FAA
Continuous Lower Energy, Emissions and Noise (CLEEN II)
Technologies Development – TAPS III Combustor

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List of Acronyms and Abbreviations

CAEP	Committee on Aviation Environmental Protection
CFD	Computational fluid dynamics
CO	Carbon Monoxide
DTDR	Detailed Test Design Review
EICO	Emissions Index for CO (grams of CO per kilogram of fuel (g/kg))
EIHC	Emissions Index for HC (grams of HC per kilogram of fuel (g/kg))
EINOx	Emissions Index for NOx (grams of NOx per kilogram of fuel (g/kg))
FAR	Fuel air ratio
FAR	Full annular rig
FETT	First Engine to Test
FT	Flame tube
FTF	Flame transfer function
GRC	GE Global Research Center
HC	Hydrocarbon (emissions)
HPS	High Pressure Sector
HTP	High temperature and pressure (flame tube rig)
ICAO	International Civil Aviation Organization
LBO	Lean Blow Out
LES	Large Eddy Simulation
LTO	Landing and Take-off
NOx	Oxides of nitrogen
NPI	New Product Introduction
nvPM	Non-volatile particulate matter
OPR	Overall pressure ratio
P3	Pressure at station 3 – HPC discharge
RANS	Reynolds-averaged Navier–Stokes based CFD design process
RQL	Rich-Quench-Lean (combustor)
SAC	Single Annular Combustor
SFC	Specific Fuel Consumption
T3	Temperature at station 3 – HPC discharge
T4	Temperature at station 4 – combustor discharge
TAPS	Twin Annular Premixing Swirler
TCA	Tunable Combustion Acoustics (flametube test rig)
TOW	Time on Wing
TRL	Technology readiness level
We	Aerodynamic Weber number
WF36	Fuel flow station 36 – burner exit

TAPS III Combustor Technology

Final Report

1 Summary

In accordance with the FAA CLEEN II goals for Landing and Take-Off (LTO) NOx emissions reduction, the TAPS III Combustor Technology Program developed and matured a lean-burn combustion system design and multiple new fuel/air premixer concepts in an effort to achieve NOx emissions commensurate to 75% below CAEP/6 at 30 overall engine pressure ratio (OPR). The TAPS III combustor design is being developed for the GE9X engine, which will enter service on the Boeing 777X aircraft with the highest overall pressure ratio of any commercial engine and a projected 10% SFC improvement over the GE90-115B. The LTO NOx goal results in a target emission of 65% of CAEP/8 (35% reduction below CAEP/8) at a projected 55 OPR cycle. The TAPS III combustor technology and new fuel/air premixer concepts proceeded from CFD-based design through single cup evaluation rigs. The baseline design was further validated in a high-pressure sector rig test and 2 different full annular rig combustor tests. Outside of the CLEEN II program, the technology maturation of the TAPS III combustor was further confirmed during the GE9X First Engine to Test (FETT), including engineering emissions measurements, demonstrating TRL6 capability for TAPS III technology. Through this testing, the baseline TAPS III design and the CLEEN II new technology concepts were shown to demonstrate >42% reduction below CAEP/8 LTO NOx when projected to a 55 OPR cycle (vs. the goal of 35%), while achieving <12 EINOx and 99.9% efficiency at cruise. The technology also resulted in LTO Smoke and particulate (nvPM mass concentration) <40% of CAEP/8 and CAEP/10, respectively, and LTO CO and unburned hydrocarbons with acceptable margin to CAEP/8.

In addition to the maturation of the TAPS III combustor and fuel/air premixer concepts, the CLEEN II program also advanced modeling tools and mitigation strategies for high frequency combustion dynamics. Unmitigated, such combustion dynamic pressures can cause hardware damage. The advanced modeling tools included dynamics spray modeling, Large Eddy Simulation (LES)-based flame transfer function model development, 3D acoustic modeling, and LES-based dynamics computations. The validated modeling tools were then utilized during the TAPS III program to perform pre-test predictions and prioritize concept designs during the down-selection process prior to hardware being released. By mitigating high frequency combustion dynamics, the operation of the combustor could be optimized towards low emissions, operability, durability, and efficiency. Combustion dynamics can also be mitigated through passive damping techniques. As an additional CLEEN II dynamics strategy, passive dynamic dampers were designed and validated in a single-cup screening rig. Conceptual damper designs were also laid out for a multi-cup combustor application; however, the low measured combustion dynamics in the CLEEN II TAPS III program did not require these additional mitigation measures.

Because of the demonstrated emissions capability of the baseline design through rig component testing (and the separate FETT engineering emissions test), exceeding the LTO NOx reduction goal for the CLEEN II program, technical work on the program was ceased following the TRL3 review of the new technology fuel/air premixer concepts. This decision was taken under agreement between GE and the FAA. The best of the new technology premixer concepts were anticipated to yield only slightly better NOx (~2%) relative to the baseline design, while also providing incremental improvements in cruise efficiency (~0.03%). The program technology objectives have been successfully demonstrated.

2 Introduction

GE Aviation is a world leader in low emissions combustor designs and their integration into low fuel burn engine systems while balancing flight safety and durability. GE has extensive experience with low emissions rich burn combustion systems, and more recently lean burn systems. The 25+ year journey of proven innovation in combustion science, materials, and manufacturing is highlighted in *Figure 1*. The following presents GE's combustion systems and historical perspective, with the intent of explaining how CLEEN II combustion technologies fit into GE's program plans.

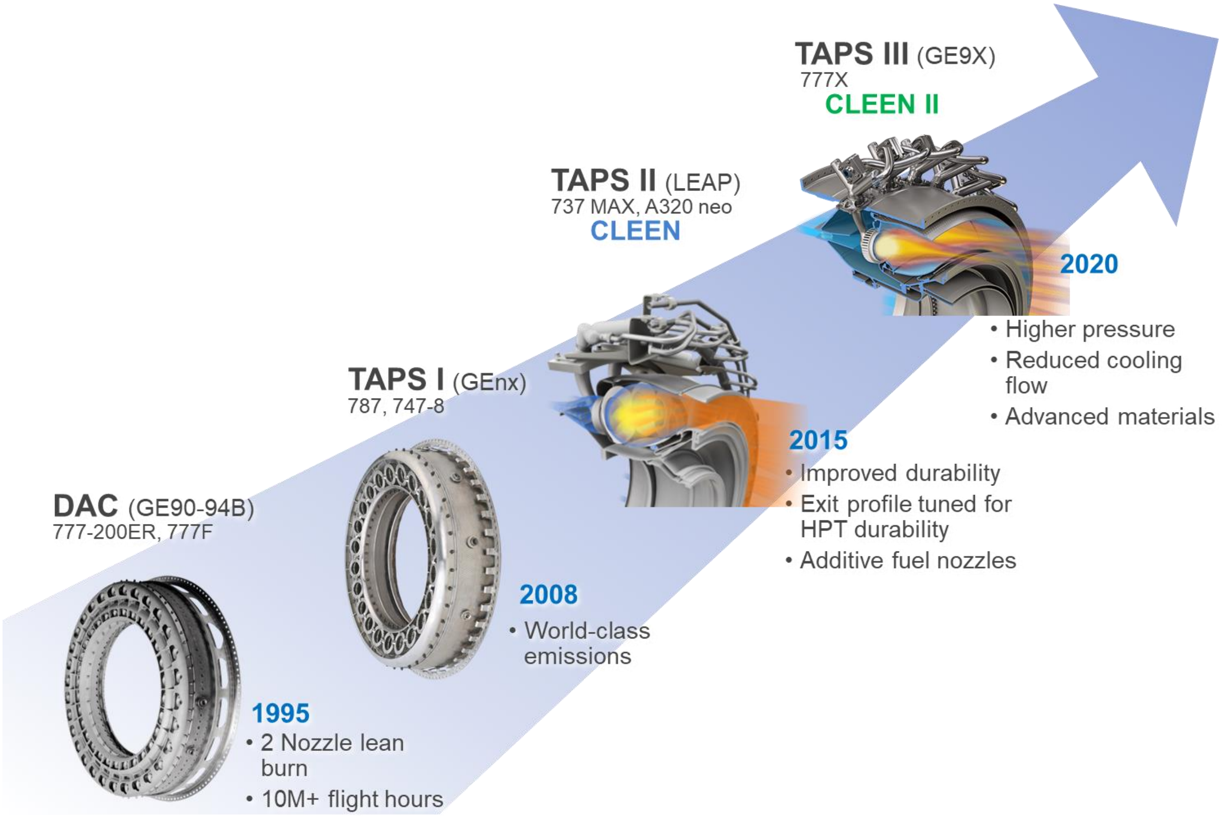

Figure 1: 25+ Year Journey to Low NOX Technology

Most production aviation combustion systems are rich burn designs. Optimization of the quench air in a rich burn design can lead to modest NOx reductions, and GE Aviation has experience with these Rich Quench Lean (RQL) systems. The CFM56 tech insertion (2005) and CFM56 DAC (2006) are RQL designs that had Landing and Take-Off (LTO) cycle NOx levels 26% and 35% below CAEP/6, respectively, at an engine pressure ratio of 26. However, more significant NOx reduction, particularly at higher engine pressure ratios (pressure ratio >35), requires lean burn combustion technology.

GE has demonstrated the ability to take lean-burn, low NOx technology from concept, to demonstration, to a fielded product; providing a breakthrough in NOx emission levels compared to RQL designs. Twin Annular Premixing Swirler (TAPS) I development initiated more than 21 years ago with NASA AST mixer studies and included a technology demonstration on a CFM56 engine. The basic TAPS mixer concept is depicted in *Figure 2*. The design consists of two independently controlled, swirl stabilized, annular flames for low power (pilot) and high power (cyclone) operation. The central pilot flame provides good low power operability and low CO and HC emissions. The cyclone or main flame is concentric with the pilot flame and is designed to produce low NOx emissions during high power operation.

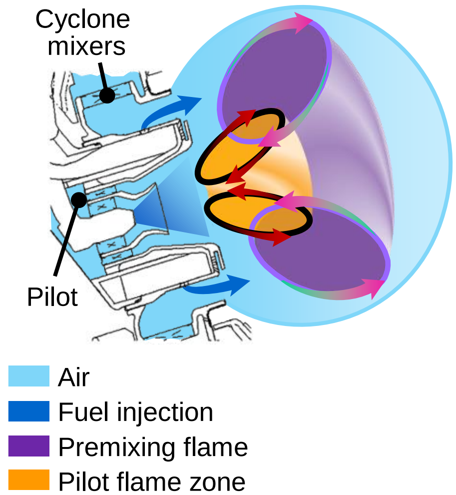

Figure 2: TAPS Mixer Concept

GE has continued to advance the TAPS combustor design into multiple platforms, with each generation driving additional emissions performance and building on prior learnings. The evolution of combustor and fuel/air premixer technology features has continued during the CLEEN II program, with close integration to the GE9X engine that has now received Part 33 Certification as of 9/25/2020.

The GEnx TAPS I combustor, flying on Boeing 747 and 787 aircraft, demonstrated LTO NOx 64% and 43% below CAEP/6 requirement at 35 and 45 pressure ratios. TAPS II, developed for the LEAP engine in partnership with FAA CLEEN, is scaled down and enhanced for narrow-body applications. The TAPS II combustor entered service in LEAP engines on the Airbus A320neo (2016) and Boeing 737max (2017); and is projected on the COMAC C919 (2021). It met the NASA N+1 NOx goal of 60% below CAEP/6 requirement at a 45 overall engine pressure ratio during the CLEEN program.

TAPS III development for the GE9X engine was undertaken to meet anticipated future CAEP requirements with a target LTO NOx emission of 65% CAEP/6 at 55+ overall engine pressure ratio. The GE9X engine will enter service on the Boeing 777X by 2022, with the highest overall pressure ratio of any commercial engine and a 10% SFC improvement over the GE90-115B. This program has benefited from early demonstration of key design features under Phase 1 of a NASA N+2 funded effort. In that program, high-pressure sector test results with innovative fuel/air mixing technologies and advanced materials exceeded the LTO NOx emissions reduction goals of 75% below CAEP/6 without any compromise to unburned hydrocarbons and

CO emissions, and also demonstrated cruise NOx 76% lower than 2005 best-in-class with >99.9% combustion efficiency.

The GE9X engine application brings unique challenges to TAPS III technology development. While the GE9X maintains a similar cup size as the GEnx, therefore minimizing scaling, the high 55+ OPR cycle requires new features to balance all of the key combustion criteria: LTO and cruise NOx, combustion dynamic pressures, durability, operability, and cruise efficiency. Fuel nozzle design and additive manufacturing techniques leverage the significant development under the CLEEN TAPS II program. While all aero features of the fuel nozzle had to be scaled and reconsidered to meet the high OPR cycle for CLEEN II TAPS III, the mechanical, thermal, and manufacturing design processes learned and matured during the TAPS II program were key to enabling the successful capability advancement for TAPS III.

During the CLEEN II TAPS III Combustor Technology Program, GE has partnered with the FAA to advance the development of the next generation low NOx TAPS III combustor. The baseline GE9X technology was pushed even further, leveraging additional N+2 learnings/concepts where needed, to achieve even lower CLEEN II NOx emissions targets while continuing to maintain overall engine SFC performance. The CLEEN II effort developed and matured new combustion technologies to TRL3, on the original path to a TRL6 demonstration through core testing.

The specific Goals and Performance Objectives of the CLEEN II TAPS III program were as follows:

Program Goals:

- ✓ TRL6 demonstration of CLEEN II fuel-air mixer technology and NOx capabilities in a GE9X Product Core; implementable as Technology Program for GE9X as early as 2025
- ✓ Technology development to mitigate combustion dynamics at high OPR and facilitate concept evaluation/down-select:
  - ➢ Passive damping & design tools; implement in high-TRL vehicles as required
  - ➢ Advanced modeling techniques for combustion dynamics; application to concept evaluation & decision points for CLEEN II
- ✓ Evaluation of alternative fuels & fuel blends via FAR and Core testing *(*CLEEN II – Alt Fuels program)*

Key Performance Objectives:

- ➢ LTO NOx emissions (FAA Goal): 35% margin to CAEP/8 @ 55 OPR
- ➢ Cruise NOx emissions (GE Goal): < 12 g/Kg fuel at average cruise
- ➢ Solid Particulate Matter (GE Goal): 60% margin to CAEP/10 (based on Smoke)
- ➢ Efficiency (GE Goal): Maintain combustor > 99.9% at cruise

The relationship of the CLEEN II TAPS III program LTO NOx reduction goal to the FAA CLEEN II goal of 70% margin to CAEP/8 NOx is depicted in *Figure 3*. Recent CAEP stringencies have maintained the slope of DP/Foo vs OPR for OPR >30; this slope is presumed for future CAEP targets, and thus the commensurate CLEEN II objective for LTO NOx reduction at the TAPS III 55 OPR cycle conditions is 35% relative to CAEP/8.

