1B	April 2014	2017

Figure 12 TAPS II Applications and Entry Into Service Dates

5.4 Continued Development

The lean burn TAPS combustion systems have successfully demonstrated significant NOx reduction and have met all the requirements of a product combustor. There is still room for continued development:

1. **Simplification.** Continued development to simplify the combustion system will help reduce the cost of this low NOx technology.

2. **Reduced Combustion Dynamics.** Combustion dynamics are typical in lean burn systems. The TAPS design uses fuel staging to avoid regions of dynamics. Improved fundamental understanding of combustion dynamics and better design tools will expand the operating range and simplify fuel staging requirements. Another approach would be active combustion dynamics control or passive damping which may allow for additional optimization of the fuel system with the potential to further reduce emissions.

3. **Operability.** The TAPS systems have demonstrated acceptable operability despite the challenges of a lean burning primary combustion zone

4. **Autoignition and Mixing.** A great deal of development work on the TAPS system has centered on the main fuel injection and mixer design. Improving mixing and reducing autoignition risk is the key to reduced NOx and operation at higher pressure ratios. The current design has autoigntion margin and is partially premixed but continued development can lead to additional improvements.

5. **Fuel Nozzle durability.** The TAPS fuel nozzle is a key component of this lean burn system. It provides the rich burn pilot fuel injection for low power and the lean burn main stage fuel injection for high power. The thermal design protects the aft face of the nozzle from the combustor radiative heat load and the fuel circuits maintain temperature levels that minimize carbon build up even during fuel staged operation. The fuel nozzle is in a very challenging environment that will get tougher with higher pressure ratio engines. Continued develop in cooling and thermal protection is key to increase the durability of this component.

6. **Cruise Efficiency.** Lean burn combustors just optimized for the ICAO landing and take-off cycle can tend to roll off on efficiency at the lower fuel air ratio cruise conditions. The TAPS II product design will balance high cruise combustor efficiency and good LTO NOx levels.

In addition to the technology development listed above, PM measurement on baseline rich burn and TAPS combustion systems could be worked in follow on efforts. The PM data was originally planned for this program, but measurement techniques were not in place. Future programs could build the PM database and show the advantages of lean burn technology.

Any of these items are potential elements for a future CLEEN combustor technology development program.

6.0 References

[1]Foust, M., Thomsen, D., Stickles, R., Cooper, C., and Dodds, W., "Development of the GE Aviation Low Emissions TAPS Combustor for Next Generation Aircraft Engines," AIAA Paper, October 2011.

[2]Ratliff, G., Sequeira, C., Waitz, I., Ohsfeldt, M., Thrasher, T., Graham, M., and Thompson, T., "Aircraft Impacts on Local and Regional Air Quality in the United States: PARTNER Project 15 final report," PARTNER-COE-2009-002, October 2009.

[3]Waitz, I., "Energy Policy Act Study", presentation to UC Symposium on Aviation Noise and Air Quality, Palm Springs, March 2009.

[4]Barrett, S.R.H., Britter, R.E., and Waitz, I.A., "Global Mortality Attributable to Aircraft Cruise Emissions", Environ. Sci. Technol. Vol. 44, No.19, 7736-7742, 2010.

[5]Penner, J.E., et al., IPCC Special Report on Aviation And The Global Atmosphere, Cambridge University Press, 1999.

[6]Jacobson, M.Z., Testimony for the Hearing on Black Carbon and Global Warming, House Committee on Oversight and Government Reform, United States House of Representatives, October 18, 2007.

[7]"Annex 16: Environmental Protection Volume II: Aircraft Engine Emissions," ICAO 2006.

[8]"CFMI Website, www.cfmaeroengines.com

[9]Gleason, C.C. and Niedzwiecki, R.W., Results of the NASA/General Electric Experimental Clean Combustor Program, AIAA PAPER 76-763, 1976.

[10]Mongia, H. C., "TAPS – A 4th Generation Propulsion Combustor Technology for Low Emissions, AIAA Paper 2003-2657, AIAA/ICAS International Air and Space Symposium and Exposition, July 2003.

[11]Leonard, G. and Stegmaier, J., "Development of an Aeroderivative Gas Turbine Dry Low Emissions Combustion System", J. Eng. Gas Turbines Power, V 116, Issue 3, 542, July 1994.