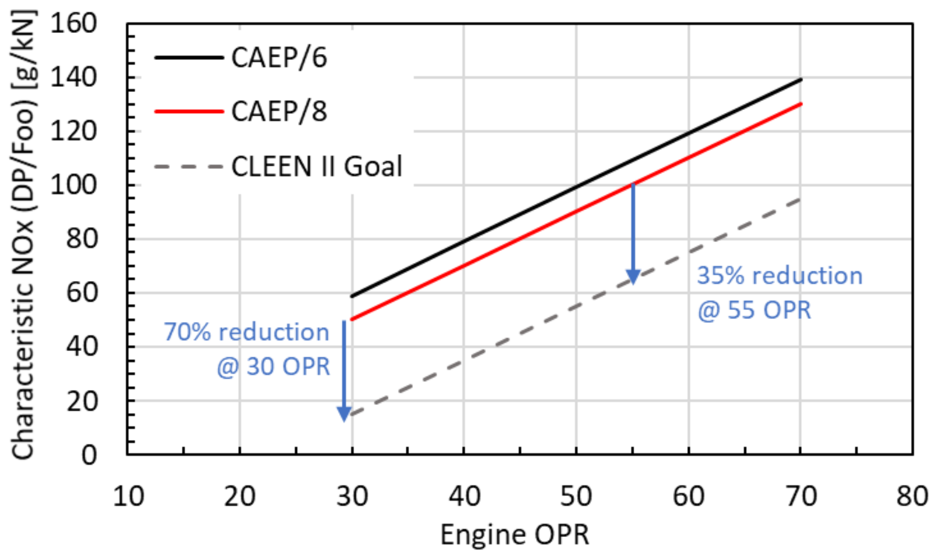

Figure 3: CLEEN II LTO NOx Goals

During the CLEEN II program GE has advanced the TAPS III technology toward the Goals and Objectives through the following series of activities:

- Starting with the GE9X baseline fuel/air premixer design, new concepts were developed to further reduce LTO NOx emissions and maintain/improve cruise efficiency and cruise NOx. These concepts underwent conceptual aero, thermal, and mechanical design and analysis. Early screening hardware was created for some low-TRL concepts and was tested at elevated T3/P3 conditions to evaluate flame shape and emissions. The prime concepts were fabricated for single-cup testing at full engine T3/P3 cycle conditions, and the resulting test data contributed to a completed TRL3 review. Multiple new concepts, as well as the baseline design, were demonstrated to be on track to meet / exceed the CLEEN II TAPS III objectives.
- The baseline TAPS III combustor and fuel/air premixer design was validated through a series of component rig tests to advance its TRL and provide a reference dataset for comparison of additional CLEEN II new technology fuel/air premixer concepts. Single cup testing was used to evaluate durability, screen emissions, and characterize combustion dynamics. A High Pressure Sector test provided emissions derivative data up to climb conditions (85% rated thrust, one of the LTO NOx emissions certification points). Finally, two different Full Annular Rigs validated operability, emissions, thermal pattern / profile, and combustion dynamics.

- Multiple modeling methods for combustion dynamics were developed, validated against test data, and applied for pre-test predictions at various stages of the combustor development program.
- Passive damping methods for mitigation of combustion dynamics were designed, tested and validated in single-cup rigs, and extended to conceptual designs for full annular combustor architectures.

Through these activities, the TAPS III combustor demonstrated the CLEEN II TAPS III program goals and objectives. Beyond the successful TRL3 review (and outside of the CLEEN II program workscope) the baseline TAPS III combustor design has achieved TRL6 during GE9X development engine testing. An early emissions test on the GE9X First Engine to Test (FETT), and now the official engine certification tests, have demonstrated LTO emissions reduction that exceeds the CLEEN II TAPS III program objectives.

3 Executive Summary of TAPS III Combustor Technology

3.1 TAPS III Combustor Technology

Starting with the legacy GEnx TAPS I design, the GE9X baseline TAPS III fuel/air premixer had achieved TRL3 prior to the start of the CLEEN II program, on plan to meet the GE9X engine program requirements. The CLEEN II performance objectives for LTO NOx are even more challenging than the GE9X engine program targets, and therefore new innovations were expected to be required to meet CLEEN II objectives. Through the CLEEN II effort, the baseline TAPS III has been validated through high TRL component rig tests and new concept fuel/air premixer designs have been designed, analyzed, tested, and reviewed to achieve TRL3. In support of reducing risk and ensuring achievement of the CLEEN II performance objectives, significant work and advancements were also made in combustion dynamics predictive modeling and dynamics mitigation methodologies. This section summarizes the key outcomes of the CLEEN II technology development activities relative to the Goals and Performance Objectives.

3.1.1 Conceptual Aero and Mechanical Design

3.1.1.1 Concept groups

In building off the TRL3 validated TAPS III baseline design, 4 new fuel/air premixer concept groups were evaluated. These concepts are, in order of maturity from most- to least-mature:

1. Concept group 1: GE9X variant fuel nozzle
2. Concept group 2: GE9X variant mixer + fuel nozzle
3. Concept group 3: Advanced premixer concept (NASA N+2)
4. Concept group 4: Low TRL concept (new)

All 4 concept groups were evaluated and optimized via CFD modeling. The least mature concepts were released for early hardware builds in order to conduct screening for air flow, fuel spray characterization, and combustion testing of flame shape and emissions. GE9X variant designs were released for single cup test hardware fabrication.

3.1.1.2 Concept analysis and selection for emissions, efficiency, and dynamics

3.1.1.2.1 GE9X variants (concept groups 1 and 2)

A summary of the GE9X variant designs and their predicted benefit to Takeoff NOx and Cruise CO is provided in *Figure 4*. Designs in the green & black box look to have benefit in cruise efficiency with similar NOx.

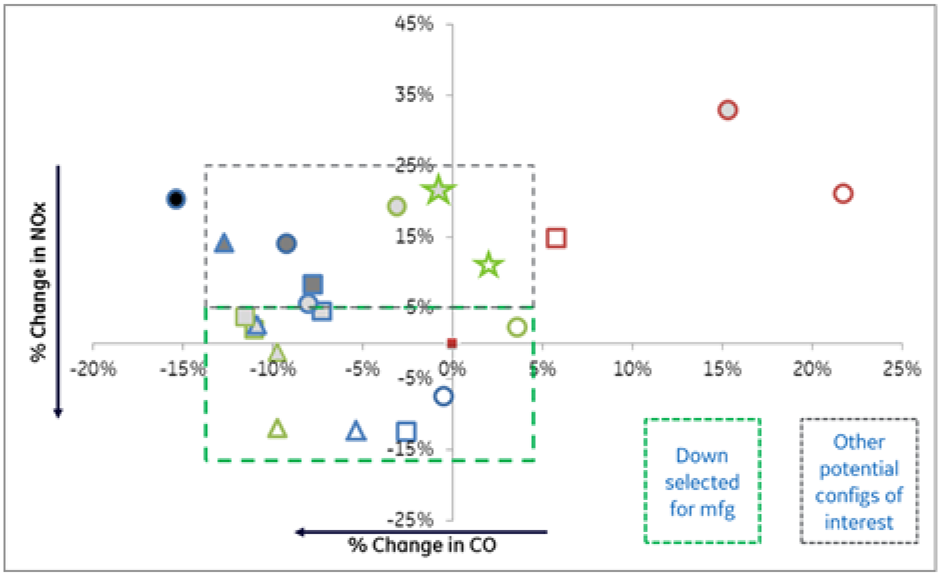

Figure 4: Concept Groups 1 & 2 - NOx and CO (efficiency) predictions

Following an aero design review, the fuel nozzle and swirler designs were down-selected for thermal/mechanical design & manufacturing release, based on predicted NOx and cruise efficiency.

The concept down-selection review was held prior to the completion of combustion dynamics pre-test predictions. The dynamics predictive modeling methods, advanced through the CLEEN II program, were then used to evaluate the GE9X variant concepts to rank them for combustion dynamics risk, and 3 were recommended for testing.

3.1.1.2.2 Additional concept group 3

Concept Group 3 was originally evaluated during the NASA N+2 program. Several new versions of this advanced premixer were designed, optimized, and screened in early rig tests. Two early Concept Group 3 fuel/air premixers were fabricated and tested at the GE Research Center. Initial testing in an optically-accessible single cup combustion test rig was executed. Combustion dynamics measurements were collected, indicating a steady tone at an amplitude greater than that observed for the baseline premixer design at similar conditions. This test result indicated that these concepts should undergo further assessment via the combustion dynamics analysis predictive tools.

The Group 3 rig hardware fabrication was stopped mid-process, once the GE9X variant concept groups had generated sufficient test and analysis evidence of meeting the CLEEN II performance objectives with their higher TRL, lower-risk designs.

3.1.1.2.3 Additional concept group 4

An early Concept Group 4 low-TRL premixer, designed prior to the start of CLEEN II, was built and spray tested. Based on these early results, and taking into consideration the mechanical constraints of the GE9X combustor geometry, a full design study was performed to evaluate various parameters for the concept. Three designs from this study were built for flow testing, and 2 of these were chosen for a combustion screening test along with the original concept design.

NOx and CO emissions data were obtained and compared with the baseline TAPS configuration. The data indicate that, overall, higher NOx and CO was observed for the concepts in comparison to the baseline TAPS. Following this initial concept testing, the group 4 concept was dropped from consideration for higher T3/P3 single cup testing. The potential advantages of the concept remain; however, the initial test results, the low TRL of this concept, the significant optimization required to advance TRL, and the favorable performance expectations of Concept Groups 1 & 2 all drove the decision to remove this from consideration and focus on the prime concepts in meeting the emissions target for CLEEN II.

3.1.2 Baseline TAPS III component rig testing

3.1.2.1 Single cup rig tests

The Tunable Combustion Acoustics (TCA) test rig is used for combustion dynamics screening at high pressure and temperature conditions. In this task, a validation study of the low dynamics operating region of the baseline mixer/nozzle sets was performed using the TCA3 rig. Dynamic amplitudes and frequencies were then assessed over a wide range of combustor inlet conditions. The results of this sub-task validate baseline TAPS III combustion dynamics capability over specific conditions of interest to engine operation and serve as a baseline for CLEEN II alternate technology concept design down-selection.

GE also conducted a validation study of emissions and durability capability of the baseline fuel nozzle / mixer. The single-cup High Temperature and Pressure (HTP) rig was used to evaluate the designs at high OPR operating conditions. The results of this sub-task confirm that the hardware meets GE9X emission and durability requirements. The results also serve as a baseline for CLEEN II new technology design down-selection.

3.1.2.2 High Pressure Sector tests

The GE9X High Pressure Sector (HPS) rig was utilized to gather combustion data for the baseline fuel nozzle/mixer configuration, over a range of operating conditions. In this test campaign, the rig was successfully run up to inlet conditions approaching 85% rated thrust (representing climb, one of the LTO NOx emissions certification points). Data of interest included combustion dynamics, combustion emissions and efficiency, and thermal exit profile. The rig proved valuable in confirming measured characteristics and comparison to behaviors of other rigs and the FETT engine.

3.1.2.3 Full Annular Rig tests

In two different full annular rigs, a 22-cup FAR1 and a 28-cup GE9X-scale FAR2, the GE9X TAPS III baseline design was tested to demonstrate emissions, combustion dynamics, operability (lightoff and lean blow-out), durability (component temperatures), and performance (pressure drops and combustion efficiency). The results provide baseline data for comparison of new CLEEN II alternate concept hardware design and down-selection.

3.1.3 Single Cup Testing and TRL3 Review

Single-cup HTP rig-based emissions data was collected to assess cruise combustion efficiency and NOx as well as high-power NOx for four CLEEN II new technology configurations from Concept Groups 1 & 2 and compared to the GE9X baseline. Durability assessment was also conducted on the HTP rig. Based on this testing, the durability capability and emissions outcomes of all configurations relative to engine requirements and CLEEN II program targets have been projected.

Results indicate:

- All tested designs demonstrated required durability capability for the GE9X NPI cycle, via either analysis or test.
- Projection for cruise efficiency show three configurations, including GE9X baseline, are 99.9%. Projection based on correlations to 55 OPR cycle indicates that 99.9% will be achieved
- Engine projection for NOx emissions suggests all tested configs will achieve the CLEEN II target of <65% CAEP/8 @ 55 OPR

The new fuel nozzle/mixer configurations designed and tested under the CLEEN II program have also demonstrated acceptable combustion dynamics behavior compared to the baseline design. This result was also predicted by the advanced dynamics models, developed and executed under Tasks B.1.4 through B.1.7.

The measurements in this task are a key metric in the validation of the new main mixer / fuel injection designs and contribute to the achievement of TRL3. Following the single cup testing of the CLEEN II new technology designs, a TRL3 review was conducted with the Chief Engineer. The summary report and decisions from the review indicate that the primary TRL3 goals for the CLEEN II program were met.

3.1.4 CLEEN II TAPS III Final Results

3.1.4.1 Emissions data

The status of the projected LTO emissions for the CLEEN II new technology concepts is determined based on the single cup data described above. The baseline GE9X emissions have been determined in prior HTP, HPS, FAR1A, and FAR2 testing (as part of the CLEEN II program). Outside of the CLEEN program, the GE9X program executed the First Engine To Test (FETT) and collected preliminary emissions data on a baseline GE9X design. With this set of data, the preliminary baseline GE9X emissions capability is fully established, and a Landing/Takeoff (LTO) emissions can be calculated relative to CAEP/8 requirements, with appropriate uncertainties and applied margins for the state of the NPI program.

Emissions data from the HTP testing of the CLEEN II new technology concepts are then utilized to determine a relative change in NOx and other pollutants for the new concepts vs. the GE9X baseline. (As mentioned above, cruise emissions were also assessed, and a comparison can be made in order to validate this CLEEN II Key Performance Objective.)

Based on the discussion above, the HTP emissions data indicates that all configurations, including the GE9X baseline design, meet the FAA CLEEN II target of 65% CAEP/8 assessed at a 55 OPR cycle (*Figure 5*). The GE9X baseline, at its current OPR, is projected to achieve roughly 46% of CAEP/8 (54% reduction below CAEP/8). For cycle conditions scaled up to 55 OPR, per the original program objectives, the baseline design capability is projected at 58% of CAEP/8. The best CLEEN II new technology concept achieves slightly lower NOx at 56% CAEP/8.

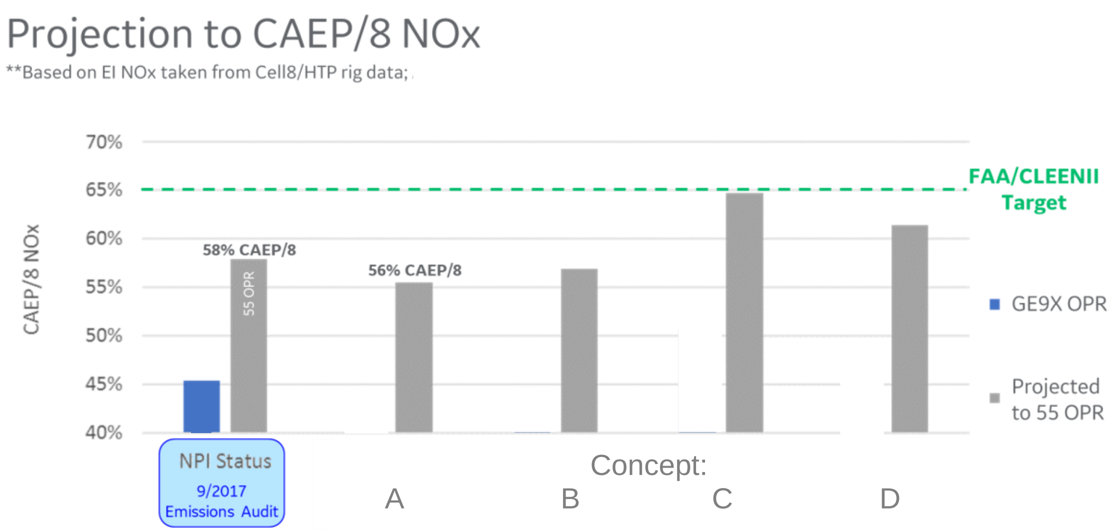

Figure 5: Projected NOx emissions capability of all tested configurations - Concept Groups 1 & 2.

3.1.4.2 Combustion dynamics assessments

The LTO NOx emissions capability of new concept designs is only valid when other key combustor criteria for performance, operability, and durability – including management of combustion dynamics – also meet requirements. The baseline TAPS III design meets all product requirements for the GE9X engine program. The CLEEN II new technology concepts were analyzed and tested in comparison to this baseline design. For combustion dynamics assessment, the single cup TCA rig data was utilized, along with the advanced modeling methodologies.

Pre-test predictions were performed using 2 different dynamics modeling methods Task B.1.5 + Task B.1.6 and Task B.1.7. The predictions were conducted at one specific condition (T3, P3, Fuel/Air ratio, and fuel split) for a large set of potential configurations as well as the baseline, as part of the down-selection/prioritization process. All CLEEN II configurations are noted to have acceptable combustion dynamics amplitude as measured in the TCA3 rig. The model predictions fairly represent the outcomes of the new configurations, relative to the baseline.

3.1.4.3 Status against CLEEN II Performance Objectives

The summary of CLEEN II emissions and performance status for TAPS III technology is provided in *Figure 6*. TAPS III combustor technology has been validated to 58% CAEP/8 (as projected to a 55 OPR cycle) based on TRL6 testing in GE9X FETT. The best new technology concept indicates as low as ~56% of CAEP/8 @ 55 OPR, with incremental improvements in efficiency and combustion dynamics behavior relative to the baseline (based on TRL3 test validation).

Emissions	CLEEN II target	Projected 55 OPR cycle	Alt. concept @ 55 OPR (TRL3)
NOx	65% of CAEP/8	**58%**	**56%**
CO	**No specific CLEEN II target Requirement = CAEP/8*	✓	✓
HC	**No specific CLEEN II target Requirement = CAEP/8*	✓	✓
Smoke	40% of CAEP/8	✓	✓
Cruise NOx	<12 g/kg fuel	✓	✓
nvPM	40% CAEP *(*no standard in CAEP/8)*	✓	✓
Cruise efficiency	*>99.9%*	✓	✓

Figure 6: Summary of CLEEN II emissions and performance status for TAPS III

4 Technical Workscope Task Reports

4.1 Task B.1.1 – Fuel Nozzle and Mixer Aero Design

4.1.1 Summary

In this task, a variety of fuel nozzle/mixer concepts were evaluated and optimized via analytical and experimental processes. The new concepts are intended to provide additional benefit toward the major CLEEN II TAPS III technology goals for emissions and performance, above and beyond the initial baseline concept – the GE9X NPI TAPS III fuel nozzle/mixer. Four major concept groups were considered, including GE9X-variant premixers (Concept Groups 1 and 2) and two lower TRL designs, Concept Groups 3 and 4. First, the mixer aero features were sized and optimized; and then fuel injection design studies were performed to determine the best configurations to meet the combined goals of low LTO NOx and high cruise efficiency, where inefficiency was modeled as cruise CO. The various concepts were also constrained to meet certain geometric and system interface requirements for the GE9X engine. The lowest TRL concepts were also released for early prototype builds and screening combustion rig tests. These combustion tests were conducted in a lower T3/P3 test rig at GE-GRC. Through continuing analysis, learnings from the rig testing of the baseline configuration, and early screening tests, a down-selected set of configs is initially identified for engine-style fuel nozzle fabrication and eventual high temperature/pressure single cup testing. Those configurations include three premixers from Concept Groups 1 & 2, and four Concept Group 3 fuel nozzles. With further learnings from the GE9X baseline rig testing and the screening tests, the Concept Group 3 configurations were eventually stopped in order to focus efforts on the higher-TRL Group 1 & 2 designs.

4.1.2 Introduction

The initial concept design (and baseline configuration for the CLEEN II program) is the GE9X NPI TAPS III fuel nozzle/mixer, which was evaluated to TRL3 prior to CLEEN II. In addition to validating and advancing the TRL for the baseline configuration (Tasks C.1.1-C.1.4 and D.1.1-D.1.5), GE Aviation concurrently evaluated ~4 alternate concept architectures as a part of Tasks B.1.2 and B.1.3.   The concepts varied in their potential advantages and maturity at the start of the CLEEN II program, but each represented unique potential to address key challenges for high-OPR lean combustion and improve upon the baseline GE9X TAPS III capability.

All the concepts were initially sized and optimized using analytical tools (CFD) in single cup models. The focus was on LTO NOx (calculated at Takeoff conditions) and cruise efficiency performance (using calculated CO from the CFD results at cruise). The results were directly compared against model results for the baseline design. Concept groups 1-3 were reviewed internally at GE in August 2016 and with the FAA shortly thereafter; and the down selected concepts were prioritized for manufacturing release to complete detailed drawings and begin fabrication of the single cup rig hardware (Task

C.1.5) for initial screening of emissions, efficiency, and dynamics (Tasks D.1.6 and D.1.7).

Following this aero review and over the next few months, additional analytical studies were completed, evaluating durability risk and combustion dynamics screening. The GE9X-variant designs (Groups 1 and 2) were found to have acceptable durability risk, while the Concept Group 3 needed additional mixer design work in order to show adequate capability.

Analytical combustion dynamics screening utilized the modeling tools developed in Tasks B.1.4 through B.1.7. These pre-test predictions were completed only for Groups 1 and 2 and were utilized to further confirm the prioritization of the configurations for testing.

The Concept 3 designs were taken through the initial sizing and optimization CFD analyses, and down-selected designs were chosen for fabrication. Due to the low maturity of this concept, the team decided to produce simpler rig test hardware for an early screening test in late 2016. Those tests were conducted in an optically accessible rig at the GE Global Research Center, at sub-cruise conditions. Results of those early screening tests are summarized in Section 4.1.4.3, where the flame shape and operational characteristics were observed. In mid-2017, the concepts' priority was decreased, and fabrication of HTP/TCA rig hardware was stopped following the initial additive fuel nozzle tip build. There were several rationales for this, including:

i. Low maturation of the design, relative to the TRL3+ designs
ii. Emissions success of the initial concept (GE9X baseline design) meeting CLEEN II objectives
iii. Expected further improvements in NOx and acceptable cruise efficiency for concept Groups 1 & 2
iv. Predicted thermal/durability risks of the design
v. Observed combustion dynamics in screening tests, relative to the baseline
vi. Desire to limit program scope and spending

Concept 4 was the lowest maturity design but held promise for unique opportunities in terms of addressing risks. A series of concepts were heavily evaluated in CFD, early concept fuel nozzle/mixer hardware was built, and screening tests performed by mid-2016. The emissions for this concept did not show adequate capability relative to the baseline concept, and it was removed from consideration due to its low maturation and expected development timeline.

The following sections describe the concepts, sizing and optimization activities, and down-selection information for each of the various concept groups. In addition, summaries of early screening results are provided for the Concept Groups 3 and 4.

All the concepts were initially evaluated using a common strategy and set of modeling tools. The designs were typically analyzed at 2 conditions; first, at takeoff to assess

NOx, and second, at cruise to assess unburned CO (as an indicator of cruise efficiency).

The concepts were constrained by certain physical and flow requirements. To fit into the GE9X combustor and case without modification of those structures, all concepts had to meet certain envelope criteria. Essentially, because of the synergy of using test rigs and a Core engine from the GE9X, new concepts were targeted to be drop-in replacements for the GE9X hardware. If any geometric or systems interface characteristics would need to deviate from the NPI design, the feature would need to move in a favorable direction for the engine system.

4.1.3 Concept Group 1 & 2: GE9X-variant

4.1.3.1 Mixer and Fuel Injection Development

The GE9X NPI combustor main mixer and variations of an alternative mixer design were evaluated, in combination with variations in fuel nozzle injection design. CFD simulations were conducted to evaluate mixing and eventually NOx and CO predictions. An example output is shown in *Figure 7*, the equivalence ratio distribution in the CFD domain. The flame tube model indicates that the overall similarity to the GE9X baseline.

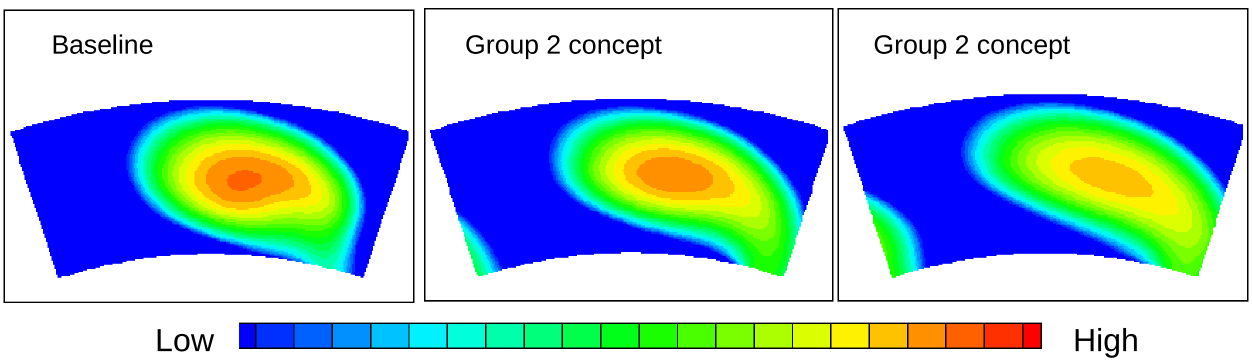

Figure 7: Equivalence ratio distribution in CFD domain

A summary of the designs and their predicted benefit to Takeoff NOx and Cruise CO is provided in *Figure 8*. Designs in the green box look to have benefit in cruise efficiency with as good or better NOx.

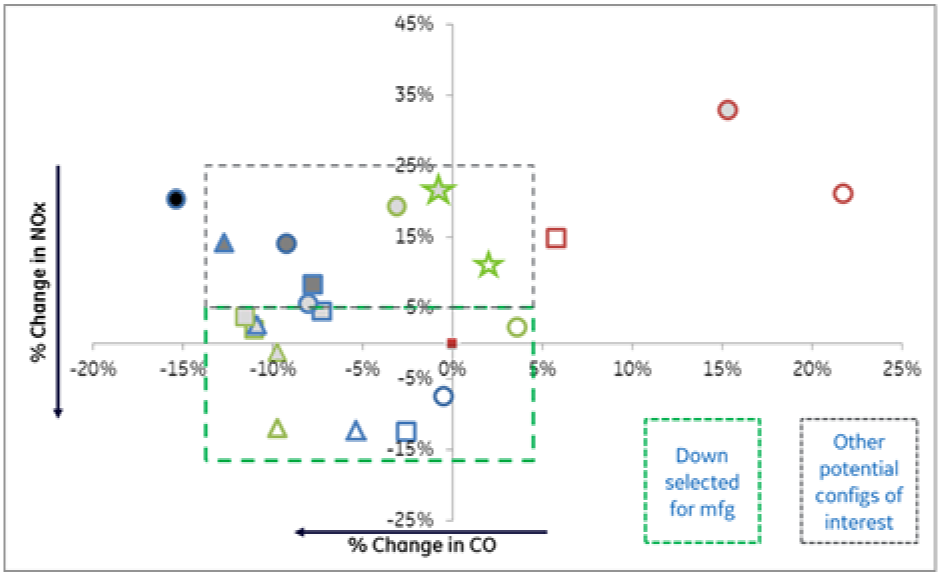

Figure 8: Concept Group 1 & 2 - NOx and CO (efficiency) predictions

Following an aero design review the fuel nozzle and swirler designs were down-selected for thermal/mechanical design & manufacturing release. Eventually, selected configs were prioritized for testing based on dynamics pre-test predictions.

4.1.4 Concept Group 3

Concept Group 3 was originally evaluated during the NASA N+2 program, where it demonstrated the potential (in high T3/P3 single-cup testing) to achieve NOx below 25% of CAEP/6 at an engine cycle similar to GE9X.

4.1.4.1 Group 3 mixer aerodynamic design

The first objective was to design mixers meeting key criteria including effective area, swirl number, velocity and turbulence in the mixer. Fuel injection patterns were then further optimized, using mixers that meet the initial design criteria, looking for optimal fuel-air mixing and thereby NOx emissions.

The concept premixers were then evaluated on a GE9X FETT 1-cup combustor model to assess mixing, thermal field and NOx predictions. *Figure 9* depicts the NOx reduction on the Group 3 concepts from the 1-cup combustor model CFD.

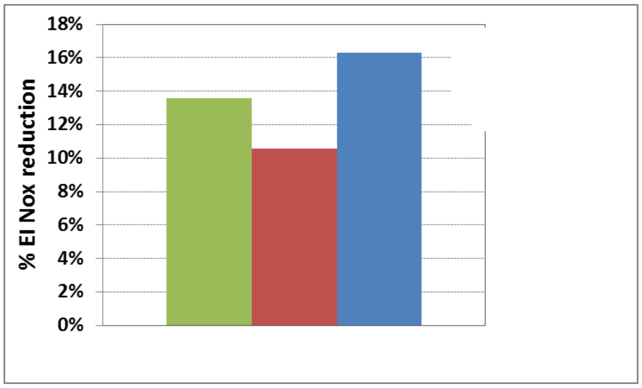

Figure 9: Group 3 NOx reduction relative to the baseline (1-cup combustor CFD results) for three different concept designs

Figure 10 depicts examples of fuel mass fraction distributions for one of the Group 3 configurations, as a comparison to the baseline design. In all, 26 injector configurations were run in CFD.

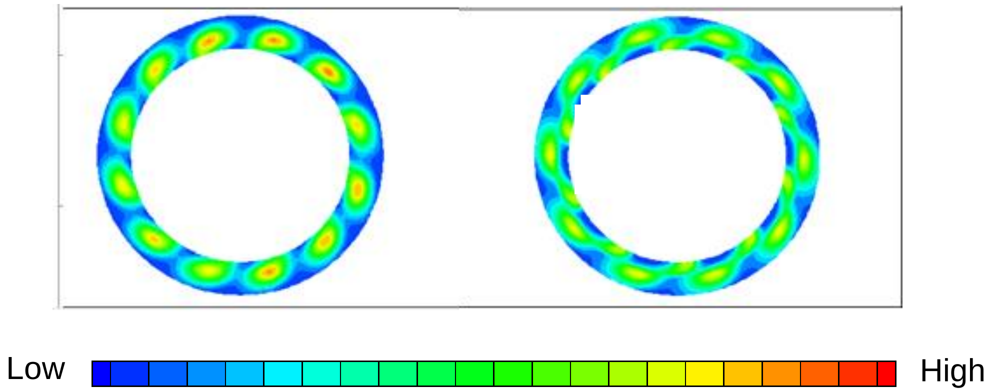

Figure 10: Examples of fuel mass fraction distributions: baseline (left); Group 3 (right)

4.1.4.2 Initial aero down select for thermal/mechanical/dynamics evaluation:

The CLEEN II mixer/fuel nozzle down select is based on both NOx and cruise efficiency predictions. *Figure 11* shows the CO & NOx percentage improvement relative to the baseline for the Group 3 designs evaluated. Designs inside the green box are of interest, as they show benefit on CO (cruise efficiency) without negative impact on the NOx. These results and the analysis were reviewed by the combustion aero design team at GE.

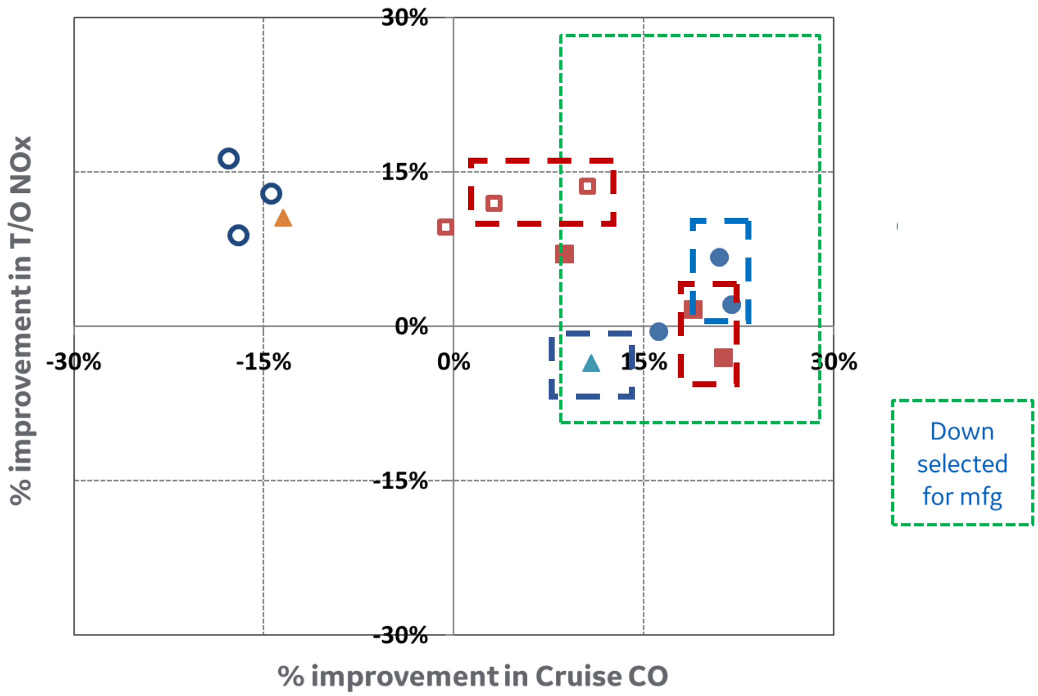

Figure 11: Group 3 Concepts - NOx and CO (efficiency) predictions

4.1.4.3 Concept Group 3 preliminary hardware & test

As part of the premixer design and screening activity for the CLEEN II technology development program, the GRC team built two premixers. The purposes of this workscope included:

- perform a trial build/manufacture of the fuel nozzle/mixer
- check air and fuel flow characteristics
- conduct preliminary combustion tests in an optically-accessible rig

The aero features of the fuel nozzle and mixer are very close to the design intent; but the mechanical features of the nozzle and mixer are simplified to ease manufacturing and enable assembly into GRC's optical rig.

4.1.4.3.1 Group 3 Combustion Visualizations

The test rig employed for the combustion characterization of the Group 3 nozzle is shown in *Figure 12*. The combustor configuration consists of a rectangular flat dome with optical windows on the side walls for flame visualization. Test conditions were limited in this campaign to sub-cruise conditions. Therefore, fuel atomization/evaporation, flame behavior and stability cannot be expected to be representative of typical cruise or high power operation.

Flame images of the baseline premixer and a Group 3 premixer are highlighted in *Figure 13*.

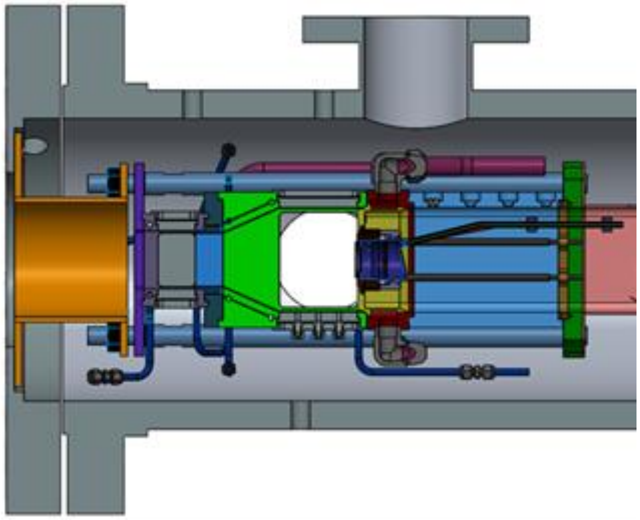

Figure 12: Test rig employed for Group 3 nozzle combustion visualizations. Flow is from right to left, to match the flame images below.

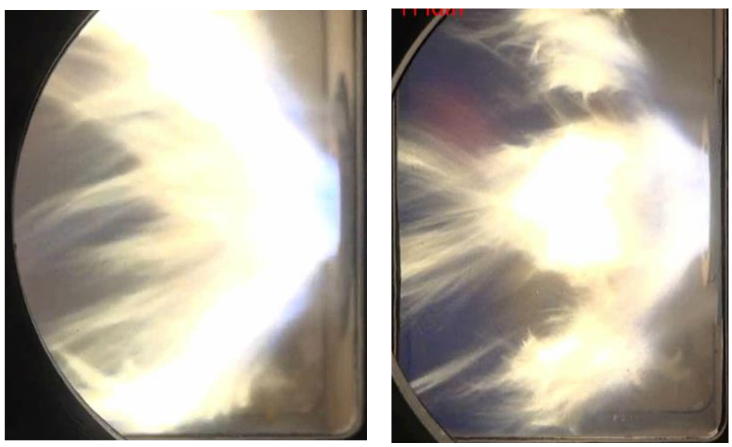

Figure 13: Flame images for the baseline configuration (left) and Group 3 configuration (right)

While there were no emissions measurements available during these screening tests, combustion dynamics were evaluated. A small self-excited combustion dynamics tone was observed for the baseline, while a stronger tone at a different frequency was observed for the Concept 3 configuration. Further advancement of this concept will need to focus on understanding the combustion dynamics challenges and contributing features.

4.1.5 Concept Group 4

4.1.5.1 Summary

Fuel injector concepts were designed and screened using Computational Fluid Dynamics (CFD) simulations. Concepts that showed favorable fuel-air mixing were down-selected for detailed large eddy simulations (LES) to study turbulence enhanced fuel-air mixing, flame structure and NOx emissions. Two Group 4 premixers were identified as the best performing designs based on fuel-air mixing, NOx, and aero flow criteria; and were consequently down-selected for 3D printing and combustion performance testing.

A combustor rig was assembled at GE Global Research Center - Niskayuna (GRC-N) for concept screening. NOx and CO emissions were obtained and compared with the baseline TAPS configuration. Overall, higher NOx and CO was observed for all the Group 4 concepts in comparison to the baseline TAPS. Following this initial concept testing, the Group 4 concept was dropped from consideration for higher T3/P3 single cup testing. The potential advantages of the concept remain; however, the initial test results, the low TRL of this concept, the significant optimization required to advance TRL, and the favorable performance expectations of Concept Groups 1 & 2 all drove the decision to remove this from consideration and focus on the prime concepts in meeting the emissions target for CLEEN II.

4.1.5.2 Concept Design

Key fuel nozzle and mixer requirements & constraints are based on the intent to leverage the GE9X combustor development and learnings through TRL3, and the expectation that any alternate concepts would integrate seamlessly into existing component test rigs and Core engine hardware. A key program requirement was that the concept fuel nozzle and mixer hardware fit within the existing envelope of GE 9X NPI combustor. Since the pilot geometry and the bulk combustor geometry was unchanged, the aero flow field was required to be consistent with that of the baseline TAPS design.

4.1.5.3 Experimental Screening

Due to the low TRL of the Group 4 concept, it was determined that it would be an advantage to perform early experimental screening of the concepts. This would permit a design iteration and 2nd round of screening prior to the aero concept review and down-selection for single cup hardware fabrication.

4.1.5.3.1 Test Rig

The test rig described below was utilized for baseline, Group 3 and Group 4 screening tests. The test article consists of a single-cup combustor placed inside an optically accessible pressure vessel. *Figure 14* shows a cross-section of the test rig. *Figure 15* shows the rig assembled for this study and located inside the combustion cell in GE Global Research's combustion test facility.

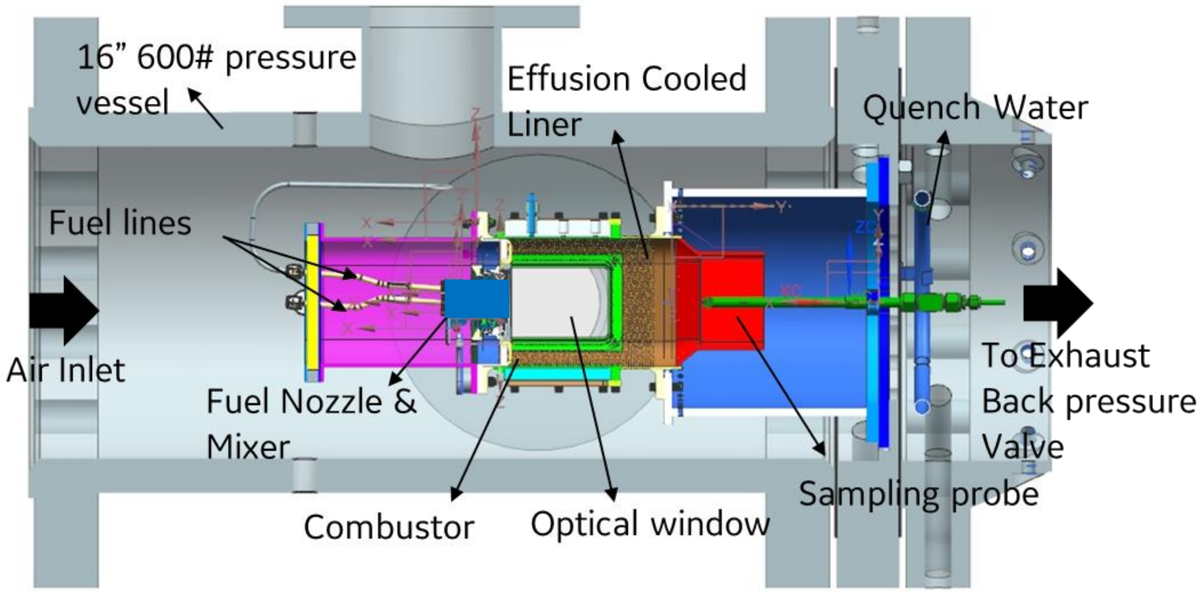

Figure 14. Cross-Section of rig. The cross section of optically accessible combustor test article is shown along with the location of the sampling probe.

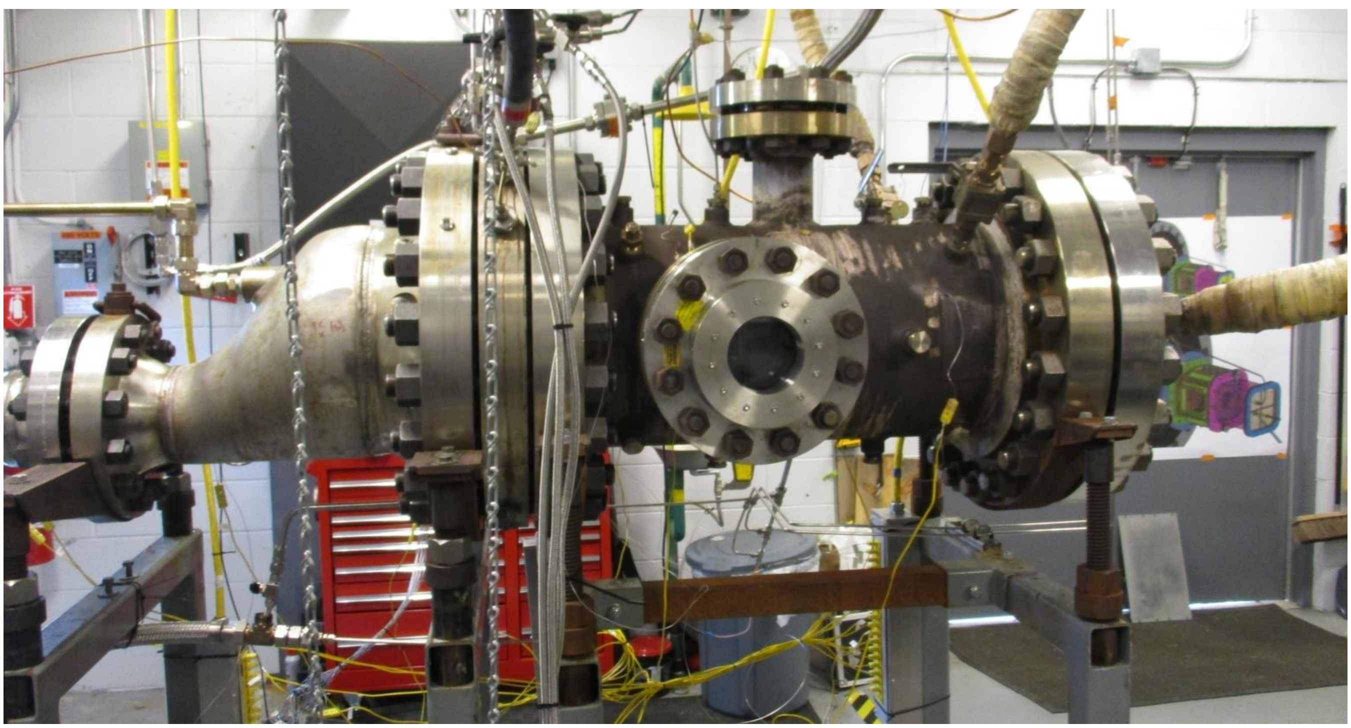

Figure 15. The assembled rig installed in the test cell. Flow is from right to left.

The test rig was designed to enable combustor nozzle concept screening, emissions measurements, and flame visualization.

4.1.5.3.2 Emissions Sampling

The gas sampling cart is a portable gas analysis cart used in combustion testing. The emissions cart houses gas analyzers, sample and calibration gas flow controls, and pressure gauges, as well as a gas cooler. The gas analyzers support the measurement of volumetric concentrations of oxygen, carbon dioxide, carbon monoxide, nitric oxide, nitrogen dioxide, and methane. In addition to their use in back-to-back emissions comparisons, the species concentrations are used to back-calculate and corroborate equivalence ratio and combustion product temperature.

4.1.5.4 Concept Evaluation and Comparisons

For each of the concept hardware, main mixer air flow path effective area measurements were performed in the rig. Initial combustion tests provided flame visualization and early emissions data.

4.1.5.4.1 Flame visualizations

Example flame images from the baseline premixer and a Concept 4 premixer taken at the same conditions are shown in *Figure 16*.

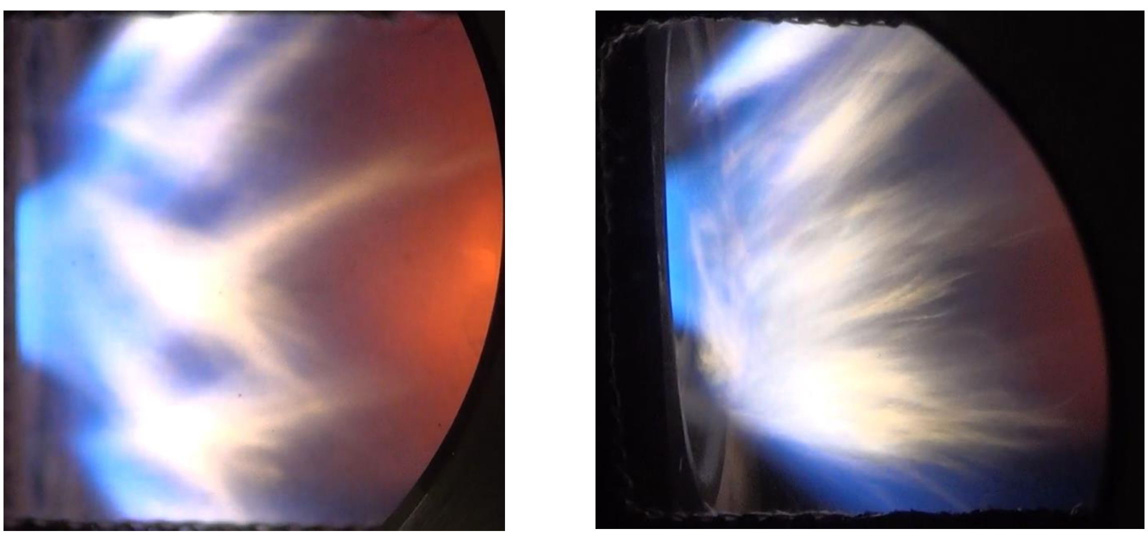

Figure 16: Flame images obtained with the baseline premixer (left) and a Group 4 concept (right)

4.1.5.4.2 Emissions Characterization

CO and NOx emissions, O2 and CO2 concentrations in the sample gas were read using gas analyzers integrated into a portable gas analyzer cart. Shown in *Figure 17* is the raw NOx concentrations observed from one of the Concept Group 4 tests. The NOx emissions are much higher than the baseline.

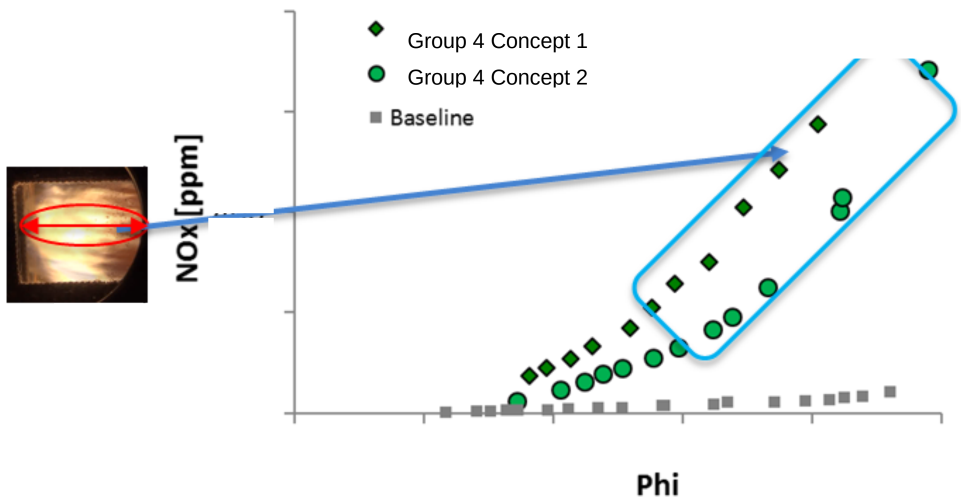

Figure 17. Comparison of raw NOx emission data among baseline and two Group 4 designs

4.1.5.5 Conclusions

NOx and CO emissions data for multiple Group 4 concepts obtained and compared with the baseline TAPS configuration indicate that, overall, higher NOx and CO was observed for all these concepts in comparison to the baseline TAPS. Following this initial concept testing, the Group 4 was dropped from consideration for higher T3/P3 single cup testing. The potential advantages of the concept remain; however, the initial test results, the low TRL of this concept, the significant optimization required to advance TRL, and the favorable performance expectations of Concept Groups 1 & 2 all drove the decision to remove this from consideration and focus on the prime concepts in meeting the emissions target for CLEEN II.

4.1.6 Results and Down-Selection of Fuel-Air Mixer Aero Designs

Following the aero assessments, 7 fuel nozzle configurations (three from Groups 1 & 2 and four from Group 3) and 6 mixer designs (three from Groups 1 & 2 and three from Group 3) were released for detailed design/drawings and fabrication.

4.1.7 Conclusions

Via analytical and test screening, a group of concepts with high probability to meet or exceed program targets for NOx, cruise efficiency, and other product criteria were evaluated. Of the major Concept Groups, the Group 1 & 2 and Group 3 premixers indicate potential for achieving the desired benefits in both high power NOx and cruise efficiency and were released to the mechanical and thermal teams for further assessment and manufacturing. The Group 4 configuration is at a much lower TRL, and in early screening tests did not show positive behaviors for NOx and CO. While it may be a concept of interest in the future, it was removed from consideration for the remainder of the CLEEN II program.

4.2 Task B.1.2 – Fuel Nozzle & Mixer Mechanical Design

4.2.1 Summary

GE completed the mechanical design of the new technology concept main mixers and fuel nozzles. For the Group 1 & 2 fuel nozzles and mixers, the effort was focused on manipulating baseline mixer and fuel nozzle models and adjusting mechanical interfaces to enable the fuel injection variants and new mixer aero layouts. Manufacturing methods are consistent with the baseline hardware. For the Group 3 concepts, new manufacturing methods and assembly procedures were conceived and trialed. Thermal and mechanical analyses were also conducted for this unique design to identify and address risk areas in the design. Work was performed to develop mechanical and thermal designs to enable the mixer and fuel nozzle aerodynamic concepts being worked in Task B.1.1. The ultimate objective is to get the fuel nozzle assembly model in a state such that down-selected aero designs can simply be "dropped in" to the GE9X combustor with minimal adjustments upstream to fuel system and combustor case interfaces. The final model and drawings were detailed and transferred to the fabricator for build. The mechanical/thermal viability of the concept designs were presented as part of the Aero TRL3 review.

4.2.2 Conclusions

The Group 1, 2, and 3 mixer aero concepts have been transferred to mechanical models for fabrication, with a variety of design studies performed to ensure acceptable interfaces and operation. Thermal and mechanical analyses were performed which show adequate capability for early TRL testing. The designs were released for manufacturing.

4.3 Task B.1.3 – High Frequency Combustion Dynamics Damper Aero and Mechanical Design

4.3.1 Summary

This work focused on the design, analysis, and down selection of integrated acoustic dampers, in preparation for the demonstration of their capability to mitigate combustion dynamics in Task D.1.8. The work was accomplished in two phases, with the test learnings from Phase I informing the designs released and tested in Phase II. In addition, a set of concepts was also designed for an architecture that is different and closer to other legacy designs.

Starting from design tools, a series of damper configurations were conceived and modeled using low-order dynamics simulation tools. The test configurations in this Task were designed and analyzed specifically for a single-cup (flame tube) test, albeit with a view towards eventual application in a full annular dome configuration. The Phase II designs and hardware incorporated learnings from Phase I. The Phase II designs also explored the impacts of geometry constraints found in the full annular combustor dome. Modeling results for down-selected configurations predicted up to 90% amplitude reduction; an outcome which was validated in later testing in Task D.1.8. A limited engine-level study was also performed to show the transferability of this technology to full annular combustors for both recent and legacy combustors. Once demonstrated and successfully implemented, the damper designs have the potential to broaden combustor operating space while limiting amplitudes of acoustic instabilities, enabling higher levels of premixing which in turn benefit NOx emissions, cruise efficiency, and engine operability.

4.3.2 Introduction

Combustion dynamics are an important consideration in the design of modern gas turbine combustors. While the design process must consider many competing criteria, such as temperature profiles, emissions, robustness /durability; dynamics is one of the most challenging to predict and design for. Combustion dynamics results from a complex system of coupled multi-physics phenomena: fuel atomization and transport, mixing, reactive kinetics and acoustics, all of which strongly affect the frequency and amplitude of the resulting dynamics. Furthermore, as dynamics are a system-level phenomenon (i.e. the acoustic modes may, for example, be circumferential around the entire engine annulus, or may depend on cup-to-cup interaction), any required design changes are likely to be highly disruptive, expensive, and cause delays to the certification of a new engine design. Therefore, there is great interest in developing effective mitigation devices which can widen the operability window and reduce the risk of durability/emissions issues due to dynamics.

Under the CLEEN II project, several activities have focused on the design, analysis and testing of such mitigation concepts. The effort culminated in the successful testing of a 'Phase I' damper concept, which was effective in reducing the pressure pulsations observed in single cup tests. 'Phase II' design efforts built on the lessons gleaned from that activity, to reproduce and improve the measured reduction in dynamics. Because of the uniqueness of the combustor construction, and with the agreement from the FAA, a portion of the funding for this task was directed toward a group of concepts focused on a more traditional style of combustor.

Finally, the design tools developed and validated on the single-cup rig tests are applied to a conceptual design for a full annular combustor with integrated dampers. The analysis of this concept leveraged dynamics modeling tools developed in Tasks B.1.4-6 and demonstrates the potential application and benefits in a full-scale aviation combustor.

4.3.3 Damper Concepts – Phase I

4.3.3.1 Modeling of Damper Effectiveness

An example of predicted performance for several Phase I damper concepts is shown in *Figure 18*. The "growth rate" is a way of characterizing whether a modeled combustion dynamic tone has the tendency to grow (positive growth rate) or diminish (negative growth rate) in amplitude.

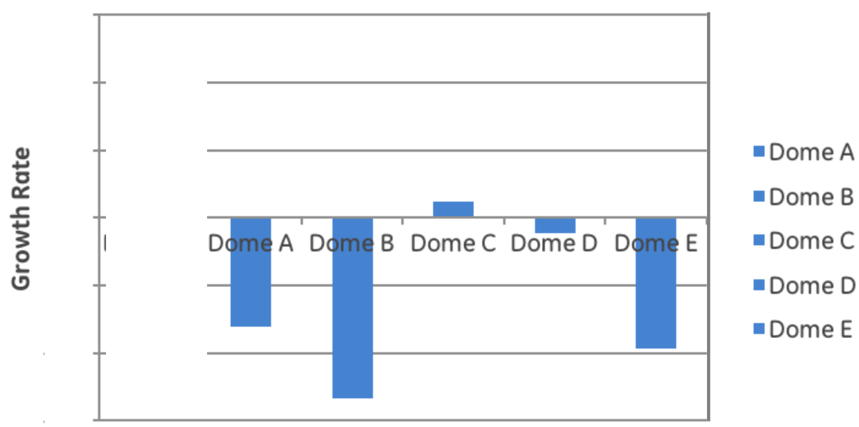

Figure 18: Model predictions of Damper performance

The simulation is run for the baseline and for each of the candidate dome damper designs. In each case, the growth rate is favorable, and becomes negative in all but one case (i.e. the mode becomes stable). Where the mode is stable, the amplitude is predicted to be much lower and noise-driven (though the linear model will predict zero).

4.3.4 Damper Concepts – Phase II

4.3.4.1 Preliminary Design & Sizing

The starting point for the Phase II design effort is the results of the Phase I tests, a summary of which is provided in Task D.1.8. The Phase I designs were successful in demonstrating a negative growth rate (diminishing dynamic amplitude).

4.3.4.2 Modeling of Damper Effectiveness

In this section, the results of the modeling methods are presented for damper design candidates (of which a subset have subsequently been fabricated and tested). Note that Dampers E and F are identical to A and C respectively except for additional cooling flow. As this will principally affect the flame response in a complex manner beyond the scope of the low-order dynamics tools used here, their performance will be predicted to be identical.

Figure 19 shows the results of the acoustics model by calculating the growth rate - a way of characterizing whether a modeled combustion dynamic tone has the tendency to grow (positive growth rate) or diminish (negative growth rate) in amplitude.

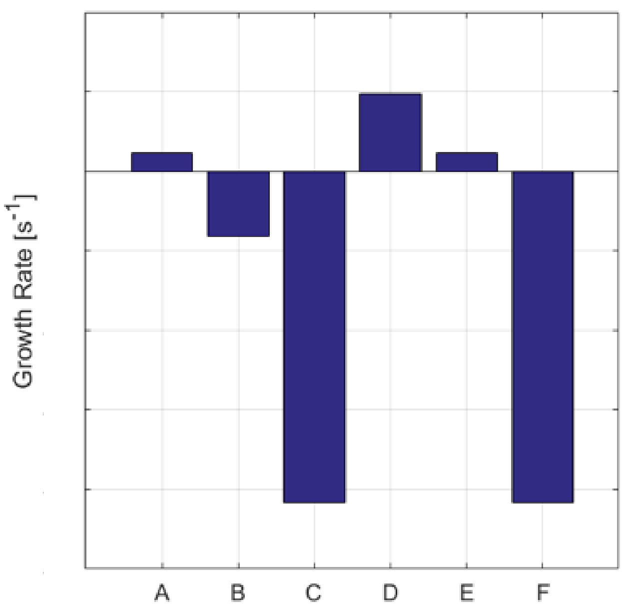

Figure 19: Predictions of Damper impact on Growth Rates

This method calculates the frequency and growth rate. The simulation is run for the baseline and for each of the candidate dome damper designs. The growth rate is found to be reduced by all the damper configurations, though the scale of the reduction varies quite considerably. Damper C is anticipated to perform best. Dampers B and F (identical to C) are also predicted to reduce the growth rate to negative values (i.e. stabilize the mode).

4.3.5 Extension to Annular Combustors

4.3.5.1 GE9X Annular Combustor Geometry

Finally, an initial feasibility study has been completed to show how the technology developed and tested might be applied to a realistic, annular combustor.

The model was run for the baseline configuration, and for configurations with damper designs C and D applied to every cup. When Damper C is applied, the prediction resembles a stable, noise-driven system which does not show any tendency to grow over time. When damper D is used, the growth rate is reduced but not as low as with Damper C.

While the results above have demonstrated the potential of integrated dampers in mitigating engine dynamics, there will always be trade-offs to be struck in terms of weight, durability, air budget, etc. Therefore, there is great value in a tool which can be used, within a realistic design cycle time, to anticipate the dynamics mitigation necessary to stabilize these tones, and the performance of various arrangement of damping devices within an annular combustor.

4.3.6 Conclusions

In this work GE has successfully designed and simulated acoustic dampers integrated into the combustor and shown their potential to mitigate combustion dynamics. Starting from design tools, a series of damper configurations were conceived and modeled using a variety of low-order dynamics simulation tools. Subsequently, the baseline configuration and a subset of the most interesting designs will be built and tested in the single cup test rig (Task D.1.8). As predicted, the dampers are expected to demonstrate positive impact in reducing self-excited acoustic amplitudes during testing.

An annular combustor-level study has also been performed to show the transferability of this technology to full annular combustors. This work demonstrated the applicability of the same designs to a full annular combustor. Future work should focus both on detailed mechanical/thermal design studies at an engine level, along with efforts to broaden the applicability of this technology to other aero-engine and aero-derivative gas turbines.

4.4 Task B.1.4 – Dynamic Spray Modeling for Pilot Sprays and Jet-in-Cross-Flows

4.4.1 Summary

Improved fuel injection modeling methods, focused on jet-in-crossflow behavior due to its importance in the main mixer of a TAPS architecture, have been chosen and validated against experimental data. Recommended model settings and methodologies are developed for use in subcritical and supercritical regimes. A new concept is also vetted, for characterization of combustion dynamics through the quantification of the fuel-air mixing process. This process is used to rank CLEEN II new technology mixer designs against each other and the baseline and suggests preference of one of the Concept Group 2 mixers for low fuel-air mixing unsteadiness.

4.4.2 Results and Conclusions

Recommended model settings and methodologies are developed. A new concept is also vetted, Dynamic Mixing, for characterization of combustion dynamics through the quantification of the fuel-air mixing process. This method suggests the new technology concept Group 2 mixer design may have altered performance in terms of fuel-air mixing unsteadiness, relative to the baseline design.

4.5 Task B.1.5 – Large Eddy Simulation (LES)-Based Flame Transfer Function Model Development

4.5.1 Summary

In this task, the LES method was established for the Flame Transfer Function (FTF) simulation for CLEEN II design application. The method was verified and validated comparing with experimental measurements. It was confirmed that the current method provides the reasonable estimation of FTFs. Finally, the FTF method was applied to CLEEN II designs, and it provided a unique pattern of FTF curves and consistent FTF pattern dependent on mixer design. The FTF result is a part of the overall prediction modeling strategy.

4.5.2 Results and Conclusions

The LES-FTF methodology was validated against experimental data and then applied to the CLEEN II new technology concepts for the purposes of creating flame transfer functions for combustion dynamics predictions. The FTF of this task are passed on to the 3D acoustic modeling to obtain final pre-test predictions.

4.6 Task B.1.6 – 3D Acoustics Modeling for High Frequency Dynamics

4.6.1 Summary

Combustion dynamics frequencies and amplitudes are predicted using a 3D acoustic modeling strategy and applied to both single-cup screening test rigs as well as a full annular combustor model. The developed and validated method enables short turnaround times such that the modeling process can be used for pre-test predictions and prioritization of designs. CLEEN II new technology concepts were evaluated using these methods and ranked according to expected combustion dynamic behaviors.

4.6.2 Introduction

A new approach has been developed to improve GE's dynamics modeling capability while retaining the short turn-around-time essential to be useful in the design process. In the following sections, the proposed model will be introduced, validated using the baseline experimental tests, and then subsequently applied to the CLEEN II candidate designs.

4.6.3 Results

The new method was validated against test data from the GE Aviation TCA3 rig. *Figure 20* shows the comparison of the predicted amplitudes for the high and low FAR conditions, and the data from the TCA3 tests. This shows the amplitude trend is well captured both qualitatively and quantitatively by the model. These model parameters were held constant for the subsequent simulations using the CLEEN II candidate designs. The approach used for the TCA3 rig can equally be applied to an annular, multi-cup configuration in a reasonable computational time.

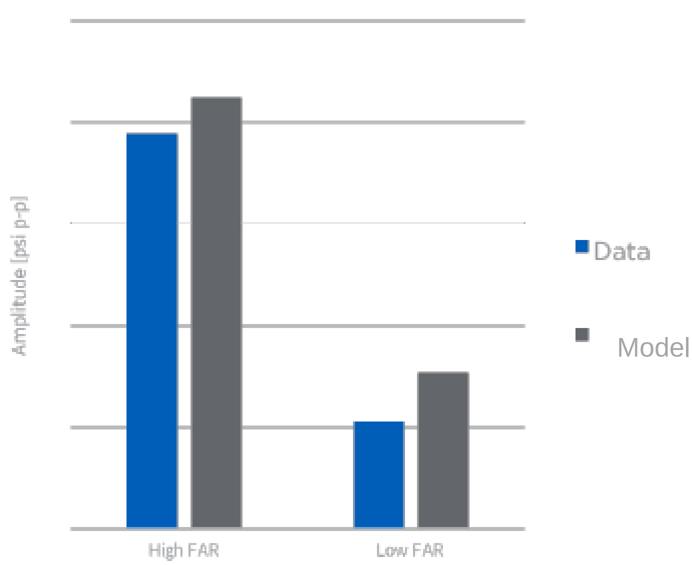

Figure 20: Validation of the model using test data for the high and low FAR operating conditions

4.6.4 Conclusions

This Task, along with Tasks B.1.4 and B.1.7, summarize the development of a series of modeling approaches to enable the design of stable aeroengine gas turbine combustors. These approaches range from fast, early-stage design tools through to full annular dynamics prediction tools. These tools have been applied to a series of CLEEN II candidate designs.

There are several CLEEN II candidate designs which offer similar dynamics performance relative to the baseline design. Based on the collection of results, a series of designs have been recommended for testing.

4.7 Task B.1.7 – LES-based Self-Excited Dynamics Computation

4.7.1 Summary

In the FAA CLEEN II program, best practices have been developed and validated for a Large Eddy Simulation-based process prediction of aviation combustors and combustor rigs. Validation has been made against single cup acoustic rigs. The process captures the dominant dynamics frequencies accurately, with acceptable accuracy for dynamics amplitude. The methodology was also applied to a full annular model of a combustor, to derive learnings both about application of the method at scale as well as gain insight into combustor behaviors.

In the final work, the team applied the latest best practice of the process for the design screening of CLEEN II new technology designs. The latest methodology was applied to perform true pre-test predictions and rank the priority for future test campaigns. In summary, the combinations of the different Concept Group 1 & 2 mixers and fuel nozzles were simulated to provide both predictions of different designs and possible underlying physics driving the difference in dynamics performances among different designs.

4.7.2 Introduction

Combustion that occurs in confined spaces at high temperatures is subject to unsteady processes that involve physical coupling of unsteady heat release and combustor chamber acoustics. There are several challenges associated with high-fidelity computational predictions of gas turbine combustion. While experimental studies have been able to analyze combustion dynamics, they are also limited by high pressures and temperatures, which tends to limit experimental data to pressure, PIV data, or PLIF/OH* images. High-fidelity LES simulations provide a powerful method of capturing the non-linear details of turbulent flame dynamics. LES capability for combustion dynamics has been validated in academic literature. High-fidelity LES can contribute additional insights into the fundamental physical processes in practical engines and can therefore serve as a physical foundation in design optimization.

4.7.3 Methods, Assumptions, and Procedures

4.7.3.1 Validation of dynamics predictions

The team has applied a robust LES CFD process to several High Pressure Tunable Combustion Acoustics 2 (HPTCA2) rig test points. The rig conditions represent a high power condition. The sensitivity of the combustor dynamic signal to fuel-air ratio was examined. The model's predictive capability will be determined by its ability to capture directional trends in the dynamics signal amplitude with respect to fuel-air ratio as well as the accuracy of the predicted dynamics amplitude and dominant frequency.

The model demonstrated a dynamic signal at a dominant frequency that was very close to the experimental data. A fuel/air ratio (FAR) sweep was then conducted. The cases predicted trends in the average signal amplitude that were representative of the experimental data. *Figure 21* shows a comparison of CFD and experimental results. Within experimental uncertainty, the approach demonstrated good dominant frequency prediction and correctly predicted the pressure amplitude trend that was observed in the experimental data.

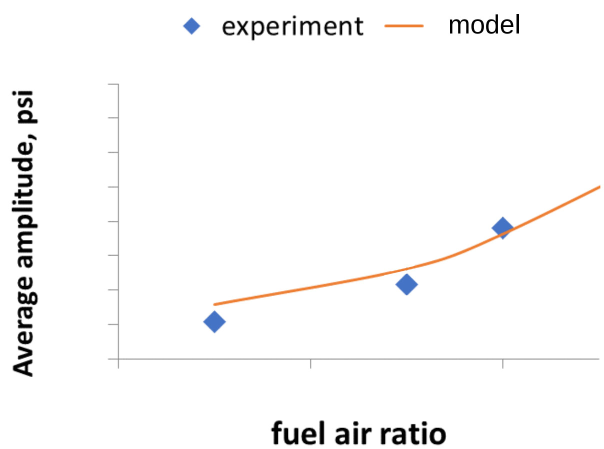

Figure 21: FAR sweep performed for the HPTCA2 test points

4.7.3.2 Predictions for HPTCA3 rig

A robust LES CFD process was next applied toward the High Pressure Tunable Combustion Acoustics 3 (HPTCA3) rig, for predictions at engine-relevant conditions at different fuel-air ratios.

Figure 22 provides a summary for the TCA3 cases, showing the comparison between measured data and CFD predictions of dynamics amplitude and frequency. Each graph shows a solid black 45-degree line, in which the CFD prediction would ideally be equal to the measured value. The dotted lines show acceptable percentage differences away from the ideal agreement.

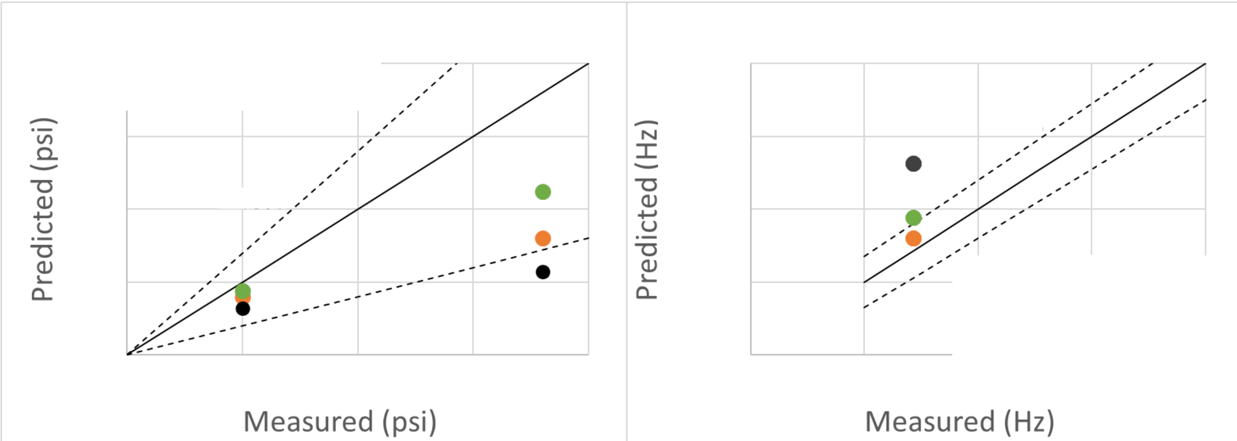

Figure 22: Comparison between CFD predictions and experimental data for amplitude (left) and frequency (right) for TCA3 cases.

4.7.3.3 Simulation of full annular combustor

A simulation of a full annular combustor was also performed. The objective of this simulation was two-fold: to evaluate the modeling challenges of attempting such a large simulation, and to benchmark the model so that it could be used to evaluate proposed design changes. Full annular combustor simulations of this type at high power conditions have not been modeled prior to this study.

4.7.3.4 Pre-test predictions for CLEEN II new technology concepts

The process was applied for the predictions of dynamics for different premixer concepts from the Concept Groups 1 and 2 in Task B.1.1. This provided a pre-test ranking of the concepts on the basis of combustion dynamics expectations.

4.8 Task B.1.8 – Monte-Carlo Analysis of Fuel Impact on Durability

4.8.1 Summary

In the course of an NPI combustor program, Monte-Carlo analyses are utilized to assess the impacts of a range of variation parameters on the risk of durability in the combustor. In this task, the flow network and Monte Carlo models were updated, and the models were re-baselined using updated manufacturing data from a legacy engine and running the model to compare to development engine experience.

4.9 Task C.1.1 – GE9X single cup rigs hardware

4.9.1 Summary

This task involved the manufacturing and instrumentation of GE9X NPI type assets for use in single cup testing, including the High Temperature and Pressure (HTP) rig and the Tunable Combustion Acoustics (TCA) rig. Fuel nozzles and mixers, as well as specialized combustor domes, were procured and modified as needed for incorporation into the rigs. The baseline hardware will be tested in Tasks D.1.1 and D.1.2 in order to characterize the GE9X design in these rig tests and provide a baseline against which new CLEEN II technology concepts will be compared in later tasks.

4.10 Task C.1.2 – GE9X High Pressure Sector (HPS) Hardware

4.10.1 Summary

In preparation for high pressure sector testing of the GE9X NPI design (Task D.1.3), to be used as baseline data for comparison of CLEEN II technologies in Task D.1.10, this task involved the completion of the test article and rig hardware. The GE9X High Pressure Sector combustor, hardware, and rig were already designed prior to the start of the CLEEN II program. As part of the CLEEN II program, a set of GE9X engine-style fuel nozzles and mixers was manufactured for use in the sector. In addition, the sector combustor and rig was fully instrumented and assembled prior to installation into GE's new Cell A20 facility. A Detailed Test Design Review (DTDR) was conducted with test and engineering focals approximately 1 month ahead of the forecasted fire date, presenting the as-installed instrumentation details and all test planning and execution material.

4.10.2 Results

All fuel nozzles have been manufactured along with the GE9X FETT-style mixers. All combustor instrumentation was completed, as was the assembly of the combustor into the rig, along with all rig instrumentation. The Detailed Test Design Review (DTDR) was completed on June 22, 2016 prior to initiation of testing. Furthermore, instrumentation and combustor perfection reviews were held to confirm accuracy of the hardware and assembly for this test, and a facility/rig Red Flag Review was held to ensure test team preparedness for cell operation. All action items were addressed and closed prior to test initiation.

4.11 Task C.1.3 – GE9X FAR2 Hardware

4.11.1 Summary

In preparation for Full Annular Rig 2A (FAR2A) testing of the GE9X NPI design (Task D.1.4), to be used as baseline data for comparison of CLEEN II technologies in Task D.1.9, this task involved the completion of the test article and rig hardware. The GE9X FAR2A combustor, hardware, and rig were already designed prior to the start of the CLEEN II program. As part of the CLEEN II program, a set of GE9X FETT fuel nozzles and mixers was manufactured for use in the full annular rig. In addition, the FAR combustor and rig was fully instrumented and assembled prior to installation into GE's test facility. A Detailed Test Design Review (DTDR) was conducted roughly 1 month ahead of the forecasted fire date, presenting the as-installed instrumentation details and all test planning and execution material.

4.11.2 Results

This task has been completed. The mixers for the combustor were delivered to the combustor assembly in early 2016. A set of FETT-style fuel nozzles were also manufactured and supplied for this test. The combustor underwent final instrumentation application/routing prior to installation in the rig. A perfection review of the assembled rig/combustor assembly was held prior to delivery to the test cell. A Detailed Test Design Review (DTDR) was held on 9/12/2016. Finally, a Red Flag Review was conducted by the operations team prior to initiation of the test campaign. All action items were addressed and closed prior to testing.

4.12 Task C.1.4 – GE9X Core Engine

4.12.1 Summary

Due to the successful emissions outcome of the GE9X TAPS III combustor testing and engine-based emissions validation, and the evaluation of new concepts to date (demonstrated to TRL3), GE and FAA agreed to stop the program prior to executing Task C.1.4.

4.13 Task C.1.5 – CLEEN II Single Cup Rigs

4.13.1 Summary

New technology fuel nozzles and mixers were fabricated for single cup testing. Concept Group 1 & 2 fuel nozzles (3) were assembled and instrumented for HTP testing. Two down-selected Concept Group 2 mixers were fabricated for HTP and TCA testing. The Group 3 fuel nozzles' fabrication was started, the initial build was completed for all concepts, and the mixer drawings were released. Concept Group 3 hardware fabrication was not completed due to the down-selection to the Group 1 & 2 designs as prime.

4.13.2 Introduction

In preparation for single cup rig testing of new CLEEN II fuel nozzle/mixer designs, the hardware for the down-selected configurations was manufactured. Three new Group 2 fuel nozzles and three mixer designs were released for manufacturing, and all have been built and instrumented for testing.

Mating hardware for the single cup rigs (TCA and HTP) was largely the same as use for the baseline design testing. The rig and dome interfaces were kept constant, as a design target. Therefore, no new interface hardware was required.

4.13.3 Conclusions

The Group 1 & 2 test assets were manufactured, meet quality requirements, and are ready for testing in Tasks D.1.6 and D.1.7. The Group 3 hardware and any other unfinished hardware pieces are set aside for future program efforts.

4.14 Tasks C.1.6 – C.1.9

4.14.1 Summary

Due to the successful emissions outcome of the GE9X TAPS III combustor testing and engine-based emissions validation, and the evaluation of new concepts to date (demonstrated to TRL3), GE and FAA agreed to stop the program prior to executing Tasks C.1.6 through C.1.9:

- **Task C.1.6**: CLEEN II Rainbow FAR
- **Task C.1.7**: CLEEN II High Pressure Sector
- **Task C.1.8**: CLEEN II FAR
- **Task C.1.9**: CLEEN II Core

4.15 Task D.1.1 – GE9X TCA Testing

4.15.1 Summary

The Tunable Combustion Acoustics (TCA) test rig is used for combustion dynamics screening at high pressure and temperature conditions. In this task, a validation study of the low dynamics operating region of the GE9X mixer/nozzle sets was performed using the TCA3 rig. Dynamic amplitudes and frequencies were then assessed over a wide range of combustor inlet conditions. The results of this sub-task validate GE9X combustion dynamics capability over specific conditions of interest to engine operation and serve as a baseline for CLEEN II alternate technology concept design down-selection.

4.15.2 Introduction

The single cup Tunable Combustion Acoustic (TCA3) rig was built to evaluate baseline fuel nozzles and main mixers at elevated compressor discharge temperature (T3) and pressure (P3) conditions. The key utilization of this rig is to provide combustion dynamics characteristics for different combustor configurations, and the primary value of the tests is for back-to-back comparison of aero design features and their impact on thermo-acoustic dynamics amplitudes. The facility and rig are designed to be capable of operation well above the takeoff conditions for the GE9X. Detailed testing at different conditions enables direct comparison of designs and design features and contributes to the ranking of configurations.

Testing of the baseline design forms the basis for comparing the CLEEN II alternate technology data in Task D.1.7.

4.15.3 Conclusions

The test method utilized for the TCA3 rig provides the combustion dynamics signature at conditions relevant to engine operation. The baseline configuration is tested, and the set of data forms the basis for later comparison of CLEEN II alternate technology configurations.

4.16 Task D.1.2 – GE9X HTP Testing

4.16.1 Summary

GE conducted a validation study of emissions and durability margin of the baseline fuel nozzle / mixer. The single-cup High Temperature and Pressure (HTP) rig was used to evaluate the designs at the GE9X high OPR operating conditions. The results of this sub-task confirm that the hardware meets GE9X emission and durability requirements. The results also serve as a baseline for CLEEN II new technology design down-selection.

4.16.2 Introduction

In this task, the baseline fuel nozzles/mixers were evaluated in the single cup High Temperature and Pressure (HTP) rig. Durability assessments and emissions screening were also conducted, for comparison to the new CLEEN II technology design data in Task D.1.6.

4.16.3 Test Results

Key results of this series of HTP tests are summarized in the form of durability capability. The performance of the baseline configurations is above the requirement and meets all durability metrics.

Emissions data for the baseline fuel nozzle/mixer design is primarily valuable as a relative reference point for the CLEEN II new technology concept designs. In the HTP rig, the data focuses on high power NOx as well as cruise CO (as an indicator of efficiency at cruise conditions). Because we have higher TRL data from the High Pressure Sector (Task D.1.3) and Full Annular Rigs (Task D.1.4), along with eventual engine data from FETT (outside of the CLEEN program), the single-cup data of the baseline fuel nozzle/mixer design helps to tie the emissions of new concept designs back to a baseline design and its higher-TRL data. The baseline emissions data taken during this task is discussed as part of task D.1.6.

4.16.4 Conclusions

HTP rig testing was completed for the baseline fuel nozzle / mixer configurations. The tests conducted here confirmed that the baseline design meets all rigorous requirements of the GE9X cycle. In addition, emissions measurements – high power NOx and cruise CO – were conducted to provide baseline data for comparison against CLEEN II new technology concepts in Task D.1.6.

4.17 Task D.1.3 – GE9X HPS Testing

4.17.1 Summary

The GE9X High Pressure Sector (HPS) rig was utilized to gather combustion data for the baseline fuel nozzle/mixer configuration, over a range of operating conditions. In this test campaign, the rig was successfully run up to climb conditions (85% rated thrust, one of the LTO NOx emissions certification points). Data of interest included combustion dynamic pressures, combustion emissions and efficiency, and thermal exit profile. The rig proved valuable in confirming measured characteristics and comparison to behaviors of other rigs and the FETT engine.

4.17.2 Introduction

The High Pressure Sector (HPS) is a 90 deg sector of the full combustor. This rig is utilized for assessment of the TAPS III aero technologies, using baseline fuel nozzles and mixers. The HPS allows evaluation at higher pressures and temperatures than other rigs.

4.17.3 Test Results

HPS testing of the baseline configuration was conducted from July thru October, 2016. The test campaign completed 5 days of acoustic and emissions testing.

4.17.3.1 Emissions testing

Emissions testing showed good agreement with other test vehicles*. Figure 23 and Figure 24* show a back-to-back comparison of HPS NOx and efficiency data with data from our Demonstration Core test and the FAR1C test campaign described in Task D.1.4 below.

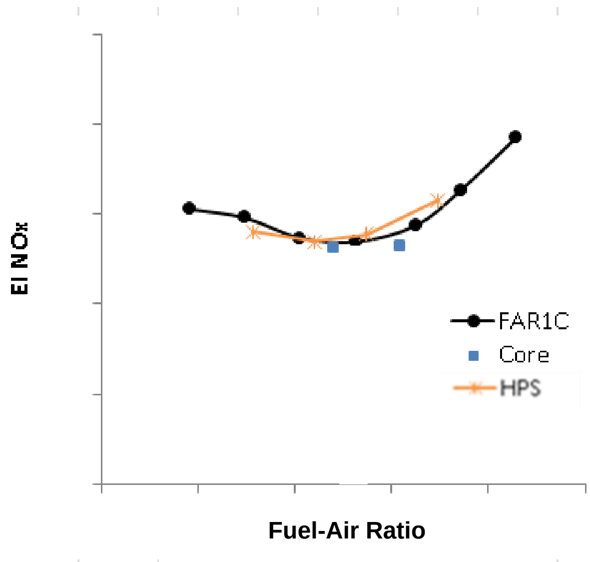

Figure 23: NOx in good agreement w/ Core, FAR1C

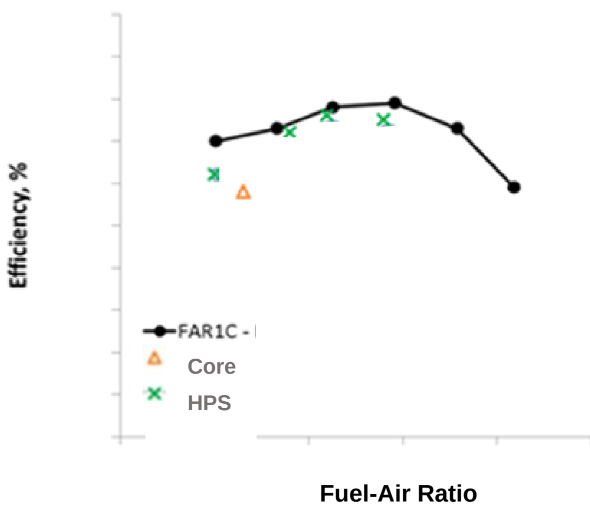

Figure 24: Rig and Demo Core idle efficiency comparisons

4.17.3.2 Durability/thermal data

Finally, the HPS provided thermal information on deflector and liner temperatures that was used to validate heat transfer models for the TAPS III combustor system.

4.17.4 Conclusions

The High Pressure Sector was a new rig, built and tested in a brand new facility. Valuable insight was gained in combustion dynamics, emissions, efficiency, and thermal exit profile for the combustor, at conditions typically not achieved in a combustor sector rig test. It provided quality and unique combustor operating data for the TAPS III/CLEEN II program.

4.18 Task D.1.4 – GE9X FAR1 and FAR2 Testing

4.18.1 Summary

In two different full annular rigs, a FAR1 and a GE9X-scale FAR2, the TAPS III baseline design was tested to demonstrate emissions, combustion dynamics, operability (lightoff and lean blow-out), durability (component temperatures), and performance (pressure drops and combustion efficiency). The results provide baseline data for comparison of new CLEEN II alternate concept hardware design and down-selection.

4.18.2 Introduction

The FAR1 rig is a combustor with similar scale/sizing and aerodynamic features as the GE9X combustor. In FAR1C, this rig is utilized for assessment of the baseline TAPS III aero technologies, using baseline fuel nozzles and mixers. Similar testing is repeated with the FAR2A rig, using an FETT combustor. These two data sets provide a comprehensive evaluation of TAPS III technology readiness for operability and emissions.

4.18.3 Test Results

FAR1C testing of the TAPS III combustion system was conducted from 12/2015 thru 6/2016. This campaign covered 16 test days and included comprehensive evaluation of the TAPS III baseline design. FAR2A extended this data set to a full GE9X environment. Emissions measurements on FAR2A were focused on determining derivatives for use in ICAO emissions certification. The combined data sets from FAR1C and FAR2A provide engineering data to demonstrate TRL5 readiness of the baseline TAPS III technology going into the engine development test campaign. All emissions, combustion dynamics, operability, and durability data have been internally reviewed and show that the combustor aero design will meet product specifications for these criteria. The following sections discuss some of these results.

4.18.3.1 Profile/Pattern Factor

Thermal measurements at the exhaust of the FAR2A combustor showed profiles and pattern factor meeting design intent.

4.18.3.2 Lightoff

Comprehensive testing of altitude relight, ground start and high-power fuel cut conditions on the FAR1C test demonstrated the required capabilities.

4.18.3.3 Lean Blow Out (LBO)

Results from the FAR1C test campaign demonstrated Lean Blow Out (LBO) required capability.

4.18.3.4 Operability Summary

Reviews of the test data shown above concluded the baseline combustor met lightoff capability to support the engine certification campaign. These results provide a standard for comparison of any proposed CLEEN II designs.

4.18.3.5 Emissions

Between FAR1C, FAR2A and HPS component testing, alongside small data sets from the demo core and FETT programs, a comprehensive set of emissions data has been obtained for the baseline TAPS III program. FAR2A results were used to develop corrections for use in reporting certification results on the GE9X program. These validated correlations will thus be used for reporting current status to the CLEEN II goals and will be set as a benchmark for any future configurations to be tested on this program.

4.18.3.6 Cruise Efficiency

FAR1C and FAR2A were similarly used to study and understand cruise efficiency. Learnings from these tests are being used for the current efficiency assessment reported for the baseline design.

4.18.3.7 Combustion Dynamics

On FAR2A, work was done to evaluate combustion dynamics on the baseline design. These results demonstrate combustion dynamics capability for the baseline design and provide targets for comparison to alternate CLEEN II configurations.

4.18.4 Conclusions

FAR1C and FAR2A provided a comprehensive data set demonstrating the readiness of TAPS III combustor technology for entry into service. This data is available as a benchmark both for current CLEEN II status with the baseline configuration and for comparison to lower TRL CLEEN concepts.

4.19 Task D.1.5 – GE9X Core Testing

4.19.1 Summary

Due to the successful emissions outcome of the GE9X TAPS III combustor testing and engine-based emissions validation, and the evaluation of new alternate concepts to date (demonstrated to TRL3), GE and FAA agreed to stop the program prior to executing Task D.1.5.

4.20 Task D.1.6 – CLEEN II HTP Testing

4.20.1 Summary

GE conducted validation tests of the emissions and durability margin of 3 new concept fuel nozzle/mixer sets. The HTP rig at GE Research Center (GRC) was used to evaluate the designs at high OPR operating conditions. The results of this sub-task, along with results from the GE9X HTP, TCA, FAR1, and FAR2 tests, determines which configurations meet CLEEN II NOx objectives while also satisfying durability margin. The outcome of this sub-task contributed to a TRL3 review of the new concepts, with a summary of HTP test results that contribute to down-selection of mixer/nozzle designs.

4.20.2 Introduction

The High Temperature and Pressure (HTP) rig is used to validate combustor aero designs for durability margin and to screen designs for emissions at high T3, P3 conditions near the maximum cycle conditions for the GE9X engine.

4.20.3 Test results

4.20.3.1 Durability validation

A single durability test was conducted with a baseline fuel nozzle and the top-ranked new technology mixer concept. This provided a clear comparison of the new mixer to the baseline mixer. Validation testing was conducted and the data indicates the mixer performance is within the baseline data, indicating an acceptable result.

4.20.3.2 Emissions screening

A series of tests were then conducted to collect NOx emissions and combustion efficiency at conditions representing climb / take-off and cruise. This data is then compared directly to the TAPS III baseline data at the same rig / test conditions in order to obtain a relative assessment. Cruise emissions data indicates that two of the four CLEEN II new technology configurations demonstrated both a slight reduction in NOx pollutant as well as incremental increases in combustion efficiency. The results are summarized in *Figure 25*.

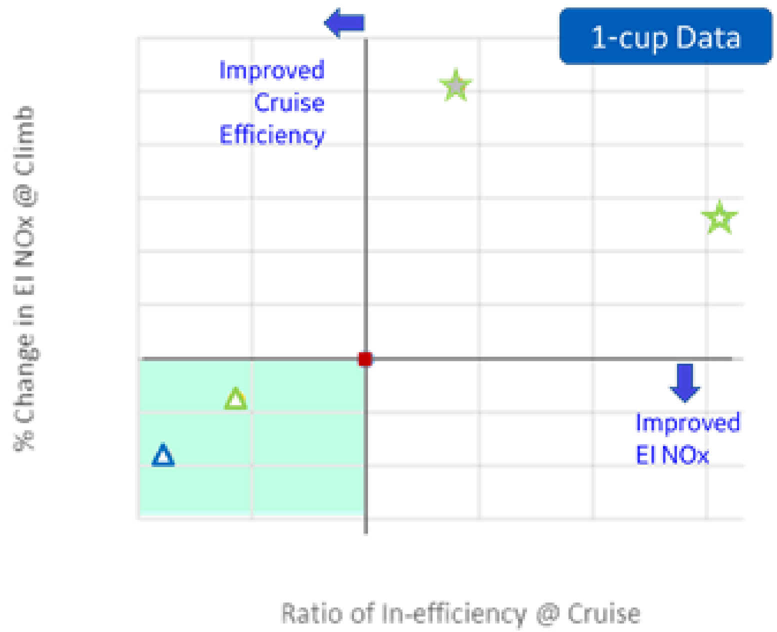

Figure 25: Summary of HTP data for CLEEN II new concepts relative to baseline design.

4.20.3.3 Emissions assessment relative to program targets

The status of the projected LTO emissions for the CLEEN II new technology concepts can be determined based on the HTP data described here, by comparison to the TAPS III baseline design. The baseline GE9X emissions have been determined in prior HTP, HPS, FAR1A, and FAR2 testing (as part of the CLEEN II program). Outside of the CLEEN program, the GE9X program executed the First Engine To Test (FETT) and collected preliminary emissions data on a baseline GE9X design. With this set of data, the preliminary baseline GE9X emissions capability is fully established; and a Landing/Takeoff (LTO) emissions can be calculated relative to CAEP/8 requirements, with appropriate uncertainties and applied margins for the current state of the NPI program.

Emissions data from the HTP testing of the CLEEN II new technology concepts are then utilized to determine a relative change in NOx and other pollutants for the new concepts vs. the GE9X baseline. (As mentioned above, cruise emissions were also assessed, and a comparison can be made in order to validate this CLEEN II Key Performance Objective.)

Based on the discussion above, the HTP emissions data suggests that all configurations, including the GE9X baseline design, meet the FAA CLEEN II target of 65% CAEP/8 assessed at a 55 OPR cycle (*Figure 26*). The GE9X baseline, at its current OPR, is projected to achieve roughly 46% of CAEP/8 (54% reduction below

CAEP/8). For cycle conditions scaled up to 55 OPR, per the original program objectives, the baseline design capability is projected at 58% of CAEP/8. The best CLEEN II new technology concept achieves slightly lower NOx at 56% CAEP/8.

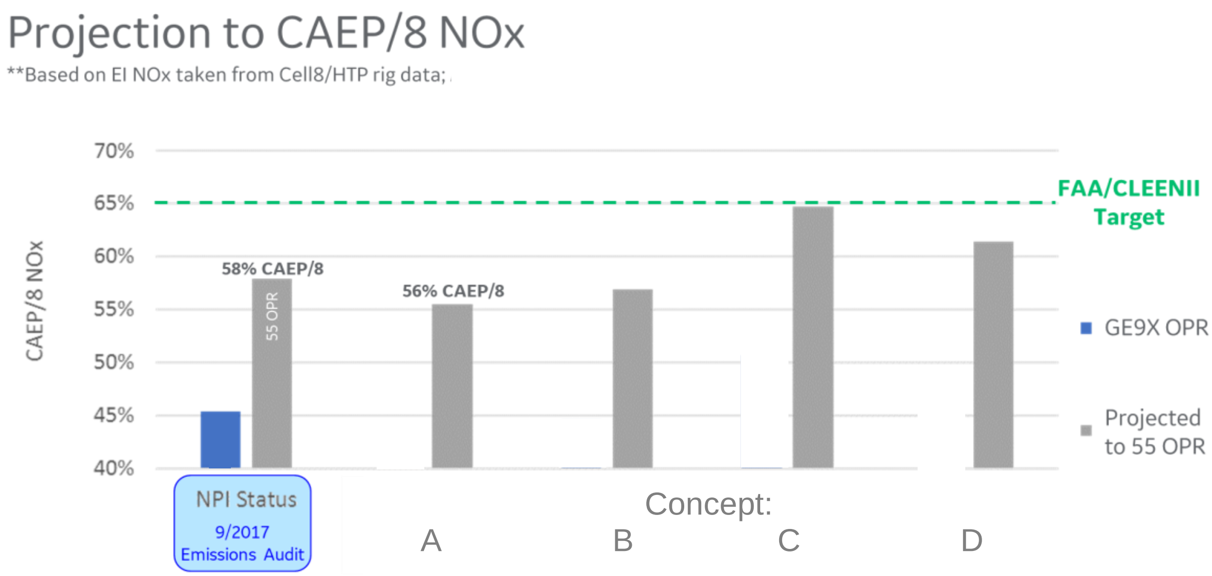

Figure 26: Projected NOx emissions capability of all tested concepts.

In addition to LTO NOx, other criteria pollutants have been assessed for all TAPS III designs - both the baseline GE9X NPI and the CLEEN II new technology concepts. High power NOx (contributing to the LTO NOx calculation above), cruise NOx, and cruise efficiency are assessed using the HTP data for CLEEN II concepts with reference to the baseline design and HTP plus higher TRL rig/engine data.

The summary of emissions status for the CLEEN II TAPS III program is tabulated in *Figure 27*, including the baseline design at the projected 55 OPR, and the best CLEEN II new technology concept at 55 OPR (based on TRL3 data from the HTP rig). The CLEEN II new technology concept meets all CLEEN II emissions targets. The GE9X baseline design also meets all targets and has been demonstrated at TRL6 in the GE9X FETT at the time that the technical work on this program came to completion.

Emissions	CLEEN II target	Projected 55 OPR cycle	Alt. concept @ 55 OPR (TRL3)
NOx	65% of CAEP/8	**58%**	**56%**
CO	**No specific CLEEN II target Requirement = CAEP/8*	✓	✓
HC	**No specific CLEEN II target Requirement = CAEP/8*	✓	✓
Smoke	40% of CAEP/8	✓	✓
Cruise NOx	<12 g/kg fuel	✓	✓
nvPM	40% CAEP *(*no standard in CAEP/8)*	✓	✓
Cruise efficiency	*>99.9%*	✓	✓

Figure 27: Summary of emissions status for CLEEN II TAPS III combustor development.

4.20.4 Conclusions

Single-cup HTP rig-based emissions data was collected to assess cruise combustion efficiency and NOx as well as high-power NOx for four CLEEN II new technology configurations and compared to the baseline. Durability assessment on the new technology mixer was also conducted on the HTP rig. Based on this testing, the durability capability and emissions outcomes of all configurations relative to engine requirements and CLEEN II program targets have been projected.

Results indicate:

- All tested designs demonstrated required durability capability for the GE9X NPI cycle, via analysis or test.
- Projection for cruise efficiency show three configurations, including GE9X baseline, achieve 99.9%. Projection based on correlations to 55 OPR cycle indicates that 99.9% will be achieved
- Engine projection for NOx emissions indicates all tested configs will achieve the CLEEN II target of <65% CAEP/8 @ 55 OPR

4.21 Task D.1.7 – CLEEN II TCA Testing

4.21.1 Summary

The assessment of combustion dynamics was conducted in a single cup TCA rig for three CLEEN II TAPS III configurations. Tests were conducted at three Temperature/Pressure operating conditions that were relevant to prior baseline TCA testing. At all tested conditions, the three new configurations demonstrated acceptable behavior relative to the baseline configuration. These results are in agreement with pre-test predictions conducted using the models developed as part of Tasks B.1.4 thru B.1.7.

4.21.2 Introduction

The tunable combustion acoustics (TCA) rig was utilized to assess the combustion dynamics behavior of the new fuel nozzle/mixer designs. The same dome and liner configuration, as well as operating methods and conditions, were used for the testing in Task D.1.7.

4.21.3 Results

The resulting combustion dynamic pressure data for the 3 configurations at 3 different conditions were collected. All three configurations demonstrated acceptable combustion dynamics behavior compared to the baseline design.

Pre-test predictions had been performed using the dynamics model (Task B.1.5 and Task B.1.6) and the LES model (Task B.1.7). The predictions were conducted at one specific condition (T3, P3, Fuel/Air ratio) for a large set of potential configurations as well as the baseline, as part of the down-selection/prioritization process.

All CLEEN II configurations are noted to have acceptable combustion dynamics amplitude as measured in the TCA3 rig. The model predictions fairly represented the outcomes of the new configurations, relative to the baseline.

4.21.4 Conclusions

The new fuel nozzle/mixer configurations designed and tested under the CLEEN II program have demonstrated acceptable combustion dynamics behavior compared to the baseline design. This result was predicted by the advanced dynamics models, developed and executed under Tasks B.1.4 through B.1.7. The measurements in this task are a key metric in the validation of the new main mixer / fuel injection designs and contribute to the achievement of TRL3.

4.22 Task D.1.8 – CLEEN II Combustion Dynamics Damper Phase 1 and Phase 2 TCA Tests

4.22.1 Summary

Two Phases of damper concepts and one set of legacy style damper concepts were successfully tested in the single cup acoustics rig. The rig was intentionally run at an unusual condition to drive higher combustion dynamic amplitudes. The Phase I dampers demonstrated up to 75% reduction of dynamic amplitudes, relative to the baseline without a damper. The Phase II dampers obtained dynamics reduction up to 80%. For the legacy style damper concepts, a reduction of more than 90% was achieved.

4.22.2 Introduction

All the experiments were conducted in a tunable combustor acoustics (TCA) test rig at GE-GRC. It is designed for the study of combustion dynamics at engine-relevant inlet conditions i.e. high pressure and high inlet temperature.

4.22.3 Phase I Damper Concepts

4.22.3.1 Test Plan

Two versions of damper A were tested with the damper blocked. Finally, the damper was unblocked to assess the effectiveness of the damper in suppressing dynamics.

4.22.3.2 Impact of damper

Plots of the dominant amplitudes that compare the effect of the damper are presented in *Figure 28*.

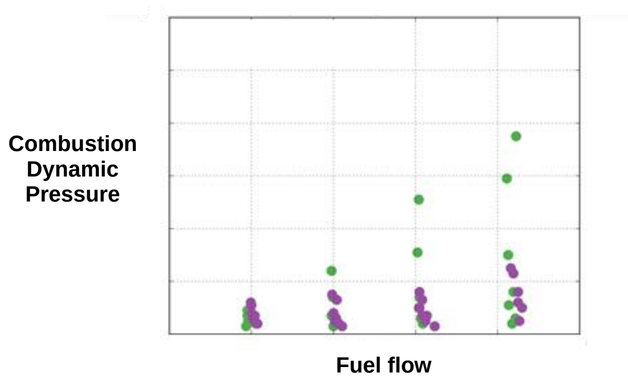

Figure 28: Effect of the damper on dynamics. Damper blocked (Green); damper active (Purple)

The amplitude plots show that as main fuel flow increases, higher dynamics are present when the damper is blocked. However, when the damper is active, the dynamics amplitudes were lower.

4.22.3.3 Conclusions for Phase I

In this work we have successfully designed, simulated, and tested acoustic dampers and shown their capability to mitigate combustion dynamics. Starting from design tools, a series of damper configurations were conceived, fabricated, and modeled using a variety of low-order dynamics simulation tools. Subsequently, the most promising design was tested in the single cup test rig. The key result of this work, summarized in *Figure 28*, is that the dampers can be highly effective in mitigating the combustion dynamics, producing a reduction of 75%. Based on the learnings of this activity, the Phase II designs were kicked off, aimed to reproduce and improve upon the mitigation effects seen in the Phase I work.

4.22.4 Phase II Damper Concepts

4.22.4.1 Test Plan

A total of three tests were conducted. First, a baseline was tested to establish the operating conditions. Then, two different dampers were tested. These tests let us determine the effectiveness of each damper design in suppressing dynamics.

4.22.4.2 Impact of damper on instability amplitudes

Figure 29 shows averaged amplitude spectra obtained from a data point at a fixed operating condition for the baseline and the two dampers. The plot shows that tones are successfully suppressed by the dampers.

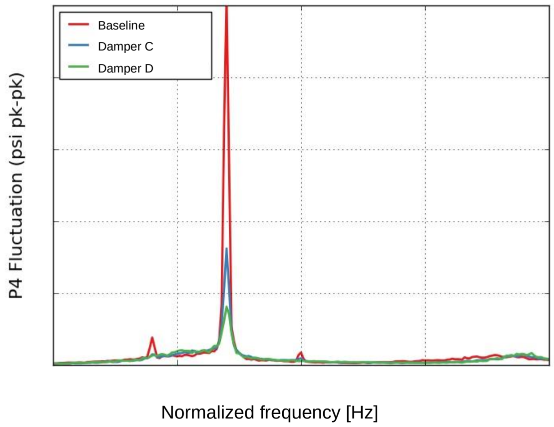

Figure 29: Amplitude spectra for baseline and dampers.

When the dampers were implemented, the dynamics amplitudes at a given operating condition were below its corresponding baseline value.

4.22.5 Conclusions

With the development of dynamics modeling and damper design tools in Task B.1.3, two Phases of damper concepts and one group of legacy-style damper concepts were successfully tested in the single cup acoustics rig.

The key result of the Phase I work is that the dampers can be highly effective in mitigating combustion dynamics seen in the rig test, resulting in a reduction of ~75%. In the Phase II concepts, significant amplitude reduction was obtained. The designs tested showed a capability of reducing the observed dynamics by up to 80%. Finally, for the legacy-style damper concepts, a reduction of more than 90% was achieved.

It should be noted that the baseline TAPS III combustor design meets all requirements, including those for combustion dynamics. Therefore, there is no need to implement the combustion dynamic dampers that were demonstrated as part of this Task.

4.23 Tasks D.1.9 – D.1.12

4.23.1 Summary

Due to the successful emissions outcome of the GE9X TAPS III combustor testing and engine-based emissions validation on FETT, and the evaluation of new concepts to date (demonstrated to TRL3), GE and FAA agreed to stop the program prior to executing Tasks D.1.9 through D.1.12:

- **Task D.1.9**: CLEEN II Rainbow FAR Testing
- **Task D.1.10**: CLEEN II HPS Testing
- **Task D.1.11**: CLEEN II FAR Testing
- **Task D.1.12**: CLEEN II Core Testing

4.24 Task E.1 – Technology Assessments and Reporting: TAPS III Combustor

4.24.1 Summary

The technologies developed and demonstrated during the course of the CLEEN II TAPS III were reported out at a Final Oral Briefing with the FAA on November 13, 2017. At that time, upon agreement between GE Aviation and the FAA, the intended technical development work had been completed. This decision was based on the demonstration of CLEEN II emissions targets by the GE9X baseline design in the GE9X FETT engine test (TRL6), along with a successful TRL3 review of additional CLEEN II new technology concepts indicating slight further improvements to the baseline design.

In addition to this Final Oral Briefing and the present Final Written Report, an Emissions Data Summary and Technology Assessment was delivered to the FAA, for use by the Georgia Tech Aerospace Systems Design Laboratory in performing assessments of fleet-level impact of CLEEN II technologies. LTO and cruise NOx emissions data points were provided, along with guidance on how to curve fit the data for interpolation/extrapolation. Additionally, estimated boundaries of applicability for engine scale and cycle, wherein CLEEN II TAPS III could be a realizable technology, were provided.

4.24.2 Results

The summary of CLEEN II emissions status for TAPS III technology is provided in *Figure 30*. TAPS III combustor technology has been validated to 58% CAEP/8 (as projected to a 55 OPR cycle) based on TRL6 testing in GE9X FETT. The best new technology concept indicates as low as ~56% of CAEP/8 @ 55 OPR, with incremental improvements in efficiency and acceptable combustor dynamics behavior relative to the baseline (based on TRL3 test validation).

Emissions	CLEEN II target	Projected 55 OPR cycle	Alt. concept @ 55 OPR (TRL3)
NOx	65% of CAEP/8	**58%**	**56%**
CO	**No specific CLEEN II target* *Requirement = CAEP/8*	✓	✓
HC	**No specific CLEEN II target* *Requirement = CAEP/8*	✓	✓
Smoke	40% of CAEP/8	✓	✓
Cruise NOx	<12 g/kg fuel	✓	✓
nvPM	40% CAEP *(*no standard in CAEP/8)*	✓	✓
Cruise efficiency	*>99.9%*	✓	✓

Figure 30: Summary of CLEEN II emissions status for TAPS III.

CLEEN II TAPS III combustor technology is a balance between many competing criteria in addition to emissions, including operability, durability, performance, weight and cost. A specific feature set, combined together, enables the TAPS III combustor technology to achieve the above emissions capability while meeting other engine requirements. Some features and/or manufacturing methods have scaling limitations. An engineering estimate of scalability of the TAPS III combustor to a range of core sizes and cycle conditions was provided to Georgia Tech.

4.24.3 Certification pathway for the TAPS III combustor

Following the conclusion of the technical work on the CLEEN II TAPS III combustor program in 4Q'2017, continued combustor-relevant activities were planned to be conducted as part of the GE9X engine development and certification program. All of these activities have now been completed, with acceptable results leading to Part 33 engine certification on 9/25/2020 and supporting Part 25 certification of the Boeing 777X aircraft.

With the completion and certification of the TAPS III design in the GE9X engine, the FAA CLEEN II objectives will have been successfully accomplished. The additional new technology fuel nozzle/mixer configurations, demonstrated during this program to TRL3, have the potential to generate a slight further improvement in LTO NOx emissions (~2% of CAEP/8).

4.24.4 Conclusions

The CLEEN II TAPS III combustor technology program has demonstrated performance of all the CLEEN II objectives via component testing and validated by testing of the GE9X FETT engine. An Emissions Data Summary and Technology Assessment was delivered to the FAA, for use by the Georgia Tech Aerospace Systems Design Laboratory in performing assessments of fleet-level impact of CLEEN II technologies. LTO and cruise NOx emissions data points were provided, along with guidance on how to curve fit the data for interpolation/extrapolation. Additionally, estimated boundaries of applicability for engine scale and cycle, wherein CLEEN II TAPS III could be a realizable technology, were provided. Part 33 certification was received on 9/25/2020.

5 Conclusions

1. The TAPS III Combustor Technology Program developed and matured a lean-burn combustion system and multiple new fuel/air premixer concepts to meet the CLEEN II LTO NOx emissions goal while also achieving low cruise NOx and high cruise efficiency, low LTO smoke and nvPM, and low LTO CO and Unburned Hydrocarbon emissions. The combustor design was validated to TRL5 via component rig testing including up to full engine T3/P3 conditions (single cup, high pressure sector, and full annular rigs). TRL6 capability of the TAPS III combustor was demonstrated in the GE9X First Engine to Test, separate from the CLEEN II program.

2. The TAPS III combustor technology demonstrated >42% reduction below CAEP/8 LTO NOx at 55 OPR (vs. the goal of 35% reduction), while achieving <12 EINOx and 99.9% efficiency at cruise. The technology also resulted in LTO Smoke and particulate (nvPM mass concentration) <40% of CAEP/8 and <40% of CAEP/10, respectively; and CO and unburned hydrocarbons with measured LTO values with margin to CAEP/8.

3. Several new fuel/air premixer technology concepts were designed and evaluated using CFD modeling. Early screening tests were performed using 2 of the concept groups, and high temperature and pressure single-cup rig tests were performed on 4 premixer designs plus the baseline. The best of these new concepts provided benefits in line with pre-test predictions: a further ~2% reduction in LTO NOx, incrementally improved cruise efficiency, and acceptable combustion dynamics – relative to the baseline TAPS III design.

4. Work was also conducted in the area of combustion dynamics modeling tools. These tools were first validated against existing rig test data, and then utilized productively for predictions of combustion dynamics for the new fuel/air premixer concepts, enabling a prioritization prior to hardware manufacturing release. When tested, the concepts' measured dynamic characteristics were in good agreement with pre-test predictions. In addition, the tools were applied to the TAPS III combustor development process, to evaluate the dynamics implications of proposed changes in aero features.

5. Passive dynamics dampers were successfully designed and tested in a single-cup rig, demonstrating reduction in self-excited dynamic pressure amplitudes.

6. The TAPS III combustor is a key enabling technology of the GE9X engine, which will enter service on the Boeing 777X aircraft with the highest overall pressure ratio of any commercial engine and a projected 10% SFC improvement over the GE90-115B.

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Clay Cooper, Section Mgr for combustion at GE Aviation, reviewed and edited the final reports.

Theresa Zeug served as the GE program manager for CLEEN II throughout the bulk of the program, guiding the efforts of multiple project teams. Her efforts in building community amongst the CLEEN contractors was appreciated by all. John Aicholtz also served as initial GE program manager, until his retirement.

John Herbon served as the TAPS III Combustion Technology program leader.

6.1 Additional Authors / Technologists

The following contributors are GE Aviation engineers, unless otherwise noted. Many other technologists beyond this list deserve recognition for their contributions to the program. The work also would not have been successful except for the expertise and efforts of several test operators; instrumentation, assembly, and test technicians; and support personnel at both GE Aviation (GEA) and GE Global Research (GE-GRC).

Task B.1.1: Sreejith Keloth, Perumallu Vukanti and Ugandhar Reddy led the conceptual design work for Concept Groups 1, 2, and 3. Krishna Venkatesan, Yuxin Zhang, and Owen Rickey from GE-GRC led the design work for Concept Group 4. They were supported by Michael Benjamin and Nayan Patel of GEA, and Arin Cross, Zekai Hong, Jason Natale, and Keith McManus of GE-GRC.
Task B.1.2: Several mechanical design engineers contributed to the design of the new concept fuel nozzle and mixer hardware, including: Chad Sutton, Marco Zulliger, Jeff Kohler, Chris Laxton, and Adam Kahn. Sean Henderson and Valentina Kaloyanova conducted analysis activities.
Tasks B.1.3-7 and D.1.8: Kwanwoo Kim had leadership over the combustion dynamics modeling and mitigation tasks as Principal Engineer.

Tasks B.1.3 and D.1.8: Owen Graham led the GE-GRC design and test team, including Janith Samarsinghe, AJ Wickersham, Steve Miske, and Fei Han.

Tasks B.1.4-6: Owen Graham led the GE-GRC modeling team, including Changjin Yoon, Nicholas Magina, and Su Cao.

Task B.1.7: Hongfa Huo, Sara Monahan, Michelle Brault, Changjin Yoon, Shashank Yellapantula, Owen Rickey and Venkat Tangirala of GE-GRC executed the modeling work

Task B.1.8: PJ Milkovits conducted activities for this task.

Task C.1.1, D.1.1, D.1.7: Nayan Patel led the hardware and test prep activities as GE9X aero lead. He also led the TCA testing for both baseline and CLEEN II new technology designs. Test monitoring/data reduction was also conducted by Anne Dord.

Task C.1.2 and D.1.3: Doug Thomsen lead HPS test activities

Task C.1.3 and D.1.4: Doug Thomsen lead FAR2 test activities and the FAR test report writeup, and Aaron Glaser led a significant amount of FAR testing for the program.

Task C.1.5: Nayan Patel led the hardware and test prep

Task D.1.2 and D.1.6: Mathew Thariyan at GE-GRC executed the HTP testing, with guidance and data reduction contributions from Nayan Patel.

Task E.1: Nayan Patel developed the emissions assessments for the baseline and CLEEN II technology concepts based on rig and engine test data.